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Study of water storage variations at the Pantanal wetlands area from GRACE monthly mass grids

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Abstract: The continental water storage is significantly influenced by wetlands, which are highly affected by climate change and anthropogenic influences. The Pantanal, located in the Paraguay river basin, is one of the world's largest and most important wetlands because of the environmental biodiversity that represents.
The satellite gravity mission GRACE (Gravity Recovery And Climate Experiment) provided until 2017 time-variable Earth's gravity field models that reflected the variations due to mass transport processes -like continental water storage changes- which allowed to study environments such as wetlands, at large spatial scales.
The water storage variations for the period 2002-2016, by using monthly land water mass grids of Total Water Storage (TWS) derived from GRACE solutions, were evaluated in the Pantanal area.
The capability of the GRACE mission for monitoring this particular environment is analyzed, and the comparison of the water mass changes with rainfall and hydrometric heights data at different stations distributed over the Pantanal region was carried out. Additionally, the correlation between the TWS and river gauge measurements, and the phase differences for these variables, were also evaluated. Results show two distinct zones: high correlations and low phase shifts at the north, and smaller correlation values and consequently significant phase differences towards the south. This situation is mainly related to the hydrogeological domains of the area.

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1 Introduction

The Pantanal is a wetland that reached an international focus position because of its unique socio-environmental characteristics. This system, considered for the UNESCO as a World Heritage and a Biosphere Reserve, and recognized for the Convention on Wetlands of International Importance Ramsar, is extremely affected by human activities – e.g. cattle industry, agriculture, fishing, tourism- and the effects of the climate change. The Upper Paraguay basin, where the Pantanal is located, has undergone a considerable loss of terrestrial ecosystems (40%) and also presents an environmental risk (CIC 2016).

This region, in particular the Brazilian Pantanal, is mainly dominated by the hydrologic cycle. As well, it contributes to the emergence of complexes ecosystems of large biodiversity (Pereira Guimarães et al. 2018). Therefore, the knowledge of this region is very important for the biodiversity conservation and minimization of the anthropogenic activities.

These requirements can be achieved by means of the remote sensing. In recent years, altimetry-based surface water levels and total water storage from space gravimetry have proved to be very helpful for studying the water balance at sub-basin and basin scales (Xavier et al. 2010).

Most of the temporal gravity changes detected by recent gravity satellite campaigns can be associated with the variations in terrestrial water storage, which includes hydrological reservoirs changes, groundwater, soil moisture, lakes, streams, snow, ice and glaciers (Wahr et al. 2004). This was certainly demonstrated in glaciers areas by Chen et al. (2007), Sørensen and Forsberg (2010) and Velicogna and Wahr (2006). Researches on the water storage variations from GRACE mission in hydrological systems are presented in Chen et al. (2006), Klees et al. (2008), Ramillien et al. (2005), Rodell et al. (2007); and specifically in South American basins, in Alves et al. (2012), Chen et al. (2010), Crowley et al. (2008), Kiss and Földváry (2017), Pereira and Pacino (2012), Pereira et al. (2012), Frappart et al. (2013) and Vaz de Almeida et al. (2012). Examples of studies related to annual water storage variations from GRACE gravimetry in combination with satellite altimetry and multi-satellite observations can be found in Andersen et al. (2018), Frappart et al. (2014).

Several investigations analyze the water storage at the Pantanal region with a remote sensing approach, mainly with altimetry missions that provide water level data. In Moreira et al. (2018), the authors studied the water balance of the Paraguay river basin by using TRMM rainfall data, water storage from GRACE and run-off information. They could detect the seasonal variations and the water storage dynamics in the wetland. The research in Evans et al. (2012) analyzes the whole region from SAR imagery, providing spatial information on hydrology in detail. The potential of satellite altimetry for the water level monitoring in the Pantanal is shown by Dettmering et al. (2016), revealing the seasonal height variations. In Smith and Berry (2007), the authors exposed the contribution to wetland monitoring of multi-mission satellite radar altimetry.

Temporal and spatial variations of the water storage in the area covered by a large basin are difficult to measure using ground data because of the hydrographic system's size. Furthermore, the monitoring of regions like the Pantanal is challenging, since they are generally located in remote areas without enough *in situ* measurements stations.

Nowadays, with the present advance of technologies, like the represented by GRACE data, it is possible to detect the monthly spatial changes in the distribution of water masses in these regions. Furthermore, GRACE can map water storage changes to a height of about 1 centimeter for areas ranging in size on the order of 400 km (or less rely on the GRACE total water storage-derived method).

Investigations using satellite gravimetry to study water storage at the Pantanal wetland region are not so common. It can be found several investigations, e.g. (Evans and Costa 2013; Hamilton et al. 2002; Girard et al. 2010; Matos et al. 2012), but they study the water extension areas based on *in situ* derived-water level time series in sparse stations in particular. This work attempts to make a contribution to the existing emptiness mainly in the studies with satellite gravimetry in the Pantanal area.

The present study proposes the temporal and spatial analysis of the water storage variability in the Pantanal region from 2002 to 2016, by using land water mass grids of Total Water Storage (TWS) obtained from monthly GRACE solutions provided by the JPL (Jet Propulsion Laboratory, NASA). Moreover, the agreement between TWS with *in-situ* data from river gauge measurements and rainfall information is analyzed in order to understand the water cycle in the region.

The obtained results showed that GRACE mission could detect the significant water mass changes in the Pantanal area. In the analysis of the TWS and hydrometric heights series over selected stations, important determination coefficients were found in the Mato Grosso State, and lower ones were detected in the south of the region (Mato Grosso do Sul State). Besides, the signals that showed higher correlation results presented a phase shift from 15 days to 1 month, and those with a lower correlation, reached values of more than 2 months.

2 Methods

2.1 Study area

The vast floodplain area known as the Pantanal region, is located along the upper Paraguay river's course, one of the main tributaries of the Paraná river. The poor natural drainage of the region which the Paraguay flows through, has created the Pantanal, one of the world's largest wetlands, with an area of 140,000 km^2 (Mechoso et al. 2001).

The largest part of this wetland is located in the center-west of Brazil, in Mato Grosso and Mato Grosso do Sul States (~ 60% of the total area); while the rest occupies the east of Bolivia and the northeast of Paraguay. The Brazilian region is the best known area, while the Bolivian part remains more inaccessible and unknown.

According to Girard et al. (2003), the topographic features of the Upper Paraguay river basin can be subdivided in three physiographic units. First, the headwater region – *Plateu* or *Planalto*- mainly constituted by a flat plain with altitudes from 250 to 750 m above sea level; the next unit is the *Depression*, where the heights go from 180 to 250 m. Finally, the Pantanal unit, with altitudes ranging from 100 to 180 m.

The slight slope of the Pantanal system is crossed by many large rivers, such as the Paraguay, Cuiabá, São Lourenço, Piquiri, Taquari, and Negro; and along with a variety of lagoons and wetlands, they constitute the floodplain of the upper part of the Paraguay river basin. In this region, the relief is marked by the contrast between the plains -the Pantanal- surrounded by high lands which acts like barriers -the elevations of the *Plateau*-. This complex hydrographic system, together with the diverse type of soils of the region, generates a variety of landscapes and sub-units that are subjects of different hydrological conditions (Girard et al. 2003).

The Pantanal region is a not homogeneous sedimentary basin, constituted by various sub-regions whose formation is a consequence of evolutionary changes occurring since the Quaternary. This probably contributed to the generation of drainage patterns and the differences in the annual dry and wet season's cycles, along with extraordinary periods of floods and droughts, which caused the retraction or expansion of the wetland (Assine et al. 2015).

Regarding the hydrographic characteristics, the Pantanal regime is periodic and seasonal. The annual flooding is caused by the sharp gradient contrast between the *Depression* and the *Plain* (Carvalho 1986). Rivers in the Brazilian upland deliver most of the water and sediments to the Pantanal, and the seasonality of the rainfall is observed in their discharge regimes. On the other hand, the water contribution of the western flatter uplands in Bolivia and Paraguay to the Pantanal region is lower, and a large amount of this water is lost by evaporation and infiltration (Hamilton et al. 2002). The delay in the water rise of about 4 months between the northern and southern region of Pantanal, is a consequence of the 0.01 m/km slope in the north-south direction.

Flooding in all these sub-regions is seasonal, but the periods may be delayed for as 6 months after the rains as a consequence of the slow floodwaters transportation through the Pantanal (Hamilton et al. 2002).

The Pantanal acts like a regulator for the entire La Plata basin by reducing the water flow of the Paraguay river before its confluence with the Paraná river (Ferrazzoli et al. 2010). If this hydrographic system did not exist, there would be a higher risk of flood of the rivers Paraguay and Paraná, with important consequences for the communities of Paraguay, Brazil and Argentina.

The climate in the Pantanal is tropical with a marked wet season from October to April, and a pronounced dry season from May to September (Girard et al. 2010). The total annual precipitations exceed the 1,300 mm; the maximum rainfall peak is in December, reaching the 200 mm, and the minimum is close to zero millimeters in July and August (García 1996). In the rainy season, the water level can raise up to 5 m more than in the dry season. In this period, the Pantanal is supplied by the groundwater, and that is the reason why in the seasonally flooded or dry plains there are also swamp areas and permanent wetlands.

The present study comprises the Brazilian Pantanal, in Mato Grosso and Mato Grosso do Sul States, which is illustrated in Figure 1.

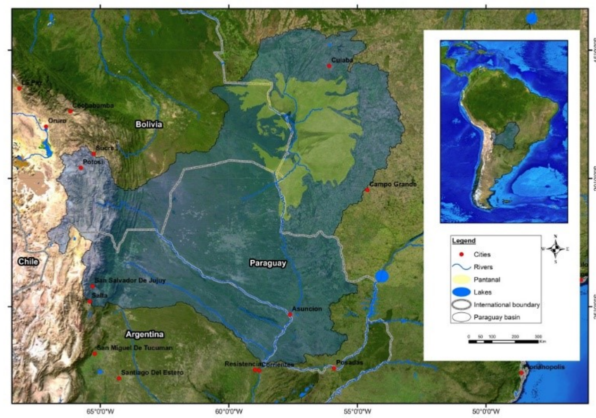

Fig. 1. Paraguay river basin and the Pantanal area.

2.2 Data

2.2.1 TWS grids

Most of the temporal gravity variations are caused by changes in the water storage of the hydrological reservoirs, by the mass movements in the oceans, atmosphere and cryosphere, and by the exchanges between them. The vertical extension of this water layer is measured in centimeters, which is much smaller than the Earth's ratio or the horizontal variations scales that are in kilometers (Wahr et al. 1998).

In this investigation, the monthly land mass grids of TWS JPL RL05 derived from GRACE data were used

(Swenson 2012; Landerer and Swenson 2012; Swenson and Wahr 2006). These grids, provided by the JPL of the NASA (https://grace.jpl.nasa.gov/data/get-data/), were analyzed in the Pantanal area for the period January 2002 to November 2016.

Surface mass variations at small spatial scales tend to be attenuated due to the sampling and post-processing of GRACE observations. The scaling technique used to obtain the land mass grids (TWS) provided by the JPL center, restores some of the signal that is lost in regionally averaged time series –due to filtering and truncation of GRACE TWS observations (Landerer and Swenson 2012).

These monthly TWS grids are basically obtained from JPL RL05 GRACE spherical harmonics solutions, with a maximum degree/order equal to 60. Then, a two-step filter is applied to the GRACE data: first, a destriping filter to minimize the effect of correlated errors, which is manifested as north-south "stripes" in GRACE TWS maps (Swenson and Wahr 2006). Next, a 300 km Gaussian averaging filter (smoothing operation) is employed to reduce errors at higher degree coefficients that were not removed by the destriping, which derives in the reduction of the spatial resolution of GRACE solutions (Landerer and Swenson 2012).

The result of this filtering process -and the truncation in the spectral domain- derives in spatially average GRACE data, and the consequent leakage error. This error is then reduced by applying a gain factor to the filtered data, thus restoring a significant portion of the attenuated signal.

Then, the original GRACE TWS spatial resolution (length scales of a few hundred kilometers) is extrapolated to finer spatial scales ($\sim$ 100 km), allowing the estimation of time series of TWS over arbitrarily shaped regions, like the Pantanal area. This approach simplifies the use of GRACE TWS observations, mainly for hydrological applications (Landerer and Swenson 2012).

2.2.2 River gauge measurements and precipitation data

The National Agency of Water of Brazil (ANA, by its initials in Portuguese) was created in 2000, and is responsible for the maintenance and management of the Brazilian hydrological network with approximately 2,100 monitoring stations. The hydrological information system offers historical series of water level, run-off, rainfall and evaporation, among others, in several stations located over rivers in the Brazilian territory.

The river gauge and precipitation time series used in this study were provided by the ANA, which offers the water level and rainfall measurements at each station through the HidroWeb site (http://www.snirh.gov.br/hidroweb). The methodology of acquisition is based on daily *in situ* water level data, by visually reading it on a river gauge scale (Vaz de Almeida et al. 2012).

In order to analyze the surface water behavior in the Pantanal, 21 stations well distributed over this region in Brazil were selected (Figure 2). The attributes of each station is presented in Table 1.

Furthermore, the Tropical Rainfall Measuring Mission TRM 3B43v7 product (http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B43_readme.shtml) was used to represent the precipitation variable for the entire Pantanal area. This dataset is a combination of monthly rainfall at a spatial resolution of 0.25° satellite-based observations and other data sources (TRMM 2011).

The TRMM 3B43v7 product merges the TRMM 3B42-adjusted infrared precipitation with the monthly accumulated Climate Assessment Monitoring System or Global Precipitation Climatology Center Rain Gauge analyses (Huffmann et al. 1995; Huffmann et al. 2007). It is available on the Goddard Earth Sciences Data and Information Services Center (GES DISC) website (http://daac.gscf.nasa.gov).

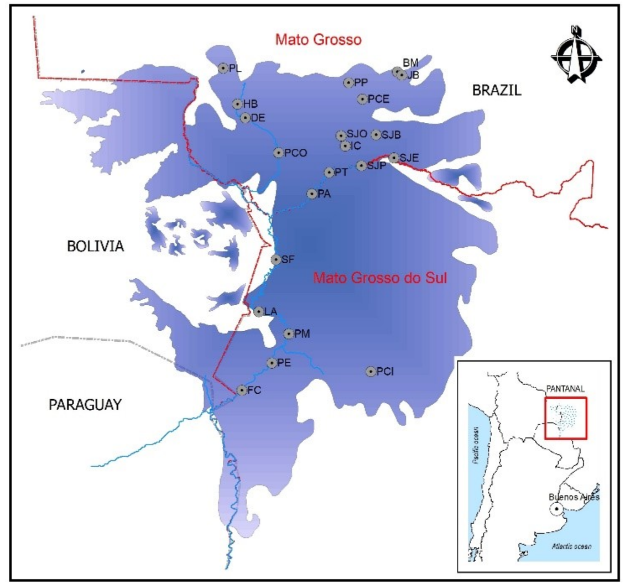

Fig. 2. River gauge/precipitation stations from ANA in the Pantanal area.

2.3 Correlation methodology

In order to make the data consistent with the TWS grids from GRACE, the *in situ* river gauge time series of 30-days intervals from ANA were computed in two steps. First, the missing data series of ANA was completed, and in case a gap in the data was found, a linear function up to 40 days of gap was applied. For the hydrometric height (HH) stations under study, this 40-day interval was almost linear. Then, moving averages were performed over 30-day periods for the river gauge series.

The coordinates of the HH stations (Table 1) were interpolated in the TWS grids by using the bilinear interpolation method, in order to obtain the water cycle at each location.

Next, a correlation analysis between the variables TWS and HH was performed, and the determination coefficient R^2 was calculated as follows:

$$R^2 = \left(\frac{Cov(TWS\,(t)\,, HH\,(t))}{\sigma_{TWS(t)} \cdot \sigma_{HH(t)}} \right)^2 \qquad (1)$$

In Equation (1), R is the Pearson coefficient -correlation- ; *TWS(t)* and *HH(t)* are the TWS from GRACE and the river gauge measurements respectively

Table 1. Name of Station, Code, River and State, for the ANA stations in the Pantanal.

Station	Code	River	State	Latitude	Longitude
Barão de Melgaço	BM	Cuiabá	Mato Grosso	-16.193	-55.967
Porto Cercado	PCE			-16.512	-56.376
São João	SJO			-16.944	-56.633
Ilha Camargo	IC			-17.056	-56.581
Pousada Taiamã	PT			-17.366	-56.775
São Jerônimo	SJE	Piquiri		-17.202	-56.009
São José do Piquiri	SJP			-17.292	-56.387
Porto Limão	PL	Jauru		-16.147	-58.009
Perto de Pocone	PP	Bento Gomes		-16.315	-56.542
J. de Barão de Melgaco	JB	Lagoa Chacorore		-16.233	-55.485
São José do Boriréu	SJB	São Lourenço		-16.925	-56.224
Hotel Baiazinha	HB	Paraguay		-16.570	-57.840
Descalvados	DE			-16.730	-57.750
Porto Conceição	PCO			-17.143	-57.359
Ladário	LA		Mato Grosso Do Sul	-19.000	-57.590
São Francisco	SF			-18.394	-57.391
Porto da Manga	PM			-19.258	-57.235
Forte Coimbra	FC			-19.919	-57.789
Porto Esperança	PE			-19.601	-57.437
Porto Ciriaco	PCI	Aquidauana		-19.697	-56.281
Porto Do Alegre	PA	Cuiabá		-17.620	-56.970

for the t-epoch; and $\sigma_{TWS(t)}$ and $\sigma_{HH(t)}$ correspond to the standard deviations of *TWS(t)* and *HH(t)* respectively.

Next, a linear adjustment of the TWS and HH time series was carried out for the 21 stations, and a local linear transfer function was computed, by assuming a linear relationship such as Matos et al. (2012):

$$HH(t) = a.TWS(t) + b \tag{2}$$

where *TWS(t)* and *HH(t)*, both in mm, are the values for the t-epoch; a (dimensionless) is the slope of the best fitted regression line; and b is the HH time series average –since TWS time series average is around zero-.

3 Results

3.1 TWS grids

The TWS monthly maps were derived from JPL RL05 land mass grids for the period 2002 to 2016. In the next figures, a selection of those maps are presented, considering some particular periods where extreme water storage values were detected in most of the Pantanal area.

Figure 3 presents the progressive decreasing of the TWS (in mm/month) for year 2010 (from June to September), one of the periods of minimum water storage in the Pantanal region. Additionally, in Figure 4, is shown the progressive increase of the total water storage in the wetland, which starts in the beginnings of 2011 and it extends throughout the entire area until May of 2011.

From the results, a water storage deficit in terms of TWS in the Pantanal region from July to November approximately, as well as a positive water balance from February to May, could be observed. The maps for all the period under study also showed the seasonality of this system, which is strongly correlated to the precipitation regime.

This results can be compared to the rainfall behavior in Figure 5, where the accumulated monthly precipitation in mm from TRMM for the Pantanal area is presented. Also, this data is shown in detail for the period 2010-2012, including the extreme TWS values detected in Figure 4.

3.2 TWS Validation with river gauge data and rainfall analysis

A comparison of the TWS with hydrometric heights series and rainfall data was performed with the purpose of validation of the GRACE land mass grids.

The resulting R^2 values for the TWS and HH variables were analyzed and are presented in Figure 6: a bar chart sorted by the determination values and their spatial distribution in the Pantanal region.

According to the figure, high determination coefficients (between 0.80 and 0.50) were found towards the north of the Pantanal, mostly at the Mato Grosso State or

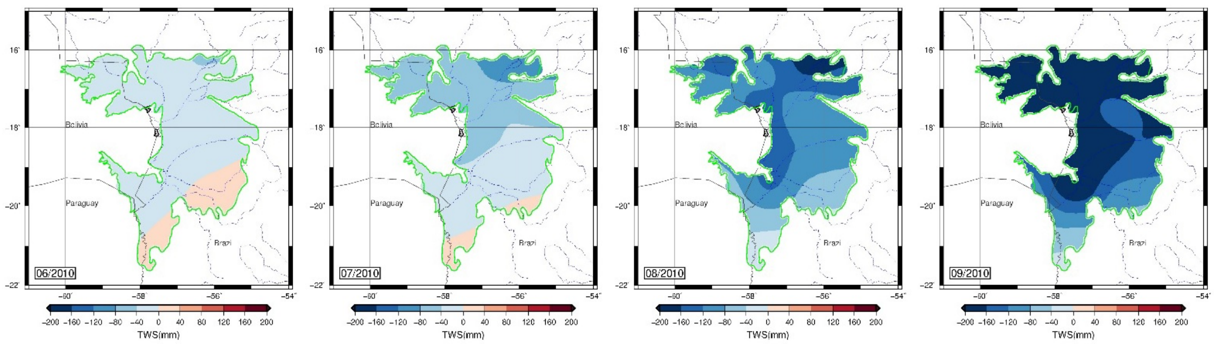

Fig. 3. TWS decrease in the Pantanal area (June to September 2010).

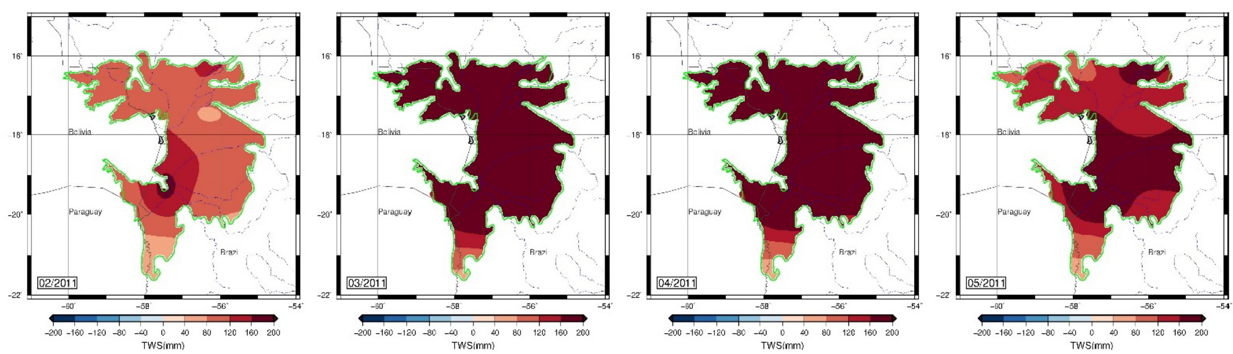

Fig. 4. TWS increase in the Pantanal area (February 2011 to May 2011).

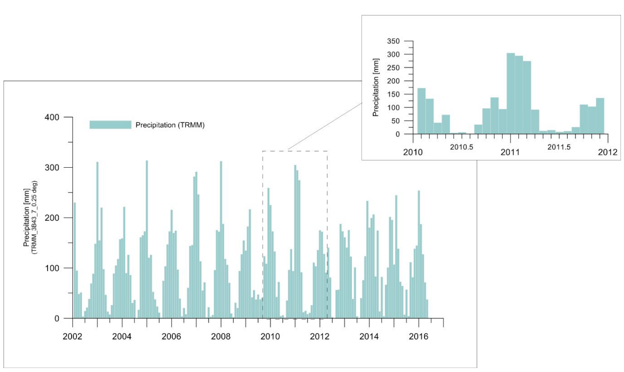

Fig. 5. Accumulated monthly precipitation in mm (TRMM) from 2002 to 2016 in the Pantanal area, and in the detail, the maximum and minimum rainfall in the period 2010-2012.

at their limits; and the lowest ones (between 0.13 and 0.35) took place at the south, in the Mato Grosso do Sul State.

The coefficient a represents the relation between the surface water and the accumulated surface water and groundwater, and it is strongly correlated with the surface water dynamics. The theoretical limit of a is equal to 1, which can occur in the ocean, and high a values means low GRACE sensitivity to the surface water mass variations (Matos et al. 2012). The results of the a coefficients of the regression line for the Pantanal analysis are presented in Figure 7, where is possible to observe that almost a 60% of the stations have values of more than 6.

Furthermore, in Figure 8, is shown the phase difference between TWS and HH, only for those stations having at least one year of uninterrupted data (e.g. LA stations is missing).

It is important to mention that the TWS data and the hydrometric heights/rainfall represent different magnitudes: while GRACE provides an estimate of the total water storage as a vertical column composed of surface water, groundwater and soil moisture integrated over a time period, the others variables represents the water level reached in a section of a river that can be measured on a daily basis and the daily precipitation obtained for each station, respectively. Therefore, the correlation analysis refers only to the signals behavior of the series.

Following Matos et al. (2012), the groundwater changes in those stations with high correlation values (> 0.5) was recovered. In order to achieve that, the TWS GRACE series were reconstructed from the regression coefficients by applying the HH data (Equation 2), thus producing series of surface water on the GRACE data scale. An estimate of the groundwater temporal varia-

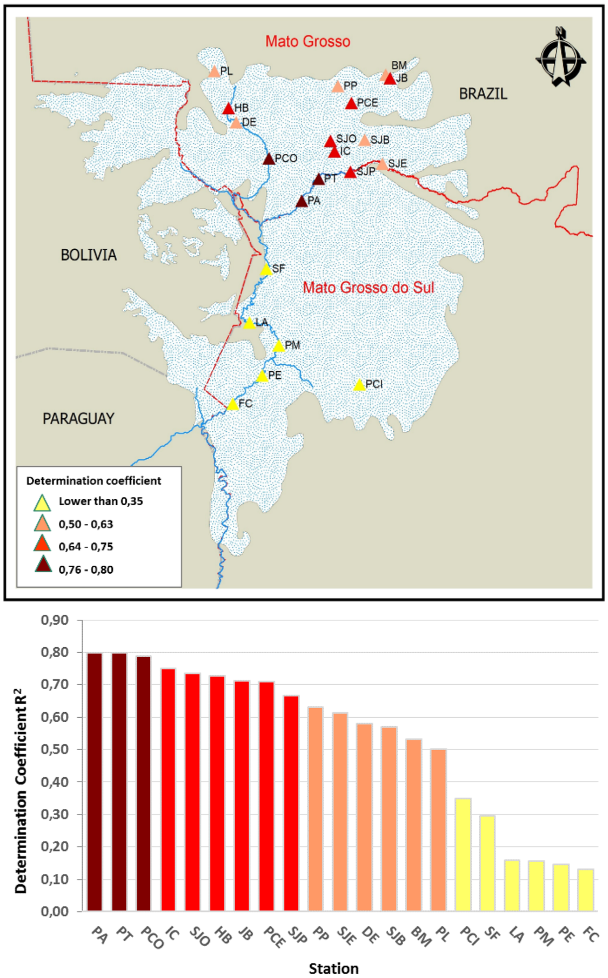

Fig. 6. Determination coefficients (R^2) for the Pantanal stations and its spatial distribution: in yellow, the ones corresponding to Mato Grosso do Sul State (downstream), and the rest of the palette, to the Mato Grosso ones (headwaters).

tion was then obtained by subtracting the TWS GRACE reconstructed series from the original TWS series.

For this study, six over the 21 stations in the Pantanal were chosen, representing different correlation values of GRACE-based TWS and HH: four of them located at the center-north area (Figure 9), and two towards the south (Figure 10). In the figures, are presented the time series of TWS and HH with their respective scatter plots, and rainfall (*in situ* ANA monthly and daily values precipitation, in green and gray, respectively), together with the determination coefficient and regression line for the period January 2002 up to November 2016. The monthly relation between the HH from ANA and TWS is also presented for each station.

From the figure, it can be detected a higher phase shift between the signals at the stations located in the south

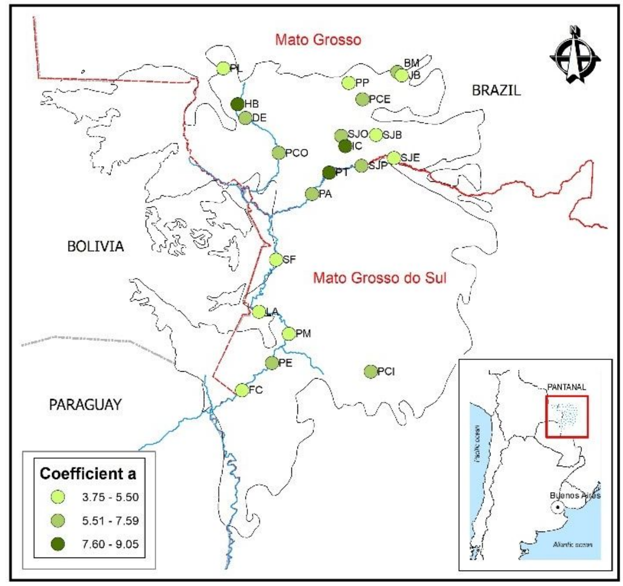

Fig. 7. Spatial distribution of the coefficient *a* of the regression line at the Pantanal.

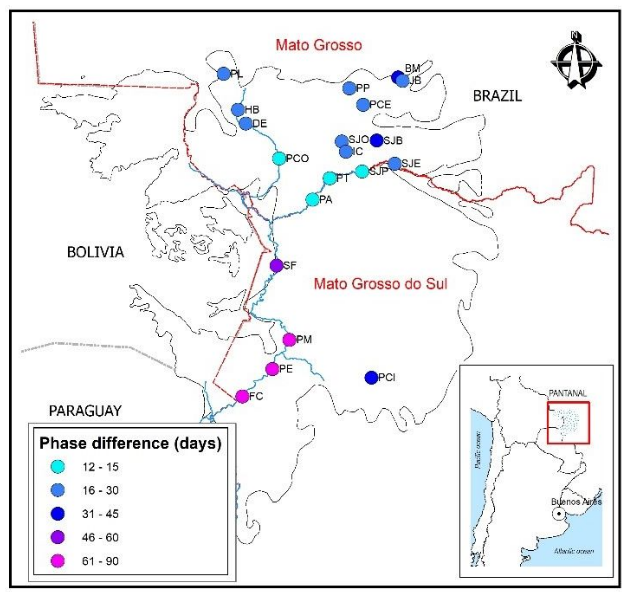

Fig. 8. Phase differences in days between HH and TWS for the Pantanal stations.

of the area under study. The signals that showed higher correlations presented a phase shift of approximately 1 month, and the ones with a lower correlation, more than 2 months.

Finally, the estimate of the groundwater changes is also presented in Figure 9, derived only for those stations with R^2 values higher than 0.60: the original series of TWS (green line), the reconstructed TWS (orange line) from HH

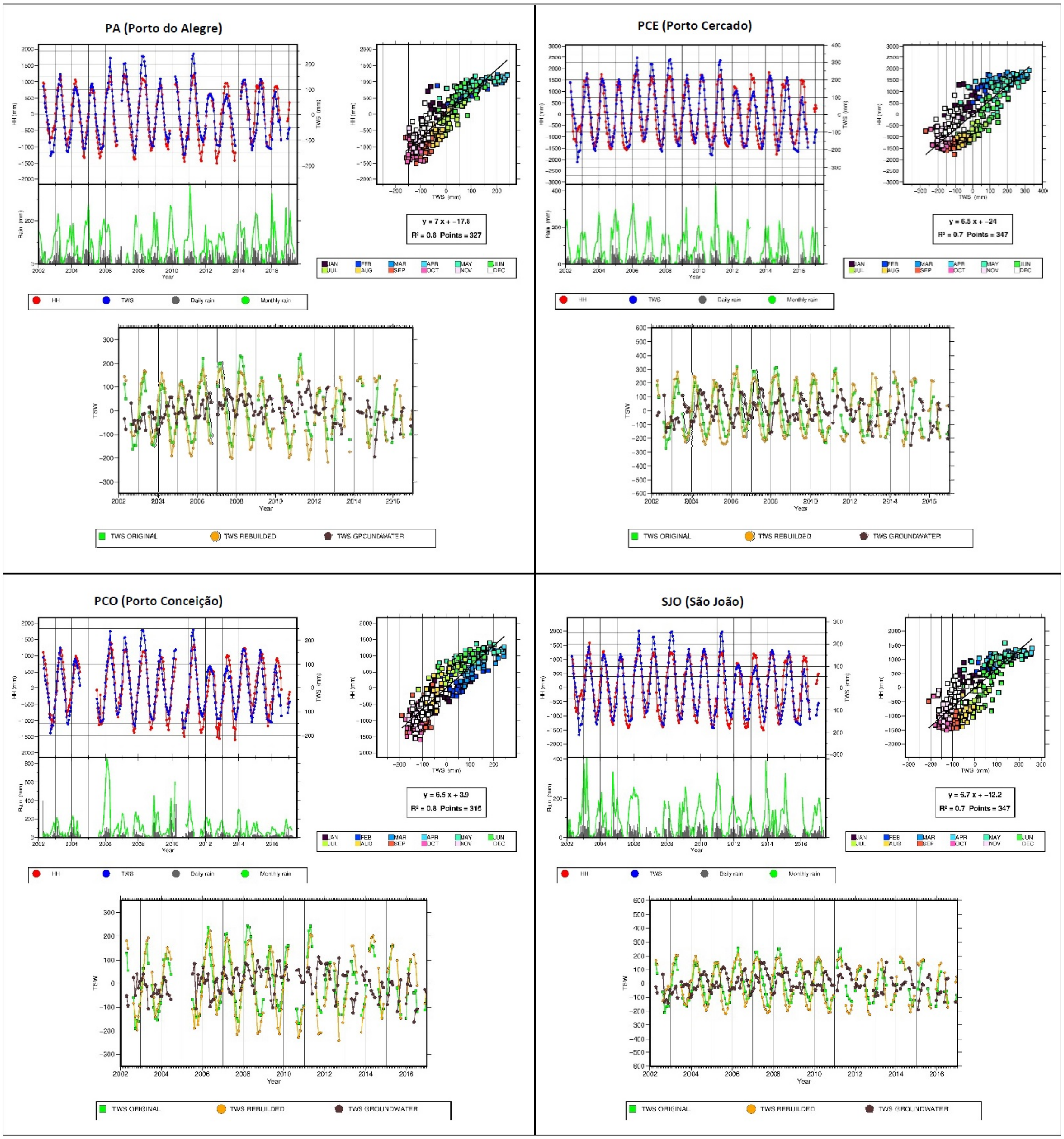

Fig. 9. Time series, determination coefficient and adjustment line, monthly TWS-HH connection and groundwater variation for six river gauge stations selected in the Pantanal area (Mato Grosso State), period 01/2002- 11/2016.

series using linear transfer function, and the series representing only the groundwater (brown line).

4 Discussion

The surface water is composed by the seasonal variability (annual and semiannual) plus the inter-annual variability. The annual cycle, its phase, as well as the correlation between GRACE TWS and *in-situ* data sets are evaluated in this research.

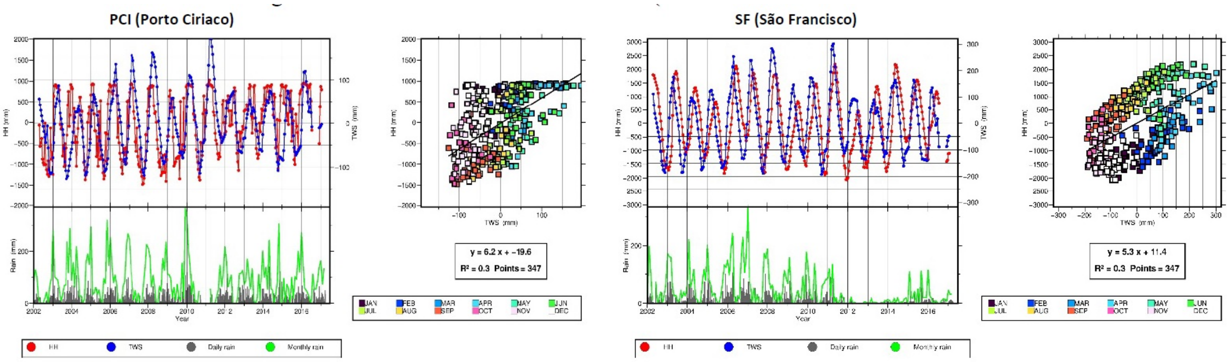

Fig. 10. Time series, determination coefficient and adjustment line, and monthly TWS-HH connection for two river gauge stations selected in the Pantanal area (Mato Grosso do Sul State), period 01/2002- 11/2016.

Regarding the TRMM precipitation analysis for the Pantanal region, it can be concluded that the maximum peaks of TWS (presented in Figure 4) can be related to the rainfall amount occurred during three consecutive months (January to March of 2011, with values close to 300 mm/month); while negative TWS results (Figure 3) agree with months of low rainfall values (June to August of 2010, with precipitation amounts lower than 10 mm/month). According to the TWS maps, these maximum and minimum estimates occurred in April 2011 and September 2010 respectively, as GRACE perceives later the precipitation contribution to the total water storage changes.

The comparison of GRACE TWS-derived with *in-situ* HH from river gauge measurements stations from ANA in the Pantanal region shows a good agreement between both times series. They also reveal the maximum and minimum TWS values that were detected in the water storage maps analysis (Figures 3 and 4).

The seasonal variations detected by GRACE, are related to water level surface and groundwater variations. Two distinct areas can be distinguished in the R^2 analysis: significant determination coefficients in the north of the Pantanal, in the Mato Grosso State (0.50 to 0.80), and lower ones in the south of the region, in the Mato Grosso do Sul State (< 0.35).

The correlation and determination coefficients of the TWS and HH signals are well adjusted over the stations that are closer to the headwaters of the Paraguay river basin; but not so over the same river downstream, where these coefficients are considerably decreased. Nevertheless, the 67% of the correlation results for TWS and HH time series is higher than 0.53. Whereas the resolution of TWS GRACE land mass grids is $\sim$ 100 km, and the *in situ* data represents single measurements, it can be concluded that these correlation values are quite high.

According to the phase differences between TWS and HH, for the stations located at the Mato Grosso do Sul State these are between ±42 and 87 days. These results indicate that a phase shift of the signals of 2-3 months approximately, and also that, in general, GRACE is detecting the water storage changes before the *in situ* measurements of the hydrometric level.

On the other hand, the northern stations (at the Mato Grosso State) were the ones presenting lower phase differences, ranging from 12 to 36 days, which means that the series can present a phase shift of an approximately 1 month maximum.

Finally, it can be observed that almost a 60% of the stations have a phase shift of less of 1 month.

This difference in the phase results between both states of the Pantanal can be due to different physical features that domain the region, geological structure, climatic conditions and the influence of nearby basins. The Brazilian Pantanal region belongs to the Cenozoic hydrogeological domain, which consists on formations of different type and thickness of sedimentary rocks that covers the oldest ones. These have a similar behavior to a porous aquifer, and present a primary porosity and a high permeability in sandy soils.

The hydrological behavior for both states is quite different. In the Mato Grosso State the slopes are more important, while in the south there is a lagoon and lake formation trend that delays the surface runoff. This can be the cause for the higher phase shift between the TWS and river gauge measurements in the Mato Grosso do Sul State, with the consequent low correlation values.

The results in Figures 9 and 10 are showing the TWS variability and the extreme water storage values, as well as the correlation between GRACE and HH data at well-distributed stations, covering the different Pantanal regions: at the boundary between Mato Grosso and Mato

Grosso do Sul States (PA), at the northeast (PCE and SJO), northwest (PCO), southeast (PCI) and southwest (SF). The ones in the north presents R^2 values of about 0.8, a phase shift between 15 and 30 days, and a good adjustment between HH and TWS series. On the other side, at the stations towards the south, the phase differences were more evident in the figures, ranging from 1 month (PCI) to 2 months (SF).

Regarding the TWS and *in situ*-rainfall signals analysis, significant TWS values are generally observed in March and April, and lower values, take place at September and October. However, maximum accumulated precipitation usually occurs from December to January, and minimum rainfall values are found every year between June and August approximately (e.g. PA station). In this sense, both signals appear to fit very well in the annual cycle, but a delay of ~ 3 months in the TWS with respect to the rainfall variable is detected.

The average monthly relation between precipitation and TWS for the entire period in Figure 9, shows that important rainfall, with the consequent increase in water storage, occurs during the summer months (Southern hemisphere); later, both variables decrease towards the winter, and the TWS remains almost constant during the spring in spite of the precipitation increase in this period.

Likewise, the phenomena of El Niño and La Niña affect the climatic variability in South America, resulting on wet or dry periods depending on the phase of these events.

The behavior of the groundwater is related to the precipitation regime and the hydrogeological domain around the station: the PCO and PA stations show that the groundwater has a semi-annual cycle; on the other hand, the PCE and SJO stations revealed annual groundwater cycles and a delay with respect to the reconstructed TWS series.

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