COMPARISON OF SEASONAL HYDROLOGIC VARIATIONS IN THE LA PLATA BASIN FROM GRACE MONTHLY SOLUTIONS WITH IN SITU TIDE GAUGE WATER LEVEL DATA

Annamária KISS [1) *] and Lóránt FÖLDVÁRY [2, 3)]

[1)] Department of Geodesy and Surveying, Budapest University of Technology and Economics, Műegyetem rkp. 3., 1111 Budapest, Hungary
[2)] Institute of Geoinformatics, Alba Regia Technical Faculty, Óbuda University, Budai út 45., 8000 Székesfehérvár, Hungary
[3)] Geodetic and Geophysical Institute, Research Centre of Astronomical and Earth Sciences, Hungarian Academy of Science, Csatkai Endre u. 6-8, 9400 Sopron, Hungary

*Corresponding author's e-mail. kiss.annamaria@epito.bme.hu

ABSTRACT

Seasonal hydrologic variations have been determined in the La Plata basin from GRACE monthly solutions for a time span of less than 6 years. The results have been compared to tide gauge water level data along several rivers of the La Plata basin. Annual and semi-annual curves have been fitted both to the GRACE water storage variation series and to the tide gauge water level series, correlations between the original series and the curves have been determined, relationship of the amplitudes and phases have been investigated. The aim of the comparison is to detect time delay between the seasonal cycle of precipitation (related to GRACE) and runoff (observed by tide gauges). The time delay may deliver information on water storage, such as groundwater aquifers, soil moisture or canopy interception. As for the results, by the comparison of the annual phases, 11-13 days of time delay between GRACE data and tide gauge data has been detected.

1. INTRODUCTION

The Earth's constantly changing mass distribution varies its gravity field over time (Wahr and Schubert, 2007). Large-scale mass variations are generated by huge mass redistributions over large areas, such as conventions in the core and in the mantle, tectonic processes, earthquakes and volcano activity, tidal deformations of crust and oceans, circulations in the atmosphere and in the oceans, the hydrologic cycle, cryospheric processes, de-glaciation or the global sea level rise. Among them, seasonal variations are mainly generated by mass redistributions of the atmosphere, oceans and hydrologic processes.

The GRACE (Gravity Recovery And Climate Experiment) satellites have been providing global gravity field models with monthly resolution for almost 15 years, enabling the investigation of seasonal mass variations. The largest impact on seasonal gravity variations is generated by the atmosphere, which is concerned to be quite well-measured due to the dense, worldwide barometric network. For most GRACE applications, atmospheric redistribution processes are taken into account as a correction, which is found to be done in the official GRACE outputs with sufficient accuracy (Zenner et al., 2012). Over the land, the remaining seasonal mass variation is affected mainly by changes of the terrestrial water storage. After removing the mean field, which is dominated by the static density distribution inside the solid Earth, changes of the vertically integrated terrestrial water storage can be determined (Ilk et al., 2005). As inside a basin GRACE data is characterized by the seasonal hydrologic mass variations, relationship with the seasonal variations of the runoff along the rivers of the catchment area can be expected. In this study water storage variations have been determined from GRACE models in the South American La Plata basin between 2002 and 2008, and compared with tide gauge water levels along the main rivers of the basin, with particular emphasis on the seasonal trends.

Earlier studies for the La Plata basin have been delivered by Pereira and Pacino (2012) and Pereira et al. (2012). Both studies deliver a regional analysis of hydrological processes based on GRACE monthly solutions. The present study does not focus on the whole basin as a region, instead point-wise comparison of the satellite derived data with tide gauge water level observations is performed. The difference of the two observations is expected to provide information on the water storage variations, since tide gauge observes the real time runoffs, while GRACE reflects all mass variations over the region, including the subsurface water variations as well. Some incomplete investigations have already been

Fig. 1	The main rivers of the La Plata basin and the locations of the available tide gauge data.

performed by Kiss and Földváry (2015), which has been refined in the processing methodology, and the conclusions have been elaborated for the present study.

2. DATA

The hydrological data from January 2002 till January 2008 is obtained in daily resolution. Gauged water level time series are available from the Argentinean area of the basin, consisting 21 hydrologic stations of 7 rivers.

Table 1 contains information of the stations, arranged by river with increasing distance from the estuary. The suitability of the tide gauge data is highly dependent of the location of the hydrologic station. The river regulations have large effects on the water level, leading to distorted seasonal signals. Many of these rivers are affected by the Guarani aquifer, located beneath most of the area of the basin (approximately 80 %). This large groundwater system causes the lack of the seasonal water level variations along the Paraná, Uruguay, Salado, Gualeguaychú and Iguazú rivers. Furthermore, there are hydroelectric

dams on the Paraná (Itaipú and Yaciretá), Uruguay (Salto Grande and Itá) and Salado (Cabra Corral) rivers. In addition, waterfalls such as the Iguazú (Paraná and Iguazú rivers) and Moconá (Uruguay River) and other reservoirs and irrigation canals make 5 out of 7 rivers infeasible for studying seasonal mass variations. The 6 hydrologic stations of the Bermejo and Pilcomayo rivers are completely free from these effects, thus water level series along these rivers are likely to reflect the seasonal characteristics. Hence, our study is limited to the results of these 6 hydrological stations.

As for the gravity field solutions, models of different processing centres may notably differ at certain regions. In fact, Klees et al. (2008) has found that phases of the models delivered by the Jet Propulsion Laboratory (JPL) and the Delft Institute of Earth Observation and Space Systems (DEOS) differ statistically significant from the phases of the Centre National d'Etudes Spatiales (CNES), the GeoForschungsZentrum Potsdam (GFZ) and the Center for Space Research, University of Texas (CSR) models over the period from February 2003 to

Table 1 Parameters of the hydrological stations.

RIVER/Station	ID	Distance (km)	Latitude	Longitude	Sampling	Interval
BERMEJO						
Puerto Velaz	2610	35	-26°39' S	-58°37' W	daily	2002.01.-2008.12.
El Colorado	2602	124	-26°20'04" S	-59°21'45" W	daily	2002.01.-2008.12.
Pozo Sarmiento	693	783	-23°08'26" S	-64°11'49" W	daily	2002.01.-2008.12.
Aguas Blancas	604	826	-22°43'30" S	-64°21'53" W	daily	2002.01.-2008.12.
Balapuca	605	858	-22°29'33" S	-64°27'49" W	daily	2002.01.-2008.12.
GUALEGUAYCHÚ						
Ruta Prov.	3030	76	-32°26'42" S	-58°33'18" W	daily	2002.01.-2008.12.
IGUAZÚ						
Perfil Tipo	3440	28	-25°40' S	-54°25' W	daily	2002.01.-2008.12.
PARANÁ						
Timbúes	3316	279	-32°43'11" S	-60°43'34" W	hourly	2003.01.-2007.12.
Chapetón	3005	430	-31°38'48" S	-60°16'44" W	daily	2002.01.-2008.12.
Chapetón	3005	430	-31°38'48" S	-60°16'44" W	monthly	2001.12.-2007.09.
Corrientes	3805	940	-27°27'55" S	-58°50'57" W	daily	2002.01.-2008.12.
Corrientes	3805	940	-27°27'55" S	-58°50'57" W	monthly	2001.12.-2007.08.
Itatí	3862	1007	-27°15'59" S	-58°14'38" W	monthly	2001.12.-2007.08.
Ita Cajón	3452	1542	-25°36' S	-54°35' W	monthly	2001.12.-2007.08.
PILCOMAYO						
La Paz	631	626	-22°22'38" S	-62°31'23" W	daily	2002.01.-2008.12.
SALADO						
Ruta Prov.	3216	34	-31°29' S	-60°47' W	daily	2002.01.-2008.12.
Puente Ruta Prov.	811	563	-28°30'13" S	-62°52'53" W	daily	2004.06.-2008.12.
Suncho Corral	804	655	-27°56'25" S	-63°26'23" W	daily	2004.06.-2008.12.
Canal de Dios	810	951	-25°37'36" S	-63°57'00" W	daily	2002.01.-2008.12.
URUGUAY						
Santo Tomé	3860	720	-28°32' S	-56°01' W	daily	2002.01.-2008.12.
Garruchos	3857	791	-28°10'37" S	-55°38'31" W	daily	2002.01.-2008.12.
San Javier	3449	856	-27°52' S	-55°08' W	daily	2002.01.-2008.12.
El Soberbio	3442	978	-27°17'55" S	-54°11'37" W	daily	2002.01.-2008.12.

February 2006. Similarly, Pereira and Pacino (2012) and Pereira et al. (2012) found slight difference of CNES, GFZ and CSR models, but all models differ notably from JPL model. Note that Pereira and Pacino (2012) have found the difference to be much less than it is stated by Klees et al. (2008). According to our tests (considering CSR, GFZ and JPL solutions only), the difference of these solutions is also not that relevant, the estimate of Pereira and Pacino (2012) and Pereira et al. (2012) is more similar to ours.

Generally, in order to avoid the use of an extreme, an 'average' model was aimed to be chosen for the present analysis. During our tests with the method and parameterization (see Methodology section), the CSR model have been found being not striking to any extremes. Based on the tests, the GRACE RL05 Level-2 products of CSR have been used (RL05). The first GRACE models dated to April 2002, thus the overlap period with the time span of 6 years of the tide gauge data is from April 2002 to January 2008. During this period 66 models of

GRACE monthly solutions are available. For practical reasons 148 models from the period of April 2002 and December 2015 have been used instead (see Methodology section).

3. METHODOLOGY

Based on the RL05 spherical harmonic coefficients derived from the GRACE measurements, surface mass density changes can be determined by the methodology of Swenson and Wahr (2002). Surface mass density variations with monthly resolution are dominated by the mass variations of ocean and hydrology over the test area. The area of the basin has been outlined by the method of Longuevergne et al. (2010) to reduce mass variation effects of the neighbouring regions and of the ocean, thus the remaining signal may be assumed to be generated by hydrological processes within the La Plata basin. Surface mass variations have been calculated to the locations of the hydrologic stations, and the observed periodic signal has been compared to

tide gauge measurements. The maximal degree of the spherical harmonics has been truncated at $l = 60$. In order to eliminate the striping features of the GRACE monthly solutions, a Gaussian smoothing with radius $r = 300$ km and a de-striping filter (Swenson and Wahr, 2006) have been applied. To quantify the results of the comparison, annual and semi-annual curves have been fitted to the tide gauge level time series:

$$f(t) = a + b \cdot t + c \cdot \sin(\omega_{annual} \cdot t + \varphi_c) + \\ + d \cdot \sin(\omega_{semi-annual} \cdot t + \varphi_d) \qquad (1),$$

and the GRACE-borne mass variation series:

$$g(t) = a + b \cdot t + c \cdot \frac{1}{\sin c\left(\frac{1}{12}\right)} \cdot \sin(\omega_{annual} \cdot t + \varphi_c) + \\ + d \cdot \frac{1}{\sin c\left(\frac{1}{6}\right)} \cdot \sin(\omega_{semi-annual} \cdot t + \varphi_d) \qquad (2)$$

where a is bias, b is trend, c and d are annual and semi-annual amplitudes, φ_c and φ_d are annual and semi-annual phases, $\omega_{annual} = 1$ and $\omega_{semi-annual} = 1/2$ correspond to annual and semi-annual variations and t is the actual date. The $1/sinc$ multipliers in equation (2) are applied to restore the temporal averaging of the GRACE measurements (Földváry, 2015).

A period of slightly less than 6 years is very short for reliable estimation of annual and semi-annual mass variations, since any non-seasonal impact, such as effects of the El Niño–Southern Oscillation during this period may influence notably the estimation. Thus, the period has been extended to much longer data, up to December 2015. The estimated annual and semi-annual amplitudes and phases were used for the comparison. However, as the analysis refers to the period from April 2002 to January 2008, a signal has been calculated only for this time span, and used for the statistics.

The adjustment of the GRACE time series was performed by least squares method:

$$x = (A^T \cdot A)^{-1} \cdot (A^T \cdot l) \qquad (3),$$

where A is the design matrix, l is the observation vector, and x is the vector of unknown parameters containing a, b, c, d, φ_c and φ_d.

As the residuals of the tide gauge water level series were found not to follow the normal distribution, those have been adjusted by a robust method:

$$x = (A^T \cdot P \cdot A)^{-1} \cdot (A^T \cdot P \cdot l) \qquad (4),$$

where the elements of P are set by an exponential weight function:

$$p = \exp\left(-k_1 \cdot \left|\frac{v}{\sigma_v}\right|^{k_2}\right) \qquad (5),$$

where v is the residual, σ_v is the standard deviation of the residuals, and the values of k_1, k_2 are determined empirically (Huber, 1964). In our case these were set to $k_1 = 0.05$ and $k_2 = 4.4$, as suggested by Soha (1986).

Equations (3) and (4) are not linear for the unknowns, thus an iterative solution has been used. Also, the correlation between the seasonal curves and the corresponding time series (GRACE surface mass anomalies or tide gauge water levels) has been determined.

4.   RESULTS AND DISCUSSION

The tide gauge time series and the fitted seasonal curves are shown in Figure 2, and summarized in Table 2. The adjustment of the tide gauge time series yields 0.7-0.9 correlation values, as it is anticipated by the visually striking seasonal characteristics of the signal. The amplitude of the annual variation generally increases by approaching the Bermejo river estuary, which is in accordance with the increasing amount of water received from the inflowing rivers. The annual phases are larger at the source, i.e. the annual period appears earlier at the estuary.

Table 2 Results of the tide gauge time series fitting.

| Station	ID	Distance (km)	Annual amplitude (m)	Annual phase (days)	Semi-annual amplitude (m)	Semi-annual phase (days)	Correlation
BERMEJO RIVER							
Puerto Velaz	2610	35	2.522	7.1	0.775	-9.7	0.9154
El Colorado	2602	124	2.334	8.4	0.816	-9.9	0.9056
Pozo Sarmiento	693	783	0.956	16.1	0.190	+0.8	0.7478
Aguas Blancas	604	826	0.527	16.6	0.112	-2.0	0.7801
Balapuca	605	858	0.916	17.5	0.206	-3.1	0.8030
PILCOMAYO RIVER							
La Paz	631	626	0.678	22.5	0.190	5.6	0.6786
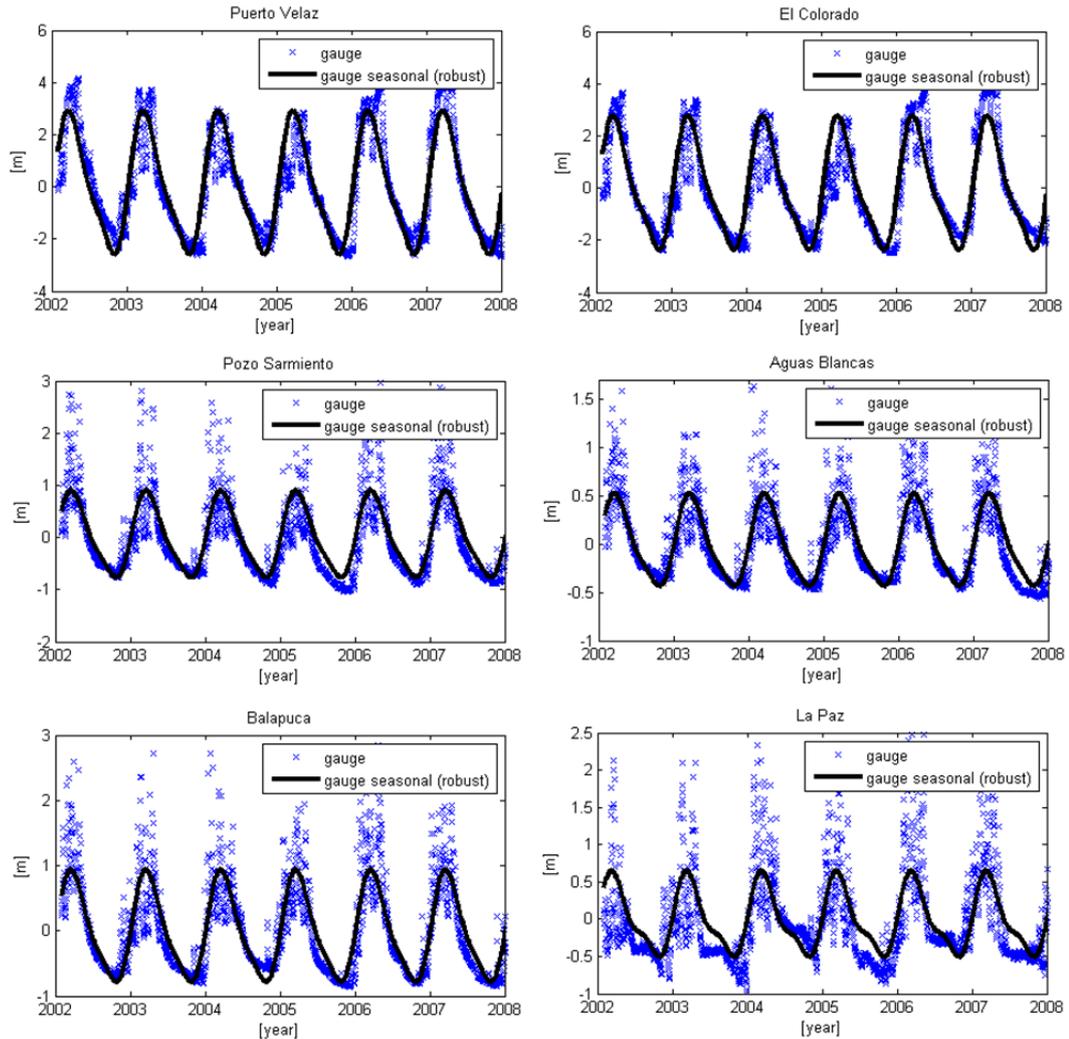
Fig. 2   Fitting of seasonal variation curves on tide gauge data of Puerto Velaz, El Colorado, Pozo Sarmiento, Aguas Blancas, Balapuca and La Paz stations.

The mass variations determined from GRACE gravity models and the fitted seasonal variations are displayed in Figure 3, and the results are collected in Table 3. The GRACE correlations show successful fitting at the river sources, where also relevant seasonal variations were observed. However, low correlation and smaller amplitudes at the estuary were found. In contrary to the tide gauge results, the GRACE annual amplitudes are higher at the sources, which can be explained by the different content of the observed signals. GRACE measures the entire water mass variation, not only the runoff, and as the hydrology related mass variation gets more complex by approaching to the estuary, including a huge contribution of the underground waters, the seasonality becomes more distorted, aliased by the variations of the wetland water storage, contributed by groundwater aquifers, soil moisture and canopy interception. Nevertheless, annual phases show consequently lower values than that of the tide gauge results.

Comparing the tide gauge and GRACE results, c.f. Figure 4, it is conspicuous that the tide gauge annual amplitudes are the multiples of the GRACE amplitudes. This is a consequence of the essential difference of water mass variation and gauged water level. In Figure 4, scaling factors have been applied to make the curves comparable, c.f. 4th column of Table 4. Generally, the annual scale was found to increase by approaching to the estuary. Earlier studies have also been applied a scale factor when compared GRACE-borne mass variation with gauged water level measurements. Andersen et al. (2008) used a value around 10 for the scaling at the Chandpur River. Vaz de Almeida et al. (2012) have been studied the Amazon basin and calculated with scale factors between 10 and 20. The observed 18-42 annual scale factors in this study are slightly higher than these results, with the exception of station Puerto Valez and El Colorado, close to the estuary of the Bermejo River, in which cases the large (>100) scale factors
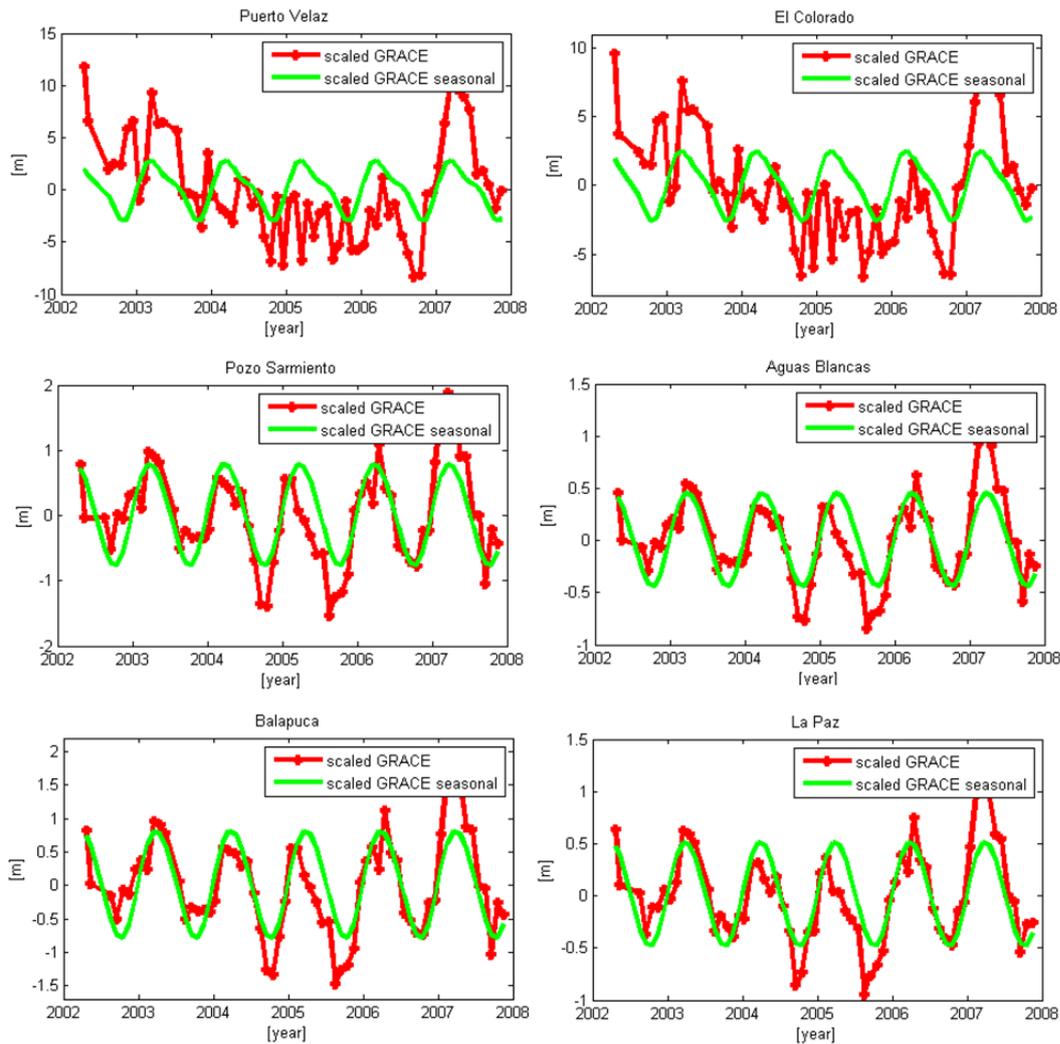
Fig. 3   GRACE-borne monthly surface mass anomaly data and the best fitting seasonal variation
curves at the Puerto Velaz, El Colorado, Pozo Sarmiento, Aguas Blancas, Balapuca and
La Paz stations.

Table 3 Results of the GRACE time series fitting, determined for the period 2002-2015, correlation for 2002-2008.

Station	ID	Distance (km)	Annual amplitude (m)	Annual phase (days)	Semi-annual amplitude (m)	Semi-annual phase (days)	Correlation
BERMEJO RIVER							
Puerto Velaz	2610	35	0.021	- 168.6	0.007	-3.4	0.2174
El Colorado	2602	124	0.017	-24.8	0.005	5.2	0.1068
Pozo Sarmiento	693	783	0.018	4.8	0.006	-34.0	0.6553
Aguas Blancas	604	826	0.019	4.5	0.006	-32.2	0.6886
Balapuca	605	858	0.019	4.6	0.006	-31.3	0.7022
PILCOMAYO RIVER							
La Paz	631	626	0.025	11.3	0.006	-16.6	0.7411

and the low correlation of the seasonal fitting are
interpreted by the aliased GRACE mass variation
estimate.

Only a few days of annual phase difference
between the GRACE and tide gauge time series were
detected, which shows how much time it takes for

precipitation to dominate in the runoff. The detected
values are in accordance with hydrologic model
results.

Semi-annual variations were found to be
approximately an order of magnitude smaller than
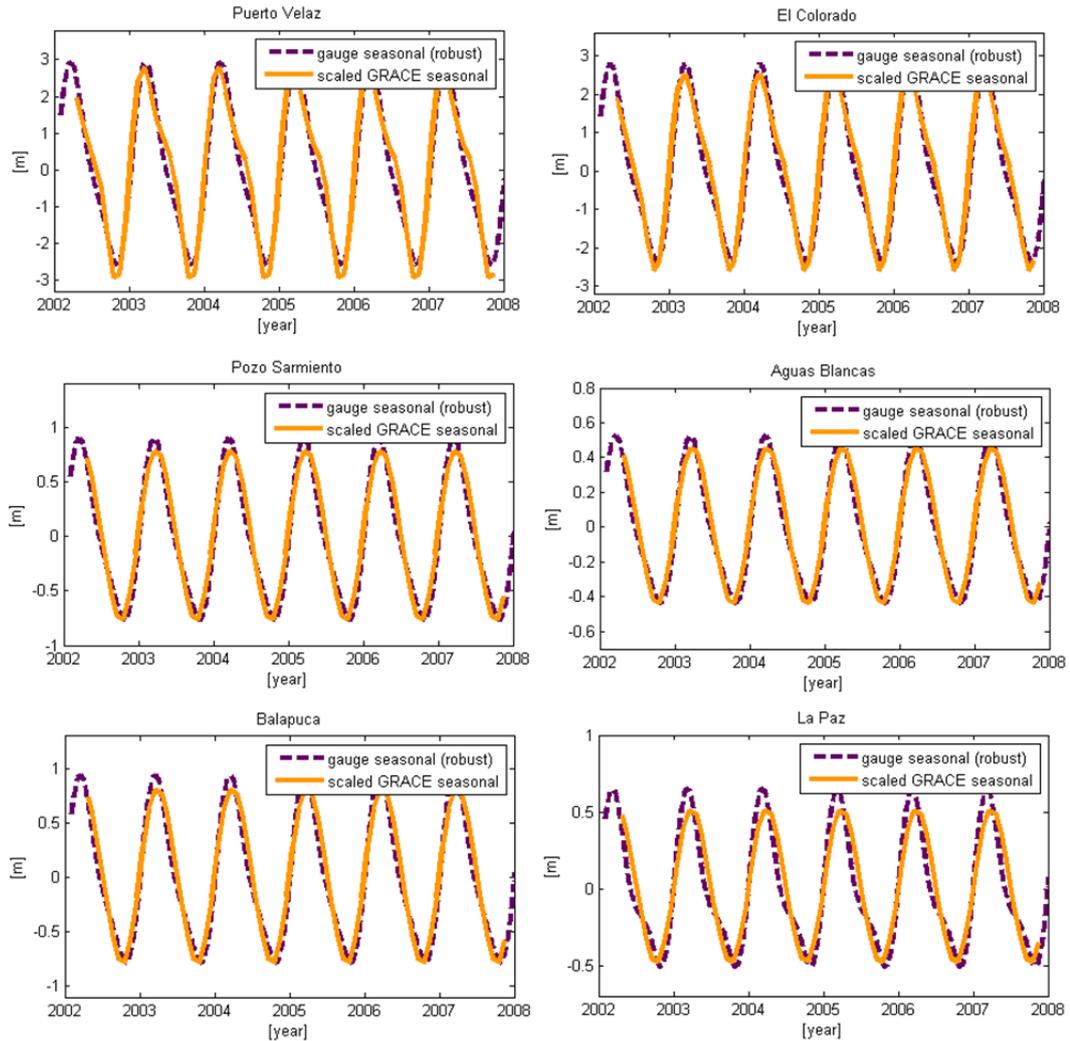annual variations. Results for the semi-annual

Fig. 4 Comparison of seasonal GRACE-borne and tide gauge mass variations at the Puerto Velaz, El Colorado, Pozo Sarmiento, Aguas Blancas, Balapuca and La Paz stations.

Table 4 Comparison of annual GRACE-borne mass variations and gauged annual water level signals.

Station	ID	Distance (km)	Annual scale	Annual phase difference (days)	Semi-annual scale	Semi-annual phase difference (days)	Tide gauge correlation	GRACE correlation
BERMEJO RIVER								
Puerto Velaz	2610	35	123.9	175.7	105.7	-6.3	0.9154	0.2174
El Colorado	2602	124	142.8	33.2	159.6	-15.1	0.9056	0.1068
Pozo Sarmiento	693	783	41.66	11.3	30.96	34.8	0.7478	0.6553
Aguas Blancas	604	826	22.82	12.1	18.45	30.2	0.7801	0.6886
Balapuca	605	858	39.47	12.9	33.83	28.2	0.8030	0.7022
PILCOMAYO RIVER								
La Paz	631	626	18.74	11.2	30.48	22.2	0.6786	0.7411

variations yielded to inconsistent results both in scale and phase shift, as the notably larger mass content of the annual frequency overwhelms the runoff characteristics.

5. CONCLUSIONS

The tide gauge time series data along rivers of the La Plata Basin have been compared with GRACE derived mass variations for a period of 6 years, between 2002 and 2008. The comparison should be considered critically as the two kinds of measurements are weakly connected to each other, since GRACE detects vertically integrated mass variation regardless the height / depth of the source, while tide gauges observe real time surface runoff only. On the other hand, it is obvious that the

phenomena are strictly connected to each other: precipitation must appear in the runoff sooner or later. The time delay between precipitation and runoff is caused by different forms of water storage, such as groundwater aquifers, soil moisture or canopy interception. The time delay due to water storage is estimated in this study as the difference in the seasonal cycle of the precipitation and water storage (GRACE) and runoff (tide gauge).

The investigation has lead to the following results.

1) It was found that rivers under heavy water control, i.e. dams, and the Guarani aquifer alias so much the periodicity of the nearby water mass variations that no relevant annual or semi-annual period can be seen neither on GRACE nor on tide gauge water level data. Among the 7 rivers only 2 could be used for further analysis.

2) Close to the estuary of a river the periods of the different influents and subsurface sources are so much mixed that no relevant annual and semi-annual period could be determined. Along the investigated 6 hydrologic stations 2 (at estuary distance of 35 and 124 km) have been excluded, the remaining 4 stations has been located from the estuary at 626, 783, 826 and 858 km.

3) Based on these 4 stations, time delay between precipitation and runoff has been found to be 11-13 days on annual period.

4) Semi-annual variations are an order of magnitude smaller than annual variations, and are overwhelmed by the annual variations. Semi-annual variations showed a time delay of 22-35 days, but these are considered to be inconsistent due to its inconsistency both in scale and phase shift.

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