VALIDATION OF THE LAND WATER STORAGE FROM GRAVITY RECOVERY AND CLIMATE EXPERIMENT (GRACE) WITH GAUGE DATA IN THE AMAZON BASIN

Validação da avaliação pelo GRACE do acúmulo de água no subsolo da bacia amazônica com base em dados de linígrafos

SONIA MARIA ALVES COSTA[1]
ANA CRISTINA OLIVEIRA CANCORO DE MATOS[2]
DENIZAR BLITZKOW[2]

[1]Instituto Brasileiro de Geografia e Estatística
Diretoria de Geociências, Coordenação de Geodésia
Av. Brasil, nº 15.671 Bloco IIIA sala 06
Parada de Lucas - Rio de Janeiro – RJ CEP 21241-051
sonia.alves@ibge.gov.br
[2]Escola Politécnica da Universidade de São Paulo- EPUSP-PTR
Laboratório de Topografia e Geodésia
Caixa Postal 61548, CEP: 05424-970,
São Paulo, São Paulo, Brasil
acocmatos@gmail.com; dblitzkow@usp.br

ABSTRACT

The Amazon basin is a region of constant scientific interest due to its environmental importance and its biodiversity and climate on a global scale. The seasonal variations in water volume are one of the examples of topics studied nowadays. In general, the variations in river levels depend primarily on the climate and physics characteristics of the corresponding basins. The main factor which influences the water level in the Amazon Basin is the intensive rainfall over this region as a consequence of the humidity of the tropical climate. Unfortunately, the Amazon basin is an area with lack of water level information due to difficulties in access for local operations. The purpose of this study is to compare and evaluate the Equivalent Water Height (Ewh) from GRACE (Gravity Recovery And Climate Experiment) mission, to study the connection between water loading and vertical variations of the crust due to the hydrologic. In order to achieve this goal, the Ewh is compared with *in-situ* information from limnimeter. For the analysis it was

computed the correlation coefficients, phase and amplitude of GRACE Ewh solutions and *in-situ* data, as well as the timing of periods of drought in different parts of the basin. The results indicated that vertical variations of the lithosphere due to water mass loading could reach 7 to 5 cm per year, in the sedimentary and flooded areas of the region, where water level variations can reach 10 to 8 m.
Keywords: GPS; GRACE; Limnimeter Stations.

RESUMO

A bacia Amazônica é uma região de constante interesse científico devido à sua importância ambiental e climática e à sua biodiversidade em uma escala global. As variações sazonais do volume d'água é um dos exemplos de temas estudados atualmente. Em geral, as variações dos níveis dos rios dependem basicamente do clima e das características físicas das bacias hidrográficas correspondentes. O fator principal de grande influência no nível d'água na bacia Amazônica são as elevadas precipitações na região em conseqüência da umidade do clima tropical. Infelizmente a bacia Amazônica é uma região com carência de informações de dados do nível da altura d'água devido a dificuldade de acesso para operações locais. A proposta deste trabalho é comparar e avaliar as grades do Equivalente à altura d'água (Ewh) da missão GRACE (Gravity Recovery And Climate Experiment), para estudar o ciclo hidrológico e sua relação com a variação da litosfera na região. Com este propósito os dados GRACE (Ewh) são comparados com observações *in-situ* obtidas dos linígrafos. Para esta validação foram calculados o coeficiente de correlação, fase, amplitude do GRACE (Ewh) e dos dados *in-situ*, bem como, os períodos de seca em diferentes partes da bacia. Os resultados indicam que as variações verticais da litosfera devido à carga da massa d'água podem chegar de 7 a 5 cm por ano nas áreas sedimentares e alagadas da região, onde as variações do nível d'água podem alcançar de 10 a 8 m.
Palavras-chave: GPS; GRACE; Estações Linimétricas.

1. INTRODUCTION

The water surface knowledge has several applications, such as monitoring and forecasting flood, sediment flows over basins and geomorphology domains. In general, the limnimeters are very sparsely located or do not exist in a sufficient number to provide a detailed evaluation of the river basin; this is the case of the Amazon. This one is the greatest river basin in the world due to its extension and to the strong seasonal water level variation, reaching 10 m near Manaus against 4 m in regions in the south, near to Alta Floresta and in the north near to Boa Vista (Figure 1).

Nowadays, with the advances of satellite technology, it is possible to monitor any information regarding hydrology, lithosphere, geomorphology and climate in a global and regional context important for ecosystems evaluation and its monitoring. A number of studies have exploited the water storage variability on land, more specifically for continental hydrology (RAMILLIEN *et al*., 2005; CHEN *et al*., 2005; CHAMBERS *et al*., 2006; TAPLEY *et al*., 2004a; WAHR *et al*., 2004). The water storage estimates used in these studies are typically presented as spatial averages over regions having scales of a few hundred km and greater. ALMEIDA (2009) concentrated his study in the Amazon region, validating GRACE Ewh with water level *in-situ* data, but did not explore the interaction of hydrosphere over lithosphere.

Considering that GRACE mission provides the gravity field variations, it means that the temporal geoid models through Stokes coefficients can be derived and an inversion procedure applied, from which the Equivalent Water Height (Ewh) anomalies are obtained. The Ewh expresses the variation of water mass storage including soil moisture, ice sheets, glaciers, oceans, etc.

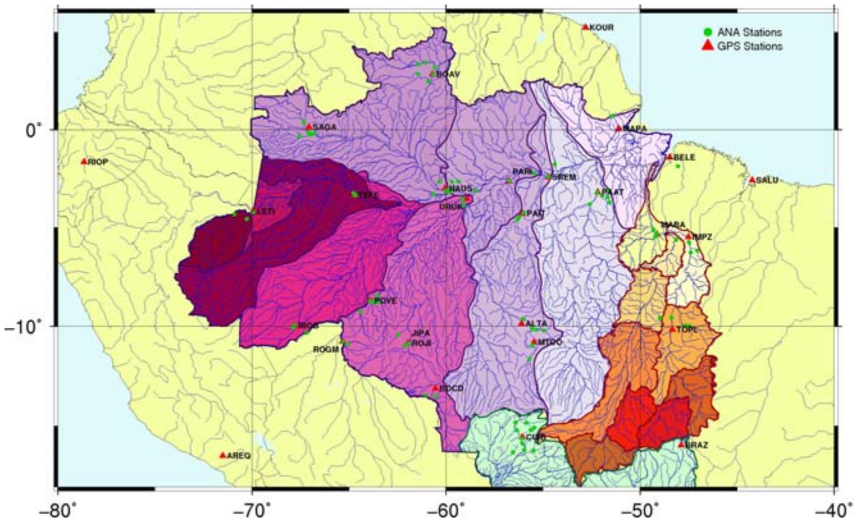
The objective of this study is to evaluate GRACE grids from Ewh anomalies with *in-situ* data from limnimeter and permanent GPS stations, respectively, in order to analyze grids agreement with *in-situ* water level observations and estimate their confidence when used for the evaluation of the water cycle and its connection with the lithosphere displacement. The *in-situ* or local lithosphere vertical displacement monitored by the coordinate time series of a GPS reference network established in the Brazilian part of the Amazon region. The data available are provided by three different projects and institutions: Brazilian Network for Continuous Monitoring of GNSS (RBMC), Low-Latitude Ionospheric Sensor Network (LISN) and *Serviço Geológico Brasileiro* (CPRM). A total of 24 stations were used, 20 of them in the Amazon Basin and four in neighbor basins, Paraná and Tocantins. The *in-situ* water level time series comes from limnimeter stations of *Agência Nacional de Águas* (ANA). A total of 84 limnimeter stations were selected in a radius of 100 km around the GPS stations. The water level variation time series of these stations were used for the comparison and analysis with Ewh grids. The time series of geodetic heights variation are used to estimate the anti-correlation with linmimeters data.

The GRACE grids came from the second release (RL02) of 10-day vertically-integrated Ewh grids inferred from GRACE gravity field models (10-day models). They were computed by the *Centre National d'Etudes Spatiales/Groupe de Recherches de Géodésie Spatiale* (CNES/GRGS) and they represent the information about the total water storage variations that includes ground and surface water and snow packs (FRAPPART *et al*, 2011). The analysis accomplishes four years of data, from January 2007 to December 2010, when a reasonable number of GPS stations were established in the Amazon basin and two neighbor basins, Tocantins and Paraná. The distribution of GPS and limnimeter stations, as well as basins and sub-basins division are presented in Figure 1.

For a better understanding, this paper is divided into 7 parts. Section 2 presents some important aspects of the study region. Section 3 describes GPS data processing and presents the results. The time series construction of *in-situ* datasets (limnimeter and GPS) is presented in section 4. The methodology and particularities of the solution strategy of CNES/GRGS Ewh grids is presented in section 5. The

Ewh anomaly time series computed from the limnimeter stations coordinates in Amazon and neighbor basins are compared with limnimeter time series and the correlation, amplitude and phase results were evaluated in section 6. The summary and conclusions are presented in section 7.

Figure 1 - Distribution of GPS stations (red), limnimeter stations (green) in basins and sub-basins division.



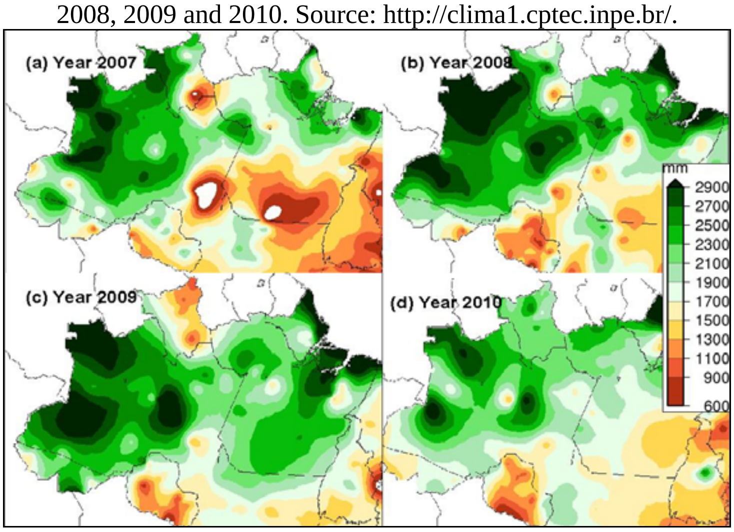
2. THE STUDY REGION – AMAZON BASIN AND NEIGHBOR BASINS

The Amazon Basin covers 6,110,000,000 m² (ANA, 2009) of the South American continent and it has the largest water volume in a continental area. The Brazilian Amazon is one of the most humid areas in the world. The main factor which influences the water level in the Amazon Basin is the intensive rainfall as a consequence of the humidity of the tropical climate. A considerable part of the rain in the Amazon basin is supplied by the ecosystems evapotranspiration, with an annual average contribution from 55% to 60% from the total precipitation (GUIMARÃES *et al.,* 2012). It is a region with a constant scientific interest due to its environmental and climate importance on a global scale and its biodiversity. The great seasonal variation of the water volume and the great amount of sediments transported by the rivers are examples of scientific fields investigated nowadays (MARENGO *et al.*, 2008; MARENGO *et al.*, 2011). Generally, river level variations depend basically on the climate and physics characteristics of the corresponding basin. The basin is dominated by an annual signal with phase peaking in different periods; for example, the maximum level in the center occurs between May and June, in the south, between January and February and in the north, near Boa Vista, it occurs in July.

The vertical ground displacement occurs when the surface of the Earth oscillates in response to seasonal loading fluctuations imposed on the lithosphere. These vertical displacements are mainly caused by the hydrosphere, indicating a strong anti-correlation with the local water level of the Amazon River. As demonstrated by CARRÈRE *et al.* (2009) and TREGONING *et al.* (2009) the large non-linear variations estimated in the GPS coordinates results, derives from elastic deformation of the Earth's surface in response to hydrologic changes and this is clearly observed in the major river basins due to large hydrologic signals (FARRELL, 1972).

Some studies in South America (VAN DAM *et al.*, 2001; BEVIS *et al.*, 2005) already indicated, from GPS time series observations, an annual cycle of vertical displacement with peak-to-peak amplitude of around 7 cm in Manaus, where the Negro river joins the Amazon River and 3 cm in Brasília. In this study is used data from permanent GPS stations where the same annual amplitude was observed, in Urucurituba and in Porto Velho, 100 km and 200 km south of Manaus, respectively. The elastic response of the crust can be even observed in the neighbor basins, 1000 km far from Manaus, but with smaller amplitude. Most rivers have low gradient, with high amount of precipitation, mainly in the sedimentary regions of the basin, which contributes to the considerable extension of the floodplains. Rainfall in the basin and neighbor basins varies greatly in term of both space and time domains as can be seen in the Figure 2 that shows the accumulated precipitation (in millimeters) for the years 2007, 2008, 2009 and 2010.

Figure 2 - Accumulated precipitation in millimeters over the Amazon basin in 2007, 2008, 2009 and 2010. Source: http://clima1.cptec.inpe.br/.



3. GPS NETWORK

As aforementioned, satellite technology provided recent advances in sciences, and GPS is one of the main tools for geosciences. For 3 decades, GPS has made a revolution in geodynamics, allowing to observe and to monitor the variations of a position on the Earth surface. In order to estimate a local vertical lithosphere displacement due to water charge, the time series of geodetic heights from permanent GPS network in the Amazon basin was used. The data are provided by IBGE (ftp://geoftp.ibge.gov.br), Low-Latitude Ionospheric Sensor Network (LISN, http://lisn.igp.gob.pe/) and *Serviço Geológico do Brasil* - CPRM, in daily files. A total of 24 stations form a local GPS network established in the region. The GPS station locations are: Alta Floresta, Belém, Boa Vista, Colider, Cuiabá, Imperatriz, Letícia, Marabá, Macapá, Manaus, Altamira, Itaituba, Parintins, Santarém, São Gabriel da Cachoeira, Rio Branco, Porto Velho, Guajara-Mirim, Colorado D´Oeste, Ji-Paraná(2), Tefé, Palmas and Urucurituba. In addition, 10 IGS stations were included in the differential GPS processing providing the reference frame stability in IGS05. Not all stations in the region were in operation along the whole period (from 2007 to 2010) of study, but they had at least one year of data, in which the annual cycle could be evaluated (Figure 3).

Data was collected and organized in 24-hours files in RINEX format. Some information of the RINEX header were checked before processing, for example, station identification, receiver type, antenna type (according to IGS standard) as well as antenna height.

The GPS data processing was carried out with Bernese software, version 5.0 (DACH *et al.*, 2007) under an automatic mode called BPE (Bernese Processing Engine). The processing applied double phase differences of carrier phase modeled in L3 (L1/L2 ionosphere free), using an elevation mask of 3º and a sampling rate of 30”. Data were processed with the International GPS Service (IGS) precise orbits and the corresponding Earth Oriented Parameters (EOP). The Bernese software uses the DE405 JPL ephemerides and the CSR3.0 (IERS Conventions 2003) tide model for the computation of site displacements due to solid Earth tides. The ocean tide loading coefficients applied in the solutions are based on ocean tide model FES2004 computed from the corresponding values provided by M.S. Bos and H.-G. Scherneck at http://www.oso.chalmers.se/~loading/. The receiver and satellite antenna phase center corrections igs05.atx was applied for the absolute phase center correction model which is compatible with the IGS reference frame IGS05.

Daily solutions were aligned to IGS05 (ALTAMIMI *et al.*, 2007) weekly solutions applying the minimum constraint approach with the proposal to preserve the original characteristics of the network and to reduce the distortions that could come from IGS05 reference frame stations: AREQ, BRFT, CHPI, CRO1, KOUR, LPGS, MANA, RIOP, SCUB and UNSA. The root mean square (RMS) of coordinate residuals between daily and IGS05 weekly solutions in the East, North and Up components were 1.37 mm, 1.51 mm and 3.62 mm, respectively. These results show a good agreement of daily solutions with IGS05.

Figure 3 – GPS network with station distribution, including IGS stations.

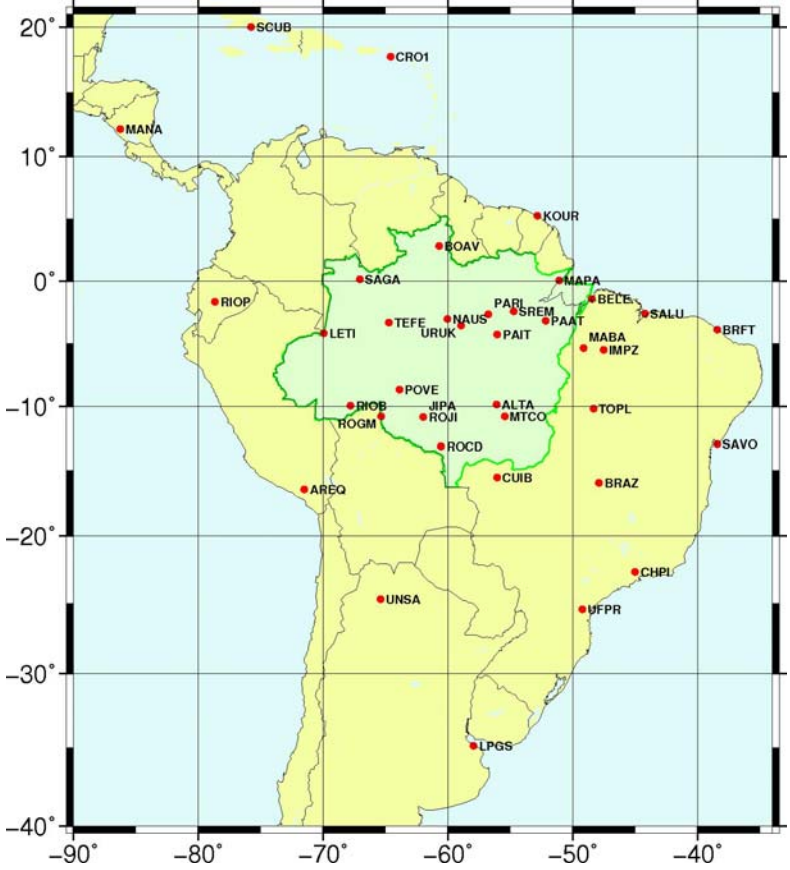
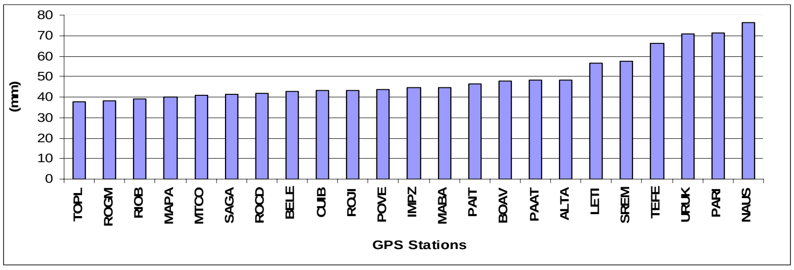


Figure 4 shows the peak-to-peak variations of ellipsoidal height in GPS stations. The figure shows values higher than 7 cm in stations Urucurituba (URUK), Parintins (PARI) and Manaus (NAUS), exactly in the center of Amazon basin and values under 4 cm in Palmas (TOPL), Guajara-mirim (ROGM) and Rio Branco (RIOB). In general, the highest values in the seasonal cycle occur between October and November when the drought period of the river is finishing and rivers have the lowest water level. The lowest values of vertical component occur between April and May when the rain season is finishing and rivers are full of water (flood period).

Figure 4 - Peak to peak variation of ellipsoidal height during the period of study.



4. *IN-SITU* TIME SERIES (LIMNIMETER AND GPS STATIONS)

ANA is responsible for the implementation of the National Water Resources Policy and for coordinating the National Water Resources Management System in the country. The purpose of the National Water Resources Information System is to collect, organize, analyze, and disseminate the data on water resources and water balance of each source and basin. ANA provides the daily measurements of water level at each station and daily estimates of discharge through HidroWeb site (http://hidroweb.ana.gov.br). The limnimeter stations inventory from April, 2011 had 26,880 stations active and deactivated from Brazil and some neighboring countries. Among this total, 2,498 are located in the Amazon basin, 774 in the Tocantins basin and 3,861 in the Paraná basin.

The methodology of acquisition is based on daily *in-situ* water level and precipitation data, by visually reading the water level on the limnimeter scale. The estimated error on the limnimeter scale (cm interval) in the visual process of data reading was of the order of 2 cm (GUIMARÃES *et al.*, 2012).

The following criteria were used for the selection of 84 limnimeter stations used in this study:

1) A radius of 100 km of GPS stations. This radius is justified because from a previous study. BEVIS *et al.* (2005) suggested that the oscillations observed in Manaus are dominated by water loading developed within 200km of the GPS station. Considering that the highest hydrological signals in the region were recorded around Manaus, the half value was adopted for the whole region.
2) Stations with records for the period of 2007 to 2010;
3) Stations installed in the main rivers of basins (Negro, Solimões, Amazonas, Madeira, Tapajós, Xingú and Tocantins) *"on the water stream"* ;

The limnimeters water level time series in 10 days intervals were computed in two steps. From the daily data, it was computed the moving average for intervals of 10 days was computed and, in the second step, values closer to the GRACE Reference Dates (RD) were extracted. The RD are dates used for the estimation of the 10 days Ewh grids. Following the procedure explained formerly, limnimeter data sampling consistent with the Ewh time series was produced.

5. METHODOLOGY

5.1 Grace-Derived Equivalent Water Height-EWH Grids

The GRACE mission was designed to map the world gravity field with high precision every 30 days. It means that temporal variations in the fluid mass on the surface of the Earth can be monitored in periods of 30 days (LEMOINE *et al.*, 2007; BRUINSMA *et al.*, 2010).

For more than 7 years, the GRACE mission contributed significantly to the understanding of the space-temporal patterns of water storage variations in the continents and, in general, to geosciences. More information about the GRACE mission can be found in TAPLEY *et al.* (2004a).

Nowadays, there are five GRACE data processing centers (*University of Texas*, *Centre for Space Research*-CSR, *Jet Propulsion Laboratory*-JPL, *GeoForschungsZentrum*-GFZ and *Centre National d'Etudes Spatiales/Groupe de Recherches de Géodésie Spatiale*-CNES/GRGS). The product provided is the residual GRACE spherical harmonic solutions, representing the variations of continental hydrology (FRAPPART *et al.*, 2011).

In order to evaluate the 10-day vertically-integrated Ewh grids deduced from the GRACE geoid computed by CNES/GRGS, the *in-situ* data from limnimeter stations was adopted. CNES/GRGS through the cooperation with GFZ, produce global gravity solutions, called EIGEN, for the static and time-varying gravity fields. The CNES/GRGS 10-day gravity field models – RL2 (release 2) uses an improved data editing and solution regularization procedure (BIANCALE *et al.*, 2006). The noise in RL2 models is approximately 15 mm (BRUINSMA *et al*., 2010). The background geoid model (time-variable reference geoid model) EIGENGRGS.RL02.mean-field was constructed using an accumulated normal matrix covering 4.5 years (March 2003 to September 2007) of GRACE and LAGEOS data. The EIGENGRGS.RL02.mean-field is used as the mean field to which all 10-day solutions are compared in order to infer temporal variations.

The water loading variations from GRGS grids are calculated from the estimated gravity model, i.e., they are based solely on the 10 days (maximum) of data available within this time interval. For each 10-day GRACE geoids, the Stokes coefficients were solved for degrees 2 through 50 and converted into Ewh anomalies (RAMILLIEN *et al*., 2005).

The 1°x 1° global grids of mass variability (Δ_G) at a point and Ewh represent the water storage variability and have a spatial resolution of approximately 450 km, corresponding to spherical harmonic coefficients up to degree 50 (BRUINSMA *et al*., 2010). The uncertainty of an individual point time series as expressed in Ewh is approximately 20 mm.

The Ewh GRGS grids are available from August 2002 through December 2010 at (http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace/release02). Details about 10-day solutions can be found in BRUINSMA *et al*. (2010).

The 10 days Ewh time series were produced by bilinear interpolation using the four nearest neighbors scheme to estimate the water storage at each ANA station position.

Pearson's correlation coefficient (r) was calculated and least squares adjustment was applied to obtain the coefficients of the regression line between GRACE data with respect to the limnimeter and GPS data. The time series pairs of GRACE Ewh and *in-situ* ANA, were adjusted by least-square linear inversion, in order to get the best fitting between these two pairs of time series, assuming the linear relationship as (GUIMARÃES *et al*., 2012; ALMEIDA, 2009).

6. RESULTS AND DISCUSSION

GRACE results are sensitive to large annual continental mass signals that are generally in agreement with amplitudes and phases of the hydrology and atmospheric prediction models. Their efficiencies were already discussed and validated by many authors, ANDERSEN *et al*. (2008), SEITZ *et al*. (2008) and GÜNTNER (2008), in different hydrological basins. For case of the Amazon basin, CPC hydrology model (FAN and VAN DEN DOOL, 2004) predicts a significantly smaller signal, with a somewhat advanced phase. The differences between the model and GRACE in the Amazon are considerably larger than the GRACE uncertainties (WAHR *et al.*, 2004).

The signal of water surface is composed by seasonal variability (annual and semiannual sinusoids) plus inter-annual variability, shown as linear trend. The annual cycle, its amplitude and phase, as well as the correlation between GRACE and *in-situ* data sets are evaluated herein.

It is important to mention the fundamental fact that the resolution in both, time and space, of the observations used for the analysis are different. The spatial and *in-situ* data do not measure the same geophysics quantity. While limnimeter data represent the water surface measured locally, the Ewh represents the water storage which includes surface and ground water, with a spatial resolution of 400 km measured each 30 days and consequently represents different entities.

Therefore, the comparison does not refer to the magnitudes, but to the behavior of the hydrological signal representing the two series, analyzing their phase displacement and correlations (ANDERSEN *et al*., 2008).

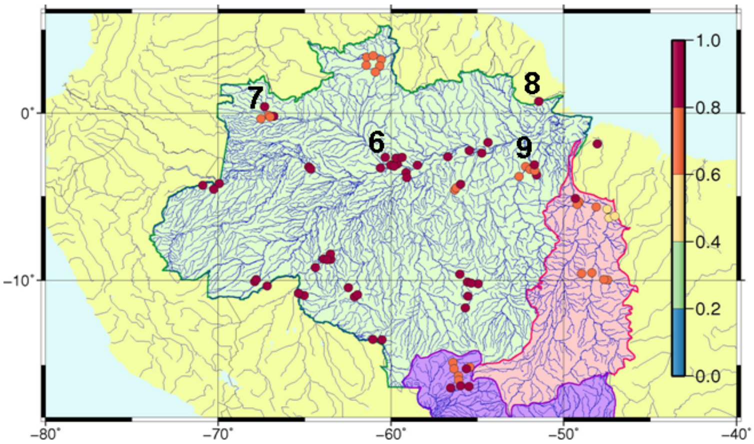
6.1 Comparison Between GRACE EWH and *In-Situ* (ANA) Time Series

This section presents the results of validation analyzing the correlation coefficient between GRACE Ewh and *in-situ* water level time series. Figure 5 shows that the signal of Ewh has a good agreement with the limnimeter water level, mainly in the regions in the center to the south of the Amazon basin between the end of the Solimões and the beginning of the Amazon rivers, as well as in the Madeira river and its tributaries in areas close to the Brazilian border with Colombia (Tabatinga) and Peru (Guajara-mirim). A strong correlation ($\boldsymbol{r} \geq 0.7$) is evident in 70% of the limnimeter stations in these areas. Lower correlation ($\boldsymbol{r} < 0.7$) was found in the Tocantins and the Paraná basins, mainly close to Palmas, Imperatriz and Cuiabá, as well as near São Gabriel da Cachoeira and Boa Vista. In these areas, as well as in regions close to the Amazonas mouth a discrepancy between seasonal cycles of limnimeter stations and Ewh was found. This was investigated using amplitude and phase results from both observations.

Figures 6a up to 9a show the time series for the period 2007 - 2010 from four limnimeter stations of the Amazon and the Tocantins basins. The ANA water level variations, GRACE Ewh variations and GPS are represented by squares/blue, circles/Green, triangles/red, respectively. The limnimeter stations locations are shown in Figure 5. Water level variation of limnimeter stations, GRACE Ewh variation and the vertical deflection of lithosphere from GPS stations near limnimeter stations (<15 km) are shown in the referred figures. The GPS cycle is presented in these figures just to show the relationship of water charge with crust loading. The scatter plots of regression line between water level variation of limnimeter stations and GRACE Ewh are presented in Figures 6b up to 9b. A delay can be observed between ANA and GRACE cycles in 29050000 station, Tocantins basin, which is clear in the regression line (Figure 9b).

The same behavior of slope coefficient of the regression line *a* observed by ALMEIDA *et al*. (2011) was found in this study. Generally decreases from up to down stream in most of major rivers of Amazon basin. In fact, the values of *a* coefficient are not link, in all cases, with the amplitude. The extreme value of *a* (27.8), was found in Solimões river, at the boundary of Brazil and Colombia, but not in areas where was found the highest amplitudes of annual cycles and the decrease of *a* is not identical for all rivers.

Figure 5 - Geographic distribution of correlation coefficient between GRACE Ewh and limnimeter stations (ANA).

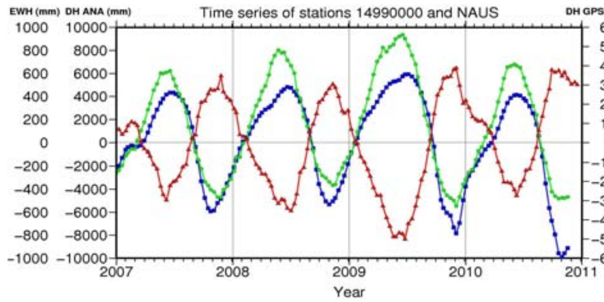


Figures 6(a), 7(a), 8(a), 9(a) - (from the top to bottom): Time series for the 2007 - 2010 period from four limnimeter stations. Squares/blue-ANA water level variations, circles/Green-GRACE-Ewh variations and triangles/red-GPS.

Figures 6(b), 7(b), 8(b), 9(b) - (from the top to bottom): the scatter plots of regression line between water level variation of limnimeter stations and GRACE Ewh.

Figure 6

(a)



(b)

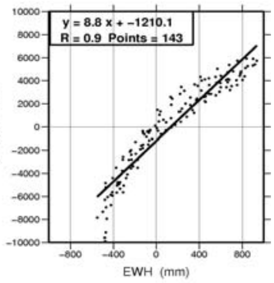
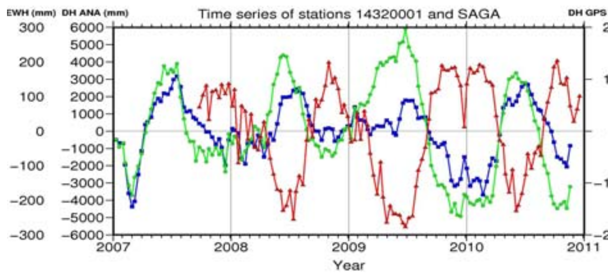


Figure 7

(a)



(b)

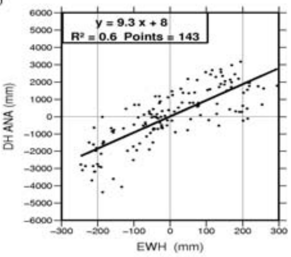
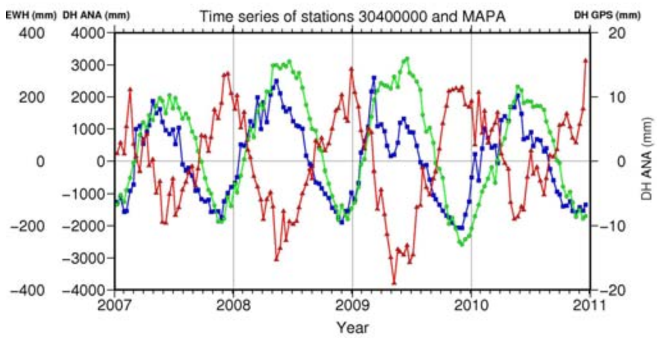


Figure 8

(a)



(b)

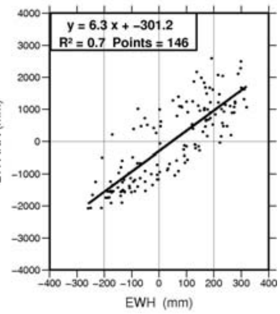
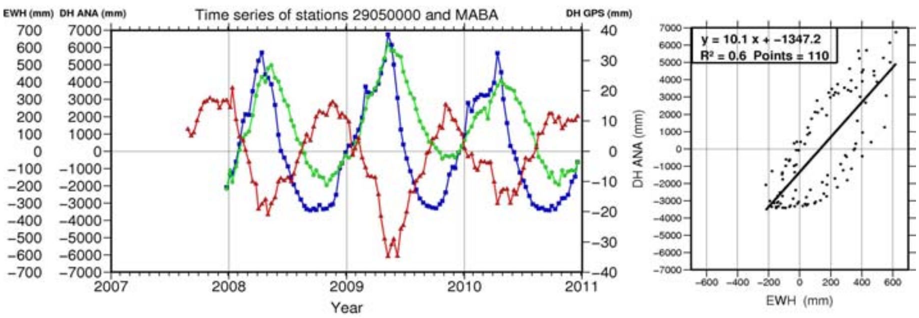


Figure 9

(a) (b)



6.2. Amplitude and Phase from Grace EWH and *In-Situ* (ANA) Time Series

The year 2010 could not be included in this evaluation because data from the whole year is necessary, which, was not available for the limnimeter stations.

Figure 10 presents a comparison between *in-situ* data and GRACE Ewh amplitudes, ordered from the smallest to highest by *in-situ* data. As can be seen the largest amplitudes of GRACE, Ewh was 500 mm in Manaus and Urucurituba areas, exactly in the center of the Amazon basin, junction of the Amazon and the Negro rivers. The amplitudes from both datasets have a good agreement, in the main rivers, i.e., Amazonas, Solimões, Tapajós, Xingú and Madeira. In some cases, the GRACE Ewh amplitudes are not proportional to the observed amplitudes of *in-situ* data. This is the case of Tabatinga, on the border of Colombia, as can be seen in Figure 10, 19^{th} bar; this is probably due to different hydrogeological domains in the Amazon basin.

The largest inter-annual amplitudes were observed between 2008 and 2009 in the Amazon and the Madeira rivers. On the other hand, in the north part of the basin, near Boa Vista, the smallest inter-annual amplitudes in 2009 were observed, indicating that the inter-annual variations have a strong connection with climate variations, which can change the annual hydrological cycle. Looking at Figure 2c (corresponding to 2009) less precipitation can be observed in the north of the basin in comparison to 2007 and 2008.

Considering the mean phase differences during 2007, 2008 and 2009, an unusual behavior of GRACE Ewh observation can be found in S.G da Cachoeira, because only in this part of the Negro River is the phase positive, indicating that GRACE Ewh cycle is around 20 days in advance of *in-situ* data cycle.

As can be seen in Figure 11, 70% of the phase differences are between -10° and -50 °, indicating that GRACE observations have a delay of ~ (10 to 50) days when compared with *in-situ* data. This delay can be observed in Figure 9a.

The greatest phase difference occurs in Boa Vista, with 59 days, and the smallest in the center of the basin, close to Manaus, with 1 day of delay.

Positive phase difference between GRACE and *in-situ* data was found only in S. Gabriel da Cachoeira (upper part of the Negro River); this is probably due to waterfalls in this area.

Figure 10 - Comparison between limnimeter data and GRACE Ewh amplitudes.

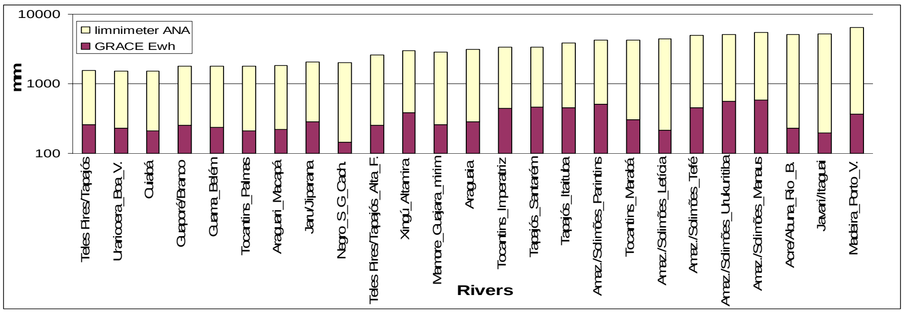
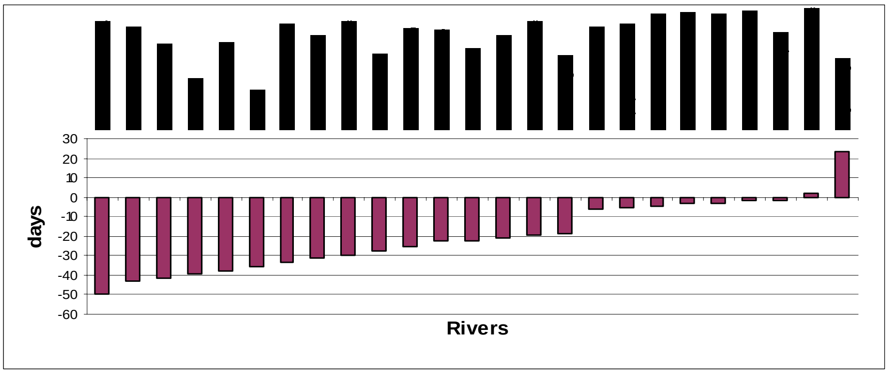


Figure 11 - Phase differences between limnimeter data and GRACE Ewh.



Figures 12 and 13 show the amplitudes and phases of annual and semiannual cycles from 43 limnimeter stations (red) and their GRACE EWh (blue), a selection of stations with strong correlation coefficient, respectively. The amplitude is indicated by the length of vectors and phase is indicated by the orientation of vectors. The vector direction is counter-clockwise starting from horizontal. Large part of Amazon basin the annual cycle is dominant and both time series have a strong energy. Stations time series in the south part of basin and neighbors basins along Tocantins, Cuiabá and Teles Pires rivers (crystalline domain), have annual phase differences, between 40° to 20°, as can be seen in the Figure 12. In the sedimentary part of the basin, along Amazonas and Madeira rivers, both time series have very small discrepancies and they can be considered in phase. The semiannual cycle can be an indicative of two distinct seasons as suggested by CHIH-PING and JOHN WALLACE (1976) in the precipitation analysis. The semiannual cycle in both time series is in phase in few areas, for example in Cuiabá and in Porto Velho, but in the same region big discrepancies can be found (Figure 13).

Figure 12 - Amplitude and phase of the annual cycle.

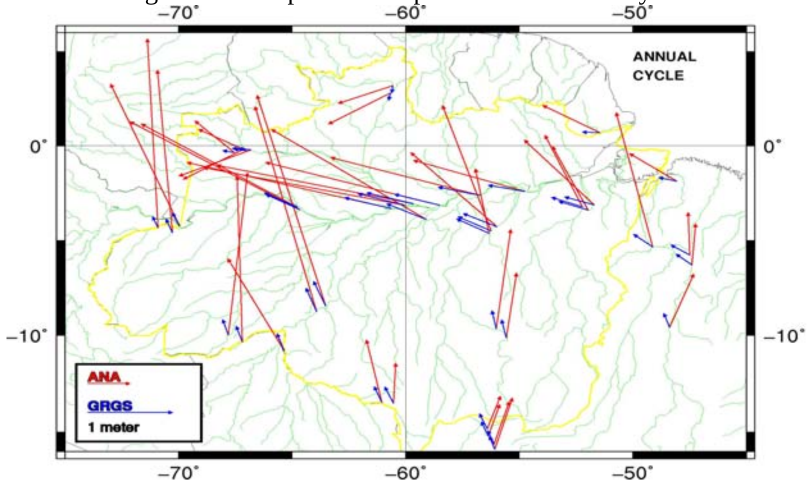
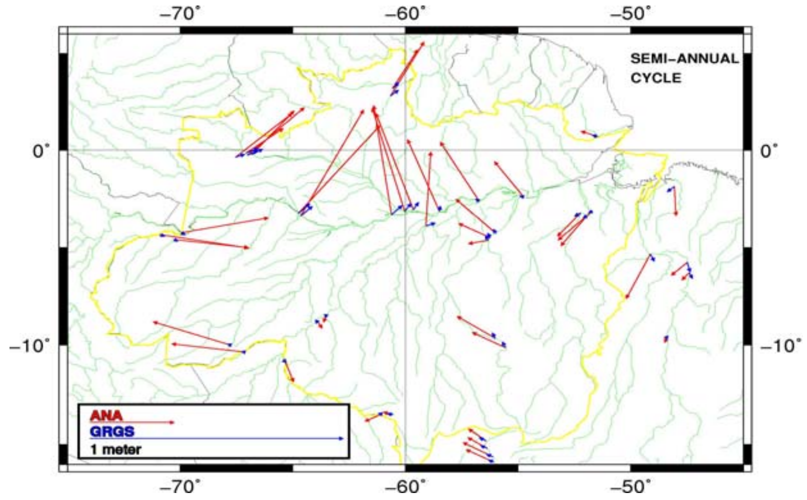


Figure 13 - Amplitude and phase of the semiannual cycle.



6.3. Comparison Between Water Level (ANA) and Heights (GPS) Time Series

This section presents the results of anti-correlation coefficient between two *in-situ* observations: water level and ellipsoidal heights time series. Figure 14 shows clearly how the strong signal from surface water affects the heights in the sedimentary part of Amazon basin, including the Madeira river and its tributaries in areas close to the Brazilian border with Colombia (Tabatinga) and Peru (Guajara-mirim). A strong anti-correlation ($\boldsymbol{r} \geq 0.7$) is evident in 50% of the limnimeter stations in these areas. Lower anti-correlation ($\boldsymbol{r} < 0.7$) was found in the Tocantins and the Paraná basins. Figure 15 shows vectors representing the amplitudes and phases from the annual cycles of water level of 62 ANA stations and ellipsoidal heights of the 15 GPS stations (the ones that had at least one year of data). These 62 limnimeter stations were selected in a radius of 100 km around the GPS stations. As expected, the vectors are in opposite directions due to anti-correlation of water level and heights. Phase differences between these two cycles are around 180° in stations close to Manaus (NAUS), Boa Vista (BOAV) and Tefé (TEFE), in the other stations of basin it is between 140° to 160°. Phase difference in stations in the neighbor basins like Palmas (TOPL), Imperatriz (IMPZ) and Cuiabá (CUIB) can reach 110°. The phase difference can be interpreted as the approximate time lag that solid Earth answers due to water loading. Semiannual cycle was not analyzed in this case because for GPS the amplitude is too small and consequently meaningless.

Figure 14 - Geographic distribution of anti-correlation coefficient between limnimeter stations (ANA) and GPS.

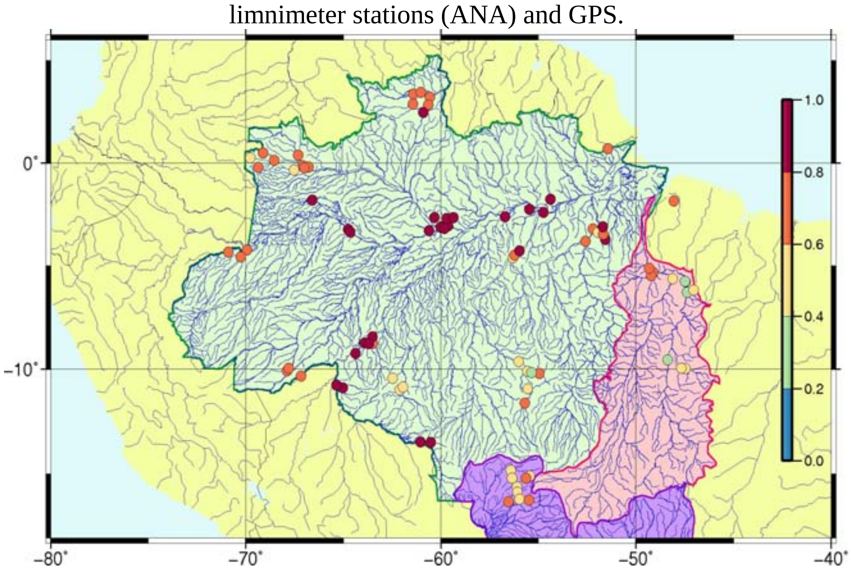
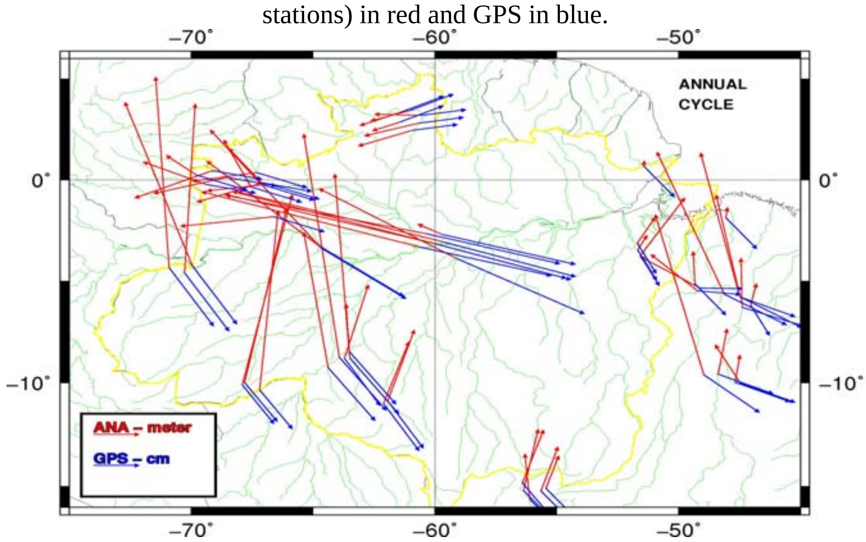


Figure 15 - Amplitude and phase of the annual cycle from limnimeter (ANA stations) in red and GPS in blue.



7. SUMMARY AND CONCLUSIONS

This study aims at a validation through the comparison of GRACE models Ewh, representing the water ground storage with two *in-situ* data: Water level from limnimeter stations and GPS heights in the Amazon basin. To achieve the goals, the following analyses were carried out:

1) Comparison of GRACE Ewh and water level variation from *in-situ* data (ANA stations);
2) Comparison of water level variation from *in-situ* data (ANA stations) and ellipsoidal height variations from GPS;
3) Trends of water level from *in-situ* data (ANA stations), GRACE Ewh and ellipsoidal height from GPS;
4) Crustal loading response due to continental water charge and droughts periods.

For all data types of data, the coefficient of correlation, phase (annual cycle) and amplitude has been estimated from a common dataset spanning the period 2007 and 2010.

The GRACE Ewh generally had good agreement in the Amazon basin, consequently it can be used to predict *in-situ* measurements mainly in the center and in the south of the basin. In the neighbor basins, a phase delay with *in-situ* data can reach 50 days. There are two possible causes for this delay: (1) the presence of noise and (2) the lack of spatial resolution between GRACE (400 km) and any local measurement. From the 84 limnimeter stations used for this evaluation, only two presented positive phase difference and they are located near São Gabriel da Cachoeira (Negro River). A possible cause for this result is the leakage error of GRACE grids, but it needs further investigation.

The anti-correlation coefficients between ANA and GPS stations in 50% of stations were higher than 0.70. It indicates the strong influence of water loading in the crust displacement. Earth surface loading due to water charge depends basically on the type of ground. For the future work, we intend to complement our evaluations with hydrogeological studies which we understand can contribute to the conclusions of some results obtained. There is a tendency of water level decreasing mainly in the center of basin and an opposite trend (uplift) in the neighbors basins.

The results obtained in this study will contribute to better monitoring and understanding the water cycle and in particular the improvements that can be expected when data from the current satellite missions are used.

ACKNOWLEDGMENTS

The authors acknowledge the institutions IBGE, CPRM, ANA, LISN and GRACE project for the data. The Activity has been undertaken with the financial support by Brazilian National Research Council of Scientific and Technological Development (CNPq) through POS-DOC fellowship.

REFERENCES

ALMEIDA, F.G.V. (2009). *Variação temporal do campo gravitacional detectada pelo satélite GRACE: Aplicação na bacia Amazônica.* PhD thesis - Escola Politécnica, Universidade de São Paulo, São Paulo, 146 p.

ALMEIDA, F. G. V. ; CALMANT, S. ; SEYLER, F. ; RAMILLIEN, G. ;BLITZKOW, D. ; MATOS, A.C.O.C. ; SILVA, J. S. (2011). *Time-variations of equivalent water heights from Grace Mission and in-situ river stages in the Amazon basin*. Acta Amazonica (in press).

ALTAMIMI, Z., X. COLLILIEUX, J. LEGRAND, B. GARAYT, AND C. BOUCHER (2007), *ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters*, *J. Geophys. Res.*, 112, B09401, doi:10.1029/2007JB004949.

ANA - Agência Nacional de Àguas (2009). *Bacía do Rio Amazonas: Informações sobre a bacia (2006).* Available: <http://www.ana.gov.br>. Accessed: 01/08/2011.

ANDERSEN, O., P. BERRY, J. FREEMAN, F. G. LEMOINE, S. LUTSCKHE, F. JAKOBSEN, AND M. BUTTS (2008). *Satellite altimetry and GRACE gravimetry for studies of annual water storage variations in Bangladesh*. Terr. Atmos. Ocean. Sci., 19, 47-52, doi: 10.3319/TAO.2008.19.1-2.47(SA).

BEVIS M., ALSDORF D., E. KENDRICK, L. P. FORTES, B. FORSBERG, R. SMALLEY, AND J. BECKER (2005). *Seasonal fluctuations in the mass of the*

Amazon River system and Earth's elastic response; *Geophysical Research Letters*, 32, L16308, doi:10.1029/2005GL023491.

BIANCALE R., J.-M. LEMOINE, G. BALMINO, S. LOYER , S. BRUISMA , F. PÉROSANZ ,J.-C. MARTY AND P. GÉGOUT (2006). *3 years of geoid variations from GRACE and LAGEOS data at 10-day intervals from July 2002 to March 2005*, CNES/GRGS products, data available on CD-ROM.

BRUINSMA, S., LEMOINE, J.-M., BIANCALE, R., VALÈS N. (2010). *CNES/GRGS 10-day gravity field models (release 2) and their evaluation*, Adv. Space Res., 45, 4, 587-601, 2010, doi: 10.1016/j.asr.2009.10.012.

CARRÈRE, P., WATSON C., RAMILLIEN G., MCQUEEN H. AND ZHANG J. (2009), *Detecting hydrologic deformation using GRACE and GPS*, Geophys. Res. Lett., 36, L15401, doi:10.1029/2009GL038718.

CHAMBERS, D. P. (2006), *Evaluation of new GRACE time-variable gravity data over the ocean*, Geophys. Res. Lett., 33, L17603, doi:10.1029/2006GL027296.

CHEN, J. L., C. R. WILSON, J. S. FAMIGLIETTI, AND M. RODELL (2005), *Spatial sensitivity of GRACE time-variable gravity observations*, J. Geophys. Res., 110, B08408, doi:10.1029/2004JB003536.

CHIH-PING F. HSU AND JOHN M. WALLACE (1976), *The Global Distribution of the Annual and Semiannual cycles in the Precipitation*, Department of Atmospheric Sciences, University of Washington, Seattle 98195.

FAN, Y., H. VAN DEN DOOL, H. (2004). Climate Prediction Center global monthly soil moisture data set at 0.5^o resolution for 1948 to present. *Journal of Geophysical Research 109(D10):* doi: 10.1029/2003JD004345. issn: 0148-0227.

FARRELL, W.E. (1972). *Deformation of the Earth by surface loads*. Rev. Geophys., 10, 761-797.

DACH R., U. HUGENTOBLER,P. FRIDEZ, M. MEINDL (2007). *Bernese GPS Software Version5.0*, Astronomical Institute, University of Bern.

FRAPPART, F., RAMILLIEN G., LEBLANC M., TWEED S.O., BONNET M.P., MAISONGRANDE P. (2011). *An independent component analysis filtering approach for estimating continental hydrology in the GRACE gravity data, Remote Sensing of Environment*,115, 187–204, doi:10.1016/j.rse.2010.08.017.

GÜNTNER, A.,(2008). *Improvement of Global Hydrological Models Using GRACE Data*, Surv Geophys (2008) 29:375–397, DOI 10.1007/s10712-008-9038-y.

LEMOINE J.-M., S. BRUISMA, S. LOYER, R. BIANCALE, J.-C. MARTY, F. PÉROSANZ AND G. BALMINO (2007). *Temporal gravity field models inferred from GRACE data*, Advances in Space Research, Volume 39, Issue 10, p. 1620-1629.

MARENGO, J.A., C.A. NOBRE, J. TOMASELLA, M.D. OYAMA, G.S. OLIVEIRA, R. OLIVEIRA, H. CAMARGO, L.M. ALVES, I.F. BROWN (2008). The Drought of Amazonia in 2005*. Journal of Climate*, 21, 495-516.

MARENGO, J. A., J. TOMASELLA, L. M. ALVES, W. R. SOARES, AND D. A. RODRIGUEZ (2011), *The drought of 2010 in the context of historical droughts in the Amazon region*, Geophys. Res. Lett., 38, L12703, doi:10.1029/2011GL047436.

GUIMARÃES, G. N., BLITZKOW, D., MATOS, A.C.O.C., ALMEIDA FILHO, F.G.V., BARBOSA, A.C.B.(2012). Analysis of the Crust Displacement in Amazon Basin. *Geodesy for Planet Earth - Proceedings* of the 2009 IAG Symposium. Berlin: Springer, 2012, v 136, 885-892

RAMILLIEN, G., F. FRAPPART, A, CAZENAVE, A. GÜNTNER (2005). Time variations of land water storage from an inversion of 2 years od GRACE geoids. *Earth and Planetary Science Letters*, 235, 283-301.

SEITZ, F., M. SCHMIDT, C.K. SHUM (2008). Signals of extreme weather conditions in Central Europe in GRACE 4-D hydrological mass variations. *Earth Planet. Sci. Lett*., 268, 165-170, doi:10.1016/ j.epsl.2008.01.001.

TAPLEY B., S. BETTADPUR, M. WATKINS, C. REIGBER (2004a). *The gravity recovery and climate experiment: mission overview and early results*. Geophys Res Lett 31:L09607. doi:10.1029/2004GL019920.

TREGONING, P., C. WATSON, G. RAMILLIEN, H. MCQUEEN, AND J. ZHANG (2009), *Detecting hydrologic deformation using GRACE and GPS*, Geophys. Res. Lett., 36, L15401, doi:10.1029/2009GL038718.

VAN DAM, T., J. WAHR, P. MILLY, A. SHMALKIN, G. BLEWITT, D. LAVALLE´E, AND K. LARSON (2001), *Crustal displacements due to continental water loading*, Geophys. Res. Lett., 28, 651– 654.

WAHR, J., S. SWENSON, V. ZLOTNICKI, AND I. VELICOGNA (2004), *Time-variable gravity from GRACE: First results*, Geophys. Res. Lett., 31, L11501, doi:10.1029/2004GL019779.

(Recebido em outubro de 2011. Aceito em abril de 2012.)