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- Crustal displacements derived from GRACE and hydrological models
- Vertical component of GPS time series over the Amazon basin
- Historical flood and drought in the Amazon basin

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- Figure S1
- Figure S2
- Figure S3

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Comparisons of observed and modeled elastic responses to hydrological loading in the Amazon basin

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Abstract In large hydrological basins, water mass loading can produce significant crustal deformation. We compare the monthly vertical component of 18 GPS sites located in the Amazon basin, with the deflection models derived from Gravity Recovery and Climate Experiment (GRACE) observations on the one hand and derived from HYDL, a global hydrological model, on the other hand. The GPS data set includes the largest deflections by hydrological loading ever recorded at two stations located in the center of the basin. The main result of the study is that the GRACE solution produced by GRGS (Groupe de Recherche en Géodesie Spatiale, Toulouse, France) produces the best agreement with the Global Navigation Satellite Systems series with a correlation coefficient up to 0.9 in the center of the basin, although 70% at best of the RMS variation in the GPS series is accounted for.

1. Introduction

Vertical crustal displacements caused by hydrological loading (hereafter VCD-HL) are poorly monitored since they mostly occur in large tropical basins, where the monitoring of the geophysical processes is complicated by the remoteness of the sites due to lack of infrastructure.

A straightforward method to monitor water load variations would be to use long and continuous coordinate time series from permanent GPS stations. However, in remote regions like the Amazon basin, such equipment is usually limited in number and the corresponding measurements recorded are of low quality due to poor maintenance. *Bevis et al.* [2005] presented, as far as the authors are aware of, the only study published in the literature of vertical displacements based on in situ measurements within the Amazon basin, the largest hydrological basin on Earth encompassing approximately 6,000,000.00 km^2. They used 2 years of noncontinuous data collected by the MANA GPS station at Manaus, at the center of the basin. This study evidenced a 7.5 cm peak to peak crustal vertical variation. This signal was identified by the referred authors as the signature of the annual flood of the river. Similarly, *Steckler et al.* [2010] explained a cyclic variation of about 5 cm in the vertical coordinate of GPS stations in Bangladesh due to the hydrological cycle of the Ganges-Brahmapoutra system. Other studies from *van Dam et al.* [2001, 2007], *Wu et al.* [2006], *Tesmer et al.* [2011], and *Tregoning el al.* [2009] have identified other regions on the Earth where VCD-HL are large enough to significantly affect geodetic station coordinates. Hence, the effects of hydrological loading have to be considered when centimeter-level accuracy positioning is expected.

Any precise geodetic survey relies on an explicit reference system. The International Terrestrial Reference Frame 2008 [*Altamimi et al.*, 2011], which is called ITRF2008, represents the state of the art in terms of the realization of such system. Its use is recommended through International conventions from the International Earth Rotation and Reference Systems Service [*McCarthy and Petit*, 2011]. According to these conventions the instantaneous position $\vec{X}(t)$ at epoch *t* of a point relative to the Earth's crust and its regularized position $\vec{X}_R(t)$ are defined by equation (1):

$$\vec{X}(t) = \vec{X}_R(t) + \sum_i \Delta\vec{X}_i(t) \quad (1)$$

The regularized position is supposed to be free of high-frequency variations. Actual standards for the $\Delta\vec{X}_i(t)$ have the following effects: solid tides arising from the direct effect of the Moon, the Sun, and the planets;

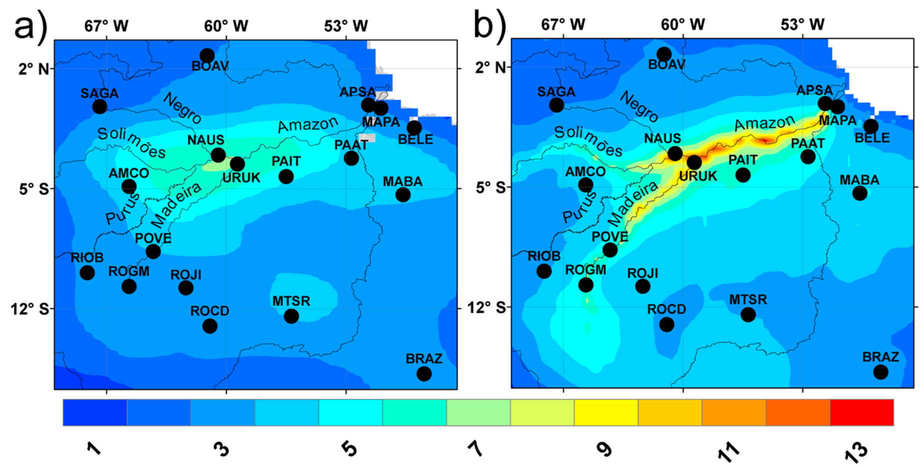

Figure 1. (a) GRACE-derived and (b) HYDL vertical displacement maximum amplitude (cm). Based on 2007–2014 GRACE (GRGS) and HYDL series. Black dots indicate the permanent GPS stations in the Amazon basin used in this study.

ocean tidal loading; diurnal and semidiurnal atmospheric pressure loading; and centrifugal perturbations caused by Earth's rotation variations, including the pole tide and the loading caused by the ocean pole tide.

In various regions on the Earth, VCD-HL cannot be neglected and should be included in this list but no standard global model exists yet to take this effect into account. In the Amazon basin, not correcting GPS positions from this effect may significantly impact geodetic experiments like network surveying, tide gauge leveling, or satellite altimeter calibration. However, VCD-HL models can be derived from rheological parameters and from either time variable gravity field (TVGF) measurements or hydrological data.

Water mass variations produce slight changes in the Earth's gravity field. Such variations are perceived by the Gravity Recovery and Climate Experiment (GRACE) space mission [*Tapley et al.*, 2004], launched in March 2002. These changes in superficial water mass represent more or less load on the Earth's crust that deflects accordingly. *Davis et al.* [2004] showed an excellent agreement between crustal deformations derived from GRACE data and variations in vertical coordinates at GPS stations using data from the first 2 years of the mission. Later on, *Tesmer et al.* [2011] compared GRACE-derived VCD-HL to time series of the vertical component at 115 permanent GPS stations spread worldwide. They showed that for 80% of the sites, including GRACE-derived time series of VCD-HL in the list of correcting displacement, $\Delta\vec{X}(t)$ reduced significantly the RMS scatter in the GPS series of vertical coordinates. However, none of these studies used stations located within the Amazon basin, while this region undergoes the largest seasonal signal of VCD-HL on Earth (Figure 1).

Van Dam et al. [2001] first used hydrological models to derive VCD-HL series. Nevertheless, the correction they obtained for station Up coordinates was much smaller than those found using GRACE data (e.g., around 3 cm peak to peak at the center of the Amazon basin). Recently, *Dill and Dobslaw* [2013] used the so-called "HYDL" land surface discharge model developed by *Dill* [2008] to compute VCD-HL. Their results better match GPS series in the Amazon basin. Figure 1b shows that the amplitude of the model reaches 5–7 cm along the central corridor. The main advantage of this model is its higher spatial and temporal resolution compared to GRACE data.

In this study we focused on the Amazon basin which has recently experienced the largest ever hydrological loading deformation. Figure 2 shows the GPS Up coordinate time series for Manaus (NAUS) station compared to vertical displacements derived from GRACE and to hydrological data. The maximal extreme difference reaches 10 cm. We wanted to assess which option, among the various GRACE solutions available and the HYDL model outputs, better reproduces seasonal VCD-HL signal by using as reference a data set made up of 18 GPS permanent stations (Figure 1) located within and near the Amazon watershed.

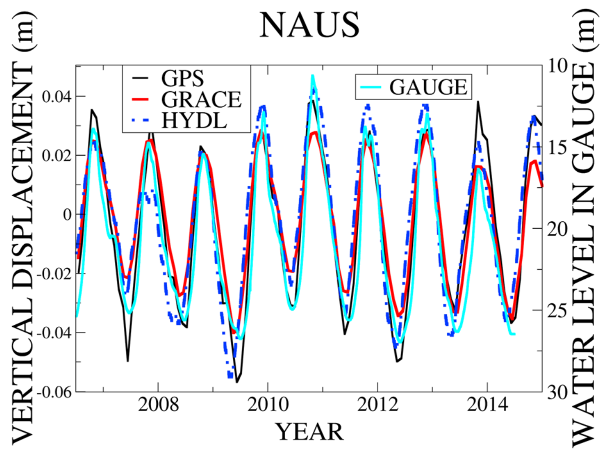

Figure 2. Vertical crustal displacement (cm) at NAUS station using different techniques, namely, the HYDL hydrological model, GRACE mission, and GPS positioning. Note that this station is at the same location in Manaus (cf. Figure 1), as the MANA station used by *Bevis et al*. [2005], now inactive.

2. Methodology

2.1. GPS Data

Our analysis is based on a network of 18 GPS stations located within the Amazon basin and at its rim (Figure 1) managed by the Brazilian Institute of Geography and Statistics (IBGE). Daily station coordinates were computed using the GINS software [*Marty et al*., 2011] developed by the French Space Agency (CNES). As it was anticipated that the entire region would be affected by significant hydrologic crustal deformation, the Precise Point Positioning (PPP) technique [*Heroux and Kouba*, 1995], which provides "absolute" positions, has been preferred to the classical relative differential approach which needs reference stations [*Zumberge et al*., 1997]. This PPP technique requires high-precision satellite orbit and clock products. We used the one delivered by the CNES-CLS IGS Analysis Center as it was produced using also the GINS software [*Loyer et al*., 2012] in order to guaranty the highest processing consistency. Coordinates were produced in the ITRF2008 frame, and all the recommended crustal deformation from the International Earth Rotation and Reference Systems Service (IERS) conventions (see section 1) were considered, including the atmospheric loading correction. Consequently, the remaining variations in the series of vertical coordinate should mainly reflect the hydrological loading as this is the dominant source of not-modeled crustal deformation in the Amazon basin. Daily solutions were averaged on a monthly basis (using a 3 sigma outlier rejection), and the expected accuracy of such processing is below 5 mm 3-D RMS.

2.2. GRACE Data Sets

We analyzed the GRACE monthly series produced by four analyses released by properly established data centers, namely, RL05 from Center for Space Research, University of Texas, U.S. (CSR) [*Bettadpur*, 2012]; RL05 from GeoForschungsZentrum, Potsdam, Germany (GFZ) [*Dahle et al*., 2012]; RL05.1 from Jet Propulsion Laboratory, U.S. (JPL) [Watkins, 2012]; and RL03-v1 from Groupe de Recherche de Géodésie Spatiale (GRGS) [*Bruinsma et al*., 2010]. The set of spherical harmonics coefficients from these groups was first filtered in order to remove the well-known striping artifact affecting GRACE solutions. Then, they were converted into crustal displacements using the methodology developed in *Wahr et al*. [1998], *Davis et al*. [2004], and *Van Dam et al*. [2007]. The GRACE solutions are provided free of atmospheric load; hence, they are natively consistent with our GPS solutions. Because of the characteristics of the mission, the spatial resolution is limited to $3° \times 3°$ in equatorial regions.

2.3. HYDL Data Sets

As an IERS Associated Product Centre, the German GFZ group delivers daily global grids of crustal deflection from the HYDL model (ftp://ig2-dmz.gfz-potsdam.de/LOADING/). These grids are distributed at a $0.5° \times 0.5°$ spatial resolution and were resampled at a monthly temporal resolution for our analysis. The hydrological inputs are based on the European Centre for Medium-Range Weather Forecasts (ECMWF) weather models which include terrestrial water storage and runoff. More information about HYDL and ECMWF can be found in *Dill and Dobslaw* [2013] and *Balsamo et al.* [2009]. VCD-HL series were calculated at the locations of the 18 GPS stations using a bicubic interpolation from the grids. Since this model only includes hydrological loading, crustal deflections are also free of atmospheric load, consistently with our GPS and GRACE solutions of crustal deformation.

2.4. Analysis

Each monthly VCD-HL from the four GRACE gravity data and the HYDL hydrological model has been compared to the averaged vertical coordinates of the 18 Amazonian GPS stations on a time span covering

Table 1. Comparison of GRACE (CSR, JPL, GFZ, and GRGS Solutions) and HYDL VCD-HL Vertical Displacement Series With GPS Component Solutions (2010 to 2014) at 18 GPS Sites in the Amazon Basin (as Shown in Figure 1): Minimum, Maximum, and Mean Values Corresponding to Scale Factors (Slope of Linear Regression Equation), Linear Correlation Coefficient, and Rate (%) of RMS Signal Reduction (Equation (2))

	Scale Factor			Correlation			RMSred (%)		
Series	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
CSR	0.38	0.96	0.67	0.56	0.93	0.85	18	65	47
JPL	0.36	0.99	0.63	0.59	0.96	0.86	18	65	48
GFZ	0.26	1.13	0.67	0.45	0.93	0.76	1	60	34
GRGS	0.43	1.06	0.7	0.71	0.99	0.9	29	72	55
HYDL	0.45	0.97	0.66	0.66	0.93	0.84	25	64	44

2008 to 2014. The comparison is based on the three following indicators: correlation coefficient, calculated from the linear fitting of the correlation plot; scale factor, given by the slope of the correlation plot; and RMS reduction, calculated from the comparison of the GPS Up coordinate series before and after applying one of the loading corrections. The normalized RMS reduction RMS_{red} was computed from equation (2):

$$RMS_{red} = \frac{RMS_{GPS} - RMS_{GPS-(GRACE\ or\ HYDL)}}{RMS_{GPS}} \times 100\% \quad (2)$$

where RMS_{GPS} is the RMS of the GPS series and $RMS_{GPS\ -\ (GRACE\ or\ HYDL)}$ is the RMS of the GPS series corrected from one of the VCD-HL models.

3. Results

At the center of the basin where the three largest tributaries converge, the NAUS (Figure 2) and URUK station series display the largest vertical variations ever recorded due to hydrological loads (up to 10 cm peak to peak). It is worth noting that the variations recorded by the GPS stations is larger than those presented by *Bevis et al*. [2005] because our series include the largest floods (2009 and 2012) and drought (2010) ever measured in the Amazon basin.

From a more general point of view, Table 1 summarizes the gravity and hydrological models evaluation for the entire network using the three indicators defined in section 2.4. The main conclusions are as follows:

1. RMS in the GPS series is significantly reduced, and it should be noted that from 20 to 70% of the GPS signal can be explained by hydrological loading.
2. On the other side around 50% of the residuals remain not modeled; this is also reflected by the scale factor estimations.
3. The high level of correlation confirms that the entire observed GPS signal is driven by seasonal processes.
4. Looking altogether over the three indicators, the VCD-HL derived from GRGS GRACE model systematically agrees better with the GPS series.

Therefore, only results from GRACE GRGS solutions and HYDL will be shown hereinafter. The four maps in Figures 3a–3d display the RMS reduction and correlation indicators obtained from both gravity (GRGS) and hydrological (HYDL) models. For most stations the gravity model exhibits a correlation greater than 0.9 (Figure 3a) and reaches 0.97 at NAUS and 0.99 at URUK where the largest deformations occur. The lowest correlations are found at PAIT (0.84) and RIOB (0.71) stations on the Tapajós and Madeira subbasins, respectively. This might be assigned to the limited spatial resolution of GRACE which cannot separate the local hydrological signals from these different tributaries.

In addition, the correlation coefficient is significantly worse in MAPA than in ASPA, while the two stations are close and similarly affected by VCD-HL. Having a closer look at the original daily GPS solutions, we noticed that the MAPA series had a significantly worse repeatability than ASPA (respectively 1.3 cm and 0.7 cm of standard deviation around the monthly averaged value). We suspect the electromagnetic environment of the MAPA antenna as being the disturbance source (i.e., multipath), but more investigation will be needed.

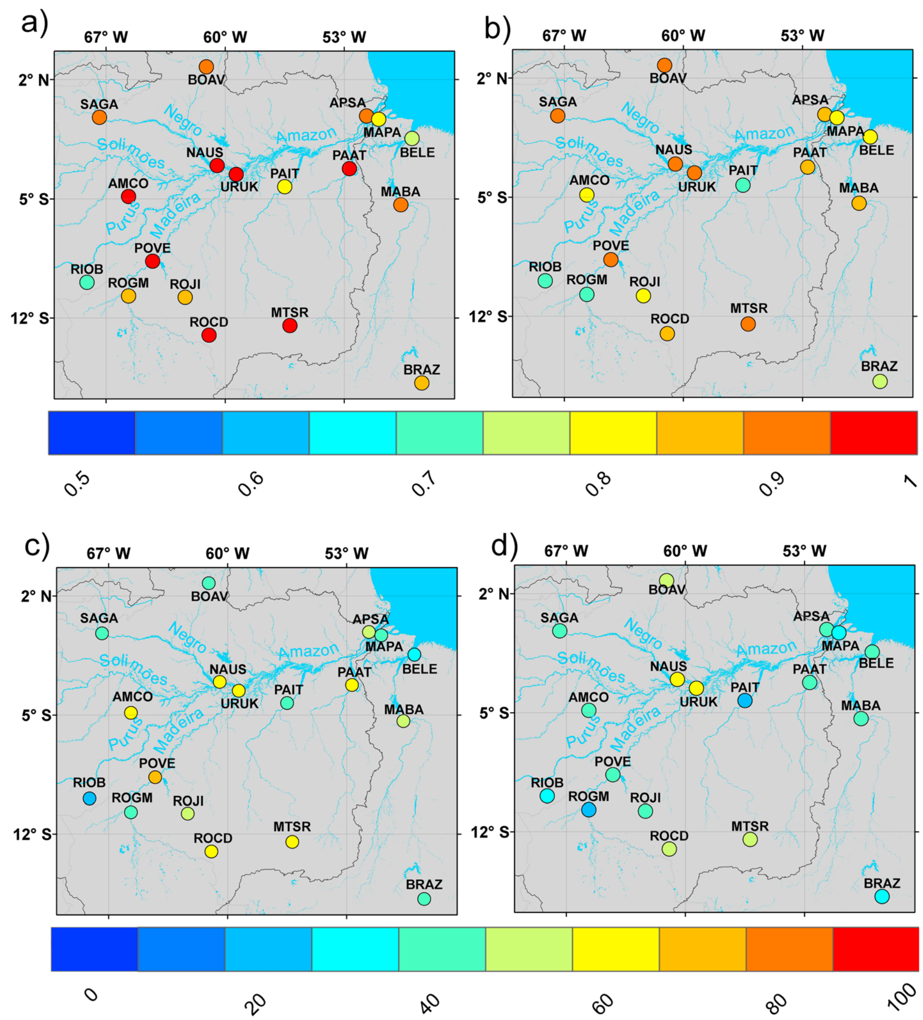

Figure 3. Correlation between GPS Up component time series and VCD-HL data derived from (a) GRACE/GRGS solutions and (b) HYDL. GPS Up series rate (%) of RMS signal reduction (equation (2)) using (c) GRACE/GRGS and (d) HYDL VCD-HL models.

Results using the HYDL VCD-HL (Figure 3b) show a less regular pattern over the watershed. Stations located in the Negro subbasin (SAGA, BOAV, and NAUS) show the greatest correlations with GPS data (0.909, 0.912, and 0.921, respectively), as well as URUK and POVE (0.932 and 0.904) on the Madeira subbasin. More results from other stations (especially at PAIT and ROGM) may indicate some quality discrepancies of the hydrological models for some subbasins. Even though HYDL model represents a great effort for evaluating hydrological load in better spatial resolution, the complex characteristics of Amazon watershed (e.g., with strong backwater effects and many important floodplains regions) would suggest the use of a more complex modeling approach in order to suitably be able to represent the basin's main hydrological processes.

Following the results presented in Figures 3c and 3d, HYDL led to a smaller reduction (44% on average for the 18 GPS stations) when compared to GRGS (55%). This difference can be explained by a lower HYDL correlation on average (0.84 versus 0.90). Nevertheless, from 30 to 70% of the GPS Up signal remains unexplained as already pointed out in Table 1.

4. Conclusions and Discussion

VCD-HL can affect station seasonal Up coordinates at the level of 10 cm in the Amazon basin area. GPS positioning in such location has to be corrected. However, the IERS International Standards have not yet published a model; therefore, most geodetic software do not include such correction. In this study we have evaluated four sources of GRACE TVGF and the HYDL hydrological model to compute VCD-HL corrections for 18 GPS sites in the Amazon basin. At most of the stations, gravity data and hydrological model were highly and similarly correlated with GPS series. However, a strong correlation up to 50% of the original signal remained unexplained by the VCD-HL models. This could be attributed to many factors, such as a difference in phase and/or amplitude between the modeled 2-D crustal deformation and the punctual measurements at the GPS sites. Moreover, some characteristics of the GRACE data features, like their coarse spatial resolution, the filtering procedure, and the signal leakage from nearby regions can impact differently the derived deformation depending on the site location. Regarding HYDL data, even though their series were available at a finer resolution, our analysis suggests that some limitations remain in the hydrologic modeling of the Amazon watershed. A longer period, including the 2009 and 2012 floods, and an updated version (1.2) of HYDL may explain that larger amplitudes are found in the present study compared to those found by *Dill and Dobslaw* [2013].

Although further work is needed on the interpretation of the RMS in the vertical component of the GPS series, the results showed herein are encouraging. The best agreement was found when using TVGF data from GRGS.

In addition to the strong VCD-HL seasonal signal, we observed a linear trend in the lower part of the Amazon basin of −1 mm/year. This result may be connected to a recent result from *Reager et al*. [2016]. They evidenced an increase of water storage in the Amazon basin in a study based on GRACE data. This corresponding increase of water storage represents a trend in the VCD-HL consistent with our results.

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