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Multi-sensor space observation of heavy flood and drought conditions in the Amazon region

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Abstract: Variations of continental water storage and related changes of water surface extensions are being observed by a variety of contemporary geometrical and gravimetrical space observation systems and in-situ measuring instruments. Within a regional multi-sensor study in the Amazon basin we elaborate on the potential of different systems for the quantification of variations of water mass and water surface extent caused by extreme flood and drought situations during 2002-2010. In particular we focus on a rapid change between a widespread flood and a drought situation in the year 2009. Observations of water mass from satellite gravimetry (GRACE), water stage from satellite altimetry (Envisat) and water extent from L-band radar remote sensing (PALSAR) are very consistent with respect to their spatial and temporal variability. On the basis of our findings we provide an outlook on the applicability of measurements of water levels and surface water extent for an independent assessment of water volume changes. Those might be used for a cross-comparison with estimates of water storage from GRACE.

Keywords: Multi-sensor analysis, extreme events, GRACE, SAR, satellite altimetry

1 Introduction

Land hydrology plays a key role in the global water cycle, but at the same time water storage on the continents is one of its most uncertain components (IPCC, 2007). Being a fundamental component of the land water balance, large-scale changes of water storage are very important for the explanation of global change phenomena such as the current rate of sea level rise. Continental water storage is composed of a variety of storage compartments, e.g., groundwater, snow/ice, soil moisture or surface water bodies. However, the contributions of the individual compartments to total storage changes and their interactions are not well known, which would be a prerequisite for a better understanding of the hydrological cycle. Over large areas in-situ observation networks are not dense and comprehensive enough to allow for assessing water storage change within all the compartments. On the other hand, hydrological models suffer from considerable uncertainties in terms of model structure, process descriptions, parameter values and forcing.

A large number of contemporary space and in-situ observation systems offer a broad spectrum of information about processes within the continental hydrology. With respect to surface water bodies, for example, storage variations and related geometrical changes of vertical and horizontal extensions map into observations of various systems, such as satellite gravimetry, satellite altimetry, multi-spectral remote sensing, SAR/InSAR and in-situ river gauges. In the following, observations from different gravimetrical and geometrical systems are analyzed with respect to signatures of extreme hydrological situations in the Amazon region that were frequent during the last decade. In particular we focus on analyzing the spatio-temporal consistency of the different observation systems and their potential by comparing the spatial patterns of water changes with respect to their temporal variability.

Variations of total water storage are based on the gravity satellite mission GRACE (Section 2). Geometrical changes (water stages and horizontal extent) are observed by the satellite altimetry missions Jason-2 and Envisat (Section 3) and Phased Array type L-band Synthetic Aperture Radar (PALSAR) scenes (Section 4), respectively. Section 5 provides an outlook towards the computation of volume changes from geometrical observations.

2 Total water storage change from satellite gravimetry

Changes of water storage are reflected in observations of temporal variations of the Earth's gravity field as they are provided since 2002 by the satellite gravity field mission GRACE (Gravity Recovery And Climate Experiment) (Tapley et al., 2004). Many studies have shown the potential of GRACE for estimating hydrological storage variations in continental regions (e.g., Ramillien et al., 2008; Schmidt et al., 2008; Seitz et al., 2008). Characteristics and height of the GRACE orbit limit the spatial resolution to regions not smaller than 200.000 km^2 (Swenson and Wahr, 2007) and the temporal resolution to approximately one month.

We analyze 97 quasi-monthly sets of spherical harmonic coefficients of the Earth's gravity field from release RL04 of the GFZ German Research Centre for Geosciences (Flechtner et al., 2010) between August 2002 and March 2011. Mass redistributions on time scales shorter than one month that would cause alias effects of the gravity estimates from GRACE (e.g. due to Earth and ocean tides, atmospheric pressure variations and ocean circulation) are a-priori reduced from the GRACE observations (Flechtner, 2007). In continental non-polar regions it can be assumed that the largest part of the remaining GRACE gravity field changes, described by the monthly Level-2 products, reflects mass redistributions within the continental hydrology.

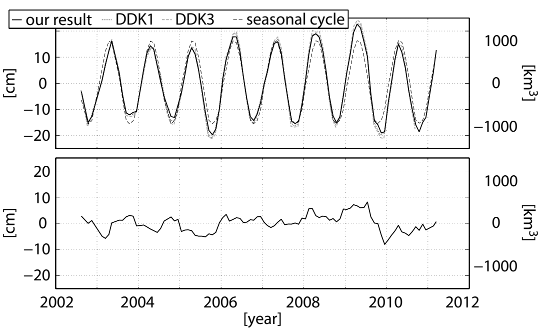

Figure 1: Water storage variations in the Amazon basin from GRACE. Top panel: Our solution in comparison with two solutions (DDK) after Kusche et al. (2009). Bottom panel: Signal after reduction of the seasonal cycle.

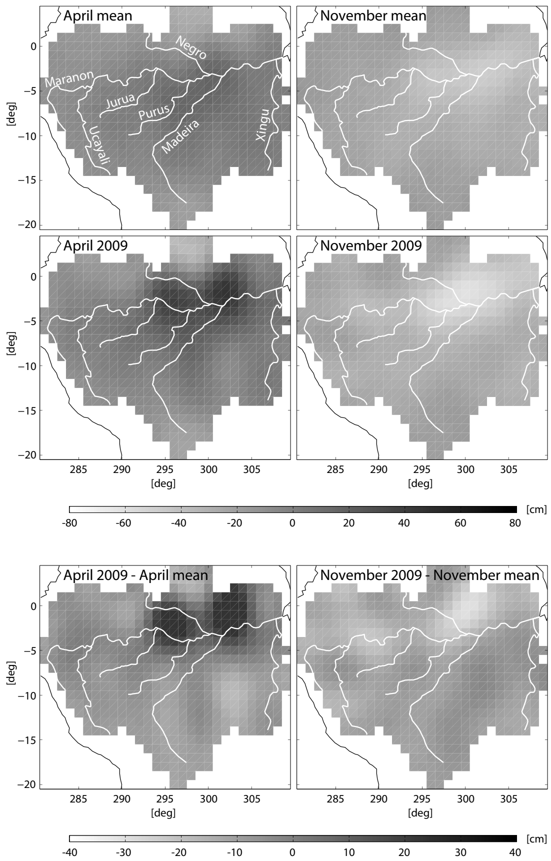

Figure 2: Spatial patterns of water storage from GRACE in units of EWH during April and November: Mean of the years 2002-2010 (top panels), situation in 2009 (middle) and the respective anomalies (bottom). Note the different colorbars.

Gravity field changes are computed with respect to a mean GRACE gravity field over the analyzed period via a spherical harmonic synthesis of the monthly solutions complete up to degree and order 60. The spherical harmonic coefficients are converted into geographical grids of equivalent water height (EWH) variations (Wahr et al., 1998). Errors in the GRACE Level-2 data due to orbit characteristics, measurement limitations and un-modelled mass changes on sub-monthly timescales are treated by the commonly applied smoothing and destriping algorithms (Swenson and Wahr, 2006; Wahr et al., 1998) in which we apply a Gaussian filter of 500 km half-wavelength.

Monthly mean averages of EWH in the Amazon region as well as the integral water volume within the basin area of 5.85 million km^2 are displayed in Fig. 1. The uncertainty of EWH estimates from GRACE is in the order of few cm. A detailed discussion of the measurement accuracy of GRACE that depends strongly on region and applied filtering is given by Wahr et al. (2006). A comparison of this solution with results based on spherical harmonic coefficients that have been de-correlated using the filters DDK1 and DDK3 after Kusche et al. (2009) shows excellent correspondence. With respect to a composite seasonal cycle the curve reflects a number of extreme events. A strong minimum in late 2005 can be attributed to the worst drought since 40 years that caused a drop of the rivers in the Amazon region to record low water levels (Shein, 2006). Between December 2008 and April 2009 heavy rainfall affected especially the north (Rio Negro Basin) and north-east of Amazonia. The precipitation that reached up to 100% above normal led to the highest ever registered water levels of Rio Negro and Amazon in the first half of 2009 and caused severe damage and impact on humans and wildlife (Arndt et al., 2010). Above-average temperatures (2-3°C warmer than normal) from July on in the north-east and ENSO-related below average precipitation in the last three months of 2009 led to a strong decrease of the water levels until the end of 2009. The related enormous change of water storage is especially striking in the residual GRACE signal reduced by a seasonal cycle (cf. Fig. 1, bottom panel). Only a few months lie between the absolute maximum and the absolute minimum of the resulting curve. The spatial patterns of water storage in the Amazon basin during the peaks of the 2009 flood (April) and drought (November) are shown in comparison with the mean situation of the respective months in Fig. 2. The strongest anomalies are observed in the north and north-east as outlined above.

3 Water levels from satellite altimetry and river gauges

Over the last decade vertical variations of the water surface of the Amazon River and its tributaries have been observed by a number of in-situ river gauges as well as by satellite altimetry. Two gauge stations, Manacapuru and Obidos, are located in the region that was affected by the 2009 flood and drought. In-situ data of water levels and discharge for these stations are available through the Environmental Research Observatory (ORE) HYBAM (geodynamical, hydrological, and biogeochemical control of erosion/alteration and material transport in the Amazon basin) in monthly resolution. In addition, water stage variations based on altimetry data from the missions Envisat (since 2002) and Jason-2 (since 2008) are studied. The potential of satellite altimetry for the observation of meaningful water stage variations in Amazonia has earlier been demonstrated by, e.g., Frappart et al. (2006).

Figure 3 shows crossings of Envisat and Jason-2 passes with the Amazon River and its tributaries for our region of interest. Two passes of Envisat (pass numbers 564, 306) and Jason-2 (pass numbers 076, 139) are relatively close to the gauge stations at Manacapuru and Obidos and allow for a direct comparison of the observation techniques. For Envisat we extracted ICE-1 retracked 18-Hz heights, which have been demonstrated to be the most suitable for inland water bodies (Frappart et al., 2006), from the Geophys-

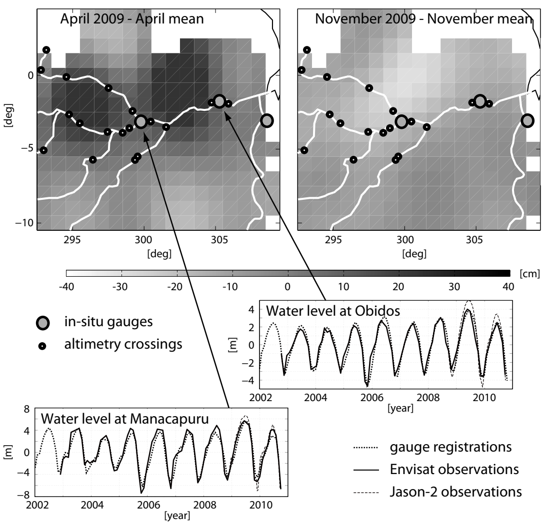

Figure 3: Distribution of altimetry crossings and in-situ gauges in north-eastern Amazonia (top) and water level variations at two stations from altimetry and gauge observations (bottom).

ical Data Record (GDR), and spatially averaged them over the satellite pass crossings. For Jason-2 we used 20-Hz retracked data contained in GDR using ICE retracker, which is similar to the ICE-1 retracker (Lee et al., 2010). Instrument corrections, media corrections (dry troposphere correction, wet troposphere correction calculated from the European Centre for Medium-Range Weather Forecasts model, and ionosphere correction based on Global Ionosphere Maps), as well as geophysical corrections (orbit, solid Earth, and pole tides) have been applied.

As shown in Fig. 3, in both cases the curves are consistent w.r.t. signal characteristics and phases. The better agreement of the amplitudes of Envisat observations and gauge registrations can be attributed to the smaller distances between Envisat crossing points and gauge locations (Envisat: 46 km from Manacapuru, 8 km from Obidos; Jason-2: 126 km from Manacapuru, 173 km from Obidos). The discrepancies of the altimetry observations among each other can partly be explained by the large distance bewteen the crossing points of the two missions (172 km at Manacapuru; 181 km at Obidos). Therefore a meaningful estimate of a potential bias between the two missions cannot be computed from these observations. The previously mentioned drought in late 2005 resulted in an outstanding minimum at both locations. The signatures of the 2009 flood and drought are clearly identifiable in the time series at Obidos. At Mancapuru which is located at the Rio Solimões, i.e. upstream of the confluence with Rio Negro, the corresponding signals are less pronounced since especially the Rio Negro Basin and the north-east of Amazonia were affected by the 2009 events.

4 Water surface extent from synthetic aperture radar

Remote sensing techniques have shown the capability to monitor surface water from space and provide a unique means to observe large regions. Surface water extent can be measured with multi-spectral sensors and by SAR (Synthetic Aperture Radar) imagery. Problems with visible band sensors include cloud cover or vegetation canopies. High resolution SAR sensors such as TerraSAR-X are applicable for calm water surfaces and for open water areas. However the benefit of X-band SAR quickly diminishes if the water's surface roughness increases or if the water surface is obstructed by vegetation cover. Longer wavelengths SAR sensors such as those measuring in L-band, however, have the potential of mitigating these performance limitations (Alsdorf et al., 2007) due to their increased ability to penetrate vegetation and their reduced sensitivity to small scale roughness.

Earlier studies of water extent in the Amazon region were based on images acquired by the L-band JRES-1 SAR sensor (Hess et al., 2003; Martinez and Le Toan, 2007). JRES-1 SAR paved the way for the L-band sensor PALSAR onboard the satellite ALOS which was launched in 2006. In particular the large coverage ScanSAR products of this horizontally polarized L-band system have proven useful for monitoring changes in water level conditions (Omura and Shimada, 2010).

In the following we use scenes from the PALSAR system in order to assess the extent of inundation areas in our study region. As PALSAR operates at L-band the scenes are assumed to be especially useful in the densely vegetated Amazon region. The data used in this study have been taken in the ScanSAR wide beam mode with a spatial resolution of 100 m and a swath width of up to 350 km. Each scene comprises approximately 12 million pixels and covers a total area of about 100.000 km^2. Figure 4 provides an overview of the scenes that are available in our study area during the flood and the drought of 2009. Four of these scenes are available for both situations and can be used in order to compute corresponding changes of the water extent. The scenes of flood and drought were taken during the March/April and October/November time frame, respectively (Fig. 5).

Flooded open water areas appear normally as

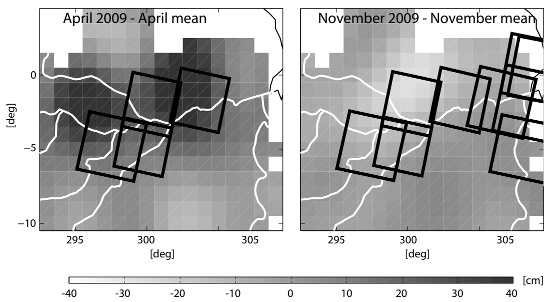

Figure 4: Available PALSAR scenes in ScanSAR wide beam mode for March/April (left) and October/November (right) 2009.

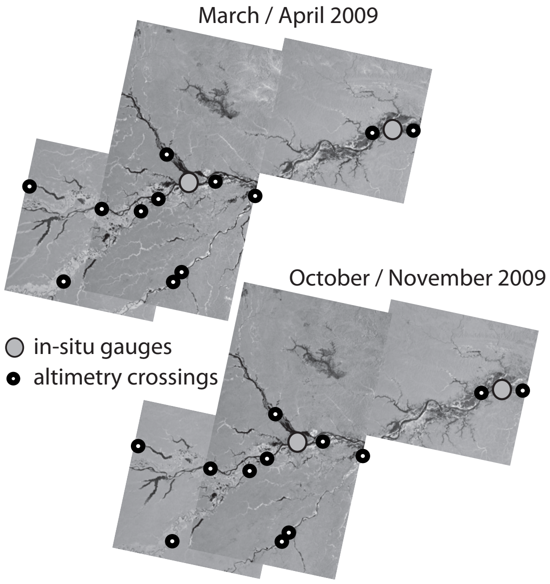

Figure 5: PALSAR scenes of the 2009 flood (top) and drought (bottom).

dark areas since the water surface acts as a specular reflector for the obliquely observed radar signals. In contrast, flooded areas in densely vegetated areas appear very bright in the image due to double bounce effects at tree stems close to the water body. Thus flooded areas can be identified in good approximation by selecting very dark and very bright pixels from the image. This can be done automatically using common histogram analysis and image processing techniques (e.g., Niedermeier et al., 2000; Mason et al., 2010).

Here we use simple despeckling and threshold techniques for an estimation of the area under water. First, the scenes are despeckled using a 6x6 pixel averaging filter that leads to a significant improvement of the separability of bright and dark areas for two reasons: In addition to reducing the data noise level, the spatial averaging also causes the data to approximate a Gaussian distribution, which is simplifying the application of thresholding algorithms to the image histograms. Second, appropriate threshold values for the selection of dark and bright pixels are empirically derived and applied to the image histograms. Exemplary results are shown for a scene located to the north at the confluence of the Rio Negro. The region in the north-eastern part of this frame was strongly affected by both the flood and the drought as indicated by GRACE (cf. Fig. 4). Figure 6 displays the

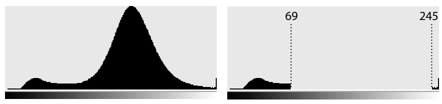

Figure 6: Histogram of the despeckled PALSAR scene (left) and threshold for the selection of inundation areas (right).

image histogram before and after the selection of the threshold values. The latter were set to intensity values of 69 (the local minimum of the histogram) and 245, respectively. We obtain the binary masks of flooded areas (water=1, land=0) for early and late 2009 shown in Fig. 7. Signals of flood and drought are clearly distinguishable. The area under water is larger by about 12% in March/April, and the rivers are much more pronounced during the flood. In particular the region in the north-east of the scene appears very different during flood and drought. This result agrees well with our expectations from the GRACE analysis and let us conclude that ALOS PALSAR scenes are a very useful source of information for the detection of inundation areas.

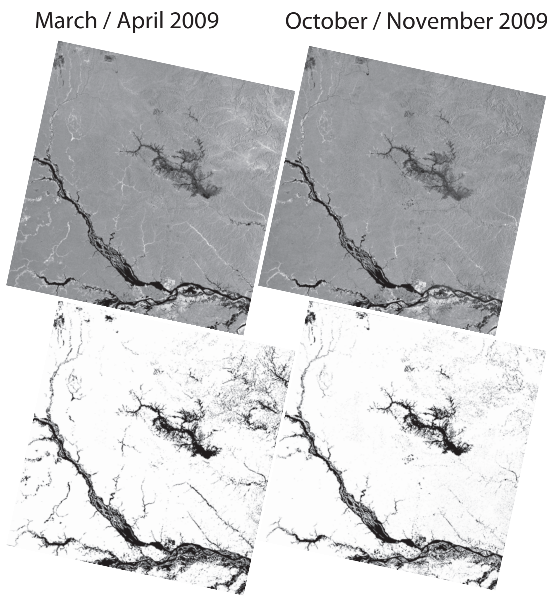

Figure 7: Resulting water masks for the 2009 flood (left) and drought (right).

5 Towards the assessment of volume changes

Ongoing research activities are oriented towards the computation of water volume changes based on geometrical observations. A subsequent transformation from volume into mass would allow for a direct comparison with water storage variations from GRACE. Even though the resolution of GRACE is comparatively coarse, unusually strong mass variations related to regional extreme hydrological situations are clearly identifiable in the signal. Therefore surface water mass changes within the affected regions estimated from geometrical observations are expected to contribute to the interpretation of exceptional GRACE signals. Water volume can be derived from a geometrical intersection of water boundaries with a high resolution digital terrain model (DTM), using water levels from gauges and altimetry as vertical constraints (Fig. 8). However, due to geometric inaccuracies of the data sets and in particular due to classification errors of the water mask the accurate combination of water masks and DTM is a complicated task (Zwenzner and Voigt, 2009). An exact determination of the water boundary of rivers becomes further complicated, since - unlike in lakes -, the sea level height of a river's water boundary is not equal along its shore, but decreases downstream. Therefore comprehensive research will be necessary before reliable results can be expected from geometrical approaches for the computation of water volume variations in river basins.

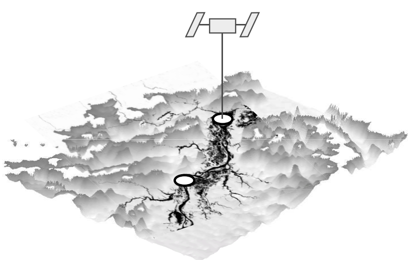

Figure 8: Towards the assessment of volume changes from geometrical observations (principle sketch): A water mask from remote sensing is geometrically intersected with a DTM. Observations of water levels from satellite altimetry and river gauges are applied as vertical constraints.

6 Summary

Different geometrical and gravimetrical space-based and in-situ observation techniques have been applied for the detection of signals related to phenomena within the continental hydrology. Extreme events (e.g. floods, droughts) are clearly identifiable in the analyzed data sets from GRACE, satellite altimetry, SAR and in-situ gauges. The study in the Amazon basin revealed a very good agreement of the data with respect to their temporal and spatial variability. In particular the L-band SAR observations from PALSAR turned out to be a valuable source of information on the spatial extent of surface water. The evaluation of heterogeneous data sets with respect to their consistency and applicability is a first step towards a multi-sensor data combination for the computation of storage variations in the compartment of surface water. This - in turn - means an important step towards the separation of integral geodetic signals (e.g. gravity field variations) and towards an improved understanding of the continental hydrology and Earth system processes in general.

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