TOWARDS THE ASSESSMENT OF REGIONAL MASS VARIATIONS IN CONTINENTAL SURFACE WATER STORAGES FROM A COMBINATION OF HETEROGENEOUS SPACE AND IN-SITU OBSERVATIONS

Florian Seitz(1), Karin Hedman(1), Christian Walter(1), Franz Meyer(2), Michael Schmidt(3)

(1)Earth Oriented Space Science and Technology, Technische Universität München (TUM), Germany, seitz@bv.tum.de
(2)Geophysical Institute, University of Alaska (UAF), Fairbanks, USA
(3)Deutsches Geodätisches Forschungsinstitut (DGFI), München, Germany

ABSTRACT

Variations of continental water masses occur in several storage compartments such as surface water, soil moisture, snow and groundwater. These mass variations map into a considerable number of space based or in-situ observation systems such as the GRACE gravity field mission, radar and laser altimeter systems, radiometers, optical sensors, synthetic aperture radar (SAR), and river gauges. Surface water extensions and high resolution topography can also be extracted from remote sensing techniques. While GRACE is sensitive to the integral effect of water mass in all storage compartments, an optimal combination of various complementary observation techniques in a multi-sensor approach is promising for the detection and separation of individual contributions to continental water mass variations, meaning a splitting of the GRACE signal into specific contributors. Here we report on a regional study in the Amazon basin: First, total storage variations within the area are computed from GRACE observations for a period of more than 8 years. Second, an approach for the quantification of water mass variations in the compartment surface water due to extreme situations of droughts and floods is presented which is based on a combination of radar images with a high resolution digital elevation model (DEM).

1. CONTINENTAL WATER STORAGE – A KEY UNKNOWN IN THE WATER CYCLE

The latest IPCC assessment report [1] identified the land hydrology as the most uncertain component of the global water cycle. Continental water storage plays a key role in the Earth's water, energy and biogeochemical cycles. Water fluxes between atmosphere, continents and oceans contribute significantly to mass redistributions in the system Earth and cause variations in continental water storage. These variations are a fundamental component of the land water balance, where precipitation that reaches the land surface is repartitioned into evapotranspiration, runoff and storage change. Continental water storage is composed of a variety of storage compartments, including water storage on vegetation surfaces, in the biomass, in the unsaturated soil or rock zone, as groundwater, snow and ice, and in surface water bodies such as rivers, wetlands, natural lakes and man-made reservoirs The contributions of individual compartments to total storage variations and the interactions between compartments are not well known. This, however, would be a prerequisite for a better understanding of processes of the hydrological cycle and of mass variations on the continents in general.

2. OBSERVATIONS OF CONTINENTAL WATER STORAGE FROM SPACE

Monitoring surface water storages at large scales is not possible by in-situ measurements alone. Yet there is no ground-based observation network dense and comprehensive enough to allow for assessing water storage change within all its compartments over large areas [2]. With regard to space based techniques, the GRACE mission allows for estimating total continental water mass changes at large scales. But due to its integrative nature, GRACE cannot resolve the contributions of individual compartments to the total storage variations. However, mass variations in individual compartments map into the observations of various contemporary space based and in-situ observation systems such as altimeter systems, radiometers, optical/ infrared sensors, (In)SAR, and in-situ river gauges. Within a joint project at TUM, DGFI, UAF, GFZ and DLR we perform a regional multi-sensor study in which the total variation of water mass from satellite gravimetry is balanced with the individual contributions of different storage compartments. In the following we report on first results of a regional study within the Amazon basin where numerous exceptionally dry and wet periods alternated during the last years (see Fig. 1). After we present the results of the total water storage change in this region between mid-2002 and the end of 2009 from GRACE gravimetry (Section 3), we concentrate on an approach towards the quantification of surface water storage and its variation especially as a consequence of extreme weather situations (Section 4).

Proc. 'ESA Living Planet Symposium', Bergen, Norway
28 June – 2 July 2010 (ESA SP-686, December 2010)

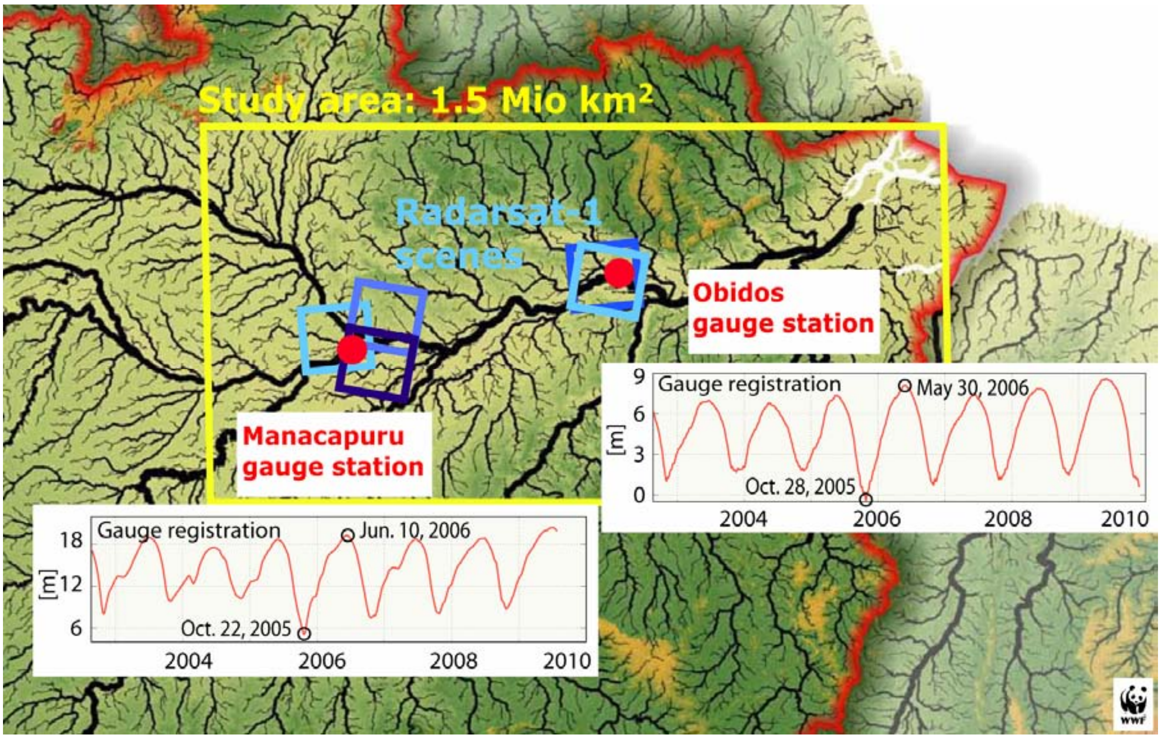

Fig. 1: Study area in the Amazon basin (yellow) and locations of two in-situ river gauges at Obidos and Manacapuru. Blue boxes indicate Radarsat-1 scenes being available for the quantification of water mass, see Section 4.

3. TOTAL WATER STORAGE CHANGE

Our study area is characterised by a strong temporal variability of the natural inflow of water. Fig. 2 displays the net effect of precipitation minus evaporation (P-E) over the region. The curve is computed from the atmospheric moisture budget, i.e. the change in precipitable water and the atmospheric water vapour flux divergence from NCEP atmospheric reanalysis data [3]. For details on the computation of P-E and its application in the analysis of water storage variations in the Amazon region see [4] and [5]. Particularly striking is an enormous increase of inflow between 2005 and 2006 that caused a major Amazon flood after a severe drought which was the worst in 40 years and caused rivers to drop to record low levels [6].

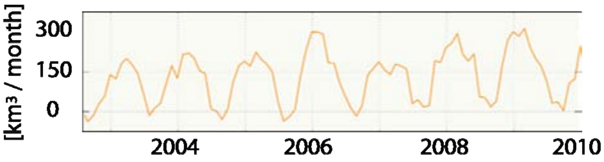

Fig. 2: Net inflow of water (precipitation minus evaporation) into the study area computed from the atmospheric moisture budget.

Variations of water mass map into the observations of the GRACE gravity field satellite mission, that has been continuously monitoring temporal variations of the Earth's gravity field since mid 2002 [7]. Large parts of the signal (tides, atmosphere, and oceans) are removed during pre-processing of the observations, so that remaining gravity field variations over non-polar regions are assumed to mainly reflect changes of terrestrial water storage. Data errors due to GRACE orbit characteristics and measurement limitations show up in maps of gravity field variations in the form of longitudinal stripes [8]. Those effects are reduced applying a 2nd degree Savitzky-Golay smoothing filter. Furthermore noisy short wavelength components due to high-frequent aliasing are reduced using an isotropic Gauss filter of 400 km half-width.

Monthly GRACE observations of gravity field changes from two solutions based on spherical harmonic coefficients, namely the solutions GFZ RL04 [9] and ITG-GRACE2010 from the University of Bonn [10], are applied. In addition a spatiotemporal regional gravity model from GRACE based on a four-dimensional multi-resolution representation (MRR) of the geopotential computed at DGFI is used for comparison [5]. GRACE observations of gravity field changes are transformed into grids of equivalent water height (EWH) variations over the study region, averaged over the area of 1.5 Mio km^2 and converted into units of km^3 water. These values (shown in Fig. 3) represent the total variation of equivalent water with respect to a long-term average over 2002–2009. The drought and subsequent flooding of 2005/2006 can clearly be identified in the curve as they manifest themselves in a strong increase of water mass.

In Fig. 3 also results from the WaterGAP Global Hydrology Model (WGHM) [11] for total water storage change are shown. WGHM is a state-of-the global water balance model that simulates the continental water cycle including its most important water storage components, i.e., interception, soil water, snow, groundwater and surface water in rivers, lakes, inundation areas and man-made reservoirs. The model uses simplifying conceptual approaches to represent the hydrological processes and the water cycle on the continents. WGHM has a 0.5° spatial resolution and a daily computation time step.

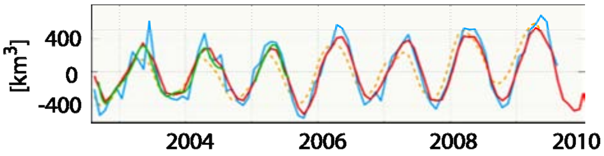

Fig. 3: Total variation of water mass in the study area: Results from GRACE (two global spherical harmonic solutions: GFZ RL04 (red) and ITG-GRACE2010 (blue); one regional solution from DGFI based on multi-resolution representation; green) and from the WaterGAP Hydrology Model (brown).

4. TOWARDS A QUANTIFICATION OF SURFACE WATER MASS VARIATIONS

Surface water variations are one of the most important contributors to total water change in the Amazon region where the strong temporal variations of net water inflow (Fig. 2) lead to highly variable water stages of the Amazon River, being recorded by river gauges (Fig 1), and in adjacent floodplains. Surface water extent can be observed by a range of remote sensing techniques such as altimeter systems, radiometers, optical/infrared sensors and Synthetic Aperture Radar (SAR) sensors. Compared to the sensors operating in the visible/infrared region, SAR is capable of operating during bad weather conditions. High resolution SAR sensors such as TerraSAR-X are applicable for calm water surfaces and for open water areas [12]. However as soon as the surface roughness increases due to waves or if high vegetation is nearby, longer wavelength sensors will better be able to mitigate these performance limitations [13].

4.1. Proposed Approach and Data Set

Changes of surface water mass in the study area due to anomalous low or high water levels of the Amazon River are estimated from a geometrical approach: Satellite images of the horizontal extent of the water surface are intersected with a high-resolution digital elevation model (DEM). River gauge registrations at the stations Obidos and Manacapuru (Fig. 1) (and in a later stage of our project also continental altimetry) are applied as vertical constraints. In particular, the study focuses on the time between the drought of 2005 and the flood in 2006 following the strong increase of net water inflow.

As DEM the ACE2 (altimeter corrected elevations) dataset is used, containing merged elevation data of the SRTM mission and satellite radar altimetry. The DEM consists of tiles spanning 18,000 by 18,000 pixels each, covering an area of 15° latitude by 15° longitude [14].

For mapping the spatial extent of the river at high and low water levels geo-referenced Radarsat-1 C-band images are applied. Each scene is 8192 pixels per row and column, covering an area of 100 x 100 km (~25 m resolution). High resolution SAR sensors have clearly shown the capability to monitor variations of surface water extent for open areas such as the Amazon River. A combination of C-band and longer wavelengths SAR sensors such as L-band would be desirable in order to mitigate existing performance limitations of C-band systems under rough surface conditions due to vegetation or waves. However, due to the unavailability of L-band data for the region in the years 2005/2006 solely Radarsat-1 data is applied. Fig. 4 (left) shows a raw Radarsat-1 scene over Manacapuru taken during low water at October 11, 2005.

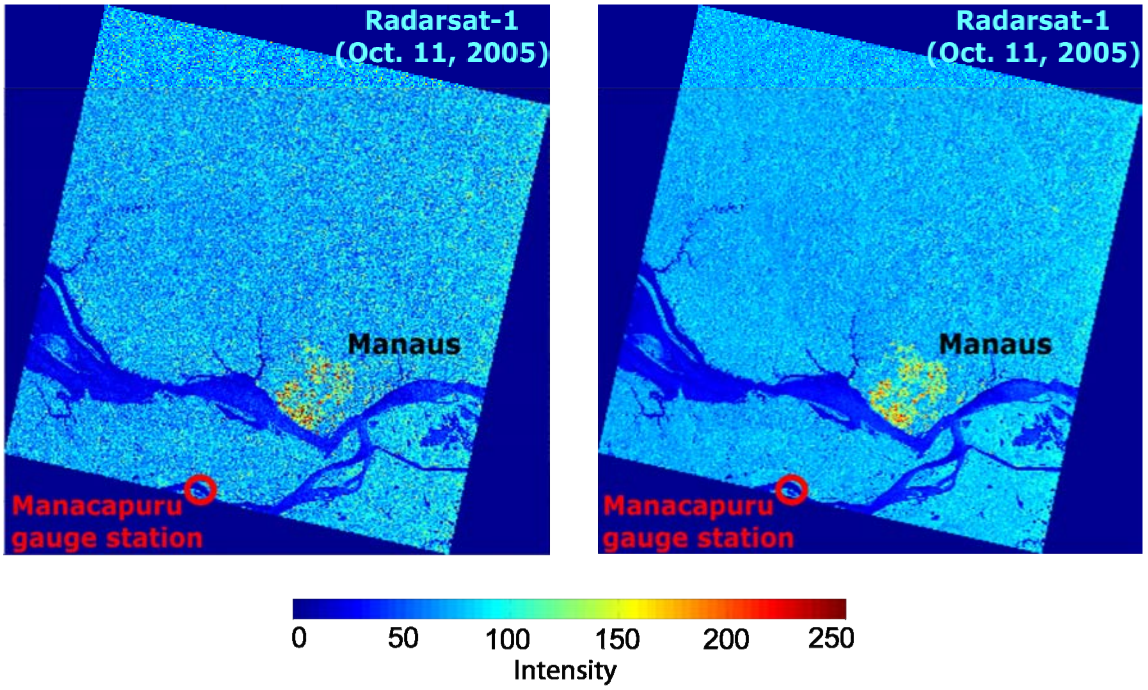

Fig. 4: Radarsat-1 scene from October 11, 2005, i.e. during low water in the study region. Left: Original scene; right: after despeckling using a 6x6 pixel averaging filter.

4.2. Extracting Water Areas

Flooded calm water areas appear normally darker than the surrounding in SAR images. The smooth water surface acts as a reflector. Hence the flooded area can be automatically extracted by using common image processing techniques. For instance wavelet methods can be applied for the delineation of flooded areas [15]. Statistical active contour models for identifying homogeneous speckle statistics, which is characteristic for flooded areas, as described in [16] has also turned out to be successful. Water bodies can also be extracted on a coarser scale by applying texture analysis followed by morphology [17].

In this work we have used simple despeckling and threshold techniques in order to extract the water areas. First the scenes are despeckled using a 6x6 pixel averaging filter (Fig. 4, right). In future more sophisticated filters such as the multiplicative speckle model-based Frost-Filter, Lee-Filter or the product model-based Gamma MAP filter shall be applied. Second, an appropriate threshold is empirically derived from the image histogram (Fig. 5). It is obvious that the separability of bright and dark areas is significantly improved after despeckling. Based on the blue curve in Fig. 5, we set the threshold to an intensity value of 44 which corresponds to the local minimum of the histogram of the despeckled image.

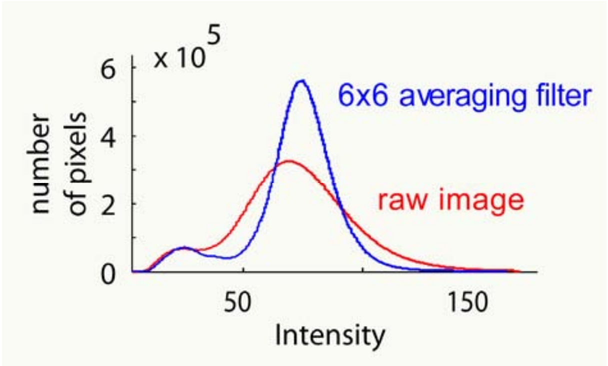

Fig. 5: Histograms of raw and despeckled Radarsat-1 scene. The local minimum of the blue curve at the intensity value 44 is applied as threshold for the water surface detection.

Applying the threshold to the despeckled image and after morphological noise reduction we obtain a binary mask for inundation areas (water=1, land=0) which is shown in Fig. 6. From this mask closed water boundary curves are computed by means of a Canny edge detector; see [18] for details.

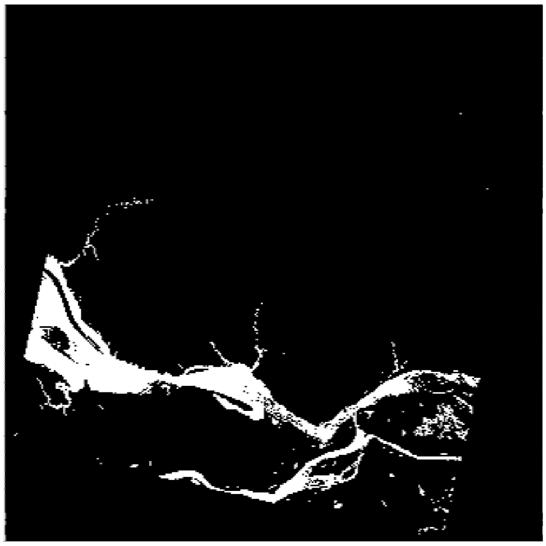

Fig. 6: Extracted surface water extent during low water at October 11, 2005.

4.3. Estimating Surface Water Volume

Water volume follows from a geometrical intersection on pixel level of water boundaries and DEM, where gauge registrations and (in a further step) land altimetry are applied as vertical constraints. Finally, temporal variations of water mass result from the volume change between low and high water situations. However, the accurate combination of water masks and DEM is a complicated task due to geometric inaccuracies and classification errors [19]. Finding the water boundary of rivers becomes further complicated, since - unlike in lakes - , the absolute height above sea level of a river's water boundary is not equal along its shore, but instead is decreasing downstream. Here further research will be necessary before reliable results can be expected.

5. CONCLUSION AND OUTLOOK

The aim of this paper was to present the first steps of a joint project for monitoring regional water mass changes by a multi-sensor approach. First GRACE gravimetry observations for a period of more than 8 years were used for estimating total storage variations. Second an approach for quantification of surface water mass variations of droughts and floods based on SAR images and a high resolution digital elevation model (DEM) was presented.

Still left to do is to combine the two observation approaches in order to quantify the different water storage compartments. Also the estimation of surface water mass variations from SAR data must be completely implemented, further refined and analyzed in depth.

REFERENCES

1. IPCC (2007). Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
2. Lettenmeier, D. & Famiglietti J. (2006). Hydrology – Water from on high. Nature, 444(7119), pp 562-563.
3. Kalnay, E., Kanamitsu, M., Kistler, et al. (1996). The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, 77, 437-471.
4. 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., 268/1-2*, 165-170, doi: 10.1016/j.epsl.2008.01.001.
5. Schmidt, M., F. Seitz, C.K. Shum (2008): Regional 4-D hydrological mass variations from GRACE, atmospheric flux convergence and river gauge data. *J. Geophys. Res.*, *113*, doi:10.1029/2008JB005575.
6. Shein, K. (Ed.) (2006). State of the climate in 2005, Bull. Am. Meteorol. Soc., 87, S1–S102.
7. Tapley, B.D., S.V. Bettadpur, J.C. Ries, P.F. Thompson, M.M. Watkins (2004). GRACE measurements of mass variability in the Earth system. *Science, 305*, 503-505.
8. Wahr, J., Molenaar, M., Bryan, F. (1998). Time-variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J. Geophys. Res. 103, 30205–30229.
9. Schmidt, R.; Flechtner, F.; Meyer, U.; Neumayer, K.-H.; Dahle, Ch.; König, R.; Kusche, J. (2008). Hydrological Signals Observed by the GRACE Satellites. Surveys in Geophysics, 29, 4-5, 319-334.
10. Kurtenbach, E., T. Mayer-Gürr, and A. Eicker (2009). Deriving daily snapshots of the Earth's gravity field from GRACE L1B data using Kalman filtering, Geophys. Res. Lett., 36, L17102, doi:10.1029/2009GL039564.
11. Döll, P, F. Kaspar, B. Lehner (2003). A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology, 270,105-134.
12. Martinis, S., Twele A. & Voigt, S., (2009). Towards operational near real-time flood detection using a split-based automatic thresholding procedure on high resolution TerraSAR-X data. Natural Hazards and Earth System Sciences, 9, pp. 303-314.
13. Alsdorf, D. E., E. R. & Lettenmaier, D. P., (2007). Measuring surface water from space Reviews of Geophysics, *45,* RG2002.
14. Smith,R.G., Berry, P.A.M, Benveniste,J. (2007). Representation of Rivers and Lakes in the

forthcoming ACE2 GDEM. In: Benveniste, J. et al. (eds.) Proceedings of the 2nd Space for Hydrology Workshop 'Surface Water Storage and Runoff: Modeling, In-Situ Data and Remote Sensing', ESA Publication WPP-280, 11/2007.

15. Niedermeier A., Romaneeßen, E. & Lehner, S., (2000). Detection of Coastlines in SAR Images using Wavelet Methods, IEEE Transactions on Geoscience and Remote Sensing, 38, pp. 2270-2281.
16. Mason, D.C., Speck, R., Devereux, B., Schumann, G. J.-P., Neal, J.C. & Bates, P.D., (2010). Flood Detection in Urban Areas Using TerraSAR-X, IEE Transactions on Geoscience and Remote Sensing, 48(2), pp. 882-894.
17. Dell'Acqua, F., Gamba, P. & Lisini, G., (2009). Rapid mapping of high resolution SAR scenes ISPRS Journal of Photogrammetry and Remote Sensing*,* 64*,* pp. 482 – 489.
18. Canny, J. (1986) A Computational Approach To Edge Detection, IEEE Trans. Pattern Analysis and Machine Intelligence, 8(6):679–698.
19. Zwenzner, H. & Voigt, S. (2009). Improved estimation of flood parameters by combining space based SAR data with very high resolution digital elevation data, Hydrology and Earth System Sciences*,* 13, 567-576