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# Constrained Regional Recovery of Continental Water Mass Time-variations from GRACE-based Geopotential Anomalies over South America

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# Surveys in Geophysics

## Constrained regional recovery of continental water mass time-variations from GRACE-based geo-potential anomalies --Manuscript Draft--

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<b>Abstract:</b>	<p>We propose a « constrained » least-squares approach to estimate regional maps of equivalent-water heights by inverting GRACE-based potential anomalies at satellite altitude. According to the energy integral method, the anomalies of difference of geo-potential between the two GRACE vehicles are derived from along-track K-Band Range-Rate (KBRR) residuals that correspond mainly to the continental water storage changes, once a priori known accelerations (i.e., static field, polar movements, atmosphere and ocean masses including tides) are removed during the orbit adjustment process. The first Newton's law merely relates Difference of Potential Anomalies (DPA) from accurate KBRR data and the equivalent-water heights to be recovered. Spatial constraints versus spherical distance between elementary surface tiles are introduced to stabilize the linear system to cancel the effects of the north-south striping. Unlike the « mascons » approach, no basis of orthogonal functions (e.g., spherical harmonics) is used, so that the proposed regional method does not suffer from drawbacks related to any spectrum truncation. Time series of 10-day regional maps over South America for 2006-2009 also prove to be consistent with independent datasets: hydrological models outputs, "mascons" and global GRACE solutions.</p>
<b>Response to Reviewers:</b>	<p>To the Reviewer and Editors:</p> <p>First, we thank the reviewer for his comments that contributed to improve the quality of the manuscript. All his remarks have been considered and corrected (see annotated text).</p>

The document has also benefit from slight corrections in second readings of my co-authors.

In particular:

\* Paragraph 1.2.3, page 6: The text part presenting the GRACE-based ICA solutions has been re-written to clarify how they are computed, and which ones are used for comparison with the regional solutions for South America. As mentioned in the text, more details on ICA of the monthly GRACE solutions can be found in Frappart et al., (2010) and Frappart et al., (2011).

\* Loading effects, page 8: a new sentence has been added to precise that elastic compensation can be in the regularization as Legendre polynomials, and thus elastic Love numbers, are introduced. This point is also referred to Eq.24 from Ramillien et al., (2011).

\* Eq. 11, page 10: we agree the definition of  $B_{i,j}$  for the cases 3 and 4 was completely wrong, so that it is now corrected with new formula, as it is now mentioned in the revised document.

\* Spherical harmonics, page 12: Spherical harmonics. We agree about the fact that north-south striping is not only due to the mode of representation in spherical harmonics, but the orbit configuration and time aliasing of short-term phenomena as well. This ambiguous sentence has been simply removed from the text and replaced by the explanation provided by the reviewer.

\* Explanation of acronym "MOY" is now given in Eq.11a, page9, and this latter equation is mentioned in the caption of the Figure 3.

--- End of document ---

1 **Constrained regional recovery of continental water mass time-variations from GRACE-**  
2 **based geo-potential anomalies**

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1

## 2 **Abstract**

3 We propose a « constrained » least-squares approach to estimate regional maps of equivalent-  
4 water heights by inverting GRACE-based potential anomalies at satellite altitude. According  
5 to the energy integral method, the anomalies of difference of geo-potential between the two  
6 GRACE vehicles are derived from along-track K-Band Range-Rate (KBRR) residuals that  
7 correspond mainly to the continental water storage changes, once a priori known  
8 accelerations (i.e., static field, polar movements, atmosphere and ocean masses including  
9 tides) are removed during the orbit adjustment process. The first Newton's law merely relates  
10 Difference of Potential Anomalies (DPA) from accurate KBRR data and the equivalent-water  
11 heights to be recovered. Spatial constraints versus spherical distance between elementary  
12 surface tiles are introduced to stabilize the linear system to cancel the effects of the ~~n~~North-  
13 ~~s~~South striping. Unlike the « mascons » approach, no basis of orthogonal functions (e.g.,  
14 spherical harmonics) is used, so that the proposed regional method does not suffer from  
15 drawbacks related to any spectrum truncation. Time series of 10-day regional maps over ~~the~~  
16 South America for 2006-2009 also prove to be consistent with independent datasets:  
17 hydrological models outputs, “mascons” and global GRACE solutions.

18

## 19 **INTRODUCTION**

20

21 Since its launch in March 2002, the Gravity Recovery and Climate Experiment (GRACE)  
22 mission provides a global mapping of the variations in time and space of the Earth's gravity  
23 field (Tapley et al., 2004a; Tapley et al., 2004b; Schmidt et al., 2006). The originality of this  
24 geodetic mission is to measure very accurately the distance (and velocity) variations between  
25 two co-orbiting vehicles named A and B, using a line-of-sight K-Band Range-Rate (KBRR)  
26 of a precision of  $\sim 0.1 \mu\text{m/s}$  or equivalently  $10 \mu\text{m}$  after integration versus time. Consequently,  
27 the level of precision of this system enables for the first time the detection of gravity  
28 signatures of mass redistributions inside the fluid envelopes of our planet.

29 Three official processing centers forming the Science Data Center, Center for Space Research  
30 at University of Texas (UTCSR), Austin, TX, USA; GeoForschungsZentrum (GFZ),  
31 Potsdam, Germany; Jet Propulsion Laboratory (JPL), Pasadena, CA, USA, routinely use the  
32 positions, velocities and accurate KBR data (i.e., Level-1 GRACE parameters) to produce  
33 monthly global fields developed in “Stokes” coefficients (i.e., spherical harmonics of the  
34 geopotential) after correction of known a priori mass variations via models: atmosphere,

1 barotropic ocean and tides (solid Earth, ocean and pole). These Level-2 residuals should  
2 reflect the sum of noise, errors in the correcting gravity models, non modelled phenomena,  
3 which is mainly the time-varying continental hydrology component of the total gravity field  
4 measured from space.

5 The measured gravity signals also contain “errors” with respect to the correcting models for  
6 the ocean tides, especially over poles, and atmosphere and ocean mass, but with magnitudes  
7 smaller than the primary hydrology signal and at various temporal frequencies. Unfortunately,  
8 due to the resonance of orbits, important short-wavelength north-south striping effects  
9 deteriorate the Level-2 global solutions, and thus require post-processing low-pass filtering  
10 before any geophysical exploitation. Systematic correlated errors associated with the  
11 incomplete modelling of relatively well-known mass variations to resonant orders of monthly  
12 mean spherical harmonics have been reported by Han et al. (2004). Significant degradation of  
13 the monthly global solutions have been reported by Wagner et al. (2006), due to sparse repeat  
14 tracks of 61/4 (rev/day) of the GRACE orbits in deep orbit resonance.

15 Various spatial smoothing techniques were developed to mitigate optimally the ill-determined  
16 harmonic coefficients of higher degrees and orders (Wahr et al., 1998; Davis et al., 2004; Han  
17 et al., 2005; Ramillien et al., 2005; Swenson and Wahr, 2006; Chen et al., 2006; Kusche,  
18 2007). The post-processed Level-2 monthly solutions have been largely used to study mass  
19 balance of recently evolving hydrological systems in different regions, such as large river  
20 basins (Tapley et al., 2004), ice fields (Velicogna and Wahr, 2006) and oceans (Chambers et  
21 al., 2004; Zlotnicki et al., 2007). A review of important results based on Level-2 GRACE  
22 products for continental hydrology can be found in Ramillien et al. (2008).

23 Alternatively, the “mascons” approach consists of solving a linear combination of spherical  
24 harmonics of surface elements, instead of solving individual spherical harmonic coefficient  
25 globally (Rowlands et al., 2005). This method uses inherently constraints among the  
26 coefficients that are dependent on geographical locations. Han et al. (2005) use downward  
27 continuation of the in situ geopotential difference that is pre-determined from the satellite  
28 tracking data analysis. Both methods demonstrated enhancement of the solutions in space and  
29 time for recovering the time-varying regional gravity field. So far, no spherical harmonics  
30 approach for mass flux deviation from GRACE has been able to produce that type of both  
31 spatial and time resolution.

32 Numerous developments have been made on regional methods (Lemoine et al., 1998; Jekeli,  
33 1999; Garcia, 2002; Han et al., 2003, 2004, 2005; Rowlands et al., 2002, 2005, 2010; Luthcke  
34 et al., 2006). For example, 10-day resolution mascons revealed each year’s distinct meltings

1 and accumulations (Luthcke et al., 2006), and resolution of 2 degrees over individual glaciers  
2 (Luthcke et al., 2008). Besides, the mascons approach has revealed more information about  
3 interannual variability in the subregions than any Stokes coefficients-based approach  
4 (Luthcke et al., 2008). Global and mascons methods based on spherical harmonics have  
5 provided very similar results for the mass trend in the drainage basins, especially when no  
6 spatial constraints are taken into account (Rowlands et al., 2010).

7 | Spherical harmonics-based methods are band-limited in [the spectral domain](#), thus they  
8 suffer from errors of spectrum truncation, so that recovered signals remain quite smooth, and  
9 it generates spatial leakage of energetic signals everywhere on the terrestrial sphere.

10 Instead of considering another spherical harmonics-type approach, we propose here to invert  
11 regionally the linear Newtonian operator plus a constraint matrix for regularization, in order  
12 to estimate the time-variations of water mass over continents with no striping. Compared to  
13 the previous Singular Value Decomposition (SVD) method proposed by Ramillien et al.  
14 (2011) where the choice of the regularization parameter is made by L-curve analysis, the  
15 solution of the normal equations is here stabilized by adding geographical constraints (i.e.,  
16 | correlation coefficients between equivalent-water heights) which are physically ~~much~~  
17 meaningful. The originality of the study is that the solution does not depend on global  
18 smoothing orthogonal functions (i.e., band-limited spherical harmonics), but on estimating  
19 directly equivalent-water heights of discrete surface elements. This study will have the  
20 following structure. First, we present the GRACE-based data we used for water mass change  
21 estimation. Secondly, the methodology is presented to explain: (1) how KBRR residuals are  
22 converted into along-track potential difference anomalies following the energy integral  
23 method; (2) the regularization of the Newtonian operator using geographical constraints of  
24 different types (i.e., exponential, Gaussian, uniform) and lengths. Regional solutions are also  
25 computed for elementary surfaces of various resolutions (e.g., 1, 2 or 4 degrees). Thirdly, the  
26 error analysis of the predicted estimates is made using potential difference simulations,  
27 especially by adding random noise in the data to be inverted. Finally, the proposed  
28 constrained regional method is applied to produce time series of regional water mass change  
29 over South America for demonstration of its feasibility. Amplitudes of these regional  
30 solutions are compared to GRACE-based products and independent datasets for validation at  
31 least for the seasonal cycle.

32

### 33 **1. Data used in this study**

34

1 **1.1 GRACE-based KBRR residuals**

2 The Géodésie par Intégrations Numériques Simultanées (GINS) satellite orbitography  
3 software developed by the GRGS/CNES in Toulouse, France, has been used for least-squares  
4 orbits adjustment from a priori model accelerations, and thus KBRR data reduction. GRACE  
5 data have been reduced in 24-hour arcs and processed covering the complete years 2006 and  
6 2009. The a priori gravitational force models applied to the GRACE vehicles A and B for  
7 numerical orbit integration have been: (1) a static gravity field model EIGEN-  
8 GRGS.RL02.MEAN-FIELD to order and degree 160; (2) 3D body perturbations DE403 of  
9 Sun, Moon and six planets (Standish et al. 1995); (3) solid Earth tides IERS conventions 2003  
10 (McCarthy and Petit 2003); (4) solid Earth pole tide IERS conventions 2003; (5) oceanic tides  
11 FES2004 to degree and order 100 (LeProvost et al. 1994); (6) oceanic pole tide from Desai  
12 model (Desai 2002); (7) atmospheric pressure model ECMWF 3-D grids per 6 hours and (8)  
13 oceanic response model MOG2D (Carrère and Lyard 2003). The non-gravitational forces  
14 have been corrected using 3-axis accelerometer measurements. In order to reduce the errors in  
15 the inter- satellite range rate observations, empirical parameters (bias, bias rate per  
16 revolution, terms of 1-, 2-, 3- and 4- cycle per revolution) have been also adjusted and  
17 removed from the KBRR data. The final residuals of KBRR obtained after all corrections  
18 should reflect the non modelled geophysical phenomena (post-glacial rebound, earthquakes,  
19 models errors and mainly continental hydrology) plus ~~model errors and~~ short-wavelength  
20 noise.

21

22 **1.2 Datasets used for comparison**

23

24 **1.2.1 Mascons solutions**

25 In this local approach, the mass of water in surface blocks has been explicitly solved using the  
26 GRACE inter-satellite KBR Rate (KBRR) data for continental hydrology and collected over  
27 the region of interest. The local representation of gravity minimizes the leakage error from  
28 other areas due to aliasing or mis-modelling (Rowlands et al., 2005; Lemoine et al., 2007).  
29 The mass changes have been solved at 10-day intervals using  $4^\circ \times 4^\circ$  blocks using temporal  
30 and spatial constraints. These “mascons” solutions can be downloaded at: [http://grace.sgt-](http://grace.sgt-inc.com)  
31 [inc.com](http://grace.sgt-inc.com).

32

33 **1.2.2 CNES GRGS global solutions**



1 The Level-2 GRGS-EIGEN-GL04-10day models are derived from Level-1 GRACE  
2 measurements including KBRR, and from LAGEOS-1/2 SLR data for enhancement of lower  
3 harmonic degrees (Lemoine et al., 2007; Bruinsma et al., 2010). These gravity fields are  
4 expressed in terms of normalized spherical harmonic coefficients from degree 2 up to degree  
5 50-60 using an empirical stabilization approach without any smoothing or filtering. 10-day  
6 Total Water Storage (TWS) grids of 1-degree spatial resolution are available for 2002-2010  
7 at: <http://grgs.obs-mip.fr>.

8

### 9 **1.2.3 ICA-filtered solutions**

10 A post-processing method based on Independent Component Analysis (ICA) was applied to  
11 the Level-2 GRACE solutions from different official providers (i.e., UTCSR, JPL, GFZ) pre-  
12 filtered with 400-km radius Gaussian filters. This approach does not require a priori  
13 information, except the assumption of statistical independence between the elementary  
14 sources that compose the measured signals (i.e., useful geophysical signals plus noise).  
15 Separation consists of solving a linear system relating the GRACE solutions provided for a  
16 given month, to the unknown independent sources. The contributors to the observed gravity  
17 field are forced to be uncorrelated numerically by imposing diagonal cross-correlation  
18 matrices. Time series of ICA-based global maps of continental water mass changes from  
19 combined UTCSR, JPL and GFZ GRACE solutions, computed over the period 08/2002 –  
20 12/2010, are used in this study. For a given month, the ICA-filtered solutions only differ from  
21 a scaling factor, so that the GFZ-derived ICA-filtered solutions are only presented. The  
22 efficiency of the ICA in separating gravity signals from noise by combining Level-2 GRACE  
23 solutions has previously been demonstrated over land (Frappart et al., 2010, 2011).

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24 ~~An approach based on Independent Component Analysis (ICA) has been applied on the~~  
25 ~~monthly Level 2 RL04 GRACE solutions from CSR, JPL and GFZ, to separate the~~  
26 ~~statistically independent components of the gravity field, i.e., useful geophysical signals from~~  
27 ~~important striping undulations (Frappart et al., 2010, 2011). We use the monthly ICA~~  
28 ~~solutions prefiltered with a 400 km Gaussian filter, with a 1° degree spatial resolution and~~  
29 ~~computed for 2003-2009.~~

30

### 31 **1.2.4 WGHM land water storage**

32 The WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003; Hunger and Döll,  
33 2008) is a conceptual model that simulates the water balance at a spatial resolution of 0.5  
34 degree. It represents the continental water cycle using several water storage compartments

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1 which include interception, soil water, snow, groundwater and surface water (rivers, lakes,  
2 wetlands). WGHM has been widely used to analyze spatio-temporal variations of water  
3 storage globally and for large river basins (Güntner et al., 2007). In this study, we use 1-by-1  
4 degree daily TWS grids from the latest WGHM version described by Hunger and Döll (2008)  
5 for 2002-2007.

6

## 7 **2. Methodology**

8

### 9 **2.1 Differences of potential anomaly from KBRR data**

10

11 In a quasi-inertial frame, according to the energy integral method, the Differences of Potential  
12 Anomaly (DPA) between GRACE vehicles A and B is related to the KBRR residuals  $\dot{\alpha}_{AB}^*$   
13 using the scalar product (see the energy integral method proposed by Ramillien et al., 2011):

14

$$\delta V_{AB}^* \approx \dot{\Gamma}_{AB} \dot{\alpha}_{AB}^* \quad (1)$$

15

The upper script symbol “\*” is for residuals quantities once the effects of the a priori known  
16 accelerations on the KBRR data are removed during the least-squares orbit adjustment for  
17 positions and velocities from Level-1 GRACE measurements (see paragraph 1.1).  $\dot{\Gamma}_{AB}$  is the  
18 arithmetic mean of the velocities of the two GRACE satellites. A similar expression for the  
19 determination of the DPA was previously found by Jekeli (1999).

20

For solving the problem of the important long-wavelength differences between the DPA  
21 segments and stabilizing the inversion, low-degree polynomials are simply removed from  
22 the north-southlatitudinal DPA tracks. Obviously, the risk of this operation is to looseave  
23 useful long-wavelength water mass signals which extensions exceed the dimension of the  
24 considered region. In the following numerical estimations, we will see that the predicted  
25 regional solutions need to be completed by long-wavelength components for comparison with  
26 other datasets, when the geographical region is not large enough to contain these wavelengths.

27

### 28 **2.2 The forward problem**

29

The linear system of equations to be solved is:

30

$$\Gamma X = Y \quad (2)$$

31

1 where  $Y$  is the vector which contains the  $i=1, \dots, N$  observations (i.e., the reduced DPA  $\delta V_{AB}^*$   
 2 obtained from KBRR residuals (Eq.1) during the period  $\Delta t$  of survey), and  $X$  is the vector of  
 3 the  $j=1, \dots, M$  parameters (i.e., the equivalent-water heights).  $\Gamma$  represents the N-by-M design  
 4 matrix which elements are derived from a discrete version of the first Newton's law of  
 5 attraction of masses:

$$6 \quad \Gamma_{i,j} = G\rho_w \delta S_j \left( \frac{1}{\xi_{B,j}} - \frac{1}{\xi_{A,j}} \right) \quad (3)$$

7 where  $G$  is the gravitational constant ( $\sim 6.67 \cdot 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ ),  $\rho_w$  is the mean density of water  
 8 ( $\sim 1000 \text{ kg m}^{-3}$ ); and  $\delta S_j$  is the elementary surface number  $j$ .  $\xi_{A,j}$  and  $\xi_{B,j}$  are the Cartesian  
 9 distances between each GRACE vehicle (A and B) and the centres of the elementary surface  
 10 tiles. If the inverses of the Cartesian distances in the latter equation are approximated by a  
 11 discrete sum of Legendre polynomials, the elastic Love numbers  $k_n$  versus degree harmonic  $n$   
 12 can be introduced, in order to take the compensation effects of the Earth's surface in response  
 13 of loading into account (see Eq.24 in Ramillien et al., (2011)).

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14 In the case of a geographical grid, the surface elements are simply given by:

$$15 \quad \delta S_j = R^2 \Delta \lambda \Delta \theta \cos(\theta_j) \quad (5)$$

16 where  $R$  is the mean Earth's radius ( $\sim 6371 \text{ km}$ ),  $\Delta \lambda$  and  $\Delta \theta$  are the sampling angle intervals  
 17 along the longitude and the latitude respectively, and  $\theta_j$  is the latitude of the elementary  
 18 surface element number  $j$ .

### 20 **2.3 The ill-conditioned inverse problem and its regularization**

21  
 22 The Hadamard's conditions (i.e., existence, continuity and unicity) need to be checked before  
 23 inversion. The solution of the classical gravity inverse problem usually exists and is  
 24 continuous, but also is not unique. By computing the SVD of  $F$ , the rank of the operator (i.e.,  
 25 the number of non-zero singular values) - and thus the dimension of its kernel - can be easily  
 26 determined. For example, the set of singular values in the case of differences of potential  
 27 anomalies over South America for August 2009, simultaneously contains very small and large  
 28 quantities. Consequently, the generalized condition number of the system is large. In practice,  
 29 the Newtonian operator is simply constructed with Cartesian distances  $\xi_{A,B}$  that are very close  
 30 numerically, and thus they produce nearly identical lines and columns in the matrix  $F$ .

1 Regularization consists of finding the optimal solution vector  $\hat{X}$  which minimizes the  
2 quadratic form:

$$3 \quad \varepsilon^2 = \|Y - \Gamma X\|^2 + \alpha \|CX\|^2 \quad (6)$$

4 where an extra squared term is added to the classical least-squares term  $\|Y - \Gamma X\|^2$  to stabilize  
5 the linear system to solve.  $\alpha$  is here the regularization parameter that counterbalances the  
6 weights of the model with the constraints from the M-by-M element matrix C. As the solution  
7  $\hat{X}$  corresponds to the minimum of the Eq.6. By differentiating this latter expression is  
8 differentiated versus each component element of the vector X, and setting these new equations  
9 are set them to zero. This set of conditions of extremum yields the regularized least-squares  
10 solution: the conditions for extreme values are obtained, and then the numerical solution of  
11 this set of conditions is given by:

$$12 \quad \hat{X} = (\Gamma^T \Gamma + \alpha C^T C)^{-1} \Gamma^T Y \quad (7)$$

13 Note that the unstable ~~least-squares~~ solution is easily found when  $\alpha = 0$ .

14 The difficulty is to keep a numerical compensation between the normal matrices  
15  $\Gamma^T \Gamma$  and  $C^T C$ . In practice, the regularization parameter  $\alpha$  can be chosen as the square-root of  
16 the squared elements of the normal matrix  $\Gamma^T \Gamma$  (see Dimri, 1992, p.145). In our case of  
17 inversion of GRACE-derived ~~DPA differences of potential, were regularization parameters are~~  
18 evaluated for each 10-day period, and numerical values ranging from  $1.83 \times 10^{-4}$  to  $1.15 \times 10^{-3}$   
19 are found following this simple expression.

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20 ~~have the condition~~  $\alpha = \sqrt{\lambda}$

## 21

### 22 2.4 Definition of the spatial constraints

23

24 Let B be the M-by-M elements matrix containing the spatial constraints with diagonal entries  
25 equal to zero such as:

$$26 \quad X = BX \quad (8)$$

27 In other words, each value of X is simply a linear combination of the other values of the  
28 solution itself. We have equivalently:

$$29 \quad CX = 0 \quad (9)$$

30 with:

$$31 \quad C = Id - B \quad (10)$$

1 where Id denotes the identity matrix, so that C has a dominant diagonal.  
 2 Let  $\varphi_{i,j}$  be the spherical distance between the surface elements numbers i and j, and  $\varphi_0$  the  
 3 maximum radius of the correlation.  $L(\varphi_0)$  is the number of surface tiles inside the  
 4 geographical disk of radius  $\varphi_0$  and of which the surface element number i is the center.

5 Different correlations versus spherical distance can be defined for  $\varphi_{i,j} \leq \varphi_0$ :

6 - Case 1: Uniform weighting (**MOY**):

$$7 \quad B_{i,j} = 1/L(\varphi_0) \quad (11a)$$

8 - Case 2: Linear weighting (**LIN**):

$$9 \quad B_{i,j} = (1 - \frac{|\varphi_{i,j}|}{\varphi_0})/L(\varphi_0) \quad (11b)$$

10 - Case 3: Exponential-type weighting (**EXP**):

$$11 \quad B_{i,j} = \exp(-|\varphi_{i,j}/\chi|)/L(\varphi_0) \text{ with } \chi = \frac{\lambda}{2\ln 2} \quad (11c)$$

12 - Case 4: Gaussian-type weighting (**GAU**):

$$13 \quad B_{i,j} = \exp(-(\varphi_{i,j}/\chi)^2)/L(\varphi_0) \text{ with } \chi = \frac{\lambda}{2\sqrt{\ln 2}} \quad (11d)$$

14 And in these **fourthree** cases,  $B_{i,j} = 0$  if  $\varphi_{i,j} > \varphi_0$ . The extra term  $\chi$  is a spatial “damping”  
 15 factor that depends upon the length of correlation  $\lambda$ , such as  $B_{i,j} = \frac{1}{4L(\varphi_0)}$  **and**

16  $B_{i,j} = \frac{1}{16L(\varphi_0)}$  if  $\varphi_{i,j} = \lambda$  (i.e., the half height at a chosen correlation length) for **eitherthe**

17 **cases-numbers 3 or caseand 4, respectively**. By construction, the matrix B is symmetric (i.e.,

18  $B_{ij} = B_{ji}$  for any pair of integers i and j), and its diagonal entries are zeros.

19

## 20 **3. Numerical applications**

21

### 22 **3.1 Preliminary tests**

23 Level-1 GRACE data are used to adjust daily orbits with known a priori accelerations as  
 24 explained in paragraph 1.1. Residual KBRR data are used to compute trend-corrected DPA  
 25 tracks passing over the selected area (e.g., South America [60°S-20°N; 90°W-30°W]) for 1-  
 26 | 10 **AugustSeptember**, 2009, after having implemented the modified least-squares estimator

1 (Eq.7). A regional solution is inverted from 10-day DPA for a given set of correlation radius  $\lambda$   
2 and size of elementary tiles. Note that the case of  $\lambda=0$  corresponds to a determination of  
3 spatially uncorrelated water heights, and ~~leads yields~~ to a noisy solution with unrealistic short-  
4 wavelength amplitudes. Figure 1 presents 10-day regional solutions considering surface  
5 elements of decreasing sizes  $\Delta\theta$  (i.e., or  $\Delta\lambda$ ), revealing the estimated amplitudes remain  
6 roughly the same for surface mass elements from 1 to 4 degrees. Figure 2 shows the loss of  
7 spatial resolution due to the smoothing when considering increasing exponential-type  
8 correlation radii. Errors of recovery versus combination of  ~~$\alpha$ ,  $\lambda$ , and  $\Delta\lambda$~~   ~~$\Delta\theta$  and~~  
9  ~~$\Delta\theta$~~  parameters are determined using simulated hydrology-based DPA tracks over South  
10 America from the WGHM global hydrology model (Döll et al., 2003; Hunger and Döll, 2008)  
11 by using simply the Newtonian operator  $\Gamma$  associated with the whole region, and these errors  
12 are plotted on Figure\_3. Errors of recovery (i.e., differences between reference model values  
13 and regularized least-square estimates from Eq.7) ~~are is larger generally more important~~ for  
14 Gaussian-type (i.e., GAU) weighting (Eq.11d) than for exponential-type (i.e., EXP) and  
15 linear/uniform-type weightings (i.e., LIN and MOY resp.) (Eq.11a-b-c). ~~They suggest that~~  
16 ~~the smoothing with a correlation radius~~ reduces the long-wavelength error, but ~~surely still~~  
17 ~~removes miss the~~ short-wavelength details. When white noise generated with various  
18 numerical seeds ~~is are~~ input into the simulated DPA data, spatial correlations enable to  
19 attenuate efficiently the effect of this polluting noise in the recovery (Figure 4), the reduction  
20 of error amplitude represents at least 50% when  $\lambda > 600$  km for a realistic noise level of  $10^{-3}$   
21  $\text{m}^2/\text{s}^2$ , and then almost unchanged after 800 km.

### 22 3.2 Computation of regional solution time series for South America

23 Small surface elements (~1 degree) could be estimated to improve the level of details in our  
24 solutions. However, as mentioned previously by Ramillien et al. (2011), the intrinsic optimal  
25 spatial resolution of the GRACE data remains limited at ~200-300 km, so that considering 2-  
26 degree tiles computation is enough to catch all the GRACE resolution. As illustrated on Fig.1,  
27 there is no change of amplitude by decreasing the size of the tiles and no gain of details. Four  
28 years (2006-2009) of KBRR residuals for continental hydrology were used to estimate  
29 regional mass changes by solving daily normal equations  $I^T \Gamma$  obtained from residual DPA  
30 using Eq.7 and considering an exponential-type weighting. Dealing with factorization of  
31 symmetric normal equations remains faster than using a SVD decomposition of normal  
32 equations before L-curve regularization (Ramillien et al., 2011).

1 As shown by testing different input parameters (Figures 2 and 4), a correlation radius of 600  
2 km for continental hydrology is a good compromise between reduction of noise and  
3 smoothness. In order to damp unrealistic oscillations over oceans, a longer radius of  
4 thousands of km can be used. By using a geographical mask, we can distinguish different  
5 spatial constraints over continents and oceans (*i.e.*, 600 and 5000 km, respectively). The  
6 corresponding 2-degree constrained regional solutions are presented on Figure 5a and Figure  
7 5b for the whole ~~recent~~ year 2009, and they reveal a complete seasonal water cycle for South  
8 America. Estimated equivalent-water heights over the continent are detailed and in the annual  
9 range of +/-300 mm locally. As expected, regional solutions exhibit important ~~seasonal~~  
10 amplitudes, especially over the large drainage basins of the Amazon, Orinoco, Tocantins, and  
11 Parana rivers. A persistent mass depletion is also observed for the coastal Patagonian glaciers.  
12 However, strong spatial constraints have efficiently damped the long-wavelength DPA signals  
13 over the oceanic areas. The remaining signals over the ocean are probably due to aliasing  
14 versus time and errors in correcting models. Loss of energy from continental hydrology  
15 signals cannot be excluded as well. Besides, short-term water mass events can be easily seen  
16 on these regional maps, corresponding to large floods occurring over the north east of the  
17 Amazon basin in June 2009 and over the Parana in November 2009, as seen in (Figure 5b).

#### 18 4. Discussion

19  
20 Introducing spatial correlations between surface elements enables us to stabilize numerically  
21 the inversion and to cancel the effects of the ~~longitudinal~~latitudinal striping. This method  
22 eliminates the unrealistic signals errors in de-aliasing models over the oceans, when a  
23 geographical mask is used.

24 The regional approach proposed here suppresses drawbacks of striping error inherent to  
25 ~~measurement configuration and temporal aliasing, as global spectral representation because:~~

26 (i) the reduction of the north-south striping in the solution as using constrained  
27 regularization with a geographical radius remains more flexible with space localizing  
28 ~~representation, no spherical harmonics coefficient is fitted and satellite tracks are corrected of~~  
29 long-term trend, and (ii) by construction there is no contamination of signals from other parts  
30 of the world.

31 2 and 4-degree solutions provide very comparable averages versus time, this remains  
32 consistent with the previous test on the impact of choosing different sizes for surface tiles in  
33 the inversion (see results of Figure 1).

1 For validation, our regional estimates of change in continental water storage are confronted to  
2 time series from other GRACE-based products (“mascons”, GRGS, ICA) and WGHM global  
3 hydrology model outputs. We consider local (i.e., at the size of a surface tile) and averaged  
4 water mass signals versus time over the Amazon basin, as it is the biggest drainage basin of  
5 the world (~6 millions of square kilometres), and where redistributions of large amounts of  
6 surface waters occur.

7 Regional solutions for March and September 2006 are confronted to other GRACE-based  
8 solutions (i.e., (a) “stabilized” 10-day and 4-degree global solutions from GRGS, (b) 10-day  
9 and 4-degree NASA “mascons” and (c) monthly and 4-degree ICA global solutions) in Figure  
10 6. For comparison purposes, the 10-day solutions were averaged over a month to be  
11 consistent with the global monthly solutions. They show similar structures of water mass  
12 anomaly, especially in the southern part of the Amazon basin. However, the amplitudes of the  
13 regional solutions are ~~larger~~ ~~more important~~ (up to +/-395 mm and +/-450 mm of equivalent-  
14 water height for March and September, respectively) and appear to contain more details. Once  
15 the one-degree global grids are interpolated into 2-degree tiles, the spatial correlations with  
16 these other datasets for March 2006 are high: 87% and 83% for (a) and (c) respectively. Six  
17 months later they are of 87% and 88%. 4-degree solutions have been also computed to be  
18 compared at the same spatial resolution to the available “mascons” solutions, and they present  
19 water mass structures of comparable water mass amplitudes. For the same periods and at the  
20 scale of the whole South America continent, power spectrum analysis reveal that the regional  
21 solutions are more energetic than the band-limited global solutions (GRGS, ICA, “mascons”)  
22 at short and medium spatial wavelengths (<4000 km) (Figure 7). Regional solutions logically  
23 contain more energy at very short wavelengths (by a factor 10 of the other power spectra)  
24 near the Nyquist frequency (~400 km), as the spatial sampling (i.e., the size of the surface  
25 tiles) is better (~200 km).

26 The seasonal variations of the water mass averaged in the ~~large~~-Amazon basin are clearly  
27 sinusoidal with a positive maximum in April-May (Figure 8). As previously suspected by  
28 Rowlands et al. (2010), once averaged over a large region, 4-degree “mascons” estimates are  
29 comparable to global approaches that are also based on spherical harmonics. Both global and  
30 “mascons” solutions present seasonal amplitudes reaching +/-180 mm of equivalent-water  
31 thickness. As presented on Figure 9, the differences of amplitudes between the spherical  
32 harmonics and constrained regional solutions for 2006 are clearly seasonal with peak-to-peak  
33 amplitudes of +/-90 mm of equivalent-water height. These latter differences are completely  
34 explained by the loss of very long wavelengths (or equivalently, lower harmonic degrees of



1 the observed gravity signals) due to the de-trending of the DPA tracks made over South  
2 America before regional inversion, as explained at the end of paragraph 2.1. Latitudinal  
3 extend of the studied region being of  $80^\circ$  (i.e., distance of  $d \sim 8000$  km), the cut-off degree of  
4 the signals lost by linear de-trending should be  $n \sim \frac{2\pi R}{d}$ , thus numerically  $n \sim 5$ . The  
5 numerical verification is presented on Figure 9, where the best agreement between 2-degree  
6 regional and global 10-day solutions and long-wavelength gravity signals from GRGS is  
7 found for harmonic degree 5, with a Root Mean Square (RMS) difference of only 11 mm of  
8 equivalent-water height. Once this bias is corrected in the Total Water Storage (TWS) time  
9 series, global and regional techniques both yield to comparable spatial averages.

10 Another way ~~to for-avoiding to-losing~~ long-wavelengths in the inversion is to increase the  
11 latitudinal extension ~~in latitude~~ of the considered area, as presented Figure 10, where the  
12 “stabilized” GRACE GRGS solution for the first 10 days of March 2009 is compared to the  
13 smooth regional solution computed on nearly a third of the Earth’s surface. The localisations  
14 and amplitudes of water mass anomalies on continents are comparable, ~~howeverbut~~ the  
15 GRGS solution contains ~~n~~North-s~~S~~ striping. Consequently, the differences between the  
16 two solutions correspond to these spurious undulations due to aliasing effects in the spherical  
17 harmonics (Figure 10c).

18 Manaus ( $3^\circ\text{S}$ - $60^\circ\text{W}$ ) is located roughly at the center of the Amazon basin, at the mouth of the  
19 Negro River, slightly upstream the convergence of the two major rivers forming the Amazon  
20 River: Solimoes and Rio Negro tributaries. Local time series are simply interpolated from  
21 gridded values or from surface tiles centered on Manaus, they are presented on Figure 11. All  
22 the Manaus time series show that the main seasonal variation for 2006 are very consistent to  
23 each others, in particular the slow increase of water mass until the middle of June and up to  
24 400-500 mm of equivalent-water height, and the rapid decrease afterwards. However, the 4-  
25 degree “mascons” signal at Manaus ~~has~~ve less amplitudes (reaching only  $\sim 350$  mm in  
26 Spring), and is smoother than the other profiles. This smoothing is probably due to the  
27 damping effects of correlations of 10-30 days and the 4-degree averaging used in the  
28 processing of “mascons” solutions (Luthcke et al, 2006; Lemoine et al., 2007). The WGHM-  
29 derived TWS time series shows important intra-annual variability during the first six months  
30 of the year, which ~~is~~—corresponds to important rainfall events that occurred in  
31 October/November 2005, causing floods in January/February 2006, especially in the Rio  
32 Negro basin (Marengo et al., 2008). The signature of this unusual flood can be noticed by the  
33 presence of a peak of water level in the gauge records, as for instance, at the Observatoire

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1 Régionale de l'Environnement (ORE) Hybam (<http://www.ore-hybam.org/>) station of  
2 Serrinha (0.48°S-64.82°W).

3

#### 4 **CONCLUSION**

5

6 We proposed a new regional least-squares approach to estimate surface water mass variations  
7 from GRACE-based KBRR residuals for continental hydrology. Spatial constraints have been  
8 added to stabilize the ill-conditioned linear system of equations to solve, as well as for  
9 attenuating the effects of the noise. In particular, there is no difference in predicted water  
10 mass amplitudes considering grid samplings of 1, 2 and 4 degrees, suggesting the final spatial  
11 resolution of the regional grids is limited by the intrinsic resolution of the GRACE data  
12 (~200-300 km) available for the chosen period. Different types of spatial constraints have  
13 been implemented, and they provided similar amplitudes once the smoothing radius is fixed.  
14 It is clear that a compromise between averaging radius and the final spatial resolution has to  
15 be found. Inversion of simulated error-free potential differences provided formal uncertainties  
16 of ~3-4 cm of equivalent-water height for smoothing radii from 200 to 2500 km. Random  
17 large-band noise of  $10^{-2} \text{ m}^2/\text{s}^2$  magnitude produces errors of 1-2 cm of equivalent-water  
18 height. Time series of successive 10-day regional maps of water mass over South America  
19 have been successfully computed for several years, so that short-term hydrological variations  
20 have been detected, such as sudden inundation events. Regional maps are consistent with  
21 other independent datasets, however they are more detailed. The promising regional inversion  
22 of GRACE KBRR data will be extended to the full multi-year period of GRACE  
23 observations. Obviously, constrained regional solutions can be easily estimated ~~—easily—~~  
24 in other continental areas, such as Africa, Europe, North America and Australia, and they offer  
25 interesting applications in the detection of continental water mass changes.

26

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29 methods of regularization. We would like to thank an anonymous reviewer for his fruitful  
30 comments on the manuscript.

31

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16

17

1 **Figure caption**

2

3 **Figure 1:** 4-degree (a), 2-degree (b), and 1-degree “constrained” regional solutions over  
4 South America computed with KBRR residuals of 1-10 August, 2006, ~~and for different grid~~  
5 ~~samplings~~. The correlation radius is 600 km for the three cases. They reveal roughly similar  
6 amplitudes of water mass anomaly.

7

8 **Figure 2:** 1-degree regional solutions computed with different lengths of correlation: (a) 200  
9 km, (b) 400 km, (c) 600 km and (d) 800 km. Note the important smoothing (i.e., loss of short-  
10 wavelength details) as the correlation radius increases.

11

12 **Figure 3:** Decrease of the recovery error versus the correlation radius for a simulated case of  
13 GRACE tracks over South America. Star, triangle and circle symbols are for MOY, EXP and  
14 GAU types of geographical correlation respectively [\(see Eq.11 a-d\)](#). Grey curves are for the  
15 1-degree grid inversion, whereas black and dotted curves are for 2 and 4-degree grids  
16 respectively.

17

18 **Figure 4:** Errors of recovery from noisy potential anomaly data. Noise is generated randomly  
19 using different seeds and added before inversion. Smoothing clearly attenuates s the effects of  
20 the noise.

21

22 **Figure 5a and 5b:** Time series of 2-degree regional solutions over South America from  
23 January to December, 2009. The correlation radii are 600 km and 5000 km over the  
24 continents and oceans, respectively.

25

26 **Figure 6:** Six-month interval water mass solutions derived from GRACE data (from top to  
27 bottom): 2-degree constrained regional solutions; 4-degree NASA “mascons” solutions; ICA-  
28 filtered solutions (Frappart et al., 2011); 10-day GRGS global solutions (Lemoine et al.,  
29 1997). First and the second columns are for March and September, 2006, respectively.

30

31 **Figure 7:** Radial power spectrum of water mass variations over South America for (a) March  
32 2006 and (b) September 2006: 2-degree regional solutions (solid lines), 10-day GRGS global  
33 solutions (dashed lines) and 400-km ICA global solutions (grey lines).

34



1 **Figure 8:** GRACE-based products and WGHM global hydrology model averaged on the  
2 Amazon River basin for the year 2006. Symbols: crosses: 10-day GRGS solutions; circles:  
3 400-km ICA solutions; dashed line: 4-deg. “mascons” from NASA; solid line: daily WGHM  
4 outputs; and black and white stars: 2 and 4-deg. regional solutions, respectively.

5

6 **Figure 9:** Time series of the differences between 10-day GRGS global solutions and 2-  
7 degree constrained regional solutions for 2006 (solid line). Spherical harmonics from GRGS  
8 averaged over the Amazon basin for maximum degrees:  $n=4$  (black circles),  $n=5$  (black stars)  
9 and  $n=6$  (white circles). A minimum value of root mean square differences of  $\sim 11$  mm of  
10 equivalent-water height is found for  $n=5$ .

11

12 **Figure 10:** (a) “stabilized” 10-day GRGS solution and (b) regional solution computed over  
13 the same large area [ $60^{\circ}\text{S}$ - $70^{\circ}\text{N}$ ;  $180^{\circ}\text{W}$ - $30^{\circ}\text{W}$ ] of the two Americas, for the beginning of  
14 March 2009. The map of difference (a) minus (b) reveals the important North-South striping  
15 on the continents (c).

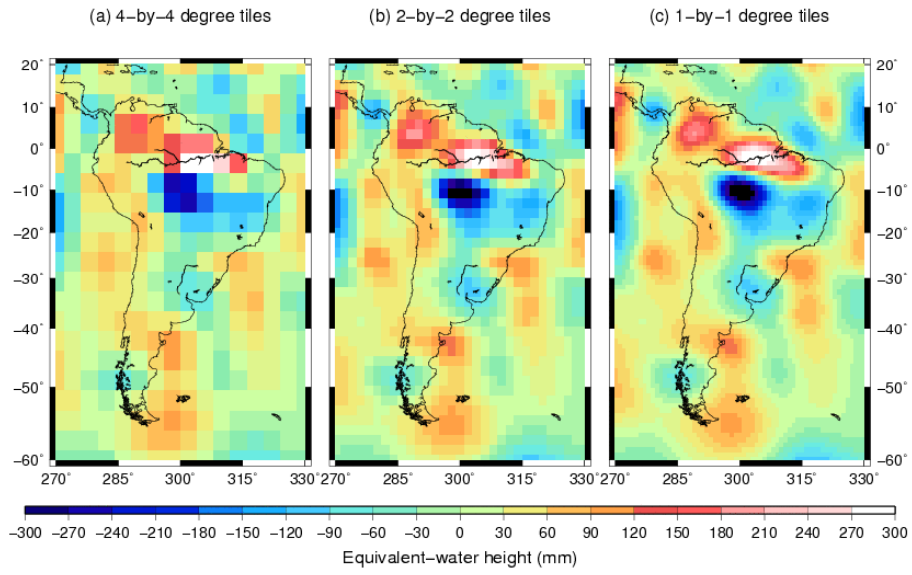
16

17 **Figure 11:** Time series of equivalent-water height at Manaus station for 2006 according to the  
18 datasets presented on Fig.6. Symbols are the same as for Fig.8.

19

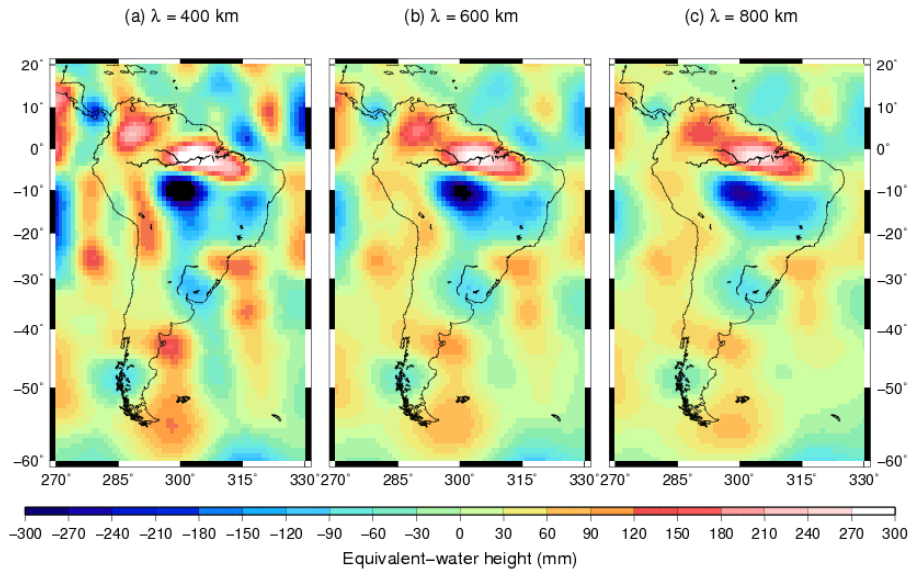
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1 **Figure 1**



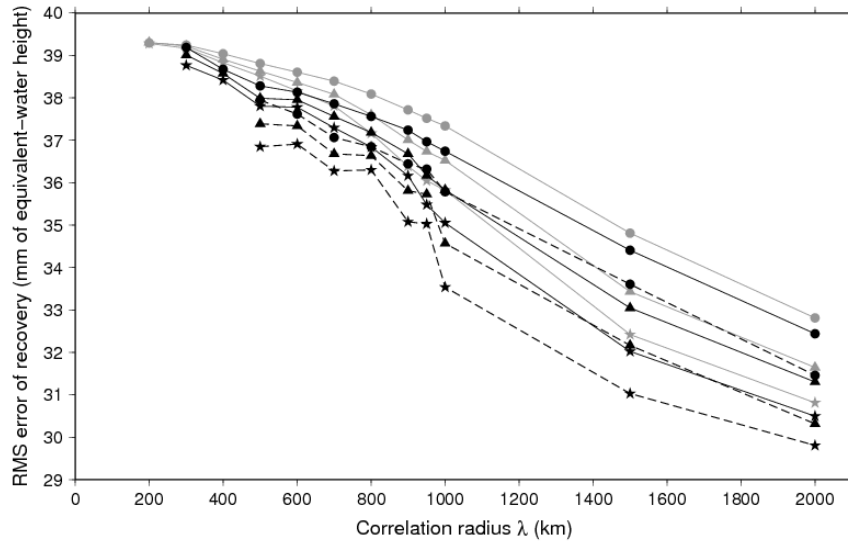
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1 **Figure 2**



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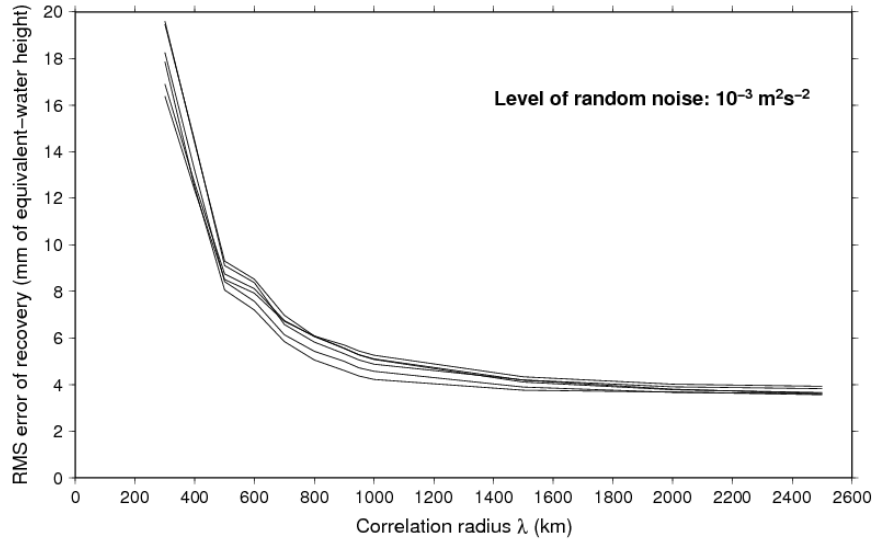
1 **Figure 3**



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1 **Figure 4**

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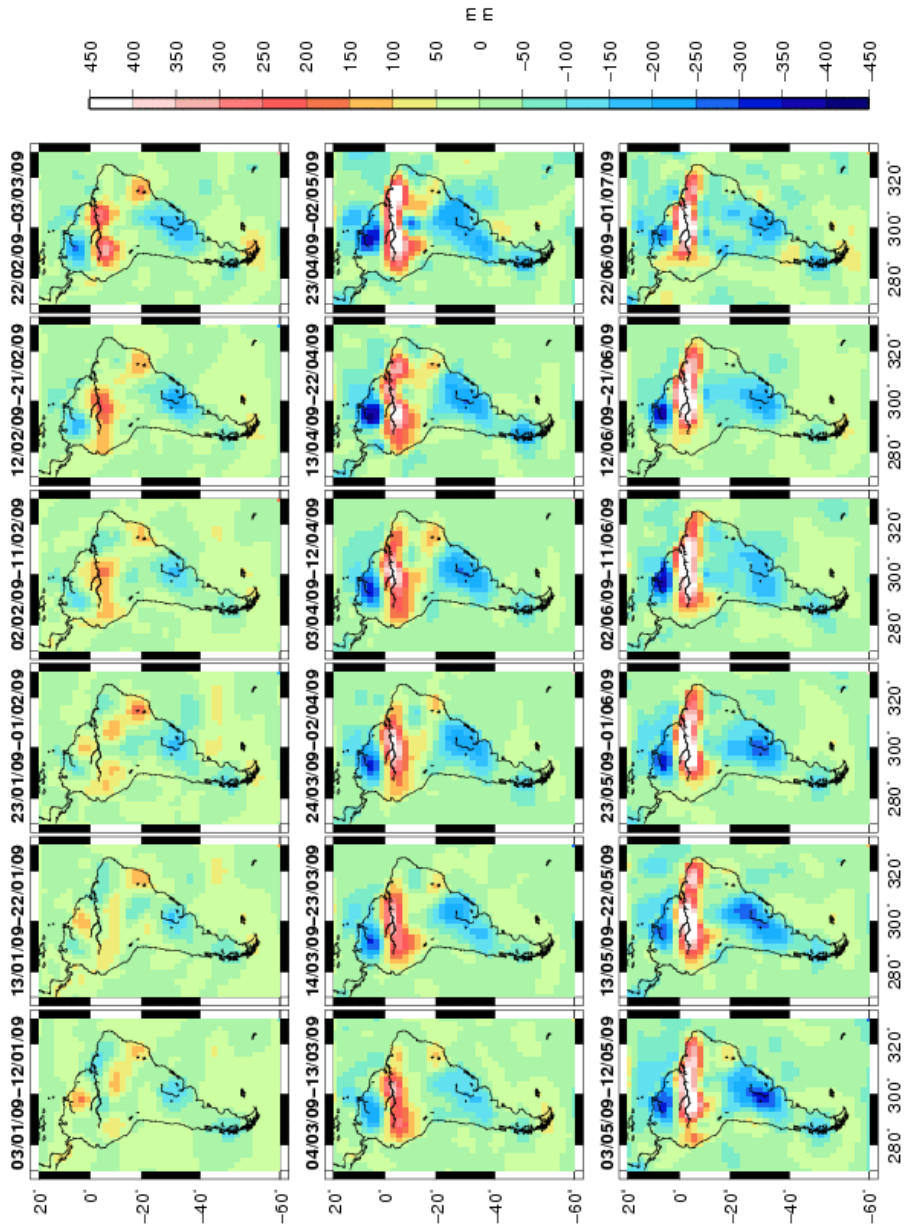


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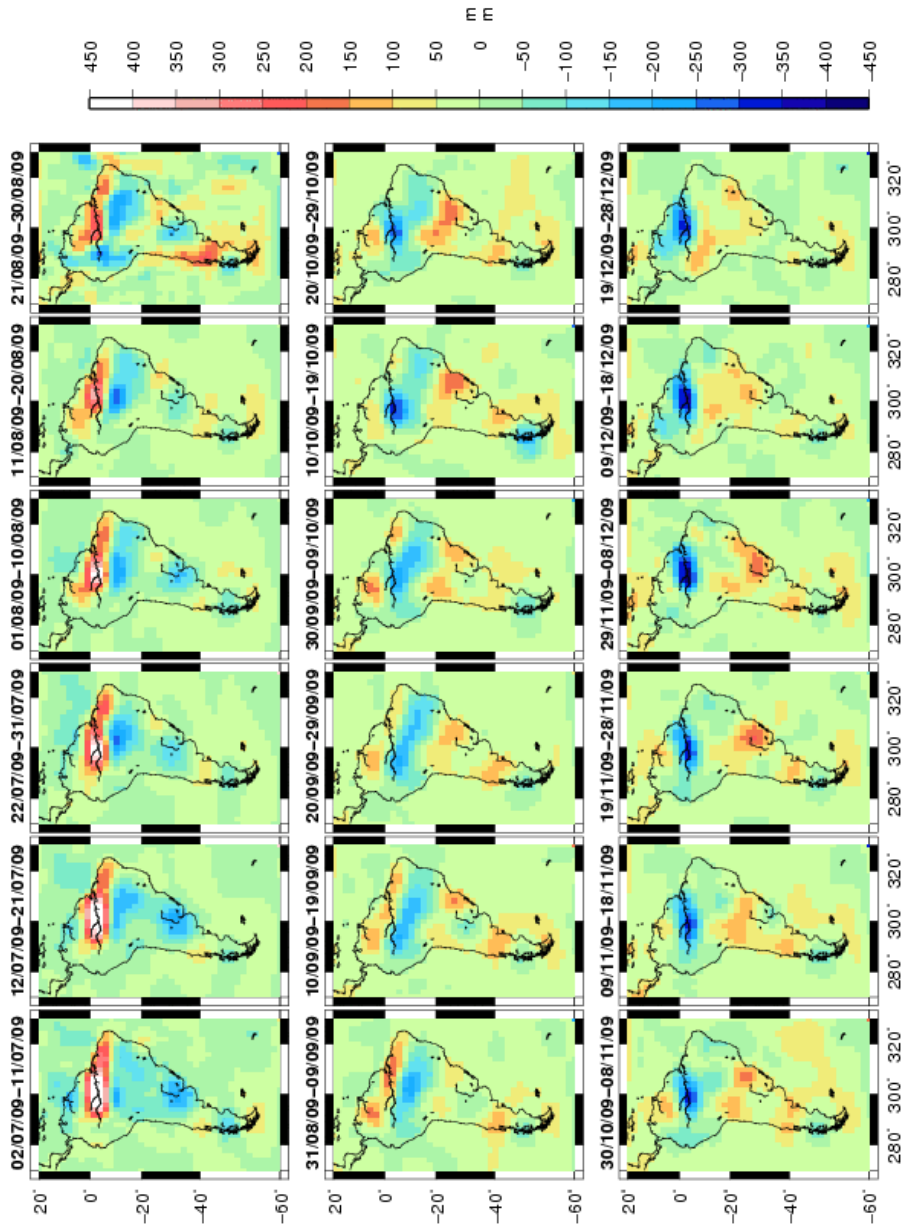
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1 Figure 5a



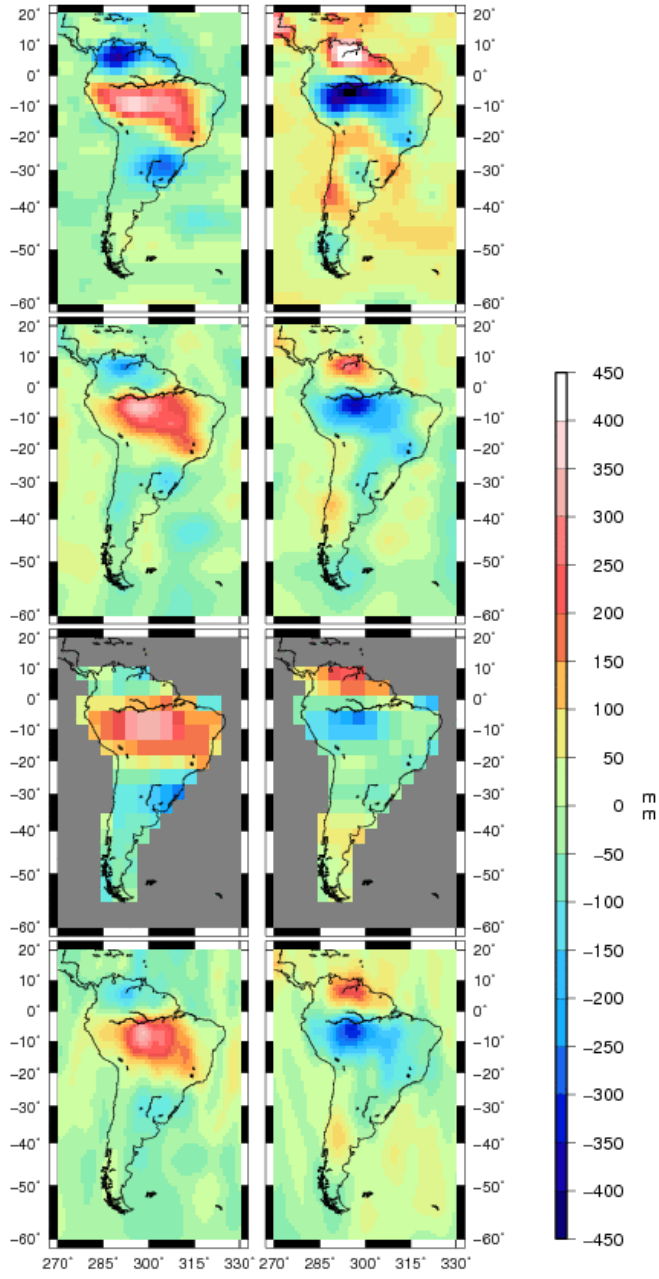
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1 Figure 5b



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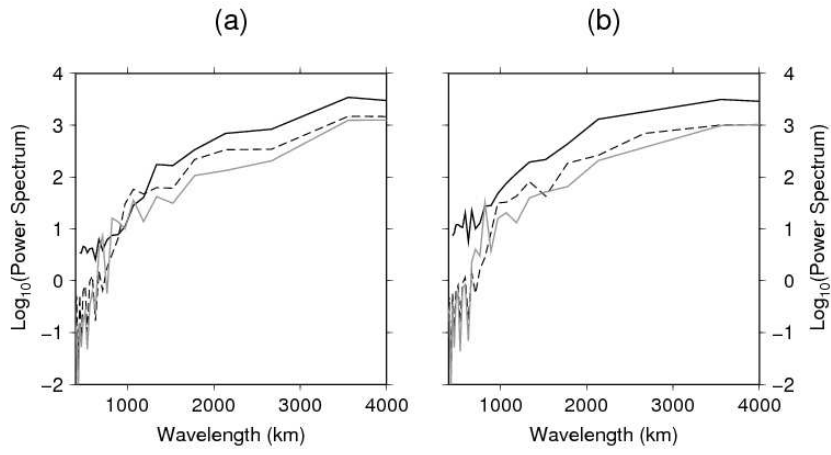
1 **Figure 6**  
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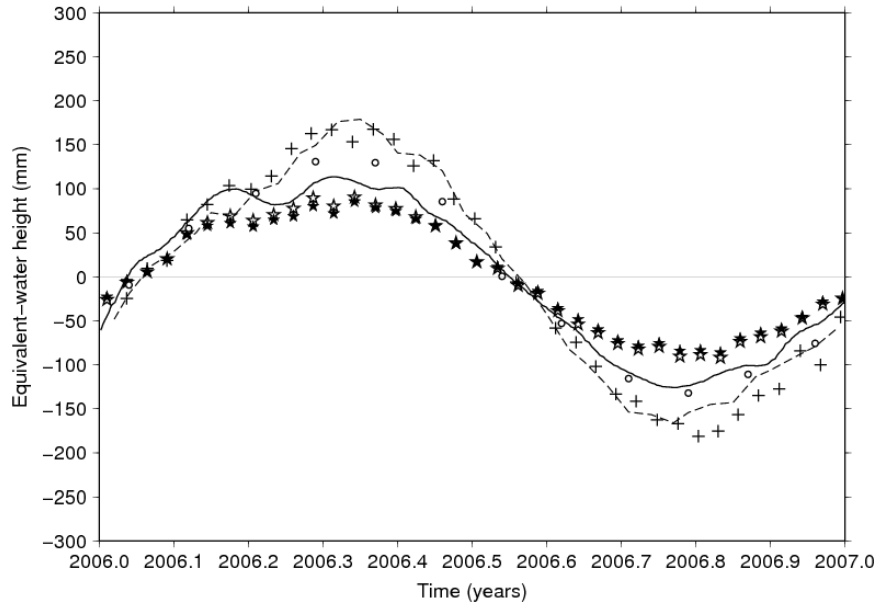
1 **Figure 7**



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1 **Figure 8**

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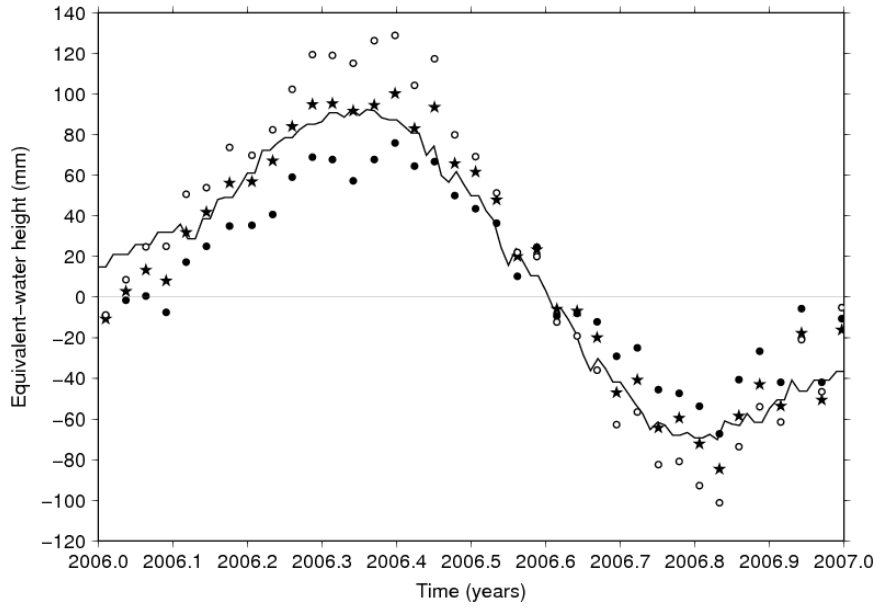
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1 **Figure 9**

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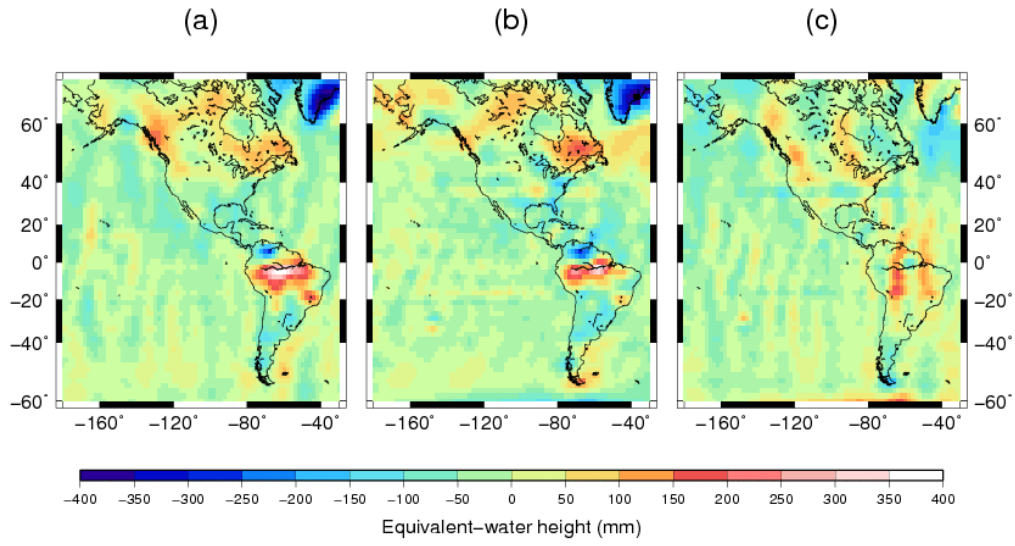
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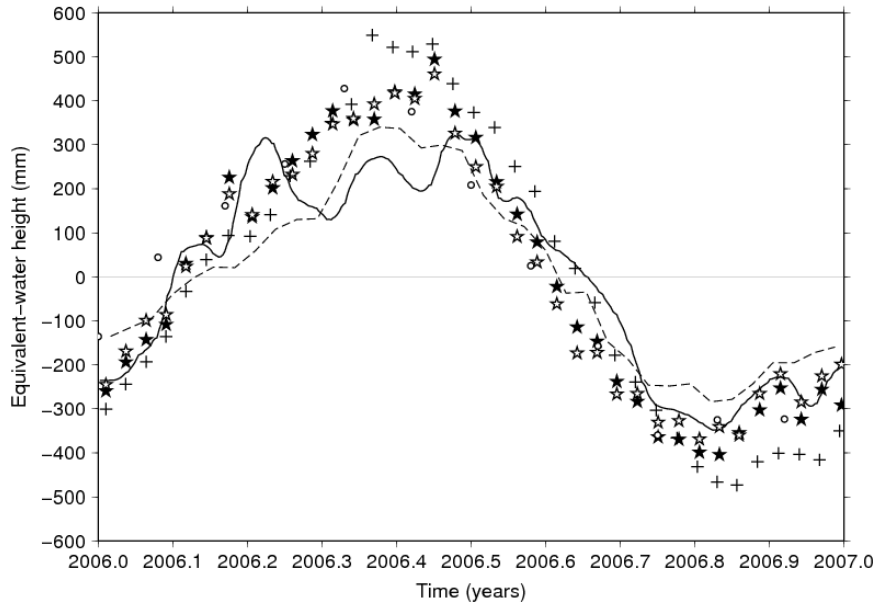
1 **Figure 10**  
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1 **Figure 11**

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**Revised version of ms. GEOP 294 (Surveys in Geophysics):**

“Constrained regional recovery of continental water mass time-variations from GRACE-based geopotential anomalies”

**Authors:**

G. Ramillien, L. Seoane, F. Frappart, R. Biancale, S. Gratton, X. Vasseur, S. Bourgogne.

January, 2012.

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Dear Editors,

Would you please find enclosed the revised version of our manuscript. All the minor corrections suggested by the reviewer have been made. As we enclose here an annotated Word file, it is possible to follow easily these corrections in the text.

Our answers to specific reviewer’s comments are indicated below.

Best regards,

G. Ramillien and his co-authors.

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**To the Reviewer and Editors:**

First, we thank the reviewer for his comments that contributed to improve the quality of the manuscript. All his remarks have been considered and corrected (see annotated text).

In particular:

\* Paragraph 1.2.3, page 6: The text part presenting the GRACE-based ICA solutions has been re-written to clarify how they are computed, and which ones are used for comparison with the regional solutions for South America. As mentioned in the text, more details on ICA of the monthly GRACE solutions can be found in Frappart et al., (2010) and Frappart et al., (2011).

\* Loading effects, page 8: a new sentence has been added to precise that elastic compensation can be in the regularization as Legendre polynomials, and thus elastic Love numbers, are introduced. This point is also referred to Eq.24 from Ramillien et al., (2011).

\* Eq.11, page 10: we agree the definition of  $B_{i,j}$  for the cases 3 and 4 was completely wrong, so that it is now corrected with new formula.

\* Spherical harmonics, page 12: Spherical harmonics. We agree about the fact that north-south striping is not only due to the mode of representation in spherical harmonics, but the orbit configuration and time aliasing of short-term phenomena as well. This ambiguous sentence has been simply removed from the text and replaced by the explanation provided by the reviewer.

\* Explanation of acronym “MOY” is now given in Eq.11a, page9, and this latter equation is mentioned in the caption of the Figure 3.

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