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Contribution of GRACE Satellite Gravimetry in Global and Regional Hydrology, and in Ice Sheets Mass Balance

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1. Introduction

Continental water storage is a key component of global hydrological cycle which play a major role in the Earth's climate system via controls over water, energy and biogeochemical fluxes. In spite of its importance, the total continental water storage is not well-known at regional and global scales because of the lack of *in situ* observations and systematic monitoring of the terrestrial water reservoirs, especially the groundwaters component (Alsdorf & Lettenmaier, 2003). Although some local hydrological monitoring networks exist, the current description of water storage comes primarily from global hydrology models (*e.g.*, WaterGAP Global Hydrology Model - WGHM (Döll et al., 2003) or Global Land Data Assimilation System - GLDAS (Rodell et al., 2004a)), which still suffer from important limits, such as the absence of different compartments of the terrestrial water compartments (*e.g.*, groundwater and floodplains), the errors introduced by external forcings (mostly the precipitation), the lack of reliability of external parameters as the soil type or the vegetation cover, the parameterization. Unfortunately, direct hydrological measurements are fairly limited, while imaging satellite techniques and satellite altimetry only give access to surface water and superficial soil moisture variations, that represent just the more accessible components of total water storage. Since its launch in 2002, the Gravity Recovery and Climate Experiment (GRACE) gravimetry from space mission offers a unique alternative to classical remote sensing technique for measuring changes in total water storage (ice, snow, surface waters, soil moisture, groundwater) over continental areas, representing a new source of information for hydrologists and the global hydrological modelling community.

We propose a review of the major techniques and results in extracting continental hydrology signals from GRACE satellite gravimetry, aiming at studying large-scale processes in hydrology and glaciology and the impact of the climatic variations on the global hydrological cycle. The two first parts describe the principle of the GRACE mission and the nature of the data measured. The third part is devoted to the post-processings applied to the GRACE-based products to improve their quality and accuracy. The last part presents the most significant results obtained for land hydrology and ice sheets mass balance using GRACE.

2. Principle of GRACE space gravimetry mission

GRACE, a joint US-German (NASA/DLR) mission, was launched in March 2002 and placed at low altitude on a quasi-polar orbit (inclination of 89.5°), to map the time variations of the Earth's gravity field.

2.1 Description of the "Low-Low" time-variable gravity measurements

The mission consists of two identical satellites moving along the same orbit at an altitude of ~ 450 km, one following the other with a mean inter-satellite distance of approximately 220 km in a satellite-to-satellite tracking configuration in the low-low mode initially proposed by Wolf (1969). The satellites use K-Band microwave ranging (KBR) system (Tapley et al., 2004a) to monitor continuously the relative motion of the spacecraft (*i.e.*, the range and the range rate), which varies proportionally to the integrated differences of the gravity accelerations felt by the satellites (Schmidt et al., 2008). The KBR system provides measurements of the distance between the two satellites with an accuracy better than 1 micrometre using carrier phase measurements in the K (26 GHz) and Ka (32 GHz) frequencies. Each GRACE satellite contains a 3-axis accelerometer which gives access to the dynamical effects of the non-conservative forces such as solar pressure and atmospheric drag. Once removed the non-gravitational effects from the inter-satellite range, the corrected variations of distance are used to estimate the geopotential with an unprecedented accuracy.

2.2 Time-variations of mass in the Earth system

Models of the Earth's geopotential are classically obtained by inverting GRACE data at monthly timescales and a spatial resolution of a few hundred kilometres (Tapley et al., 2004b). For the very first time, GRACE has enabled the monitoring of the spatiotemporal variations of the mass in the Earth system. The tiny variations of the Earth gravity field are due to the redistribution of fluid mass inside the surface fluid envelopes of the planet (atmosphere, oceans, continental water storage) (Dickey et al., 1999).

2.3 Expected accuracy and resolution for continental hydrology

The main application of GRACE is quantifying the terrestrial hydrological cycle through measurements of vertically-integrated water mass changes inside aquifers, soil, surface reservoirs and snow pack, with a precision of a few millimeters in terms of water height and a spatial resolution of ~ 400 km (Wahr et al., 1998; Rodell & Famiglietti, 1999). Pre-launch studies focused on the ability of GRACE to provide realistic hydrological signals, especially on continents. Wahr et al., (1998) highlighted the need to consider short-wavelength noise and leakage errors, as well as the size of the river basin. This early work largely inspired subsequent studies addressing the accuracy of recovering continental water mass signals from synthetic GRACE geoids (Rodell and Famiglietti 1999, 2001, 2002; Swenson and Wahr, 2002; Ramillien et al., 2004). The results of these simulations suggest that final accuracy would increase with spatial and temporal scales. The comparison of a large a number of modelled outputs of Terrestrial Water Storage (TWS) and the expected GRACE measurements accuracy showed that water storage changes would be detectable at spatial scales greater than 200,000 km^2, at monthly and longer timescales, and with monthly accuracies of roughly 1.5 cm (Rodell & Famiglietti, 1999). Similar conclusions were obtained using a network of hydrological observations of snow, surface water, soil moisture (SM) and groundwater (GW) in Illinois (Rodell & Famiglietti, 2001).

At basin-scale, the accuracy of GRACE measurements is expected to be 0.7 cm equivalent water height (EWH) for a basin with an area of 0.4 x 10^6 km², and about 0.3 cm EWT for a basin with an area of 3.9 x 10^6 km² (Swenson et al., 2003).

Combined with external information, GRACE offers the potentiality to monitor large-scale groundwater changes. Using a dense network of soil moisture data for the High Plains aquifer in the Central USA, Rodell and Famiglietti (2002) demonstrated the feasibility to dectect changes in aquifers since the uncertainties of mean variations of GRACE-derived GW for the ~ 450,000 km² aquifer was approximately 8.7 mm, whereas the amplitudes of the groundwater storage change signals were 20 and 45 mm for annual and 4-year periods respectively.

3. The GRACE data

Three processing centers including the Centre for Space Research (CSR), Austin, Texas, USA, the GeoForschungs Zentrum (GFZ), Potsdam, Germany, and Jet Propulsion Laboratory (JPL), Pasadena, California, USA), and forming the Science Data Center (SDS) are in charge of the processing of the GRACE data and the production of Level-1 and Level-2 GRACE products. They are distribruted by the GFZ's Integrated System Data Center (ISDC – http://isdc.gfz-potsdam.de) and the JPL's Physical Oceanography Distributive Active Data Center (PODAAC – http://podaac-wwww.jpl.nasa.gov). Preprocessing of Level-1 GRACE data (*i.e.*, positions and velocities measured by GPS, accelerometer data, and KBR inter-satellite measurements) is routinely made by the SDS, as well as monthly GRACE global gravity solutions (Level-2).

3.1 Level-2 GRACE products

The Level-2 GRACE gravity solutions consist of monthy time-series of Stokes coefficients (*i.e.*, dimensionless spherical harmonics coefficients of the geopotential) developed up to a degree between 50 and 120, that are adjusted for each monthly time-period from raw along-track GRACE measurements. Formal errors associated with the estimated Stokes coefficients are provided to the users. A dynamic approach, based on the Newtonian formulation of the satellite's equation of motion in an inertial frame centered at the Earth's center combined with a dedicated modelling of gravitational and non-conservative forces acting on the spacecraft, is used to compute the monthly GRACE geoids (Schmidt et al., 2008). During the process, atmospheric and ocean barotropic redistribution of masses are removed from the GRACE coefficients using ECMWF and NCEP reanalyses for atmospheric mass variations and ocean tides respectively, and global circulation oceanic models (Bettadpur, 2007; Fletchner 2007). The GRACE coefficients are hence residual values that should represent continental water storage, errors from the correcting models, and noise over land. The monthly solutions differ from one group to another due to differences in the data processing, the choice of the correcting models, and the data selection during the monthly time-period. Four different completely reprocessed releases were distributed yet presenting a continuous improvement in the quality of the GRACE data. Some other research groups also propose alternate processing of the GRACE data at monthly or sub-monthly time-scales using global (harmonics coefficients) and regional approaches. They include the Groupe de Recherche en Géodésie Spatiale (GRGS), Toulouse, France, the Institute of Theoretical

Geodesy (ITG) at the University of Bonn, Germany, the Delft Institute of Earth Observations and Space Systems (DEOS), Delft, Nederlands, the Goddard Space Flight Center (NASA GSFC), Greenbelt, Maryland, USA.

3.2 Conversion into coefficients of water mass anomalies

Variations in continental water storage cause changes of mass distribution in the Earth system, and thus spatiotemporal changes of the geoid, defined as the gravitational equipotential surface that best coincides with the mean sea surface. In global representation, it can be expressed as (Heiskanen & Moritz, 1967):

$$\begin{Bmatrix} \delta C_{nm}(t) \\ \delta S_{nm}(t) \end{Bmatrix} = \frac{1+k_n^{'}}{(2n+1)} \frac{R_e^{\,2}}{M} \iint_S \delta q(\theta,\lambda,t) \begin{Bmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{Bmatrix} P_{nm}(\cos\theta)\delta S \quad (1)$$

for a given time t, where δq is the surface distribution of mass, M and S are the total mass and the surface of the Earth, respectively, θ and λ are co-latitude and longitude. δC_{nm} and δS_{nm} are the (dimensionless) fully-normalized Stokes coefficients and P_{nm} are associated Legendre functions, n and m are harmonic degree and order respectively. R_e is the mean Earth's radius (~6,371 km). N is the maximum degree of the development, ideally $N \to \infty$. In practice, the Stokes coefficients are estimated from satellite data with a finite degree $N < \infty$ and this maximum value defines the spatial resolution of the geoid ~ $\pi R_e/N$. The load Love number coefficients k'_n account for elastic compensation of Earth's surface in response to mass load variations. A list of values of the first Love number coefficients can be found in Wahr et al. (1998).

By removing harmonic coefficients of a reference ''static'' gravity field from GRACE solutions, time-variations of the Stokes coefficients ΔC_{nm} and ΔS_{nm} are computed for each monthly or 10-day period Δt.

For a monthly period Δt, the surface water storage anomaly within a region of angular area Ω (*i.e.*, surface of the studied basin divided by R_e^2) can be obtained as the scalar product between time variations of Stokes coefficients ΔC_{nm}(t) and ΔS_{nm}(t), and averaging kernel coefficients A_{nm} and B_{nm} corresponding to the geographical region to be extracted (Swenson & Wahr, 2002):

$$\Delta\sigma_\Omega(\Delta t) = \frac{\rho_e R_e}{3\Omega} \sum_{n=1}^{N} \sum_{m=1}^{n} \frac{2n+1}{1+k_n^{'}} \{\Delta C_{nm}(\Delta t) A_{nm} + \Delta S_{nm}(\Delta t) B_{nm}\} \quad (2)$$

where ρ_e is the mean Earth's density (~5,517 kg/m^3). In case of a perfect kernel and error free data, A_{nm} and B_{nm} are the harmonic coefficients of the basin function or mask, which is equal to 1 inside the basin and zero outside.

3.3 The problem of aliasing

The monthly or sub-monthy GRACE solutions have a sufficient temporal resolution to monitor the long wavelengths variations of the gravity over land. The phenomenon of short term mass variability with period of hours to day, ocean tides and atmosphere are removed using de-aliasing techniques consisting of removing model outputs of these contributions. If the atmospheric pressure fields from ECMWF allow a reasonable de-aliasing of the higher frequencies caused by non-tidal atmospheric mass changes, errors due to tide models appear in the GRACE solutions, especially the aliasing from diurnal (S1) and semi-diurnal (S2) tides (Han et al., 2004; Ray & Lutcke, 2006). The aliasing and the modelling errors are responsible for the spurious meridional undulations present in the GRACE monthly grids and known as north-south striping. They are associated to spherical harmonics order 15 and its multiples (Swenson & Wahr, 2006a; Schrama et al., 2007; Seo et al., 2008). Thompson et al. (2004) showed that the degree error increased by factors ~ 20 due to atmospheric aliasing, ~ 10 due to the ocean model, and ~ 3 due to continental hydrology model. The S2 aliasing errors have also a strong impact on the C_{20} spherical harmonics coefficient of the geopotential and (Seo et al., 2008; Chen et al., 2009a) and are significant over the Amazon basin but dismish using longer time-series (Schrama et al., 2007; Chen et al., 2009a).

3.4 Accuracy of GRACE measurements: formal, omission and leakage errors

3.4.1 Formal error

The degree amplitude of the GRACE error is defined as:

$$\sigma_N(l) = R_e \sqrt{\sum_{m=0}^{l} \left(\sigma_{C_{lm}}^2 + \sigma_{S_{lm}}^2 \right)} \quad (3)$$

where $\sigma_{C_{lm}}$ and $\sigma_{S_{lm}}$ are the errors on the gravity potential coefficients.

It can be seen as the square-root of the total variance from all terms of a given spatial scale, as the degree l is the measure of the spatial scale of a spherical harmonics (*i.e.*, a half wave-length of 20,000/l km). These errors increase at degrees 20 to 30 and become dominent at degrees 40 to 50. As a consequence, GRACE monthly solutions are low-pass filtered at degree 50 or 60 to remove the noise contained in the high frequency domain.

3.4.2 Omission or cut-off frequency error

Error in frequency cut-off represents the loss of energy in the short spatial wavelength due to the low-pass harmonic decomposition of the signals that is stopped at the maximum degree N_1. For the GRACE land water solutions; N_1=60, thus the spatial resolution is limited and stopped at ~330 km by construction. This error is simply evaluated by considering the difference of reconstructing the remaining spectrum between two cutting harmonic degrees N_1 and N_2, where $N_2 > N_1$ and N_2 should be large enough compared to N_1 (*e.g.*, N_2=300):

$$\sigma_{truncation} = \sum_{n=0}^{N_2} \xi_n - \sum_{n=0}^{N_1} \xi_n = \sum_{n=N_1}^{N_2} \xi_n \quad (4)$$

using the scalar product:

$$\xi_n = \sum_{m=0}^{n} \left(\Delta C_{nm}(\Delta t) A_{nm} + \Delta S_{nm}(\Delta t) B_{nm} \right) \quad (5)$$

These errors are generally lower than 1% of the amplitude of the signal.

3.4.3 Leakage error

Due to the limited space resolution of the GRACE solutions, the estimate of mass variations inside a region of interest such as a drainage basin is affected by the leakage effect in two different ways. First, the mass changes inside a region spread out the whole globe. On the contrary, signals from other regions of the world pollute the estimate inside the considered region of interest. These two opposite effects have to be accounted for to estimate accurate mass variations at the surface of the Earth. Several techniques were proposed to quantify the leakage error. Swenson & Wahr (2002) proposed a geometric formulation of the leakage departure of the shape of the smoothed averaging kernel from that of the exact averaging kernel, Ramillien et al. (2006a) used an « inverse » mask, which is 0 and 1 in and out of the region respectively, developed in spherical harmonics and then truncated at degree 60, Baur et al. (2009) proposed an iterative approach based on forward modelling, Longuevergne et al. (2010) used a method optimizing the basin shape description. The leakage effects are generally estimated using global models as they can not be determined directly from the GRACE observations. Leakage effects are smaller close to the ocean. Over large areas, the signals leaking in and out tend to compensate each other. For the Amazon basin, leakage was found to have a small impact on TWS estimates (Chen et al., 2009b, Xavier et al., 2010). For small basins, such as the High Plain Aquifers (with an area ~ 450,000 km^2), an error due to the leakage is of 25 mm in terms of EWH and remains important, compared with annual variations of TWS varying from 100 to 200 mm (Longuevergne et al., 2010).

4. Post-processing techniques

To filter out the spurious north-south stripes present in the GRACE TWS products different techniques based on empirical, statistical, inverse, or regional approaches were applied.

4.1 Empirical methods

4.1.1 Isotropic and non-isotropic filters

The simple isotropic Gaussian filter proposed earlier by Jekeli (1981) was commonly used in pre-launched studies (Wahr et al., 1998), and then applied to real data (Wahr et al., 2004; Tapley et al., 2004b) to demonstrate the abilities of GRACE to retrieve time variations of water mass anomalies over land. The choice of the smoothing radius and the inhability of this type of filter to distinguish between geophysical signals and noise are its major drawbacks. More elaborate filters were then developed to reduce the errors on the GRACE signals. Several averaging kernels based on the separate minimization of measurement and leakage error to signal were proposed, by using Lagrange multipliers and a leakage function defined as the difference in shape between exact and smoothed averaging kernels, with no *a priori* (Swenson & Wahr, 2002), or *a priori* (*i.e.*, the shape of the covariance function assuming it is azimuthally symmetric) information and then then minimizing the sum of variance of the satellite and leakage errors (Swenson & Wahr, 2003; Seo & Wilson, 2005).

To take into account the meridian structures of the noise polluting the GRACE signals, several non-isotropic smoothing kernels were applied, using spectral Legendre coefficients dependent on both degree and order (Han et al., 2005), or Tikhonov-type regularization (Kusche, 2007).

4.1.2 Destriping method

This filtering technique, known as destriping or correlated-error filter, was designed to remove the correlated errors in the Stokes coefficients responsible for the north-south stripes in the GRACE solutions. For a particular order *m*, the Stokes coefficients are smoothed with a quadratic polynomial in a moving window of width *w* centered about degree *l*. The sum only concerns the terms of the same parity as *l* (Swenson and Wahr, 2006a). This method provides better results at high latitudes than close to the equator as residual errors due to the near-sectorial coefficients ($l \sim m$) are not completely removed (Swenson and Wahr, 2006a; Klees et al., 2008a). Besides, some short-wavelength features are removed, mainly at high latitudes. Monthly CSR, GFZ and JPL destriped and smoothed EWH grids of 1-degree spatial resolution are available over 2002-2010 at: http://grace.jpl.nasa.gov.

4.1.3 Stabilization criteria

The Level-2 GRGS-EIGEN-GL04 models are derived from Level-1 GRACE measurements including KBRR, and from LAGEOS-1/2 SLR data for enhancement of lower harmonic degrees (Lemoine et al., 2007a; Bruinsma et al., 2010). These gravity fields are expressed in terms of normalized spherical harmonic coefficients from degree 2 up to degree 50-60 using an empirical stabilization approach without any smoothing or filtering. This stabilization approach consists in adding empirically determined degree and order dependent coefficients to minimize the time variations of the signal measured by GRACE over ocean and desert without significantly affecting the amplitude of the signal over large drainage basins. Monthly (Release-1) and 10-day (Release-2) TWS grids of 1-degree spatial resolution are available over 2002-2010 at: http://grgs.obs-mip.fr.

4.2 Statistical methods

4.2.1 Wiener filtering

The spatial averaging of monthly GRACE using the Wiener filter data is based on the least-square minimization of the difference between modelled and filtered signals. This filter is isotropic, depending only on the degree power of the signal and noise models. Using hydrology and ocean models outputs for simulating the degree power spectrum of the GRACE signal, the formal error of the GRACE coefficients, and GRACE solutions, Sasgen et al. (2006) were able to determine the optimal coefficients of the Wiener filter, and to demonstrate that this method is robust approach for low-pass filtering the GRACE data which does not need the specification of any averaging radius.

4.2.2 Principal Components Analysis

Principal Components Analysises (PCA) were performed on time-series of Gaussian-filtered EWH grids (Schrama et al., 2007) and Stokes coefficients (Wouters & Schrama, 2007). PCA was able to efficiently separate modes of geophysical signals from modes corresponding to the North-South striping in the EWH grids. The three first modes explain 73.5% of the continental hydrology with a Gaussian prefiltering of 6.25° of radius. The residual modes contain S2 aliasing errors and a semiannual continental hydrology signal contained in the Global Land Data Assimilation Systems (GLDAS) model (Schrama et al., 2007). Directly applied to the Stokes coefficients, PCA also successfully removes the meridian undulations present in the GRACE solutions. The results of this technique are expected to be better as the time-series of the GRACE solutions become longer (Wouters & Schrama, 2007).

4.2.3 Independent Components Analysis

The Independent Component Analysis (ICA) approach is used to extract hydrological signals from the noise in the Level-2 GRACE solutions by considering completely objective constraints, so that the gravity component of the observed signals is forced to be uncorrelated numerically. This blind separation method is based on the assumption of statistical independence of the elementary signals that compose the observations, *i.e.*, geophysical signals and spurious noise, and does not require other *a priori* information (Frappart et al., 2010a). Comparisons at a global scale showed that the ICA-based solutions present less north–south stripes than Gaussian and destriped solutions on the land, and more realistic hydrological structures than the destriped solutions in the tropics. ICA filtering seems to allow the separation of the GIA from the TWS as negative trends were found over the Laurentides and Scandinavia. Unfortunately, this important geophysical parameter does not appear clearly in an independent mode yet. At basin-scale, the ICA-based solutions allowed us to filter out the unrealistic peaks present in the time series of TWS obtained using classical filtering for basins with areas lower than 1 million km^2 (Frappart et al., 2011a). The major drawback of this approach is that it cannot directly be applied to the GRACE Level-2 raw data, as a first step of (Gaussian) prefiltering is required. Monthly CSR, GFZ and JPL ICA-filtered TWS grids of 1-degree spatial resolution are available over 2002-2010 at: http://grgs.obs-mip.fr.

4.2.4 Kalman smoothing

Daily water masses solutions have been derived from GRACE observations using a Kalman filter approach. They are estimated using a Gauss Markov model, the solution at day $t+1$ slightly differs from solution at day t from the noise prediction (first-order Markov process) estimated using a Kalman filter. A *priori* information on the hydrological patterns from the WGHM model was introduced in the covariance matrix to compensate the small number of available observations over a daily time-span. This approach enables to produce temporarily enhanced solutions without loss in spatial resolution and resolution (Kurtenbach et al., 2009). Daily TWS Stokes coefficients are available over 2002-2010 at: http://www.igg.uni-bonn.de/apmg.

4.3 Inverse methods

4.3.1 Iterative least-squares approach

This method is based on the matrix formalism of the generalized least-squares criteria (Tarantola, 1987) and consists in estimating separately the spherical harmonics coefficients, in terms of EWH, of four different fluid reservoirs (atmosphere, oceans, soil water, and snow) from the monthly GRACE geoids. For each water reservoir, the anomaly of mass is estimated after the convergence of an inverse approach combining the GRACE observations with stochastic properties of the unknown hydrological signal (Ramillien et al., 2004; 2005).

4.3.2 Optimal filter

This method takes into account the statistical information present in each GRACE monthly solution. The noise and full signal variance-covariance matrix is used to tailor the filter to the error characteristics of a particular monthly solution. The resulting filter was found to be both anisotropic and non-symmetric to accommodate noise of an arbitrary shape as the north-south stripes present in the GRACE monthly solutions. It is optimal as it minimizes the difference between the signal and the filtered GRACE estimate in the least-squares sense. This filter was found to perform better than any isotropic, or anisotropic and symmetric filters preserving better the signal amplitudes better (Klees et al., 2008a). Monthly GRACE-derived TWS grids of 1-degree spatial resolution computed using the optimal filter are available over 2002-2010 at: http://lr.tudelft.nl/en/organisation/departments-and-chairs/remote-sensing/physical-and-space-geodesy/data-and-models/dmt-1/

4.4 Regional approaches

Since the begining of the low-low satellite gravimetry missions dedicated to Earth's gravity field measurement (*i.e.*, CHAMP, GRACE, GOCE), determining locally the time variations of the surface water storage has been of great interest for region where very localized strong mass variations occur, such as flood and glaciers fields. Moreover, it represents an alternative to the problem of numerical singularity at poles by choosing a suitable geometry of surface tiles. So far, rectangular surface elements have been considered but other geometries have successfully tested (Eicker, 2008; Ramillien et al., 2011).

4.4.1 Mascons

In this local approach, the mass of water in surface 4-by-4 degree blocks has been explicitly solved using the GRACE inter-satellite KBR Rate (KBRR) data for continental hydrology and collected over the region of interest. This size of the surface elements has been chosen as the limit of *a priori* spatial resolution of the GRACE data (*i.e.*, 400 km). This method uses inherently empirical spatial and temporal constraints among the coefficients that are dependent on geographical locations. The local representation of gravity minimizes the leakage error from other areas due to aliasing or mis-modelling (Rowlands et al., 2005; Lemoine et al., 2007b). It has revealed more information about interannual variability in the subregions than any Stokes coefficients-based approach. Global and mascons methods based on spherical harmonics have provided similar results for the mass trend in the drainage basins, especially when no spatial constraints are taken into account (Rowlands et al., 2010). But, inherent problem of spectral truncation such as leakage are not avoided while using spherical harmonics. 10-day and 4° Mascons solutions and corresponding GLDAS model time series for each continental surface element are available at: http://grace.sgt-inc.com/V2/Global.html.

4.4.2 Regional method

Another type of regional approach has been recently proposed by adjusting the surface mass density from the Level-1 GRACE data, in particular the accurate satellite-to-satellite velocity variations (Ramillien et al., 2011). Once these observations are corrected from known accelerations (atmosphere and ocean mass changes, tides, static gravity field…), along track residuals of KBR-rate are used to compute kinetic energy (or equivently potential anomaly) variations between the twin GRACE satellites, corresponding mainly to continental water redistributions. The linear system of equations to solve between observations (*i.e.*, potential anomalies) and parameters (*i.e.*, surface elements) is built according to the first Newton's law of attraction of masses. Unlike the mascons solutions, spherical harmonics are not used as a basis of regional orthogonal functions, consequently this regional method does not suffer from the drawbacks related to any spectral truncation. Singular Value Decomposition (SVD) and L-curve analysis are considered to compute regularized 10-day 2-by-2 degree solutions of the ill-posed of gravimetry. Lately, another version of the inversion scheme takes spatial correlations versus the geographical distance between surface elements into account (Ramillien et al., in press). Time series of regional solutions over South America have been produced and compared to global solutions and mascons, they reveal very comparable amplitudes of seasonal cycle over the Amazon basin, as well as sudden flooding events.

5. Applications to continental hydrology: results and discussion

5.1 Application in continental hydrology and validation

Once sufficiently long series of GRACE solutions were made available by the former official providers (CSR, JPL, GFZ), various regional studies for validating these products were made. Examples of GRACE-based TWS maps are given in Figure 1 showing the ability of the gravimetry from space mission to restitue both seasonal and interannual variability.

Comparisons with global hydrology model outputs and surface measurements revealed acceptable agreements between GRACE-derived and model changes of continental water storage versus time, especially at seasonal time scale. GRACE provides directly the term of TWS variation of the net balance equation. In general, GRACE-based estimates of TWS compare favourably with those based on land surface models as well as atmospheric and terrestrial water balances (Rodell et al., 2004a; Ramillien et al., 2005; Syed et al., 2005; Klees et al., 2008b). The structures seen on global maps of seasonal amplitudes are comparable to those described by the WaterGap model developed by Döll et al. (2003) and GLDAS (Rodell et al., 2004a). Over the entire Northern Hemisphere, GLDAS water storage simulations with a resolution of 1,300 km and accuracy of 9 mm in terms of EWH were found to have a spatial correlation of 0.65 with GRACE data, suggesting that gravity field changes may be related to TWS variations (Andersen & Hinderer, 2005). However, TWS variations tend to be slightly over-estimated by GRACE (Schmidt et al., 2006; Syed et al., 2008). GRACE-based TWS changes were also validated by accurate observations of superconducting gravimeters during the 2003 heat wave that occured in Central Europe (Andersen et al., 2005). They were used to detect the exceptional drought (Chen et al., 2009b) and flooding (Chen et al., 2010) affected the Amazon basin in 2005 and 2009 respectively (Figure 2a). Correlations of 0.7-0.8 between GRACE-based TWS and *in situ* measurements of water level along the Amazon River were found by Xavier et al. (2010). Combined with other satellite techniques such as imagery, GRACE geoid data were used to study the mechanisms of seasonal flooding in large inundation areas like the Mekong delta (Frappart et al., 2006a) and large river basins as the Amazon River (Frappart et al., 2008; Papa et al., 2008).

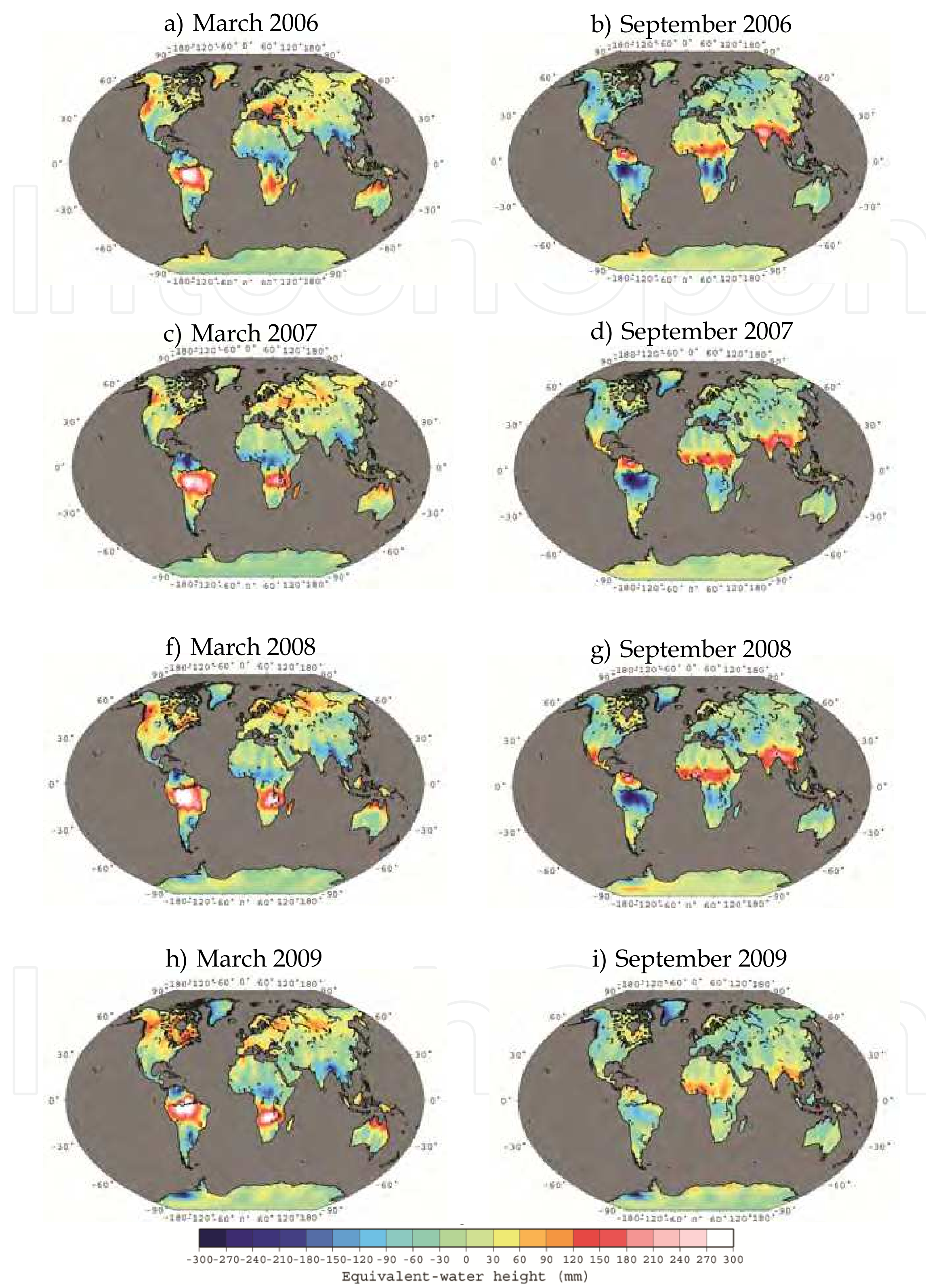


Fig. 1. Examples of GRACE-derived TWS maps processed using a Gaussian filtering of radius 400 km and ICA (Level-2 Release 4 GFZ solutions) for a) March 2005, b) September 2005, c) March 2006, d) September 2006, e) March 2007, f) September 2007, g) March 2008, h) September 2008, i) March 2009, j) September 2009.

5.2 Isolating groundwater changes

Variations in the groundwater storage can be extracted from *TWS* measured by GRACE using external information on the other hydrological reservoirs. The time variations in *TWS* are the sum of the contributions of the different reservoirs present in a drainage basin:

$$\Delta TWS = \Delta SW + \Delta SN + \Delta TSS \tag{6}$$

with:

$$\Delta TSS = \Delta RZ + \Delta GW + \Delta P \tag{7}$$

where *SW* represents the total surface water storage including lakes, reservoirs, in-channel and floodplains water, *SN* is the snow storage, *TSS* is the total soil storage including *RZ* the water contained in the root zone of the soil (generally representing a depth of 1 or 2 m), *GW* the groundwater storage in the aquifers, and *P* the permafrost storage at boreal latitudes.

Post-launch studies of GRACE-based groundwater remote sensing have clearly demonstrated that when combined with ancillary measurements of surface waters and soil moisture, either modeled or observed, GRACE is capable of monitoring changes in groundwater storage with reasonable accuracy. Important seasonal correlations of 0.8-0.9

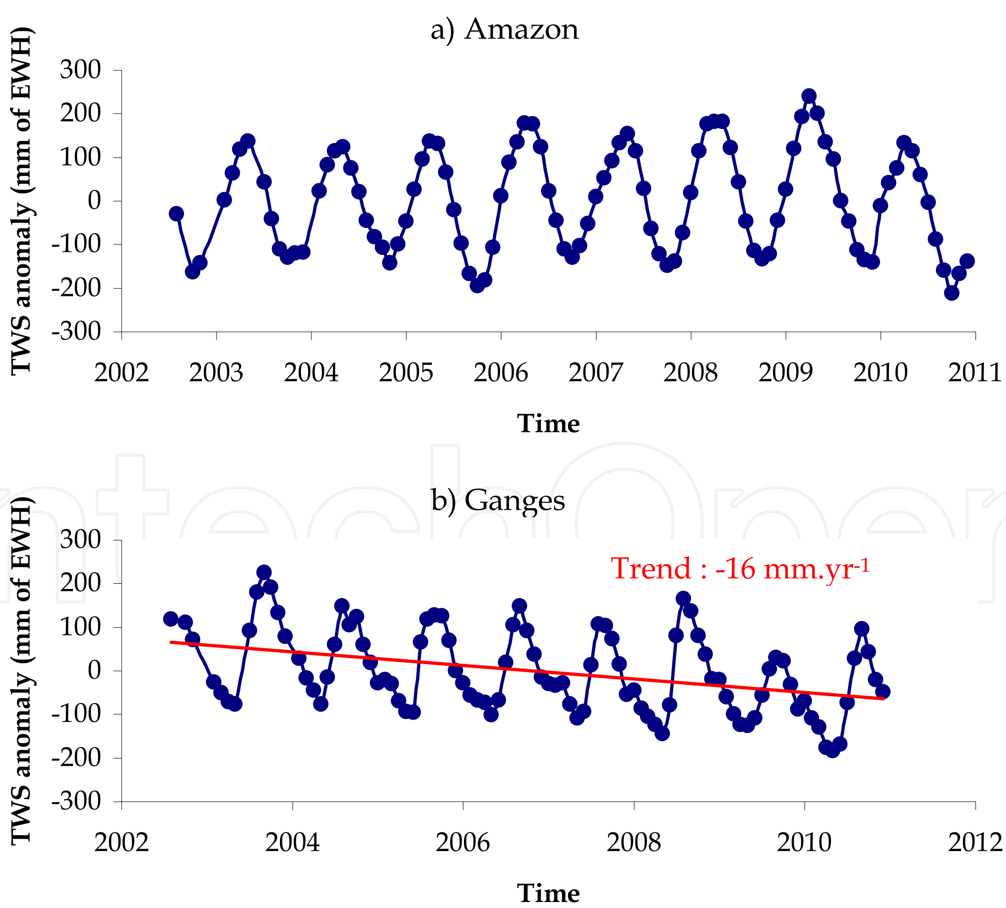


Fig. 2. Time series of TWS anomalies (mm of EWH) from Level-2 Release 4 GFZ GRACE solutions (Gaussian filtering of radius 400 km and ICA) for a) Amazon, b) Ganges.

were found by confronting GRACE to recordings of well network in Illinois (Yeh et al., 2006), Oklahoma (Swenson et al., 2008), the High Plain aquifer (Strassberg et al., 2007) and the Mississippi basin (Rodell et al. 2007). This method was successfully applied to monitor large-scale climatic and anthropogenic impacts on water resources, as the detection of the recent severe drought in the Murray-Darling basin in Southern Australia (Leblanc et al., 2009) or the depletion of the aquifers in India (Rodell et al., 2009) (Figure 2b), but also to estimate aquifer storage parameters as the specific yield or storativity (Sun et al., 2010). For large drainage basins covered with extensive floodplains, changes in water stored in the aquifer is isolated from the TWS measured by GRACE by removing contributions of both the surface reservoir, derived from satellite imagery and radar altimetry, and the root zone reservoir simulated by hydrological models (Frappart et al., 2010b; 2011b). In the Negro River basin, the groundwater anomalies show a realistic spatial pattern compared with the hydrogeological map of the basin (DNPM, 1983), and similar temporal variations to local in situ groundwater observations (Figure 3).

5.3 Estimates of snow mass changes at high latitudes

After a separation of water and snow contributions from observed gravity field using an inverse iterative approach based on the least-squares criteria, Frappart et al. (2006b) used satellite microwave data and global hydrological model outputs to validate GRACE-derived snow mass changes at high-latitudes. In particular, rms errors of 10-20 mm were found for Yenisey, Ob, McKenzie and Yukon basins. Comparison at basin scales between GRACE-derived snow mass variations, GRACE-based TWS variations and river discharge temporal evolution shows that the snow component has a more significant impact on river discharge at high latitudes than TWS, and that snow and streamflow present similar interannual variabilities (Frappart et al., 2011c).

5.4 Estimates of regional geo-hydrological parameters

5.4.1 River discharges

GRACE-based estimates of river discharges are based on the resolution of the water balance equation at basin-scale:

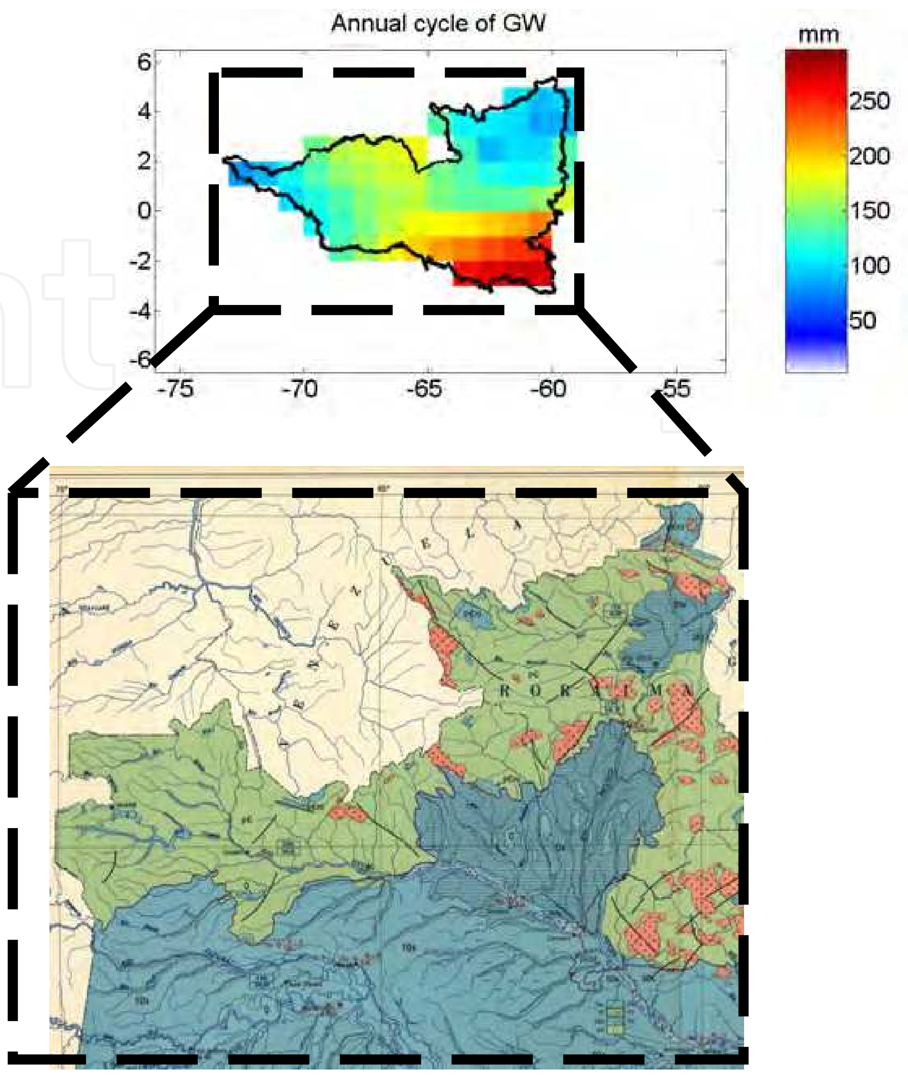
$$\frac{\partial S}{\partial t} = P - ET - R \tag{8}$$

where S is land water storage (TWS), P and ET the basin-wide totals of precipitation and evapotranspiration, and R the total basin discharge, or the net surface and groundwater outflow.

As ET presents large uncertainties, the quantity $P\text{-}ET$ is eliminated using the water balance of the atmospheric branch of the water cycle:

$$\frac{\partial W}{\partial t} = ET - P - div\vec{Q} \tag{9}$$

where W is the vertically-integrated precipitable water, $div\vec{Q}$ the divergence of the vertically-integrated average atmospheric moisture flux vector, computed using the following equations:



Continuous aquifers of regional extension, free or confined. Medium hydrogeological reservoir.

Local aquifers or continuous aquifers of limited extension. Two levels of water: free and/or confined. Small hydrogeological reservoir.

Local aquifers restricted to fractured zones. Small hydrogeological reservoir.

Almost no aquifer. Very small hydrogeological reservoir.

Fig. 3. When combined with other data, GRACE-derived TWS anomalies provide valuable information on changes affecting the aquifers. Above a comparison between a) Map of annual amplitude of GW in the Negro River Basin. b) Hydrogeological map of Brazil from DNPM (1983), available at: http://eusoils.jrc.ec.europa.eu/esdb_archive/EuDASM/EUDASM.htm, in the framework of the European Commission — Joint Research Centre through the European Digital Archive of Soil Maps (EuDASM) (Panagos et al., in press). Adapted from Frappart et al. (2011b).

$$W = \int_{p_T}^{p_s} \frac{q}{g} dp \quad (10)$$

$$\vec{Q} = \int_{p_T}^{p_s} \frac{q}{g} \vec{V} dp \quad (11)$$

where p_s and p_T are the pressure at the surface and the top of the atmosphere respectively, q is the specific humidity, g is gravitational acceleration and $\vec{V}$ is the horizontal wind vector.

This approach was firstly applied to the Amazon and the Mississippi River basins (Syed et al., 2005), and extended to obtain a global volume of freshwater discharge estimated here is 30,354 ± 1,212 km^3/y (Syed et al., 2009).

5.4.2 Vertical water fluxes

GRACE-based TWS can be also used to estimate changes in vertical water fluxes solving the water balance equation (8). Changes of regional evapotranspiration (ET) rate over Mississippi basin were estimated by combining 600-km low-pass filtered GRACE TWS data with observed precipitation and streamflow in the water balance equation (Rodell et al., 2004b). Similarly, Ramillien et al. (2006b) solved the water balance equation for ET rate. Time variations of ET were evaluated over 16 large drainage basins solving the water balance equation and using precipitation from GPCC and runoff from the WGHM model (Döll et al., 2003), and they revealed that GRACE-based ET variations were comparable to the ET value simulated by four differend global hydrology models. Swenson and Wahr (2006b) estimated the difference precipitation minus evapotranspiration using the water balance framework and comparing to surface parameters variations from global analysis.

5.5 Contribution of TWS to sea level variations

Seasonal and interannual changes in land water storage derived from GRACE were used to estimate the contribution of land hydrology to the sea level variations for 27 of the largest drainage basins in the world. Estimation of 2002-2006 sea level contribution of GRACE-derived TWS of the largest basins was made using the GRGS GRACE solutions, and corresponds to a water loss of ~ 0.5 mm per year ESL (Ramillien et al., 2008). Wouters et al. (2011) recently estimated the global mean eustatic cycle, i.e., the total amount of water exchanged between continents and ocean, to be 9.4 ± 0.6 mm equivalent water level over the period 2003-2010. In the Pan Arctic regions, snow volume derived from the Special Sensor Microwave/Imager (SSM/I) radiometric measurements over 1989-2006 and GRACE over 2002-2007 is a key driver of the sea level seasonal cycle, but snow volume trend indicates a negligible and not statistically significant contribution to sea level variations (Biancamaria et al., 2011).

5.6 Optimization and assimilation into hydrological models

The GRACE data have been widely confronted to global hydrological ouputs for comparison and validation, and then to improve the description and parameterization of the hydrological processes in the models. The GRACE geoid data were used as a proxy to test and improve the efficiency of surface waters schemes in the ORCHIDEE land surface hydrology model (Ngo-Duc et al., 2007). Unfortunately, a lack of consistency in the seasonal cycle and a time shift between GRACE TWS and global hydrology models may persist. The comparison between six GRACE-derived TWS and 9 land surface models forced with the same forcings over West Africa permits to identify the processes needing improvement in the land surface models, especially the correct simulation of slow water reservoirs as well as evapotranspiration during the dry season for accurate soil moisture modeling over West Africa (Grippa et al., 2011).

Güntner (2008) pointed out the importance of integrating the GRACE data into hydrological models for improving the reliability of their prediction through advanced methods of multi-objective calibration and data assimilation. A multicalibration approach to constrain model predictions by both measured river discharge and TWS anomalies from GRACE was apllied to the WGHM model, improving simulation results with regard to both objectives. Using only monthly TWS variations, the RMSE was reduced of about 25 mm for the Amazon, 6 mm for the Mississippi and 1 mm for the Congo river basins (Werth et al., 2009). GRACE-derived monthly TWS anomalies were also assimilated into one of the GLDAS models using a Kalman smoother approach. Compared with open-loop simulations, assimilated ones exhibited better performance thanks to improvements in the surface and groundwater estimates (Zaitchik et al., 2008).

5.7 Detecting long-term variations over ice sheets

GRACE-derived mass balance estimates of Antarctica (Velicogna & Wahr, 2006a), Greenland (Velicogna & Wahr, 2006b; Chen et al., 2006) or both ice sheets (Ramillien et al., 2006a) have been determined from the Level-2 solutions of the GRACE project. Velicogna and Wahr (2006b) found a lost rate of -82 ± 28 Gt/y for Greenland with an acceleration of melting in Spring 2004. Mass changes of this ice sheet resolved by drainage basin were estimated using the NASA mascons solutions as -101 ± 16 Gt/y after correction for post-glacial rebound (Luthcke et al., 2006). This latter result is consistent with the one found previously by Ramillien et al. (2006a) using 10-day GRGS GRACE solutions. Velicogna & Wahr (2006a) estimated an extreme decrease of ice mass of 152 ± 80 Gt/y for Antarctica. The problem is that this main value represents the Post-Glacial Rebound (PGR) correction itself that the authors removed from the GRACE data using the IJ05 (Ivins and James, 2005) and ICE-5G (Peltier, 2004). If GRACE data are not corrected from PGR, the mass balance of Antarctica appears close to zero, with large uncertainties due to North-South striping and leakage effects. This result shows it is not clear whether this continent actually looses or gains ice mass during the recent period (Ramillien et al., 2006a). PGR phenomena are not well-modelled, especially over the whole Antarctica where available long-term observational constraints remain rare. Consequently, removing PGR that still cannot be modelled accurately represent a source of important errors. Velicogna & Wahr (2002) have shown earlier that the detection of PGR remains possible by combination of different satellite techniques, using 5 years of simulated GRACE and Laser GLAS data over the whole Antarctica. However, an effective extraction of PGR signals using GRACE products still needs to be demonstrated.

As mentioned by Baur et al. (2009), even if the PGR correction is less than 10 Gt/y over Greenland, mass balance for this continental area using GRACE solutions can vary strongly from simple to twice, according to which provider (CSR, JPL, GFZ) is considered, and which processing is applied. Velicogna and Wahr (2005) found a constant decrease of -84 ±-28 Gt/y for the period 2002-2004. Later, Wouters et al. (2008) adjusted a rate of -171 Gt/y for 2003-2008, with an acceleration during summer. Interestingly, Ramillien et al. (2006a) and Luthcke et al. (2006) found comparable loss rates of about 110 Gt/y considering 10-day GRGS and mascons solutions, respectively, for 2003-2005. Recent re-evaluation of Greenland ice mass loss provides -65 Gt/y using ICA-400 solutions and around 100 Gt/y using classical Gaussian filtered solution for 2003-2010 (Bergmann et al., 2012). It is clear that an interannual variations of Greenland ice sheet exists, as an acceleration of the ice melting in Spring 2004 and 2007-2009 (Velicogna & Wahr, 2006b; Velicogna, 2009). A recent study pointed a clear de-acceleration of the ice melting over Greenland for the very last years (Bergmann et al., 2012), which was confirmed by a recent analysis of Rignot et al. (2011).

Level-2 GRACE solutions have also been used to quantify ice mass loss of coastal glaciers in Western Antarctica, Patagonia (Chen et al., 2007) and in the Gulf of Alaska (Luthcke et al., 2008) as the response of the recent global warming. Chen et al. (2007) found a depletion of mass of -27.9 ± 11 Gt/y for the Patagonian glaciers between April 2002 and December 2007. For glaciers in Alaska, negative trends of -84 Gt/y during 2003-2007 and -102 Gt/y for 2003-2006 were deduced from mascon solutions. Once again, trend estimates depend strongly upon either using a model of PGR, or estimating it together with the current mass loss. Another complication is the coarse footprint of GRACE which mixes signals from neighbouring basins (Horwath and Dietrich, 2009).

6. Conclusion

Many studies have demonstrated the possibility of satellite gravimetry to detect and monitor spatial versus time, at a precision of only tens of mm of EWH and spatial resolution of 400 km. Accuracy of the results still depends upon the level of noise in the GRACE data and the post-processing used. In addition to measurement errors and loss of signals by low-pass filtering, uncertainty on model-predicted GIA represents a major source of error in the mass balance estimates of the ice sheets melting, in particular for Antarctica. Besides, a resolution of 400 km still represents an important limitation for small-scale studies, especially in field hydrology, which often requires surface resolution of tens of kilometers. Improvements in pre- and post-processing techniques should increase the quality of the GRACE products, such as the "regional" or local approaches. Steady improvement of precision and resolution of GRACE products remains encouraging and it opens a wider class of applications than previously possible.

Even if the dying GRACE mission may not be able to provide data of the same accuracy to be exploitable in continental hydrology in 2012, other follow-on projects have already been proposed by a motivated community to ensure the continuity of such a satellite system. Satellite gravimetry remains the only remote sensing technique to map directly large scale mass variations. Any Follow-On GRACE mission in preparation by NASA and GFZ would be of first interest for studying the impacts on surface redistribution forced by climate change.

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8. References

Alsdorf, D.E. & Lettenmaier, D.P. (2003). Tracking fresh water from space. *Science*, Vol.301, No.5639, (September 2003), pp. 1491−1494, ISSN 0036-8075.

Andersen, O. B. & Hinderer, J. (2005). Global inter-annual gravity changes from GRACE: Early results. *Geophysical Research Letters*, Vol.32, No.1, (January 2005), pp. L01402, ISSN 0094-8276.

Andersen, O.B.; Seneviratne, S.I.; Hinderer, J. & Viterbo P. (2005). GRACE-derived terrestrial water storage depletion associated with the European heat wave. *Geophysical Research Letters*, Vol.32, No.18, (September 2005), pp. L18405, ISSN 0094-8276.

Baur, O.; Kuhn, M. & Featherstone, W.E. (2009). GRACE-derived ice mass variations over Greenland by accounting for leakage effects. *Journal of Geophysical Research*, Vol.114, No.B13, (June 2009), pp. B06407, ISSN 0148-0227.

Bergmann, I.; Ramillien, G. & Frappart, F. (2012). Climate-driven interrannual variations of the mass balance of Greenland, *Global and Planetary Change*, Vol.82-83, (February 2012), pp. 1-11, ISSN 0921-8181

Bettadpur, S. (2007). *CSR Level-2 processing standards document for level-2 product release 04, GRACE*. The GRACE project, Center for Space Research, University of Texas at Austin, pp. 327–742.

Biancamaria, S.; Cazenave, A.; Mognard, N.M.; Llovel, W. & Frappart, F. (2011). Satellite-based high latitudes snow volume trend, variability and contribution to sea level over 1989-2006. *Global and Planetary Change*, Vol.75, No.3-4, (February 2011), pp. 99-107, ISSN 0921-8181.

Bruinsma, S.; Lemoine, J.M.; Biancale, R. & Valès, N. (2010). CNES/GRGS 10-day gravity field models (release 2) and their evaluation. *Advances in Space Research*, Vol.45, No.4, (February 2010), pp. 587–601, ISSN 0273-1177.

Chen, J.L.; Wilson, C.R.; Blankenship, D.D. & Tapley, B. D. (2006). Antarctic mass rates from GRACE. *Geophysical Research Letters*, Vol.33, No.11, (June 2006), pp. L11502, ISSN 0094-8276.

Chen, J.L.; Wilson, C.R.; Tapley, B.D.; Blankenship, D.D. & Ivins, E.R. (2007). Patagonia Icefield melting observed by Gravity Recovery and Climate Experiment (GRACE). *Geophysical Research Letters*, Vol.34, No.22, (November 2007), pp. L22501, ISSN 0094-8276.

Chen, J.L.; Wilson, C.R. & Seo, K.W. (2009a). S2 tide aliasing in GRACE time-variable gravity solutions. *Journal of Geodesy*, Vol.83, No.7, (July 2009), pp. 679-687, ISSN 0949-7714.

Chen, J.L.; Wilson, C.R.; Tapley B.D.; Zang, Z.L. & Nyu, G.Y. (2009b). 2005 drought event in the Amazon River basin as measured by GRACE and estimated by climate models. *Journal of Geophysical Research*, Vol.114, No.B5, (May 2009), pp. B05404, ISSN 0148-0227.

Chen, J.L.; Wilson, C.R. & Tapley B.D. (2010). The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE. *Water Resources Research*, Vol.46, No.12, (December 2010), pp. W12526, ISSN 0043-1397.

Dickey, J.O.; Bentley, C.R.; Bilham, R.; Carton, J.A.; Eanes J.A.; Herring, T.A.; Kaula, W.M.; Lagerloef, G.S.E.; Rojstaczern S.; Smith, W.H.F.; van den Dool, H.; Wahr J.M. & Zuber, M.T. (1999). Gravity and the hydrosphere: new frontier. *Journal des Sciences Hydrologiques – Hydrological Sciences Journal*, Vol.44, No.3, (June 1999), pp. 407-415, ISSN 0262-6667.

Departamento Nacional da Produção Mineral/DNPM (1983). Mapa hidrogeológico do Brasil, escala 1:5,000,000.

Döll, P.; Kaspar, F. & Lehner, B. (2003). A global hydrological model for deriving water availability indicators: Model tuning and validation. *Journal of Hydrology*, Vol.270, No.1-2, (January 2003), pp.105–134, ISSN 0022-1694.

Eicker, A. (2008). *Gravity Field Refinement by Radial Basis Functions from In-situ Satellite Data*, Dissertation Univ. Bonn D 98, pp. 137, Univ. Bonn, Bonn.

Fletchner, F. (2007). *GFZ Level-2 processing standards document for level-2 product release 04, GRACE*. Department 1: Geodesy and Remote Sensing, GeoForschungZentrum, Potsdam, pp. 327-742.

Frappart, F.; Do Minh K.; L'Hermitte, J.; Cazenave, A.; Ramillien, G.; Le Toan, T. & Mognard-Campbell, N. (2006a). Water volume change in the lower Mekong basin from satellite altimetry and imagery data. *Geophysical Journal International,* Vol.167, No.2, (November 2006), pp. 570-584, ISSN 0956-540X.

Frappart, F.; Ramillien, G.; Biancamaria, S.; Mognard, N. M. & Cazenave, A. (2006b). Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002–2004). *Geophysical Research Letters*, Vol.33, No.2, (January 2006), pp. L02501, ISSN 0094-8276.

Frappart, F.; Papa, F.; Famiglietti, J. S.; Prigent, C.; Rossow, W. B. & Seyler, F. (2008). Interannual variations of river water storage from a multiple satellite approach: A case study for the Rio Negro River basin. *Journal of Geophysical Research*, Vol.113, No.D12, (November 2008), pp. D21104, ISSN 0148-0227.

Frappart, F.; Ramillien, G.; Maisongrande, P. & Bonnet, M.P. (2010a). Denoising satellite gravity signals by independent component analysis. *IEEE Geoscience and Remote Sensing Letters*, Vol.7, No.3, (July 2010), pp. 421−425, ISSN 1545-598X.

Frappart, F.; Papa, F.; Güntner, A.; Werth, S.; Ramillien, G.; Prigent, C.; Rossow, W.B. & Bonnet, M-P. (2010b). Interrannual variations of the terrestrial water storage in the Lower Ob' basin from a multisatellite approach. *Hydrology and Earth System Sciences*, Vol.14, No.12, (December 2010), pp. 2443-2453, ISSN 1812-5606.

Frappart, F.; Ramillien, G.; Leblanc, M.; Tweed, S.O.; Bonnet, M.P. & Maisongrande, P. (2011a). An independent component analysis filtering approach for estimating continental hydrology in the GRACE gravity data. *Remote Sensing of Environment*, Vol.115, No.1, (January 2011), pp. 187–204, ISSN 0034-4257.

Frappart, F.; Papa, F.; Güntner, A.; Werth, S.; Santos da Silva, J.; Seyler, F.; Prigent, C.; Rossow, W.B.; Calmant, S. & Bonnet, M.P. (2011b). Satellite-based estimates of groundwater storage variations in large drainage basins with extensive floodplains, *Remote Sensing of Environment*, Vol.115, No.6, (June 2011), pp. 1588-1594, ISSN 0034-4257.

Frappart, F.; Ramillien, G. & Famiglietti, J. S. (2011c). Water balance of the Arctic drainage system using GRACE gravimetry products. *International Journal of Remote Sensing*, Vol.32, No.2, (January 2011), pp. 431-453, ISSN 0143-1161.

Grippa, M.; Kergoat, L.; Frappart, F.; Araud, Q.; Boone, A.; de Rosnay, P.; Lemoine, J-M.; Gascoin, S.; Balsamo, G.; Ottlé, C.; Decharme, B.; Saux-Picart, S. & Ramillien, G. (2011). Land water storage over West Africa estimated by GRACE and land surface models. *Water Resources Research*, Vol.47, No.5, (May 2011), pp. W05549, ISSN 0043-1397.

Güntner, A. (2008). Improvement of global hydrological models using GRACE data. *Surveys in Geophysics*, Vol.29, No.4-5, (October 2008), pp. 375−397, ISSN 1573-0956.

Han, S.-C.; Jekeli, C. & Shum, C. (2004). Time-variable aliasing effects of ocean tides, atmosphere, and continental water mass on monthly mean GRACE gravity field. *Journal of Geophysical Research*, Vol.109, No.B04, (April 2004), pp. B04403, ISSN 0148-0227.

Han, S.-C.; Shum, C.; Jekeli, C.; Kuo, C.; Wilson, C. & Seo, K.W. (2005). Non-isotropic Filtering of GRACE Temporal Gravity for Geophysical Signal Enhancement. *Geophysical Journal International*, Vol.163, No.1, (September 2005), pp. 18-25, ISSN 0956-540X.

Heiskanen, W.H. & Moritz H. (1967). *Physical Geodesy*. W.H. Freeman and Co Ltd, ISBN 978-071-6702-23-37, San Francisco, USA.

Horwath, M. & Dietrich, R. (2009). Signal and error in mass change inferences from GRACE: the case of Antarctica. *Geophysical Journal International*, Vol.177, No.4, (June 2009), pp. 849–864, ISSN 0956-540X.

Ivins, E.R. & James, T.S. (2005). Antarctic glacial isostatic adjustment: A new assessment. *Antarctic Science*, Vol.17, No.4, (December 2005), pp. 541-553, ISSN 0954-1020.

Jekeli C. (1981). *Alternative methods to smooth the Earth's gravity field*. Report 327, Department of Geodesy Sciences and Survey, Ohio State University, Columbus, USA.

Klees, R.; Revtova, E.A.; Gunter, B. C.; Ditmar, P.; Oudman, E.; Winsemius, H. C. & Savenije, H.H.G. (2008a). The design of an optimal filter for monthly GRACE gravity models. *Geophysical Journal International*, Vol.175, No.2, (November 2008), pp. 417−432, ISSN 0956-540X.

Klees, R.; Liu, X.; Wittwer, T.; Gunter, B. C.; Revtova, E.A.; Tenzer, R.; Ditmar, P.; Winsemius, H. C. & Savenije, H.H.G. (2008b). A comparison of global and regional GRACE models for land hydrology. *Surveys in Geophysics*, Vol.29, No.4-5, (October 2008), pp. 335−359, ISSN 1573-0956.

Kurtenbach, E.; Mayer-Gürr, T. & Eicker, A. (2009). Deriving daily snapshots of the Earth's gravity field from GRACE L1B data using Kalman filtering. *Geophysical Research Letters*, Vol.36, No.17, (September 2009), pp. L17102, ISSN 0094-8276.

Kusche, J. (2007). Approximate decorrelation and non-isotropic smoothing of timevariable GRACE-type gravity field models. *Journal of Geodesy*, Vol.81, No.11, (November 2007), pp. 733−749, ISSN 0949-7714.

Leblanc, M. J.; Tregoning, P.; Ramillien, G.; Tweed, S.O. & Fakes, A. (2009). Basin-scale integrated observations of the early 21st century multiyear drought in southeast Australia, *Water Resources Research*, Vol.45, No.4, (April 2009), pp. W04408, ISSN 0043-1397.

Lemoine, J.M.; Bruinsma, S.; Loyer, S.; Biancale, R.; Marty, J.C.; Perosanz, F. & Balmino, G. (2007a). Temporal gravity field models inferred from GRACE data. *Advances in Space Research*, Vol.39, No.10, (May 2007), pp. 1620–1629, ISSN 0273-1177.

Lemoine, F.G.; Luthcke, S.B., Rowlands, D.D.; Chinn, D.S.; Klosko, S.M. & Cox, C.M. (2007b). The use of mascons to resolve time-variable gravity GRACE, In: *Dynamic Planet: Monitoring and Understanding A Dynamic Planet with Geodetic and Oceanographic Tools*, P. Tregoning & C. Rizos, (Eds.), 231-236, Springer, ISBN 978-3-540-49349-5, Berlin, Germany.

Longuevergne, L.; Scanlon, B.R. & Wilson, C.R. (2010). GRACE hydrological estimates for small basins : evaluating approaches on the High Plains aquifer, USA. *Water Resources*, Vol.46, No.11, (November 2010), pp. W11517, ISSN 0043-1397.

Luthcke, S.B.; Zwally, H.J.; Abdalati, W.; Rowlands, D.D.; Ray, R.D.; Nerem, R.S.; Lemoine, F.G.; McCarthy, J.J. & Chinn, D.S. (2006). Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations. *Science*, Vol.314, No.5803, (November 2006), pp. 1286–1289, ISSN 0036-8075.

Luthcke, S.B.; Arendt, A.A.; Rowlands, D.D.; McCarthy, J.J. & Larsen, C.F. (2008). Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. *Journal of Glaciology*, Vol.54, No.188, (December 2008), pp.767-777, ISSN 1727-5652.

Ngo-Duc, T.; Laval, K.; Ramillien, G.; Polcher, J. & Cazenave, A. (2007). Validation of the land water storage simulated by Organising Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) with Gravity Recovery and Climate Experiment (GRACE) data. *Water Resources Research*, Vol.43, No.4, (April 2007), pp. W04427, ISSN 0043-1397.

Panagos, P.; Jones, A.; Bosco, C. & Senthil Kumar P.S. (in press). European digital archive on soil maps (EuDASM): preserving important soil data for public free access. *International Journal of Digital Earth*, ISSN 1753-8947.

Papa, F.; Güntner, A.; Frappart, F.; Prigent, C., & Rossow, W.B. (2008). Variations of surface water extent and water storage in large river basins: A comparison of different global data sources. *Geophysical Research Letters*, Vol.35, No.11, (June 2008), pp.L11401, ISSN 0094-8276.

Peltier, W.R. (2004). Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE. *Annual Review of Earth and Planetary Sciences*, Vol.32, (May 2004), pp. 111-149, ISSN 0084-6597.

Ramillien, G.; Cazenave, A. & Brunau, O. (2004). Global time-variations of hydrological signals from GRACE satellite gravimetry. *Geophysical Journal International*, Vol.158, No.3, (September 2004), pp. 813– 826, ISSN 0956-540X.

Ramillien, G.; Frappart, F.; Cazenave, A. & Güntner, A. (2005). Time variations of land water storage from the inversion of 2-years of GRACE geoids. *Earth and Planetary Science Letters*, Vol.235, No.1-2, (June 2005), pp. 283−301, ISSN 0012-821X.

Ramillien, G.; Lombard, A.; Cazenave, A.; Ivins, E.R.; Llubes, M.; Remy, F. & Biancale, R. (2006a). Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change,* Vol.53, No.3, (September 2006), pp. 198–208, ISSN 0921-8181.

Ramillien, G.; Frappart, F.; Güntner, A.; Ngo-Duc, T.; Cazenave, A. & Laval, K. (2006b). Time-variations of the regional evapotranspiration rate from Gravimetry Recovery And Climate Experiment (GRACE) satellite gravimetry. *Water Resources Research*, Vol.42, No.10, (October 2006), pp. W10403, ISSN 0043-1397.

Ramillien, G.; Bouhours, S.; Lombard, A.; Cazenave, A.; Flechtner, F. & Schmidt, R. (2008). Land water storage contribution to sea level from GRACE geoid data over 2003-2006. *Global and Planetary Change*, Vol.60, No.3-4, (February 2008), pp. 381-392, ISSN 0921-8181.

Ramillien, G.; Biancale, R.; Gratton, S.; Vasseur, X. & Bourgogne, S. (2011). GRACE-derived surface water mass anomalies by energy integral approach: application to continental hydrology. *Journal of Geodesy*, Vol.85, No.6, (June 2011), pp. 313-328, ISSN 0949-7714.

Ramillien, G.; Seoane, L.; Frappart, F.; Biancale, R.; Gratton, S.; Vasseur, X. & Bourgogne, S. (in press). Constrained regional recovery of continental water mass time-variations from GRACE-based geopotential anomalies. *Surveys in Geophysics* ", ISSN 1573-0956.

Ray, R.D. & Lutcke, S.B. (2006). Tide model errors and GRACE gravimetry: towards a more realistic assessment. *Geophysical Journal International*, Vol.167, No.8, (December 2006), pp.1055-1059, ISSN 0956-540X.

Rignot, E.; Velicogna, I.; van den Broeke, M.R.; Monaghan, A. & Lenaerts, J. (2011). Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters*, Vol.38, No.5, (March 2011), pp. L05503, ISSN 0094-8276.

Rodell, M. & Famiglietti, J.S. (1999). Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. *Water Resources Research*, Vol.35, No.9, (September 1999), pp. 2705– 2723, ISSN 0043-1397.

Rodell, M. & Famiglietti, J.S. (2001). An analysis of terrestrial water storage variations in Illinois with implications for GRACE. *Water Resources Research*, Vol.37, No.5, (May 2001), pp. 1327– 1339, ISSN 0043-1397.

Rodell, M. & Famiglietti, J.S. (2002). The potential for satellite-based monitoring of groundwater storage changes using GRACE: The High Plains aquifer, central US. *Journal of Hydrology*, Vol.263, No.1-4, (June 2002), pp. 245–256, ISSN 0022 1694.

Rodell, M.; Houser, P.R.; Jambor, U.; Gottschalck, J.; Mitchell, K.; Meng, C.-J.; Arsenault, K.; Cosgrove, B.; Radakovich, J.; Bosilovich, M.; Entin, J.K.; Walker, J.P.; Lohmann, D. & Toll, D. (2004a). The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society*, Vol.85, No.3, (March 2004), pp. 381−394, ISSN 1520-0477.

Rodell, M.; Famiglietti, J.S.; Chen, J.; Seneviratne, S.I.; Viterbo, P.; Holl, S. & Wilson, C.R. (2004b). Basin scale estimates of evapotranspiration using GRACE and other observations. *Geophysical Research Letters*, Vol.31, No. 20, (October 2004), pp. L20504, ISSN 0094-8276.

Rodell, M.; Chen, J.; Kato, H.; Famiglietti, J.S.; Nigro, J. & Wilson C.R. (2007). Estimating groundwater changes in the Mississippi River basin using GRACE. Hydrogeology Journal, Vol.15, No.1, (February 2007), pp. 159-166, ISSN 1431-2174.

Roddell, M.; Velicogna, I. & Famiglietti, J. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, Vol.460, No.7257, (August 2009), 999-1003, ISSN 0028-0836.

Rowlands, D.D.; Luthcke, S.B.; Klosko, S.M.; Lemoine, F.G.R.; Chinn, D.S.; McCarthy, J.J.; Cox, C.M. & Andersen, O.B. (2005). Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements. *Geophysical Research Letters*, Vol.32, No.4, (February 2005), pp. L04310, ISSN 0094-8276.

Rowlands, D.D.; Luthcke, S.B.; McCarthy, J.J.; Klosko, S.M.; Chinn, D.S.; Lemoine, F.G.; Boy, J.P. & Sabaka, T.J. (2010). Global mass flux solutions from GRACE: a comparison of parameter estimation strategies – Mass concentrations versus Stokes coefficients. *Journal of Geophysical Research*, Vol.115, No.B1, (January 2010), pp. B01403, ISSN 0148-0227.

Sasgen, I.; Martinec, Z. & Fleming, K. (2006). Wiener optimal filtering of GRACE data. *Studia Geophysica et Geodaetica*, Vol.50, No.4, (October 2006), 499−508, ISSN 1573-1628.

Schmidt,R.; Schwintzer, P.; Flechtner, F.; Reigber, C.; Güntner, A.; Döll, P.; Ramillien, G.; Cazenave, A.; Petrovic, S.; Jochmann, H. & Wünsch, J. (2006). GRACE observations of changes in continental water storage. *Global and Planetary Change*, Vol.50, No.1-2, (February 2006), pp. 112–126, ISSN 0921-8181.

Schmidt, R.; Flechtner, F.; Meyer, U.; Neumayer, K. -H.; Dahle, Ch.; Koenig, R. & Kusche, J. (2008). Hydrological signals observed by the GRACE satellites. *Surveys in Geophysics*, Vol.29, No.4-5, (October 2008), pp. 319−334, ISSN 1573-0956.

Schrama, E. J. O.; Wouters, B. & Lavallée, D.A. (2007). Signal and noise in Gravity Recovery and Climate Experiment (GRACE) observed surface mass variations. *Journal of Geophysical Research*, Vol.112, No.B8, (August 2007), B08407, ISSN 0148-0227.

Seo, K.W. & Wilson, C.R. (2005). Simulated estimation of hydrological loads from GRACE. *Journal of Geodesy*, Vol.78, No.7–8, (March 2005), pp. 442–456, ISSN 0949-7714.

Seo, K.W.; Wilson, C.R.; Chen, J. & Waliser D. (2008). GRACE's spatial errors. *Geophysical Journal International*, Vol.172, No.3, (January 2008), pp.41-48, ISSN 0956-540X.

Strassberg, G.; Scanlon, B.R. & Rodell, M. (2007). Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the

High Plains Aquifer (USA). *Geophysical Research Letters*, Vol.34, No. 14, (July 2007), pp. L14402, ISSN 0094-8276.

Sun, A.Y.; Green, R.; Rodell, M. & Swenson S. (2010). Inferring aquifer storage parameters using satellite and in situ measurements: Estimation under uncertainty. *Geophysical Research Letters*, Vol.37, No. 10, (May 2010), pp. L10401, ISSN 0094-8276.

Swenson, S. & Wahr, J. (2002). Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research*, Vol.107, No.B9, (September 2002), pp. 2193, ISSN 0148-0227.

Swenson, S. & Wahr, J. (2003). Monitoring changes in continental water storage with GRACE. *Space Science Reviews*, Vol.108, No.1–2, (January 2003), pp. 345–354, ISSN 0038-6308.

Swenson, S.; Wahr, J. & Milly, P. C. D. (2003). Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, Vol.39, No.8, (August 2003), pp. 1223, ISSN 0043-1397.

Swenson, S. & Wahr, J. (2006a). Post-processing removal of correlated errors in GRACE data. *Geophysical Research Letters*, Vol.33, No.8, (April 2006), pp. L08402, ISSN 0094-8276.

Swenson, S. & Wahr, J. (2006b). Estimating Large-Scale Precipitation Minus Evapotranspiration from GRACE Satellite Gravity Measurements. *Journal of Hydrometeorology*, Vol.7, No.2, (April 2006), pp. 252-270, ISSN 1525-755X.

Swenson, S., Famiglietti, J.; Basara, J. & Wahr, J. (2008). Estimating profile soil moisture and groundwater variations using GRACE and Oklahoma Mesonet soil moisture data. *Water Resources Research*, Vol.44, No.1, (January 2008), pp. W01413, ISSN 0043-1397.

Syed, T.H.; Famiglietti, J.S.; Chen, J.; Rodell, M.; Seneviratne, S.I.; Viterbo, P. & Wilson, C.R. (2005). Total Basin Discharge for the Amazon and Mississippi River Basins from GRACE and a Land-Atmosphere Water Balance. *Geophysical Research Letters*, Vol.32, No.24, (December 2005), pp. L24404, ISSN 0094-8276.

Syed, T.H.; Famiglietti, J.S.; Rodell, M.; Chen, J. & Wilson, C.R. (2008). Analysis of terrestrial water storage changes from GRACE and GLDAS. *Water Resources Research*, Vol.44, No.2, (February 2008), pp. W02433, ISSN 0043-1397.

Syed, T.H.; Famiglietti, J.S. & Chambers, D.P. (2009). GRACE-Based Estimates of Terrestrial Freshwater Discharge from Basin to Continental Scales. *Journal of Hydrometeorology*, Vol.10, No.1, (February 2009), pp. 22–40, ISSN 1525-755X.

Tapley, B.D.; Bettadpur, S.; Watkins, M. & Reigber, C. (2004a). The Gravity Recovery and Climate Experiment : Mission overview and Early results. *Geophysical Research Letters*, Vol.31, No.9, (May 2004), pp. L09607, ISSN 0094-8276.

Tapley, B. D.; Bettadpur, S.; Ries, J.C.; Thompson, P.F. & Watkins, M.M. (2004b). GRACE measurements of mass variability in the Earth system. *Science*, Vol.305, No.5683, (July 2004), pp. 503– 505, ISSN 0036-8075.

Tarantola, A. (1987). *Inverse Problem Theory: Methods for data fitting and model parameter estimation*, Elsevier Science Publishers B.V., ISBN 0-444-42765-1, Amsterdam, The Netherlands.

Thompson, P.F.; Bettadpur, S.V. & Tapley, B.D. (2004). Impact of short period, non-tidal, temporal mass variability on GRACE gravity estimates. *Geophysical Research Letters*, Vol.31, No.6, (March 2004), pp. L06619, ISSN 0094-8276.

Velicogna, I. & Wahr, J. (2002). A method for separating Antarctic postglacial rebound and ice mass balance using future ICESat Geoscience Laser Altimeter System, Gravity

Recovery and Climate Experiment, and GPS satellite data. *Journal of Geophysical Research*, Vol.107, No.B10, (October 2002), pp. ETG 20-1, ISSN 0148-0227.

Velicogna, I. & Wahr, J. (2005). Greenland mass balance from GRACE. *Geophysical Research Letters*, Vol.32, No.18, (September 2005), pp. L18505, ISSN 0094-8276.

Velicogna, I. & Wahr, J. (2006a). Measurements of Time-Variable Gravity Show Mass Loss in Antarctica. *Science*, Vol.311, No.5768, (March 2006), pp. 1754–1756, ISSN 0036-8075.

Velicogna, I. & Wahr, J. (2006b). Acceleration of Greenland Ice Mass Loss in Spring 2004. *Nature*, Vol.443, No.7109, (September 2006), pp. 329–331, ISSN 0028-0836.

Velicogna, I. (2009). Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophysical Research Letters*, Vol.36, No.19, (October 2009), pp. L19503, ISSN 0094-8276.

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. *Journal of Geophysical Research*, Vol.103, No.B12, (December 1998), pp. 30205– 30229, ISSN 0148-0227.

Wahr, J.; Swenson, S.; Zlotnicki, V. & Velicogna, I. (2004). Time variable gravity from GRACE: First results. *Geophysical Research Letters*, Vol.31, No.11, (June 2004), pp. L11501, ISSN 0094-8276.

Werth, S.; Güntner, A.; Schmidt, R. & Kusche, J. (2009). Evaluation of GRACE filter tools from a hydrological perspective. *Geophysical Journal International*, Vol.179, No.3, (December 2009), pp. 1499-1515, ISSN 0956-540X.

Wolf, M. (1969). Direct measurement of the Earth's gravitational potential using a satellite pair. *Journal of Geophysical Research*, Vol.74, No.22, (November 1969), pp. 5295-5300, ISSN 0148-0227.

Wouters, B. & Schrama, E.O.J. (2007). Improved accuracy of GRACE gravity solutions through empirical orthogonal function filtering of spherical harmonics, *Geophysical Research Letters*, Vol.34, No.23, (December 2007), pp. L23711, ISSN 0094-8276.

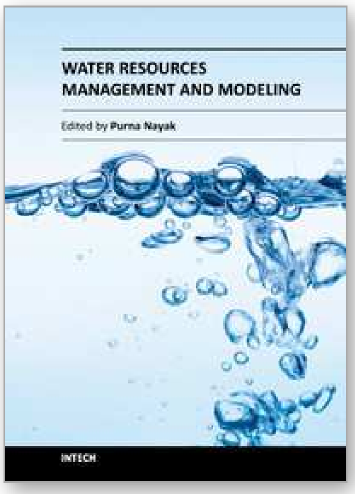
Wouters, B.; Chambers, D. & Schrama, E.J.O. (2008). GRACE observes small-scale mass loss in Greenland. *Geophysical Research Letters*, Vol.35, No.20, (October 2008), pp. L20501, ISSN 0094-8276.

Wouters, B.; Riva, R. E. M.; Lavallée, D. A. & Bamber J.L. (2011). Seasonal variations in sea level induced by continental water mass: First results from GRACE. *Geophysical Research Letters*, Vol.38, No.3, (February 2011), pp. L03303, ISSN 0094-8276.

Xavier, L.; Becker, M.; Cazenave, A.; Longuevergne, L.; Llovel, W. & Rotunno Filho, O. C. (2010). Interannual variability in water storage over 2003–2008 in the Amazon Basin from GRACE space gravimetry, in situ river level and precipitation data. *Remote Sensing of Environment*, Vol.114, No.8, (August 2010), pp. 1629–1637, ISSN 0034-4257.

Yeh, P.J.F.; Swenson, S.C.; Famiglietti, J.S. & Rodell, M. (2006). Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Water Resources Research*, Vol.42, No.12, (December 2006), pp. W12203, ISSN 0043-1397.

Zaitchik, B.F.; Rodell, M. & Reichle, R.H. (2008). Assimilation of GRACE Terrestrial Water Storage Data into a Land Surface Model: Results for the Mississippi River Basin. *Journal of Hydrometeorology*, Vol.9, No.3, (June 2008), pp. 535-548, ISSN 1525-755X.



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Hydrology is the science that deals with the processes governing the depletion and replenishment of water resources of the earth's land areas. The purpose of this book is to put together recent developments on hydrology and water resources engineering. First section covers surface water modeling and second section deals with groundwater modeling. The aim of this book is to focus attention on the management of surface water and groundwater resources. Meeting the challenges and the impact of climate change on water resources is also discussed in the book. Most chapters give insights into the interpretation of field information, development of models, the use of computational models based on analytical and numerical techniques, assessment of model performance and the use of these models for predictive purposes. It is written for the practicing professionals and students, mathematical modelers, hydrogeologists and water resources specialists.