

# Detection of Continental Hydrology and Glaciology Signals from GRACE: A Review

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Received: 30 March 2008 / Accepted: 17 October 2008 / Published online: 7 November 2008  
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**Abstract** Since its launch in March 2002, the Gravity Recovery and Climate Experiment (GRACE) has provided a global mapping of the time-variations of the Earth's gravity field. Tiny variations of gravity from monthly to decadal time scales are mainly due to redistributions of water mass inside the surface fluid envelopes of our planet (i.e., atmosphere, ocean and water storage on continents). In this article, we present a review of the major contributions of GRACE satellite gravimetry in global and regional hydrology. To date, many studies have focused on the ability of GRACE to detect, for the very first time, the time-variations of continental water storage (including surface waters, soil moisture, groundwater, as well as snow pack at high latitudes) at the unprecedented resolution of ~400–500 km. As no global complete network of surface hydrological observations exists, the advances of satellite gravimetry to monitor terrestrial water storage are significant and unique for determining changes in total water storage and water balance closure at regional and continental scales.

**Keywords** Global hydrology · GRACE satellite gravimetry · Water mass balances

## 1 Introduction

Continental water storage is a key component of the terrestrial and global hydrological cycles, having an important control over water, energy and biogeochemical fluxes, thus playing a major role in the Earth's climate system (Famiglietti 2004). In spite of its

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importance, total continental water storage remains completely unknown at regional and global scales because of the lack of observations and systematic monitoring (Lettenmaier and Famiglietti 2006). Although some local hydrological monitoring networks exist, the available description of water storage comes primarily from global hydrology models (e.g. Rodell et al. 2004a), which still suffer from important uncertainties. Unfortunately, direct hydrological measurements are fairly limited, while imaging satellite techniques and satellite altimetry only give access to surface water variations that represent just one component of total water storage.

Since early in this century, GRACE satellite gravimetry offers a very interesting alternative remote sensing technique to measure changes in total water storage (ice, snow, surface waters, soil moisture, groundwater) over continental areas, representing a new source of information for hydrologists and global hydrological modellers. As a joint venture between NASA (US) and DLR (Germany), the Gravity Recovery and Climate Experiment (GRACE) mission was launched on the 17th of March, 2002 and placed on a quasi polar orbit (89°). The mission consists of two identical satellites in identical orbits at an altitude of ~450 km, one following the other in a “Low–Low” configuration. The satellites use K-Band microwave ranging (KBR) system (Tapley et al. 2004a) to monitor continuously their separation distance of ~220 km and its rate versus time, which varies as the satellite passes through gravity highs and lows. Each GRACE satellite contains 3-axis accelerometers that measure the dynamical effects of the non-conservative forces such as solar pressure and atmospheric drag. After removing the non-gravitational effects from the inter-satellite range measurements, these corrected variations of distance are used to solve for the geopotential with unprecedented accuracy.

Models of the Earth’s geopotential are classically obtained from GRACE by inverting for monthly global estimates with spatial resolution of a few hundreds of km (Tapley et al. 2004b), with higher accuracy at larger scales (Swenson et al. 2003; Wahr et al. 2004). For the first time, GRACE has enabled the production of monthly global maps of the gravity field and, thus to estimate time-variations of the mass in the Earth system. Tiny variations of the gravity field are due to the redistribution of fluid mass inside the surface fluid envelope of the planet (atmosphere, oceans, continental water storage) (Dickey et al., NRC Report, 1997).

A demonstration of the ability of GRACE to detect hydrological signals with sufficient accuracy was made first as pre-launch assessments (Rodell and Famiglietti 1999, 2001, 2002). Since then, several post-launch studies have clearly demonstrated its capacity to monitor water storage variations (Wahr et al. 2004; Ramillien et al. 2004), as well as to estimate the mass balance of the ice sheets (Velicogna and Wahr 2006a, b; Ramillien et al. 2006a), to quantify water fluxes such as evapotranspiration (Rodell et al. 2004b; Ramillien et al. 2006b), precipitation minus evapotranspiration (Swenson and Wahr 2006a, b) and river discharge (Syed et al. 2005, 2007, 2008a, b), and to quantify the continental water variability in time and space (Wahr et al. 2004; Swenson and Milly 2006; Schmidt et al. 2006; Ramillien et al. 2005; Chen et al. 2005a; Tamsiea et al. 2005; Tapley et al. 2004b; Seo et al. 2006; Syed et al. 2008a, b). In these studies, time-series and maps of water storage estimates are computed from GRACE data as regional averages over areas of about a 200,000 km<sup>2</sup> and greater.

Note that most of these studies have also shown good agreement between GRACE-based estimates of water storage and model outputs. Swenson et al. (2006) undertook observation-based validation of GRACE using existing, limited precise ground data, while Rodell et al. (2004b) and Syed (2005, 2007, 2008a, b) relied on coupled land-atmosphere water balances. Additionally, Davis et al. 2004 found a high consistency between the

seasonal cycle of GRACE hydrological loading and radial displacement of the GPS station at Manaus. In situ surface gravity data in Europe were also used to validate GRACE data (Crossley et al. 2005; Hinderer et al. 2006; Neumeyer et al. 2006), and demonstrated its ability in detecting hydrological variations. Although a global network for monitoring continental water storage will likely not appear in the near-future, the spatial resolution of GRACE data has been steadily improving thanks to advances in both processing of the instrument data (Thomas 1999; GRACE Science Mission Requirement Document 2000; Bettadpur et al. 2000) and post-processing of the gravity field solutions using linear filtering (Wahr et al. 1998; Swenson and Wahr 2003, 2006; Seo and Wilson 2005).

## 2 GRACE Data

Pre-treatment of Level-1 GRACE data (i.e., positions and velocities from GPS, accelerometer data and KBR inter-satellite measurements) is routinely made by different research groups that produce monthly solutions (GFZ, Potsdam, Germany; CSR, JPL, US; GRGS, Toulouse, France), and 10-day interval solutions (GRGS) computed using sliding window scheme based on  $\sim 30$  days of data (Lemoine et al. 2007b). These groups provide estimates of Stokes coefficients (i.e., dimensionless spherical harmonic coefficients of the geopotential) developed up to a degree between 50 and 120, that are adjusted for each 30-day period from raw along-track GRACE measurements. Formal errors associated with the estimated Stokes coefficients are also provided to users. In the process, GRACE coefficients are corrected for atmospheric mass variations and ocean tides using ECMWF and NCEP reanalyses respectively, as well as and global oceanic circulation models such as MOG-2D (Carrère and Lyard 2003). As such, the provided GRACE coefficients are “residual” values that should represent continental water storage variations, errors from the correcting models, and noise. Time spans of monthly solutions differ from one group to another. UTCSR provides solutions from 04/2002 to the near-present, except for June, July 2002, and June 2003 (Tapley et al. 2004a; Bettadpur 2007). JPL solutions are for April and May 2002 plus all months from September 2002 to the near-present, except June 2003. GFZ solutions cover a period that starts in August 2002 and continues to the near-present, except September, December 2002, January and June 2003, and January 2004 (Schmidt et al. 2006). Monthly solutions are available at available at: <http://www.csr.utexas.edu/grace/> and <http://podaac-www.jpl.nasa.gov/grace/>. Series of 10-day solutions computed by GRGS begin from August 2002 (Biancale et al. 2006; Lemoine et al. 2007b) and are available at <http://bgi.cnes.fr/>. Errors increase at degree 20–30 and become dominant at degrees 40–50. The solutions also exhibit unrealistic North-South “striping” (Ramillien et al. 2005; Chen et al. 2005a, b). The presence of such striping indicates a high degree of spatial correlation in the GRACE errors. While GRGS has recently produced empirically-“stabilized” GRACE solutions that contain less noise (Lemoine et al. 2007b), spatial averaging of GRACE coefficients remains necessary in order to reduce the contribution of noise and striping in the short-wavelength domain for CSR, JPL and GFZ solutions. Different strategies for filtering to extract realistic hydrological signals on continents from noisy GRACE solutions have been proposed, as will be shown in the next section.

Regional solutions independent of spherical harmonic fields and obtained using alternative approaches have also been computed by Ohio State University (Garcia 2002; Han 2004; Han et al. 2003, 2005) and NASA Goddard Space Flight Center (Rowlands et al. 2002, 2005; Lemoine et al. 2007a; Han et al. 2008). These groups have also achieved a higher temporal resolution of fifteen and ten days, respectively. The Mascons (i.e., mass

concentrations) method consists of determining surface water mass distributions in geographical blocks (w.r.t. a reference field) by using accurate K-Band Range (KBR)–Rate observations only (Lemoine et al. 2007a). Another strategy is based on the energy balance equation (i.e., by integration versus time of all orbit parameters) for solving the differences of gravitational potential along the satellite tracks, and afterwards estimating the corresponding surface mass by linear inversion of these potential anomalies (Garcia 2002).

### 3 State-of-the-Art Methods for Determining Water Mass Storage Changes

Changes of mass distribution in the Earth system due to variations in continental water storage cause spatiotemporal changes of the geoid, defined as the gravitational equipotential surface that best coincides with the mean sea surface, which can be written as a global representation:

$$\begin{Bmatrix} \delta C_{nm}(t) \\ \delta S_{nm}(t) \end{Bmatrix} = \frac{1 + k'_n R^2}{2n + 1 M} \iint_S \delta q(\theta, \lambda, t) \begin{Bmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{Bmatrix} P_{nm}(\cos \theta) dS \tag{1}$$

for a given time  $t$ , where  $\delta q$  is the surface distribution of mass,  $M$  and  $S$  are the total mass and the surface of the Earth, respectively,  $\theta$  and  $\lambda$  are co-latitude and longitude.  $\delta C_{nm}$  and  $\delta S_{nm}$  are the (dimensionless) fully-normalized Stokes coefficients and  $P_{nm}$  are associated Legendre functions,  $n$  and  $m$  are harmonic degree and order respectively.  $R$  is the mean Earth’s radius ( $\sim 6,371$  km).  $N$  is the maximum degree of the development, ideally  $N = \infty$ . In practice, the Stokes coefficients are estimated from satellite data with a finite degree  $N < \infty$  and this maximum value defines the spatial resolution  $\sim \pi R/N$ . 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  $\Delta C_{nm}$  and  $\Delta S_{nm}$  are computed for each monthly or 10-day period  $\Delta t$ .

For a monthly period  $\Delta t$ , the surface water storage anomaly within a region of angular area  $S$  (i.e., surface of the studied basin divided by  $R^2$ ) can be deduced as the scalar product between time variations of Stokes coefficients  $\Delta C_{nm}(t)$  and  $\Delta S_{nm}(t)$ , and averaging kernel coefficients  $A_{nm}$  and  $B_{nm}$  corresponding to the geographical region to be extracted (Swenson and Wahr 2002):

$$\Delta \sigma_S(\Delta t) = \frac{\rho_e R}{3S} \sum_{n=1}^N \sum_{m=0}^n \frac{2n + 1}{1 + k'_n} \{ \Delta C_{nm}(\Delta t) A_{nm} + \Delta S_{nm}(\Delta t) B_{nm} \} \tag{2}$$

where  $\rho_e$  is the mean Earth’s density ( $\sim 5,517$  kg/m<sup>3</sup>). 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. As GRACE data remains polluted by the striping, satellite and leakage errors, a number of methods have been proposed to smooth GRACE data.

One can use a simple isotropic Gaussian filter (Jekeli 1981; Wahr et al. 1998) but the choice of the averaging radius remains critical since this filter does not distinguish between noise and the energy of geophysical signals. Swenson and Wahr (2002) proposed another type of averaging kernel based on the Lagrange multipliers, corresponding to the separate minimization of contributions of measurement and leakage error to signals, by using a

leakage function defined as the difference in shape between exact and smoothed averaging kernels. This method requires no a priori knowledge of the signal. Later, these authors used an improved version of the averaging kernel built with a priori information (i.e., the shape of the covariance function assuming it is azimuthally symmetric) and then minimizing the sum of variance of the satellite and leakage errors (Swenson and Wahr 2003; Seo and Wilson 2005). An anisotropic filter based on calibration of the error spectrum was also proposed (Han et al. 2005).

Another filtering technique including a priori information from global hydrology models was developed to estimate the optimal water mass coefficients through an iterative least-squares approach (Ramillien et al. 2004, 2005). This method eliminates a large part of the noise energy at short wavelengths and allows for the separation of liquid water and snow mass contributions from the observed gravity changes (see Fig. 1). Swenson and Wahr (2006a, b) have recently developed a new filtering strategy for “de-stripping” GRACE data that uses adjusted weighting between Stokes coefficients of the same parity before applying Eq. 2.

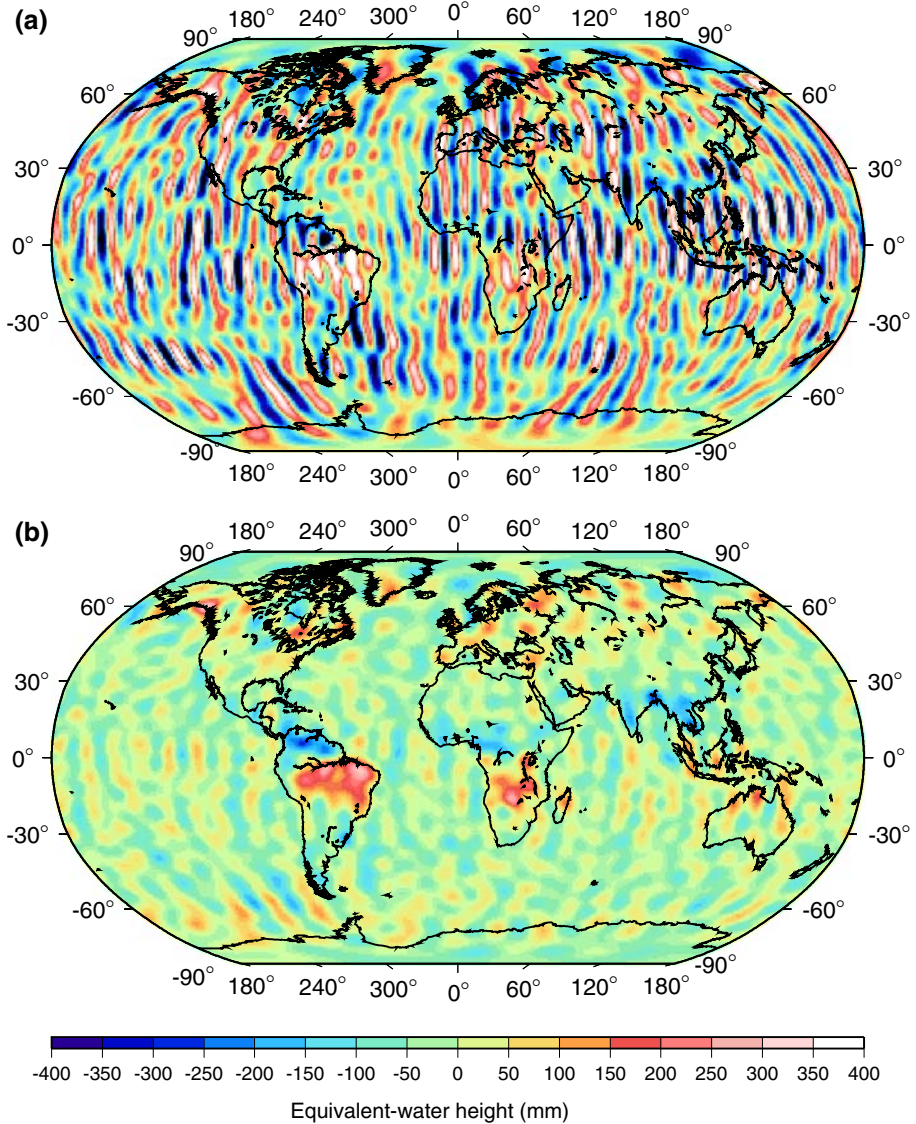
## 4 Results

### 4.1 Pre-Launch Studies

Preliminary studies focused on the ability of GRACE to provide realistic hydrological signals on the continents. For example, Wahr et al. (1998) highlighted the need to consider short-wavelength noise and leakage errors, as well as the size of the specific 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 increasing spatial and temporal scales (i.e. monthly and greater). Rodell and Famiglietti (1999) compared a number of modelled datasets of total water storage to expected GRACE instrument errors and found that water storage changes would be detectable at spatial scales greater than 200,000 km<sup>2</sup>, at monthly and longer timescales, and with monthly accuracies of roughly 1.5 cm. Rodell and Famiglietti (2001) confirmed these findings using a network of hydrological observations of snow, surface water, soil moisture (SM) and groundwater (GW) in Illinois. Rodell and Famiglietti (2002) explored the potential for using GRACE and ancillary soil moisture data to monitor groundwater storage changes in the High Plains aquifer of the central USA. These authors concluded that groundwater remote sensing using GRACE was feasible, since the uncertainties of mean variations of GRACE-derived GW for the ~450,000 km<sup>2</sup> aquifer was approximately 8.7 mm, whereas the amplitudes of the groundwater storage change signals were 20 and 45 mm for annual and 4-yr periods respectively.

### 4.2 Applications in Continental Hydrology and Validation of GRACE

Once sufficiently long series of GRACE solutions were made available, various regional studies for validation were made. Comparisons with global hydrology models outputs and surface measurements revealed acceptable agreements between GRACE-derived and modelled changes of the continental water storage versus time, especially at monthly and seasonal timescales. Over a drainage basin, the water mass balance equation to solve is (see Hirschi et al. 2006 for instance):



**Fig. 1** Example of monthly geoid solution from the latest GFZ release (October 2003) (Schmidt et al. 2006): **a** unfiltered water mass anomalies w.r.t. a reference mean field, and **b** the corresponding Land Water (LW) solution estimated by least-square inversion (see Ramillien et al. 2005) for the same period, where noisy North-South striping is attenuated. Maximum degree is  $N = 50$  (i.e., spatial resolution of  $\sim 400$  km)

$$\frac{dW}{dt} = P - E - R \quad (3)$$

where  $\frac{dW}{dt}$  is the Total Water Storage (TWS) variations, that are directly provided by GRACE over the considered region if satellite, leakage and correcting models' errors and

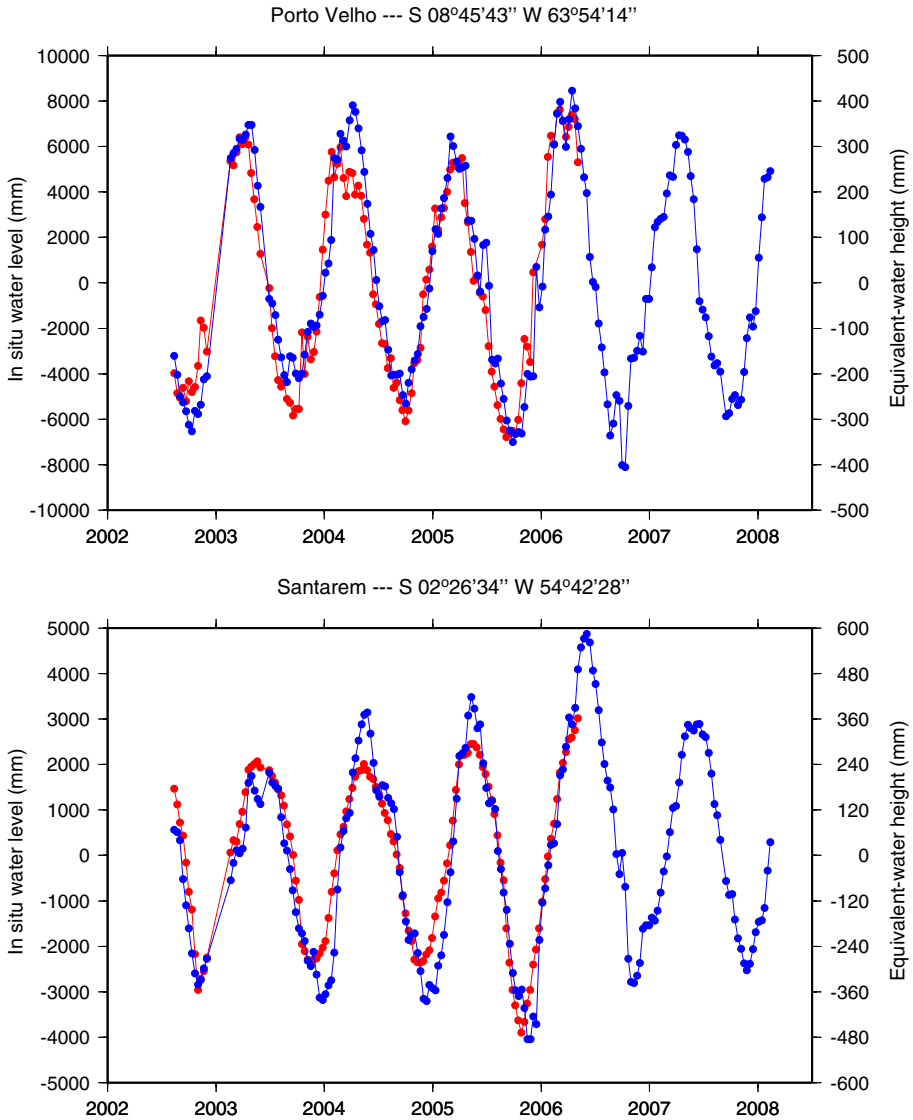
other not modelled geophysical signals are neglected. The terms  $P$ ,  $E$  and  $R$  represent precipitation and evapotranspiration rates (i.e., vertical fluxes) and run-off, respectively.

In general, GRACE-based estimates of Total Water Storage variations compare favourably with those based on land surface models and atmospheric and terrestrial water balances (Rodell et al. 2004a; Syed et al. 2005; Niu et al. 2007a, b; Seo et al. 2006). Global maps of seasonal amplitudes are comparable to those described by WGHM (Döll et al. 2003) and GLDAS (Rodell et al. 2004a) model simulations but TWS variations tend to be slightly overestimated by GRACE (Schmidt et al. 2006; Syed et al. 2008a). Rodell et al. (2007) found a good agreement between GRACE data and simulated SM and monitored GW over the Mississippi River basin. Over the entire Northern hemisphere, GLDAS water storage simulations with resolution of  $\sim 1,300$  km and accuracy of 9 mm in terms of equivalent-water height were found to have a spatial correlation of 0.65 with GRACE data, suggesting that gravity field changes are related to TWS variations (Andersen et al. 2005). After separating the water and snow contributions to the gravity field, Frappart et al. (2006a) used satellite microwave data to validate GRACE-based snow mass seasonal changes in high-latitude basins; in particular, rms errors of 10–20 mm were estimated in the Yenisey, Ob, McKenzie and Yukon basins. GRACE geoid data were also used as a proxy to test and improve the efficiency of surface water schemes in the ORCHIDEE land surface hydrology model (Ngo-Duc et al. 2007). However, a lack of consistency and a time shift between GRACE TWS and global hydrology models time series may still exist, especially at interannual timescales.

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 modelled or observed, GRACE is capable of monitoring changes in groundwater storage changes with reasonable accuracy. Important seasonal correlations of 0.8–0.9 were found by comparing GRACE data with well networks in Illinois (Yeh et al. 2006), Oklahoma (Swenson et al. 2008), the High Plains aquifer (Strassberg et al. 2007), and the Mississippi basin (Rodell et al. 2007).

Correlations of 0.7–0.8 with direct in situ measurements of water level (i.e., surface water) along the Amazon River found by Vaz de Almeida et al. (personal communication, 2008), as illustrated for in situ stations in Fig. 2. GRACE-based TWS changes were also validated by accurate observations of superconducting gravimeters during the 2003 heat wave that occurred in Central Europe (Andersen et al. 2005). Combined with other satellite techniques such as imagery, GRACE geoid data were used to study the mechanisms of seasonal flooding in large inundation areas, such as in the downstream Mekong plain (Frappart et al. 2006b) and the Amazon River (Wilson et al. 2007; Papa et al. 2008). Another application for monitoring climatic impacts was the detection of the severe drought of the Murray-Darling basin in Southern Australia (Leblanc et al. 2008). Estimation of 2002–2006 sea-level contribution of GRACE-derived TWS of the largest basins has lately been made from the GRGS GRACE solutions, and corresponds to a water mass loss of  $\sim 0.5$  mm/yr ESL (Ramillien et al. 2008).

GRACE-derived TWS can be also used to estimate changes in vertical water fluxes. Changes of regional evapotranspiration (ET) rate over the Mississippi basin were estimated by combining 600-km filtered GRACE TWS data with observed precipitation and streamflow in a water balance equation (see Eq. 3) (Rodell et al. 2004a). Similarly, Ramillien et al. (2006b) solved the water balance equation for the ET rate. Time-variations of ET were evaluated over large drainage basins, and revealed that GRACE-derived values were comparable to the ET values simulated by the WGHM. Swenson and Wahr (2006a, b) estimated precipitation minus evapotranspiration (i.e., the difference “ $P-E$ ” from Eq. 3) using the water balance framework and comparing to surface parameters variations from global reanalysis.



**Fig. 2** Time series of measured in-situ water levels from the ANA (2006) database (red), and GRACE-based hydrological signals (blue) at Porto Velho and Santarém stations in the Amazon basin (Vaz de Almeida et al. 2008, personal communication). The GRACE profile has been interpolated from the 10-day interval 400-km resolution GRGS GRACE solutions at the specific geographical location of the in situ stations. Daily ANA values were simply interpolated at the monthly periods of GRACE. Note the good agreement at seasonal timescales between the profiles of these two independent datasets. Seasonal variations of water mass storage in the Amazon basin exceed  $\pm 400$  mm of equivalent-water thickness

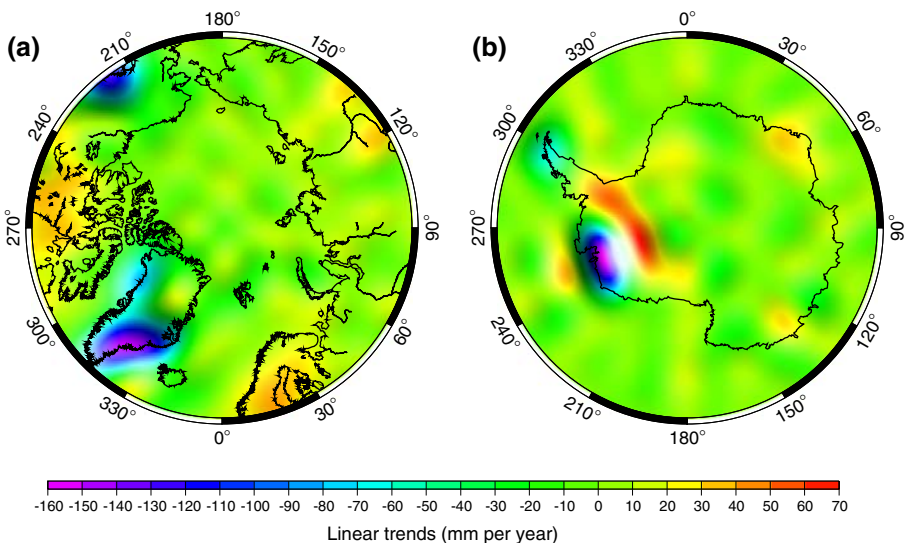
#### 4.3 Estimation of Ice Sheets and Glaciers Mass Balance

GRACE-derived mass balance estimates of Antarctica (Velicogna and Wahr 2006a), Greenland (Velicogna and Wahr 2006b; Chen et al. 2006a) or both ice sheets (Ramillien



et al. 2006a) have been determined from the gravity fields of the GRACE project. Figure 3 presents maps of the trends adjusted from the GRGS GRACE data set over polar regions. Velicogna and Wahr (2005, 2006b) found a loss rate of  $-82 \pm 28 \text{ km}^3/\text{yr}$  for Greenland with an acceleration of melting in spring 2004. Mass changes of this ice sheet resolved by drainage basin were estimated using Mascons as  $-101 \pm 16 \text{ km}^3/\text{yr}$  after correction for Global Isostatic Adjustment (GIA) (Luthcke et al. 2006). This latter result is consistent with one found previously by Ramillien et al. (2006a) using a 10-day GRGS GRACE solutions. Velicogna and Wahr (2006a) estimated an extreme decrease of ice mass of  $-152 \pm 80 \text{ km}^3/\text{yr}$  for Antarctica. This trend value mainly represents the GIA correction that these authors removed by considering the IJ05 (Ivins and James 2005) and ICE-5G (Peltier 2004) models. When GRACE-based estimates are not corrected for long-term Post-Glacial Rebound (PGR), the mass balance of Antarctica appears to be close to zero, with large uncertainties due to North-South striping noise, errors from the correction models and leakage effects. This latter result suggests that it is not clear to date whether this continent actually loses or gains mass during the GRACE observation period (Ramillien et al. 2006a). GIA phenomena are not-well modelled, especially over the whole of Antarctica, where available long-term observational constraints remain rare. Thus removing from GRACE the PGR effects that still cannot be modelled accurately results in the addition of important uncertainties in the mass balance estimates.

Velicogna and Wahr (2002) have shown earlier that the detection of PGR was possible by combining different satellite techniques. These authors used 5 years of simulated GRACE and Laser GLAS data smoothed over 250-km scales, and found level accuracies of 5.3 mm/yr and 20 mm/yr for PGR signature and ice mass trend, respectively, over the whole of Antarctica. Estimates of trends improved as GPS vertical velocities were added. However, an effective extraction of PGR signals by GRACE satellite gravimetry still needs to be proved using real data.



**Fig. 3** Polar maps of the surface mass trends over high-latitude regions evaluated from the 10-day GRACE GRGS solutions for the period 2002–2006, that reveal regions of significant loss of mass over Alaskan mountains glaciers, Greenland, West Antarctica and Antarctic Peninsula

At regional scales, mass balances of mountain glaciers of Southern Alaska have been recently estimated to have a negative trend of  $-101 \pm 22 \text{ km}^3/\text{yr}$ , and reveal good agreement with airborne laser altimetry that shows a loss of  $-96 \pm 35 \text{ km}^3/\text{yr}$  over this region (Chen et al. 2006b). After correction for GIA and hydrological effects, the same authors found a depletion of ice mass of  $\sim -27.9 \text{ km}^3/\text{yr}$  for the Patagonia Ice Field of South America, which is equivalent to a  $\sim -1.6 \text{ mm}/\text{yr}$  ice thickness change (Chen et al. 2007). Recently, Chen et al. (2008), estimated recent regional mass loss rates of  $\sim -28.8 \pm 7.9$ ,  $-81 \pm 17$  and  $-16.7 \pm 9.7 \text{ km}^3/\text{yr}$ , in the northern Antarctic Peninsula, and along the coastal regions near the Stancomb-Willis and Jutulstraumen glaciers in Queen Maud Land, respectively.

## 5 Conclusion

GRACE satellite gravimetry provides realistic spatio-temporal variations of TWS and water mass fluxes which compare with independent hydrological datasets. Many studies have demonstrated the possibilities of such a satellite system to detect and monitor spatial redistribution of TWS versus time, at the precision of only tens of mm of equivalent-water height and spatial resolution of  $\sim 400\text{--}500 \text{ km}$ . Accuracy of the results still depends upon the level of noise in the GRACE data and the low-pass filtering method used. In addition to remaining measurement errors and loss of signal by filtering the GRACE solutions, uncertainty of model-predicted GIA represents a major error source in the regional mass change estimates. Moreover, a spatial resolution of  $\sim 400 \text{ km}$  still represents a limitation for “regional” hydrology studies, which often require surface resolutions of  $\sim \text{km}$  or greater. Improvements of pre- and post-processing should increase the quality of the GRACE products, such as processing along-track GRACE measurements using the promising “mascons” approach in regional cases (Jekeli 1999; Garcia 2002; Han 2004; Han et al. 2003, 2005; Rowlands et al. 2005; Luthcke et al. 2006; Han et al. 2008). Steady improvement of GRACE gravity fields in terms of precision and spatial resolution is encouraging, and enables GRACE satellite gravimetry to be applied to a wider class of problems than previously possible.

Bibliographic references about on-going applications of GRACE are regularly updated by the pre-processing institutions and can be found at: <http://www.csr.utexas.edu/grace/publications/>, <http://www.gfz-potsdam.de/grace/> and <http://grace.jpl.nasa.gov/publications/>. GRACE data are also available at <http://grace.jpl.nasa.gov> at: <http://bgi.cnes.fr:8110/geoid-variations/> to have access to the updated 10-day interval GRGS solutions.

**Acknowledgements** We thank two anonymous reviewers for their helpful comments and suggestions that enabled the improvement of the manuscript. This work was supported in part by the NNG04GE99G and JPL-REASON1259524 grants.

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