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Title
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Permalink

Journal

ISSN

Authors
Ramillien, G
Famiglietti, JS
Wahr, J

Publication Date

DOI

Copyright Information

Peer reviewed

ORIGINAL PAPER

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

G. Ramillien · J. S. Famiglietti · J. Wahr

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 envelops 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; Tamisiea 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^2 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 exisiting, 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 fil-tering (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, acceler-ometer 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 ~ 30 days of data (Lemoine et al. 2007b). These groups provide esti-mates of Stokes coefficients (i.e., dimensionless spherical harmonic coefficients of the geo-potential) 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 coeffi-cients 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 com-puted 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 dominent 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 alter-native 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:

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

for a given time t, where 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 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 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 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 ρ_e is the mean Earth's density ($\sim 5,517$ kg/m³). 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-striping" 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 ot 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^2, 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 $\sim$450,000 km^2 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):
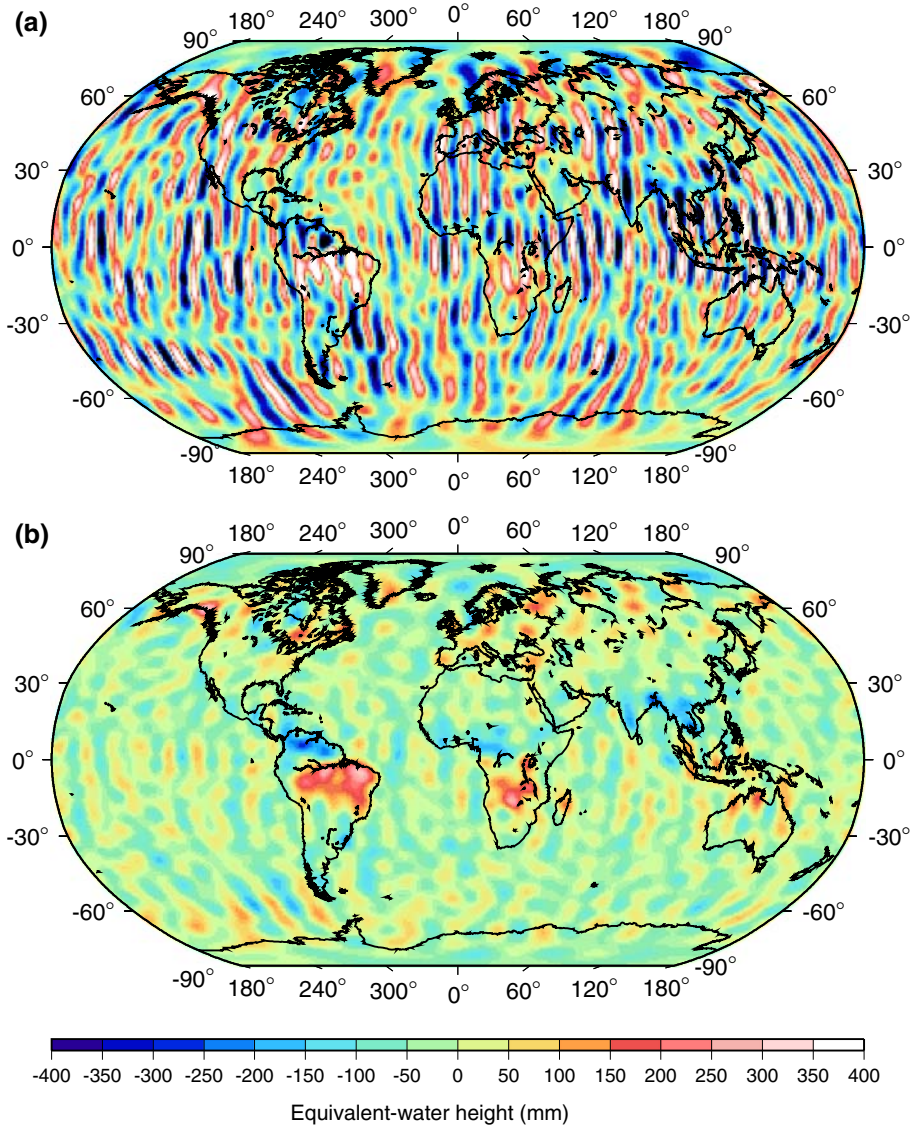
Fig. 1 Example of monthly geoid solution from the lastest GFZ release (October 2003) (Schmidt et al. 2006): **a** unfiltered water mass anomalies w.r.t. a reference mean field, and **b** the corresponding Land Water (LW) solution estimated by least-square inversion (see Ramillien et al. 2005) for the same period, where noisy North-South striping is attenuated. Maximum degree is $N = 50$ (i.e., spatial resolution of ~ 400 km)

$$\frac{dW}{dt} = P - E - R \tag{3}$$

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 ∼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-latitudes 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 ∼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.
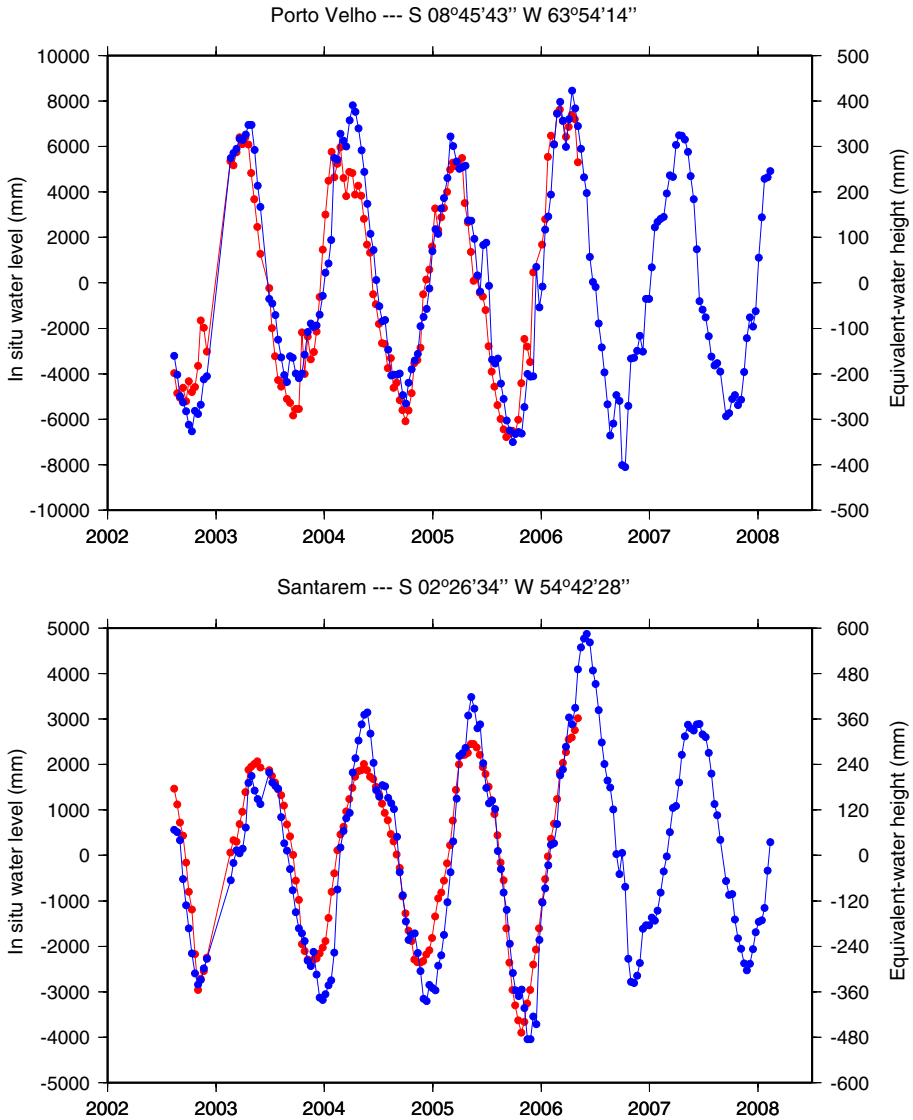
Fig. 2 Time series of measured in-situ water levels from the ANA (2006) database (red), and GRACE-based hydrological signals (blue) at Porto Velho and Santarém stations in the Amazon basin (Vaz de Almeida et al. 2008, personal communication). The GRACE profile has been interpolated from the 10-day interval 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 ±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 ± 28 km^3/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 ± 16 km^3/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 ± 80 km^3/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.
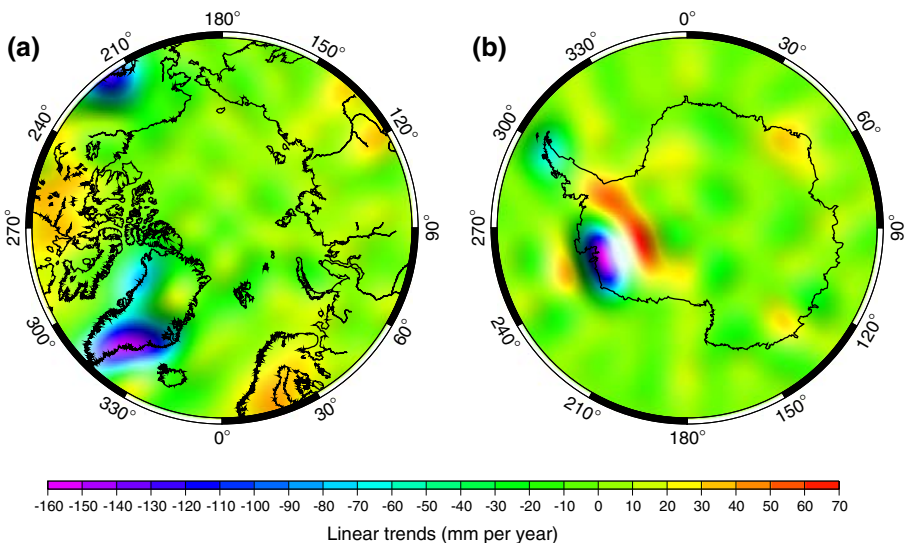

Fig. 3 Polar maps of the surface mass trends over high-latitude regions evaluated from the 10-day GRACE GRGS solutions for the period 2002–2006, that reveal regions of significant loss of mass over Alaskan mountains glaciers, Greenland, West Antarctica and Antarctic Peninsula

At regional scales, mass balances of mountain glaciers of Southern Alaska have been recently estimated to have a negative trend of -101 ± 22 km^3/yr, and reveal good agreement with airborne laser altimetry that shows a loss of -96 ± 35 km^3/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 ~ -27.9 km^3/yr for the Patagonia Ice Field of South America, which is equivalent to a ~ -1.6 mm/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 ± 17 and -16.7 ± 9.7 km^3/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 ~ 400–500 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 ~ 400 km still represents a limitation for "regional" hydrology studies, which often require surface resolutions of $\sim$ 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.

References

Agência National de Agua (ANA) (2006) Bacía do rio Amazonas: informações sobre a bacía. Data available on request at: http://www.ana.gov.br

Andersen OB, Seneviratne SI, Hinderer J, Viterbo P (2005) GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. Geophys Res Lett 32:18

Bettadpur S (2007) Level-2 gravity field product user handbook, GRACE, 327–734, GRACE Proj Cent for Space Res, University of Texas, Austin

Bettadpur S, Watkins M (2000) GRACE gravity science & its impact on mission design, AGU Spring 2000, GP51C-11, http://www.csr.utexas.edu/grace/publications

Biancale R, Lemoine J-M, Balmino G, Loyer S, Bruisma S, Pérosanz F, Marty J-C and Gégout P (2006) 3 years of geoid variations from GRACE and LAGEOS data at 10-day intervals from July 2002 to March 2005, CNES/GRGS product data available on CD-ROM

Carrère L, Lyard F (2003) Modelling the barotropic response of the global ocean to atmospheric wind and pressure forcing – comparisons with observations. Geophys Res Lett 30(6):1275

Chen J, Rodell M, Wilson CR, Famiglietti JS (2005a) Low degree spherical harmonic influences on Gravity Recovery and Climate Experiment (GRACE) water storage estimates. Geophys Res Lett 32:L14405. doi:10.1029/2005GL022964

Chen JL, Wilson CR, Famiglietti JS, Rodell M (2005b) Spatial sensitivity of the Gravity Recovery and Climate Experiment (GRACE) time-variable gravity observations. J Geophys Res, Solid Earth 110:B08408. doi:10.1029/2004JB003536

Chen JL, Wilson CR, Blankenship DD, Tapley BD (2006a) Antarctic mass rates from GRACE. Geophys Res Lett 33:L11502. doi:10.1029/2006GL026369

Chen JL, Tapley BD, Wilson CR (2006b) Alaskan mountain glacial melting observed by satellite gravimetry, 248(1–2):368–378. doi: 10.1016/j.epsl.2006.05.039

Chen JL, Wilson CR, Tapley BD, Blanckenship DD, Ivins ER (2007) Patagonia ice field melting observed by Gravity Recovery and Climate Experiment (GRACE). Geophys Res Lett 34:L22501. doi: 10.1029/2007GL031871

Chen JL, Wilson CR, Tapley BD, Blanckenship D, Young D (2008) Antarctic regional ice loss rates from GRACE. EPSL 266(1–2):140–148. doi:10.1016/j.epsl.2007.10.057

Crossley D, Hinderer J, Boy J-P (2005) Time-variation of the European gravity field from superconducting gravimeters. Geophys J Int 161(2):257–264. doi:10.1111/j.1365-246X.2005.02586.x

Davis JL, Elósegui P, Mitrovica JX, Tamisiea ME (2004) Climate-driven deformation of the solid Earth from GRACE and GPS. Geophys Res Lett 31:L24605. doi:10.1029/2004GL021435

Dickey J et al (1997) Satellite Gravity and the Geosphere: contribution to the study of the Solid Earth and its envelope. National Research Council (NRC), National Academy Press, Washington DC

Döll PF, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. J Hydrol 270(1–2):105–134. doi:10.1016/S0022-1694(02)00283-4

Famiglietti JS (2004) Remote sensing of terrestrial water storage, soil moisture and surface waters. In: Sparks RSJ, Hawkesworth CJ (eds) The state of the planet: frontiers and challenges in geophysics. Geophysical Monograph Series, vol 150. American Geophysical Union (AGU), Washington DC, pp 197–207

Frappart F, Ramillien G, Biancamaria S, Mognard-Campbell N, Cazenave A (2006a) Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002–2004). Geophys Res Lett 33:L02501. doi:10.1029/2005GL024778

Frappart F, Dominh K, Lhermitte J, Ramillien G, Cazenave A, LeTaon T (2006b) Water volume change in the lower Mekong basin from satellite altimetry and imagery data. Geophys J Int 167:570–584

Garcia RV (2002) Local geoid determination from GRACE mission, Report 43210–1275. Ohio State University, Columbus

GRACE Science Mission Requirement Document (2000) GRACE 327–720, June 2000

Han SC (2004) Efficient determination of global gravity field from satellite-to-satellite tracking mission GRACE. Celest Mech Dyn Astron 88:69–102

Han SC, Jekeli C, Shum CK (2003) Static and temporal gravity field recovery using GRACE potential difference observables. Adv Geosci 1:19–26

Han SC, Shum CK, Jekeli C et al (2005) Improved estimation of terrestrial water storage changes from GRACE. Geophys Res Lett 32:L07302. doi:10.1029/2005GL02238

Han SC, Rowlands DD, Luthcke SB, Lemoine FG (2008) Localized analysis of satellite tracking data for studying time-variable Earth's gravity fields. J Geophys Res 113:B06401. doi:10.1029/2007JB005218

Hinderer J, Andersen O, Lemoine F, Crossley D, Boy J-P (2006) Seasonal changes in European gravity field from GRACE: a comparison with superconducting gravimeters and hydrology model predictions. J Geodyn 41(1–3):59–68. doi:10.1016/j.jog.2005.08.037

Hirschi M, Seneviratne SI, Schär C (2006) Seasonal variations in terrestrial water storage for major mid-latitude river basins. J Meteorol 7(1):39–60. doi:10.1175/JHM480.1

Ivins E, James TS (2005) Antarctic glacial isostatic adjustment: a new assessment. Antarct Sci 17:541–553. doi:10.1017/S0954102005002968

Jekeli C (1981) Alternative methods to smooth the Earth's gravity field. Rep. 327, Dep. of Geod. and Sci. and Surv., Ohio State Univ

Jekeli C (1999) The determination of gravitational potential differences from satellite-to-satellite tracking. Celest Mech Dyn Astron 7582:85–101

Leblanc M, Tregoning P, Ramillien G, Tweed SO and Fakes A (2008) Basin-sacle, integrated observations of the 21st Century multi-year drought in southeast Australia, WRR (in revision)

Lemoine FG, Luthcke SB, Rowlands DD (2007a) The use of mascons to resolve time-variable gravity from GRACE, Dynamic Planet, 130, IAG Symposia, Springer Berlin Heidelberg. doi: 10.1007/978-3-540-49349-5

Lemoine J-M, Bruisma S, Loyer S, Biancale R, Marty J-C, Pérosanz F, Balmino G (2007b) Temporal gravity field models inferred from GRACE data. Adv Space Res. doi: 10.1016/j.asr.2007.03.062

Lettenmaier DP, Famiglietti JS (2006) Water from on high. Nature 444:562–563

Luthcke SB, Zwally HJ, Abdalati W, Rowlands DD, Ray RD, Nerem RS, Lemoine FG, McCarthy JJ, Chinn DS (2006) Recent Greenland ice mass loss by drainage system from satellite gravity observations. Science 314:1286–1289

Neumeyer J, Barthelmes F, Dierks O, Flechtner F, Harnisch M, Harnisch G, Hinderer J, Imanishi Y, Kroner C, Meurers B, Petrovic S, Reigber C, Schmidt R, Schwintzer P, Sun H-P, Virtanen H (2006) Combination of temporal gravity variations resulting from superconducting gravimeter (SG) recordings, GRACE satellite observations and global hydrology models. J Geod 79(10–11):573–585. doi: 10.1007/s00190-005-0014-8

Peltier WR (2004) Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE. Annu Rev Earth Planet Sci 32:111–149. doi:10.1146/annurev.earth.32.082503.144359

Ngo-Duc T, Laval K, Polcher J, Ramillien G, Cazenave A (2007) Validation of the land water storage simulated by Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE) with Gravity Recovery and Climate Experiment (GRACE) data. Water Resources Res 43:W04427. doi:10.1029/2006WR004941

Niu G-Y, Yang Z-L, Dickinson RE, Gulden LE, Su H (2007a) Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data. J Geophys Res 112:D07103. doi:10.1029/2006JD007522

Niu G-Y, Seo K-W, Yang Z-L, Wilson C, Hua S, Chen J, Rodell M (2007b) Retrieving snow mass from GRACE terrestrial water storage change with a land surface model. Geophys Res Lett 34:L15704. doi: 1.1029/2007GL030413

Papa F, Günter A, Frappart F, Prigent C, Rossow WB (2008) Variations of surface water extent and water storage in large river basins: A comparison of different global data sources. Am Geophys Union 35:L11401. doi:10.1029/2008GL033857

Ramillien G, Cazenave A, Brunau O (2004) Global time variations of hydrological signals from GRACE satellite gravimetry. Geophys J Int 158(3):813–826

Ramillien G, Frappart F, Cazenave A, Güntner A (2005) Time variations of land water storage from an inversion of 2 years of GRACE geoids. Earth Planet Sci Lett 235(1–2):283–301

Ramillien G, Lombard A, Cazenave A, Ivins E, Llubes M, Remy F, Biancale R (2006a) Interannual variations of ice sheets mass balance from GRACE and sea level. Global Planet Change 53:198–208

Ramillien G, Frappart F, Güntner A, Ngo-Duc T, Cazenave A (2006b) Mapping time variations of evapotranspiration rate from GRACE satellite gravimetry. Water Resources Res 42:W10403. doi: 10.1029/2005WR004331

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 Planet Change 60:381–392. doi:10.1016/j.gloplacha.2007.04.002

Rodell M, Famiglietti J (1999) Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. Water Resour Res 35(9):2705–2723

Rodell M, Famiglietti J (2001) An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). Water Resour Res 37(5):1327–1339

Rodell M, Famiglietti JS (2002) The potential for satellite-based monitoring of groundwater storage changes using GRACE: the High Plains aquifer, Central US. J Hydrol 263(1–4):245–256

Rodell M, Houser PR, Jambor U, Gottschalck J, Mitchell K, Meng C-J, Arsenault K, Cosgrove B, Radakovich J, Bosilovich M, Entin JK, Walker JP, Lohmann D, Toll D (2004a) The global land data assimilation system. Bull Am Meteorol Soc 85(3):381–394. doi:10.1175/BAMS-85-3-381

Rodell M, Famiglietti JS, Chen J, Seneviratne SI, Viterbo P, Holl S, Wilson CR (2004b) Basin scale estimates of evapotranspiration using GRACE and other observation. Geophys Res Lett 31:L20504. doi:10.1029/2004GL020873

Rodell M, Chen J, Kato H, Famiglietti J, Nigro J, Wilson C (2007) Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE. Hydrogeol J 15:159–166. doi:10.1007/s10040-006-0103-7

Rowlands DD, Ray RD, Chinn DS, Lemoine FG (2002) Short-arc analysis of intersatellite tracking data in a mapping mission. J Geod 76:307–316. doi:10.1007/s.00190-002-0255-8

Rowlands DD, Luthcke SB, Klosko SM, Lemoine FG, Chinn DS, McCarthy JJ, Cox CM, Anderson OB (2005) Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements. Geophys Res Lett 32:L04310. doi:10.1029/2004GL022386

Seo KW, Wilson CR (2005) Simulated estimation of hydrological loads from GRACE. J Geod 78(7–8):442–456

Seo K-W, Wilson CR, Famiglietti JS, Chen JL, Rodell M (2006) Terrestrial water mass load changes from Gravity Recovery and Climate Experiment (GRACE). Water Resour Res 42:W05417. doi:10.1029/2005WR004255

Schmidt R, Schwintzer P, Flechtner F, Reigber C, Güntner A, Döll P, Ramillien G, Cazenave A, Petrovic S, Jochmann H, Wunsch J (2006) GRACE observations of changes in continental water storage. Global Planet Change 50(1–2):112–126. doi:10.1016/j.gloplacha.2004.11.018

Strassberg G, Scanlon BR, Rodell M (2007) Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from High Plains Aquifer (USA). Geophys Res Lett 34:L14402. doi:10.1029/2007GL030139

Swenson S, Milly PCD (2006) Climate model biases in seasonality of continental water storage revealed by satellite gravimetry. Water Resources Res 42:W03201. doi:10.1029/2005WR004628

Swenson S, Wahr J (2002) Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. J Geophys Res, Solid Earth 107(B9):2193. doi:10.1029/2001JB000576

Swenson S, Wahr J (2003) Monitoring changes in continental water storage with GRACE. Space Sci Rev 108(1–2):345–354

Swenson S, Wahr J (2006a) Estimating large-scale precipitation minus evapotranspiration from GRACE satellite gravimetry measurements. J Hydrometeorol 7(2):252–270. doi:10.1175/JHM478.1

Swenson S, Wahr J (2006b) Post-processing removal of correlated errors in GRACE data. Geophys Res Lett 33:L08402. doi:10.1029/2005GL025285

Swenson S, Wahr J, Milly PCD (2003) Estimated accuracies of regional water storage variations inferred from the Gravity Recovery and Climate Experiment (GRACE). Water Resources Res 39(8):1223. doi:10.1029/2002WR001808

Swenson SC, Yeh PJ-F, Wahr J, Famiglietti JS (2006) A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois. Geophys Res Lett 33:L16401. doi:10.1029/2006GL026962

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 Resour Res 44:W01413. doi:10.1029/2007WR006057

Syed T, Famiglietti J, Chen J, Rodell M, Seneviratne S, Viterbo P, Wilson C (2005) Total basin discharge for the Amazon and the Mississippi River basins from GRACE and a land-atmosphere water balance. Geophys Res Lett 32:24404. doi:10.1029/2005GL024851

Syed TH, Famiglietti JS, Zlotnicki V, Rodell M (2007) Contemporary estimates of Pan-Arctic freshwater discharge from GRACE and reanalysis. Geophys Res Lett 34:L19404. doi:10.1029/2007GL031254

Syed TH, Famiglietti JS, Rodell M, Chen J, Wilson CR (2008a) Analysis of terrestrial water storage changes from GRACE and GLDAS. Water Resour Res 44:W02433. doi:10.1029/2006WR005779

Syed TH, Famiglietti JS, Chambers D (2008b) GRACE-based estimates of terrestrial freshwater discharge from basin to continental scales. J Hydrometeorol. doi:10.1175/2008JHM993.1

Tamisiea ME, Leuliette EW, Davis JL, Mitrovica JX (2005) Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements. Geophys Res Lett 32:L20501. doi:10.1029/2005GL023961

Tapley BD, Bettadpur S, Watkins M, Reigber C (2004a) The gravity recovery and climate experiment: mission overview and early results. Geophys Res Lett 31:L09607. doi:10.1029/2004GL019920

Tapley B, Bettadpur S, Ries J, Thompson P, Watkins M (2004b) GRACE measurements of mass variability in the Earth system. Science 305(5683):503–505. doi:10.1126/science.1099192

Thomas J (1999) An analysis of gravity field estimation based on inter-satellite dual one-way biased ranging. JPL Publication 98–15, pp 3–13

Velicogna I, Wahr J (2002) A method for separating Antarctic post glacial rebound and ice mass balance using future ICESat Geoscience Laser Altimeter System, Gravity Recovery and Climate Experiment and GPS satellite data. J Geophys Res 107(B10):2263. doi:10.1029/2001JB000708

Velicogna I, Wahr J (2005) Ice mass balance in Greenland from GRACE. Geophys Res Lett 32(18):L18505. doi:10.1029/2005GL023955

Velicogna I, Wahr J (2006a) Measurements of time-variable gravity show mass loss in Antarctica. Science 311(5768):1754–1756

Velicogna I, Wahr J (2006b) Acceleration of Greenland ice mass loss in spring 2004. Nature 443:329–331. doi:10.1038/nature05168

Wahr J, Molenaar M, Bryan F (1998) Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J Geophys Res Solid Earth 103(B12):30205–30229

Wahr J, Swenson S, Zlotnicki V, Velicogna I (2004) Time-variable gravity from GRACE: first results. Geophys Res Lett 31(11):L11501. doi:10.1029/2004GL019779

Wilson MD, Bates PD, Alsdorf D, Forsberg B, Horritt M, Melack J, Frappart F, Famiglietti J (2007) Modeling large-scale inundation of Amazonian seasonally-flooded wetlands. Geophys Res Lett 34:L15404. doi:10.1029/2007GL030156

Yeh PJF, Swenson SC, Famiglietti JS, Rodell M (2006) Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment. Water Resources Res 42:W12203. doi:10.1029/2006WR005374