

# Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE

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Received 7 March 2006; received in revised form 23 May 2006; accepted 5 June 2006

## Abstract

We propose a new estimate of the mass balance of the West/East Antarctica and Greenland ice sheets from GRACE for the recent period (July 2002–March 2005) and compute the corresponding contribution to the global mean sea level. We use new GRACE geoid solutions provided by the Groupe de Recherche en Géodésie Spatiale (GRGS/CNES), at the resolution of  $\sim 400$  km and sampled at 10-day interval. In the three regions, significant interannual variations are observed, which we approximate as linear trends over the short time span of analysis. Over Greenland, an apparent total volume loss of  $119 \pm 10$  cu km/yr water is observed. For the Antarctica ice sheet, a bimodal behaviour is apparent, with volume loss amounting to  $88 \pm 10$  cu km/yr water in the West, and increase in the East amounting to  $72 \pm 20$  cu km/yr water. These GRACE results are affected by land hydrology contamination and glacial isostatic adjustment (GIA) of the solid Earth since last deglaciation. We correct for both land hydrology contamination (using a global hydrological model) and GIA using the ICE-4G model for Greenland and the IJ05 model for Antarctica. Corrected for both land hydrology contamination and GIA, GRACE volume rates are  $-129 \pm 15$  cu km/yr,  $-107 \pm 23$  cu km/yr and  $+67 \pm 28$  cu km/yr for Greenland, West Antarctica and East Antarctica respectively. In terms of sea level rise, the GRACE-based ice sheets contributions are  $+0.36 \pm 0.04$  mm/yr for Greenland,  $+0.30 \pm 0.06$  mm/yr for West Antarctica and  $-0.19 \pm 0.07$  for East Antarctica for the time interval of study. The total Antarctica contribution to sea level over this short time span is thus slightly positive ( $+0.11 \pm 0.09$  mm/yr). The ice sheets together contribute to a sea level rise of  $0.47 \pm 0.1$  mm/yr. The results reported here are in qualitative agreement with recent estimates of the mass balance of the ice sheets based on GRACE and with those based upon other remote sensing observations. Due to the very short sampling time span for which the GRACE data are available, it is not yet possible to distinguish between interannual oscillations and long-term trend associated with climate change.

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**Keywords:** ice sheets mass balance; GRACE satellite gravimetry; sea level

## 1. Introduction

The mass balance of the ice sheets is a topic of considerable interest in the context of global warming and sea level rise. Tide gauges and satellite altimetry

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observations indicate that sea level has been rising by  $1.8 \pm 0.3$  mm/yr and  $3.1 \pm 0.4$  mm/yr during the past 50 years and last decade, respectively (Church et al., 2004; Leuliette et al., 2004; Cazenave and Nerem, 2004). The contribution of thermal expansion and mountain glaciers melting is now reasonably well known for both periods. These two processes amount respectively to 0.4 mm/yr and 0.45 mm/yr for the past 4–5 decades, and 1.6 mm/yr and 0.8 mm/yr for the last decade (Willis et al., 2004; Dyurgerov and Meier, 2005; Levitus et al., 2005; Ishii et al., 2006; Lombard et al., *in press*). Focusing on the last decade, thermal expansion plus mountain glacier melting contribute to 2.4 mm/yr. It thus appears that  $\sim 0.7$  mm/yr remain to be explained by other contributions, including change in mass of the Greenland and Antarctica ice sheets.

In recent years, remote sensing observations have provided for the first time, direct observations of the mass balance of Greenland and Antarctica. Repeated airborne laser altimetry measurements over Greenland have provided ice sheet elevation changes. Comparison of elevation changes from two surveys held in 1996–1997 and 2002–2003, indicates significant mass loss in near coastal regions of Greenland, leading to a positive contribution to sea level of 0.10–0.20 mm/yr over this time span (Krabbill et al., 2000, 2005). Previous remote sensing observations indicate that the high-elevation regions of central Greenland are close to a state of net mass balance (e.g., Thomas, 2004; Box et al., 2004). One recent study using satellite radar altimetry suggests that elevation increase in the Greenland interior was sustained during 1992–2003 (Johannessen et al., 2005). Using 10.5 years of ERS-1/2 satellite altimetry measurements, Zwally et al. (2005) find that ice mass increased in central Greenland, while thinning was determined at the Greenland margins, leading to near net balance. These results are in striking contrast with those of Rignot and Kanagaratnam (2006) who applied satellite radar interferometry to determine mass flux rates. The latter authors report that widespread glacier ice flow acceleration has occurred since 1996, with ice volume loss over 1996–2005 corresponding to  $+0.23$  mm/yr sea level rise in 1996 and  $0.57$  mm/yr in 2005. Over West Antarctica, recent laser airborne and radar satellite altimetry, as well as radar interferometry surveys, have reported accelerated ice mass loss in the Amundsen sea sector during recent years, corresponding to  $0.16$  mm/yr sea level rise (Rignot and Thomas, 2002; Thomas et al., 2004). In contrast, radar altimetry measurements over East Antarctica from the ERS-1/2 European satellites indicate elevation increase between 1992–2003 (Davis et al., 2005). If altimetry height

changes correspond to mass change, then East Antarctica mass gain corresponds to a sea level drop of  $0.12$  mm/yr. The Zwally et al. (2005)'s study also reports West Antarctica mass loss and slight ice mass increase in East Antarctica. These results suggest that on average, the continent-wide Antarctic ice sheet (not including the peninsula, see Rignot and Thomas (2002)), is in a state of slightly negative imbalance. Considerable uncertainty exists for both ice sheets due to the incomplete coverage in space and time by the combined observing strategies, and the penetration of radar-wave within the snowpack and the snow densification.

Better determination of the contribution of the ice sheets to current sea level rise is of primary importance for at least two reasons: (1) the large uncertainty that affects model projections of future sea level rise is rooted, in part, in our poor knowledge of the present behaviour of the Antarctic ice sheet (e.g., Church et al., 2001), and (2) sea level changes can have anthropogenic origins, and better ice sheet models could improve the fidelity with which analysis of data and models treat the question of the net mass transfer caused by land water storage, dam building, evaporation from irrigation, deforestation, urbanization, etc. This anthropogenic contribution is highly uncertain; even its sign is unknown. Thus precise knowledge of the sea level budget, including the ice sheets contribution, will allow placing better constraints on the anthropogenic factors.

Since 2002, space gravimetry from the GRACE mission provides a new tool for precisely measuring spatio-temporal changes in liquid and solid water mass inside the surface fluid envelopes (e.g., Tapley et al., 2004a,b; Wahr et al., 2004; Chambers et al., 2004; Ramillien et al., 2005; Schmidt et al., 2006), including the ice sheets mass change (Velicogna and Wahr, 2005; Velicogna and Wahr, 2006). Compared to satellite and airborne altimetry which measures ice elevation, hence needs to be corrected for snow compaction, GRACE directly measures the total mass change of the ice sheets. However, GRACE is also sensitive to solid Earth mass change, in particular to glacial isostatic adjustment (GIA) of crust and mantle, a response to the last deglaciation. Moreover, GRACE gives nearly complete coverage of the high-latitude regions, up to  $89^\circ\text{N/S}$ .

In this study, we analyse GRACE data to determine spatio-temporal change of the mass balance of the Greenland and Antarctica ice sheets over a  $<3$  year time span (from July 2002 to March 2005). For that purpose, we use new GRACE geoid solutions at 10-day interval computed by Biancale et al. (2006) and express them into equivalent water height solutions. Focusing on the ice sheets, we compute time series of equivalent water

volume change over the <3-year time span. Over Antarctica, we provide separate time series for West and East Antarctica, excluding the ice shelves (see Section 4). For each ice sheet, we also compute maps of equivalent volume change over the <3-year time span. Finally, from the computed linear trends, we estimate the contribution of each ice sheet to sea level change. In the present study, we do not analyse the seasonal signal, which is the object of a companion paper (Lubes et al., 2006).

## 2. GRACE data

The GRACE space mission, launched in March 2002, consists of two low-orbiting spacecrafts linked by a microwave ranging system. Measurements of the ranging system, together with GPS tracking and accelerometry data, are analysed by the GRACE project to provide, at regular time intervals (nominally on a monthly basis), global solutions of the Earth gravity field (or equivalently of the geoid) (e.g., Tapley et al., 2004a; Schmidt et al., 2006). These solutions consist of spherical harmonics coefficients, up to a given degree and order, of the gravity field. In the present study, we do not use the geoids released by the GRACE project, but rather new geoid solutions, the GRGS-EIGEN-GL04 fields, recently computed by Biancale et al. (2006). These solutions are provided at 10-day interval, from July 2002 through March 2005, up to degree and order 50 (i.e., a spatial resolution of 400 km). The data processing performed by Biancale et al. (2006) uses the GPS and K-band range rate GRACE data, as well as accelerometer data (to model surface forces — atmospheric drag and radiation pressure). Because the degree 2, order 0 coefficient of the geoid is poorly recovered by GRACE, Biancale et al. (2006) constrain this term in using LAGEOS-1/2 satellites laser ranging data. In the data processing, they also take into account the atmospheric mass perturbation using an *a priori* information based on 3-dimensional atmospheric pressure fields from the European Center for Medium Range Weather Forecast (ECMWF). Similarly in the geoid computation process, they account for oceans perturbation using an *a priori* barotropic ocean model (the MOG2D barotropic ocean model, Carrere and Lyard, 2003). As a consequence, the time-variable GRACE geoids analysed in the present study mainly represent signals due to land waters, snow, ice mass change, solid Earth processes and residual signals with respect to the *a priori* atmospheric and oceanic models. More details on the data processing and the GRGS-EIGEN-GL04 geoid solutions, including the associated errors assessment can be found in Biancale et al. (2006).

## 3. Equivalent water mass variations

Determination of the mass balance of the ice sheets is based on the estimate of equivalent water height solutions derived from the eighty-six 10-day GRGS-EIGEN-GL04 GRACE geoids (from July 2002 to March 2005). In this study, we do not apply the generalized least-square inversion method developed by Ramillien et al. (2005) to obtain the land water solutions from the GRACE geoids. This method needs *a priori* statistical information to construct the covariances matrices as well as an estimate of the initial guess (see Ramillien et al., 2004). For land waters, statistics and *a priori* solution can be easily constructed from available global hydrological models (Ramillien et al., 2005). Unfortunately, these global hydrological models either do not solve for the ice sheet mass change or provide unreliable values over the ice sheets (P.C.D. Milly, collective communication, 2005). This total lack of *a priori* information on the ice sheets may corrupt the ice mass change estimates. While we are currently working on solving this problem, here we choose an alternative approach consisting of simply expressing the geoid solutions in terms of equivalent water height, as done by other investigators (e.g., Tapley et al., 2004b; Wahr et al., 2004; Velicogna and Wahr, 2005; Velicogna and Wahr, 2006).

The geoid coefficients  $\hat{r}(t) = (\delta U_{nm}(t), \delta V_{nm}(t)) - t$  is time — are converted into units of surface mass density (mm of equivalent water height) by using an isotropic filter to obtain the spherical harmonics  $(\delta C_{nm}(t), \delta S_{nm}(t))$  of the water height solutions (e.g., Wahr et al., 1998; Ramillien et al., 2004; Chao, 2005):

$$\begin{pmatrix} \delta C_{nm}(t) \\ \delta S_{nm}(t) \end{pmatrix} = \left[ \frac{4\pi G \rho_w R}{(2n+1)\bar{\gamma}} (1 + k_n') \right]^{-1} \times \begin{pmatrix} \delta U_{nm}(t) \\ \delta V_{nm}(t) \end{pmatrix} \quad (1)$$

where  $n$  and  $m$  are harmonic degree and order respectively.  $G$  is the gravitational constant,  $\bar{\gamma}$  is the mean gravity acceleration,  $k_n'$  is the Love number of degree  $n$ ,  $R$  is the mean Earth's radius ( $\sim 6371$  km) and  $\rho_w$  is the mean water density ( $\sim 1000$  kg/m<sup>3</sup>).

Water height anomalies  $\delta h(\theta, \lambda, t)$  are computed from the  $\hat{r}_{nm}(t) = \{\delta C_{nm}(t), \delta S_{nm}(t)\}$  coefficients by computing the linear expansion up to degree  $N$ :

$$\delta h(\theta, \lambda, t) = \sum_{n=1}^N \sum_{m=0}^n \{ \delta C_{nm}(t) \cos(m\lambda) + \delta S_{nm}(t) \sin(m\lambda) \} \tilde{P}_{nm}(\cos\theta) \quad (2)$$

where  $\theta$  and  $\lambda$  are co-latitude and longitude respectively.  $N$  is the maximum degree of the development (here we consider  $N=50$ ).  $\tilde{P}_{nm}$  is associated Legendre function.

Equivalent water volume variation over the ice sheets  $\delta\Psi(t)$  is computed using the scalar product relation:

$$\delta\Psi(t) = 4\pi R^2 \sum_{n=1}^N \sum_{m=0}^n \{A_{nm}\delta C_{nm}(t) + B_{nm}\delta S_{nm}(t)\} \quad (3)$$

where  $A_{nm}$  and  $B_{nm}$  are normalized harmonic coefficients of the geographical mask used to mark the boundary of the studied area (set to 1 inside the considered region and zero outside). This procedure ensures that the resolution of the mask is the same as that of the GRACE observations (the leakage error associated with the mask is discussed in the results section; see below).

The error on the water volume change estimate is computed from the errors on the equivalent water height coefficients  $\sigma(t) = (\delta\sigma_{nm}^C(t), \delta\sigma_{nm}^S(t))$  (themselves based on the errors of the geoid coefficients through Eq. (1)):

$$\sigma(\delta\Psi(t)) = 4\pi R^2 \times \sqrt{\sum_{n=1}^N \sum_{m=0}^n \{(A_{nm}\delta\sigma_{nm}^C(t))^2 + (B_{nm}\delta\sigma_{nm}^S(t))^2\}} \quad (4)$$

The corresponding contribution to the mean sea level is estimated by dividing estimated equivalent water volume variation,  $\delta\Psi(t)$ , by the total ocean surface ( $\sim 360$  millions of  $\text{km}^2$ ).

## 4. Results

### 4.1. Ice volume variations

Analysis of the GRGS-EIGEN-GL04 geoids provides eighty-six equivalent water height solutions over Antarctica and Greenland, at 10-day interval, from July 2002 through March 2005. These solutions are expressed with respect to the mean solution over the time span of analysis (a time-average is removed to each 10-day solution). In the following, we call the latter ‘equivalent water height anomalies’. These 10-day anomalies are further analysed to provide linear trend maps of equivalent water height as well as equivalent water volume time series. Fig. 1 shows maps of linear trends (expressed in terms of equivalent water height) estimated during the time span of analysis, over Antarctica and Greenland respectively. Over Antarctica, we observe a strong decrease in the western region (Amundsen sea sector), up to 150 mm/yr equivalent water height. Some decreasing trend is also noticed over the

Antarctic Peninsula. Over the East Antarctica ice sheet, we observe either no change or locally small mass increase (on the order of  $\sim 50$  mm/yr equivalent water height) over the period. However slightly decreasing trends are noticed over the Dronning Maud Land region (sector around  $0^\circ$  longitude), and in the  $140^\circ\text{E}$ – $160^\circ\text{E}$  sector. In contrast, most of the Greenland ice sheet is characterized by ice mass loss, equivalent to  $\sim 50$  mm/yr water height decrease.

Llubes et al. (submitted for publication) analysed the GRGS-EIGEN-GL04 geoids to study the seasonal ice mass signal over Greenland and Antarctica. They provide an error assessment of the GRGS GRACE solutions and show that the overall cumulated error of these geoid solutions is less than 6 mm equivalent water height at 2000 km resolution and  $\sim 30$  mm at 666 km. But this is the global error averaged over the whole Earth. Using the covariance matrix information, they also compute the geographical distribution of this error and find a zonal pattern, with a maximum at the equator and minima at the poles where the data density is the highest. A factor of  $\sim 3$  is found between equatorial and polar errors. Using an external error check, they come to the conclusion that over the ice sheets the mean geoid error of each 10-day solution is in the range 2–5 mm equivalent water height. Recently, Wahr et al. (2006) provided an error assessment of GRACE mass estimates. They found that GRACE errors depend on latitude and smoothing radius. For 750 km resolution, errors of monthly GRACE solutions are estimated to be less than 10 mm (equivalent water height) in high latitude regions. We conclude that the trends reported in Fig. 1, of several tens of mm/yr equivalent water height is significant.

We checked whether the equivalent water height trends seen in Fig. 1 are contaminated by residual atmospheric mass anomalies. As indicated above, the atmospheric mass load was accounted for in the GRACE data processing. However the ECMWF atmospheric pressure fields may not be very accurate over ice sheets, especially Antarctica. Fig. 2 shows linear trends map of total atmospheric mass based on the ECMWF model over Antarctica and Greenland, respectively. The atmospheric trends are of very long wavelengths and their amplitude does not exceed 0.2 mm/yr (in equivalent water height). As this atmospheric model is removed, potential residual errors due to the poor observational coverage of remote regions may be small compared to the trend anomalies seen in Fig. 1.

We plotted the averaged equivalent water volume time series over the two ice sheets. For Antarctica, we excluded the Ross and Ronne (Weddell Sea region) ice



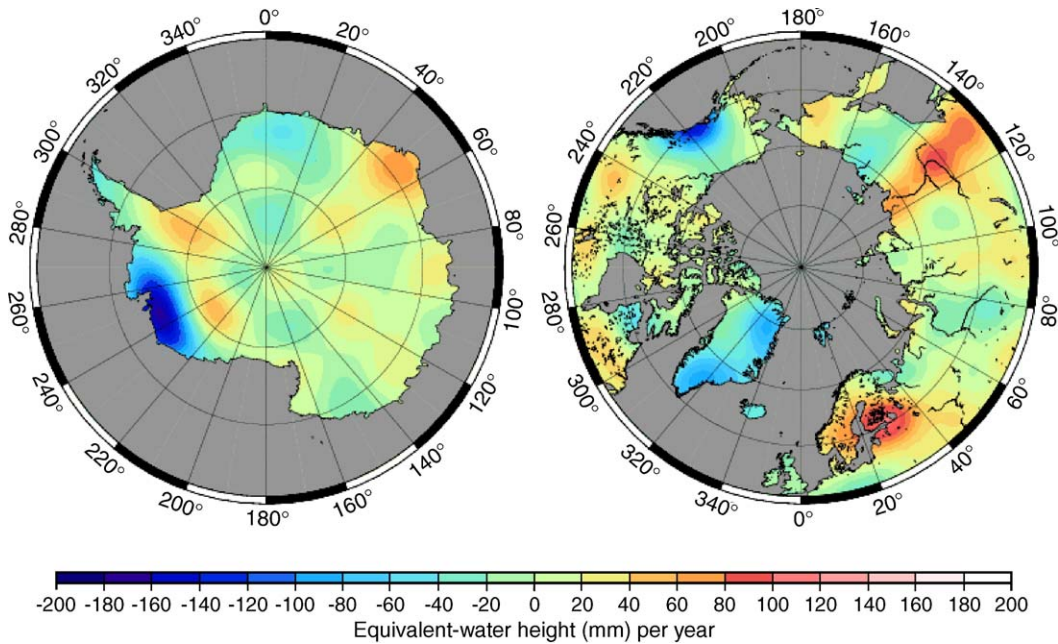


Fig. 1. Maps of the ice volume change (expressed in equivalent water height) over Antarctica and Greenland, computed from the 10-day GRGS-EIGEN-GL04 GRACE solutions for the period August 2002–March 2005.

shelves. Indeed, as ultimately we are interested in estimating the contribution of the ice sheets mass change to sea level, we do not consider the area covered by the ice shelves (ice shelves are floating bodies, thus do not contribute to sea level change). In principle, ice shelves should not provide any GRACE signal. However, we prefer to not include them to avoid error contamination. For that purpose we use the land mask shown in Fig. 3. Note that in the West Antarctic region, the mask includes three subregions: Amundsen sea sector, Antarctic Peninsula and the complement area located between 205°E and 300°E. When referring to a West Antarctica contribution, we sum the three areas. Fig. 4a, b shows water volume time series for both West Antarctica and East Antarctica (based on the mask shown in Fig. 3). In the West Antarctica region, we looked separately to the Amundsen sea sector where a large negative anomaly is visible in Fig. 1, as well as to Antarctic Peninsula. Fig. 4a shows the Amundsen and Peninsula time series as well as the total equivalent water volume time series over West Antarctica. Error bars are deduced from the errors provided with the spherical harmonic coefficients of the GRGS-EIGEN-GL04 geoids.

On Fig. 4a, the total West Antarctica time series exhibit a negative trend on which are superimposed short term oscillations, especially since early 2004. The estimated trend is  $-88 \pm 10$  cu km/yr. Most of this

trend is due to the Amundsen sea sector negative anomaly (see the other curves on Fig. 4a). In contrast, the East Antarctica time series (Fig. 4b) displays a positive trend, amounting to  $72 \pm 20$  cu km/yr. Fig. 4c shows the equivalent water volume time series over the Greenland ice sheet. A small annual signal is visible (maximum in early spring) superimposed on a decreasing trend of  $119 \pm 10$  cu km/yr. Note that associated uncertainties reported above represent the 95% level errors (2 sigmas).

A potential source of error affecting the results shown in Fig. 4a,b,c is the contamination effect (or leakage) of gravity signals due to reservoirs other than the ice sheets (atmosphere, ocean, terrestrial water reservoirs) (e.g., Velicogna and Wahr, 2005, 2006). All kinds of signals outside the domain limited by the mask shown in Fig. 3 may leak into the considered region, and thus pollute the estimated ice sheet mass value. As the ocean and atmosphere signals are removed in the data processing of GRACE geoids, corresponding effects should be small. This is unlike the land hydrology signals which dominate the corrected GRACE solutions. To estimate the land hydrology leakage, we used monthly global water storage fields from the Water Gap Hydrology Model (WGHM, Döll et al., 2003) over the period 2002 to mid-2004, and computed the contaminating signal over the ice sheets using the mask shown in Fig. 3. The model data and mask were

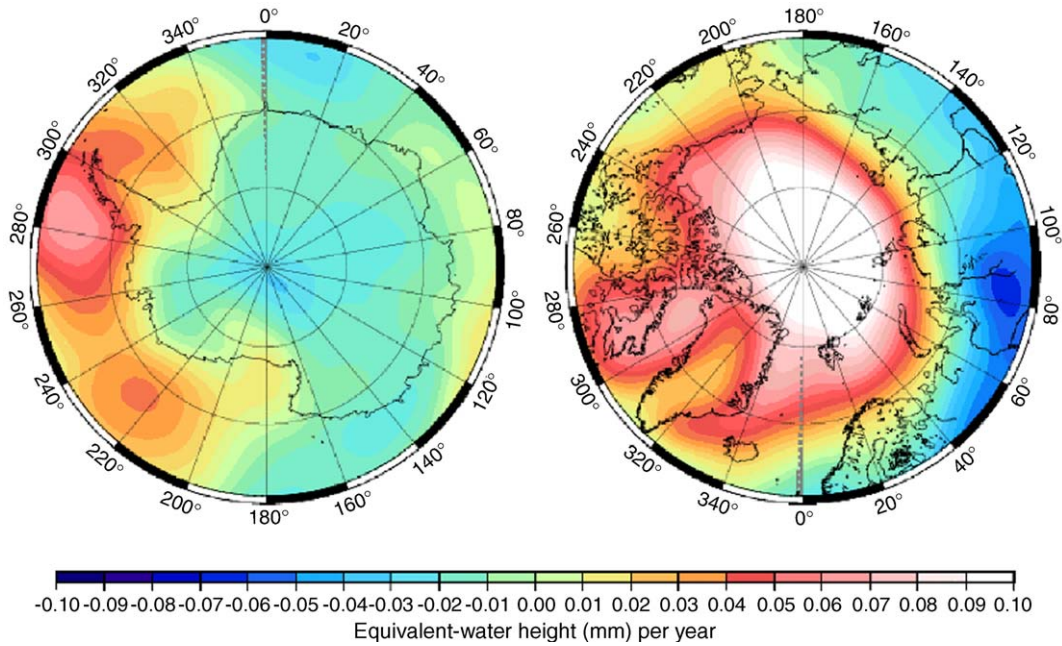


Fig. 2. Linear trends of the atmospheric mass computed from the ECMWF surface pressure data that are used as correction during the GRACE geoids processing.

developed into spherical harmonics up to degree 30 and 100. Fig. 5 shows for these two cutoff degrees, corresponding contamination effects (expressed in water

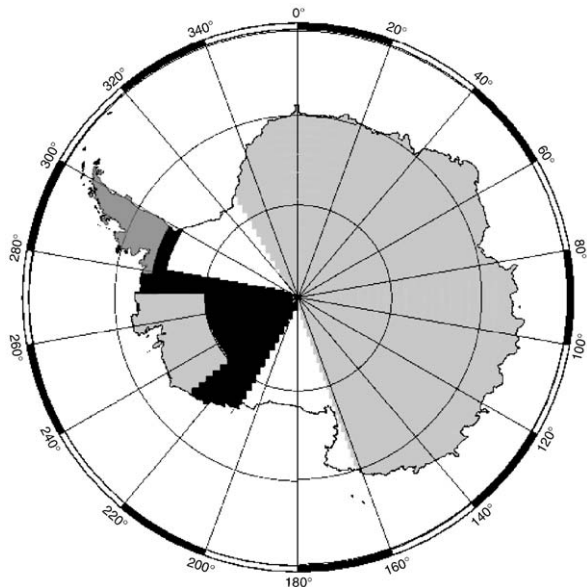


Fig. 3. Geographical masks used to compute the regional means of ice mass over West Antarctica (2.8 millions of km<sup>2</sup>) (the latter is divided in three subregions: Amundsen sea sector — light grey, Peninsula — dark grey and complement — black) and East Antarctica (10 millions of km<sup>2</sup>) (light grey). The floating ice platforms (Ross and Filchner-Ronne shelves) are excluded.

volume) over West Antarctica, East Antarctica and Greenland. Land hydrology leakage is dominated by seasonal signal (as expected considering the short time span of data). Trends computed over the 2.5-year time span are  $-1.0$ ,  $-9.7$  and  $+1.1$  water cu km/yr for West Antarctica, East Antarctica and Greenland respectively, so this effect is quite negligible for Greenland and West Antarctica, and slight for East Antarctica (see Table 1).

#### 4.2. Glacial isotatic adjustment (GIA)

Geodynamic processes related to the deformable Earth's response to spatio-temporal ice melt change (due to last deglaciation and present-day land ice melt) cause a 'secular' change in the geoid (Peltier, 2001). This effect is mainly available from modelling, but is greatly improved by supplemental vertical crustal motion data (e.g., Dietrich et al., 2005). This geoid change signature needs to be removed from the GRACE solutions. GRACE is unable alone to separate the equivalent water height change from the solid Earth's response. In the recent years several studies have provided geoid rate maps due to GIA (e.g., Peltier, 2001; Peltier, 2004; Ivins and James, 2005; Tamisiea et al., in press). Over the ice sheets (where GIA effects are most important), there is no consensus, however, on the level of contamination caused by different sources of model uncertainty. Among these, the ice load model (which represents

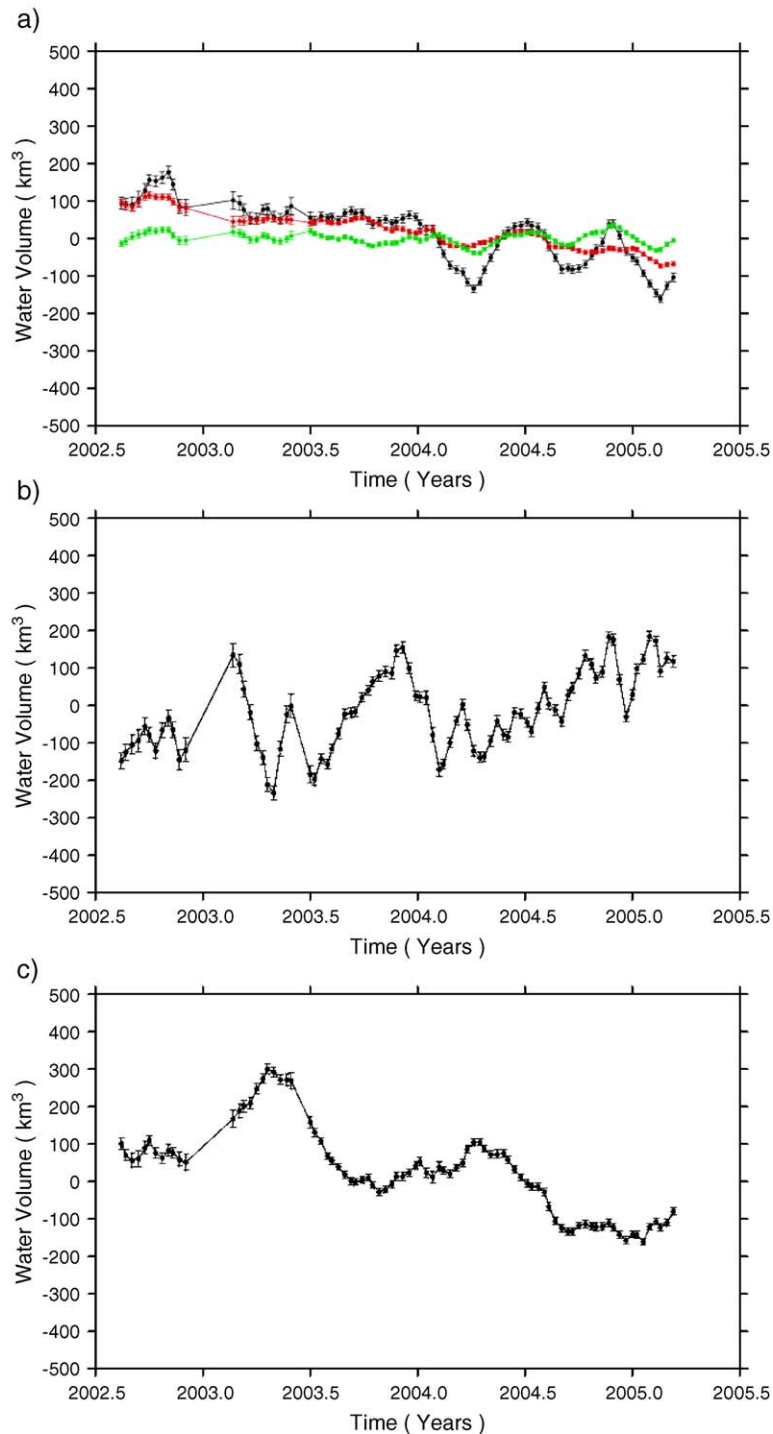


Fig. 4. Time-series of the regional variations of the water volume estimated from GRACE for (a) West Antarctica (red: Admundsen sea sector; green: Peninsula; black: total West Antarctic region, according to the mask shown in Fig. 3); (b) East Antarctica; (c) Greenland.

the deglaciation history) and the mantle viscosity structure are the two main sources of uncertainty. Over the Greenland ice sheet, [Peltier \(2001\)](#) – using the ICE-

4G ice load model – and [Tamisiea et al. \(in press\)](#) report positive geoid rates. Revised geoid rates have been recently proposed by [Peltier \(2004\)](#) with the new ICE-

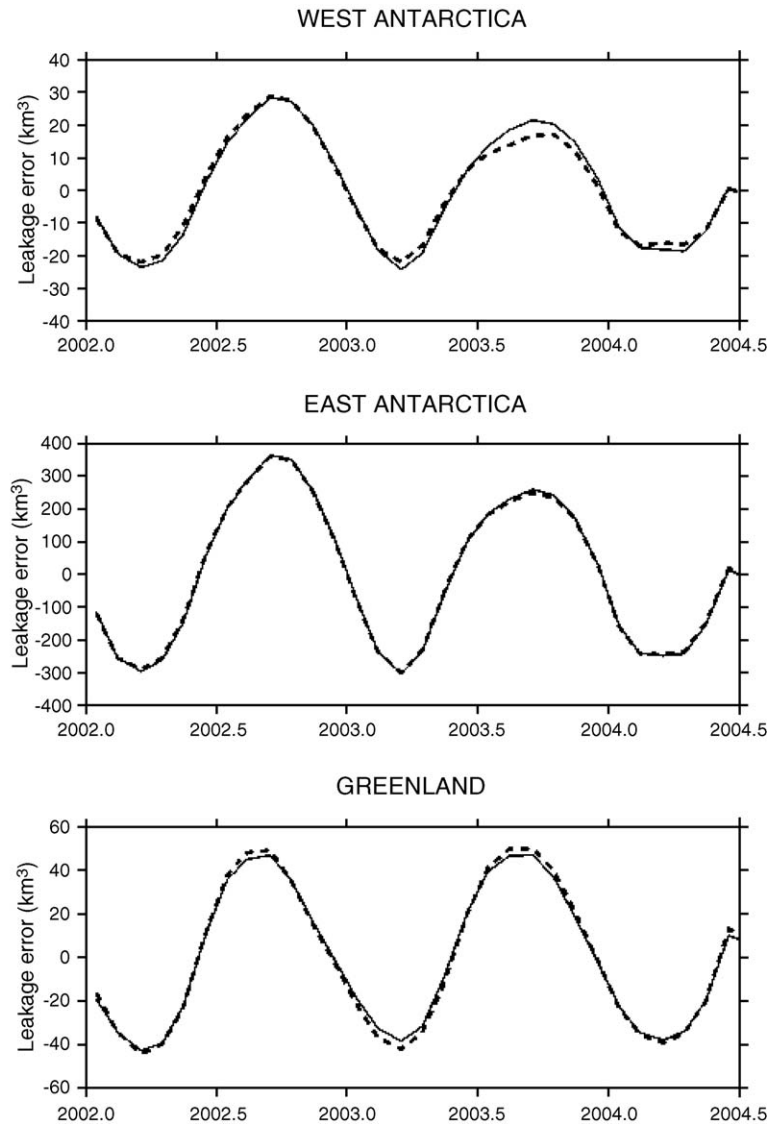


Fig. 5. Time series of land hydrology leakage estimated from the WGHM global land model for 2002 to mid-2004.

5G ice model, giving essentially negative geoid rates over Greenland. For example, [Velicogna and Wahr \(2005\)](#), using the ICE-5G model, estimate to  $-5 \pm 19$  cu km/yr (expressed in equivalent water volume) the mean GIA effect over Greenland. On the other hand, the ICE-4G and ICE-5G models give positive geoid rates over West Antarctica and most East Antarctica (with slightly negative geoid rates in some coastal regions). The GIA-induced geoid rates predicted by [Tamisiea et al. \(in press\)](#) are positive over the whole Antarctic continent. To correct for GIA, we use the ICE-4G ice load model for Greenland and the – IJ05 – model from [Ivins and James \(2005\)](#) for Antarctica. The IJ05 model considers four different scenarios of combined

deglaciation and mantle viscosity. Here we use mean geoid rates deduced from averaging values of two scenarios with factors 10 and 100 viscosity increase at the upper/lower mantle interface, and no melt water pulse since 21 kyr BP. [Fig. 6](#) shows the distribution of corresponding geoid rates over the two ice sheets (based on ICE-4G for Greenland and IJ05 – average mantle – for Antarctica). The geographically averaged GIA corrections, expressed in equivalent water volume, amount to 20 cu km/yr and 15 cu km/yr for West and East Antarctica (according to the mask shown in [Fig. 3](#)) and 9 cu km/yr for Greenland. Although we correct for these GIA values, we assign to the water volume trends estimated from the GRACE geoids a new uncertainty



Table 1

Water volume change (in cu km/yr) from GRACE over the ice sheets and corresponding contributions to the mean sea level (in mm/yr) for the period July 2002–March 2005

Units (cu km/yr)	Greenland	East Antarctica	West Antarctica	Total
GRACE rate	$-119 \pm 10$	$+72 \pm 20$	$-88 \pm 10$	
Hydrology leakage	+1	-10	-1	
GIA correction	+9	+15	+20	
Corrected GRACE rate	$-129 \pm 15$	$+67 \pm 28$	$-107 \pm 23$	$-169 \pm 39$
Corresponding sea level change (mm/yr)	$+0.36 \pm 0.04$	$-0.19 \pm 0.07$	$+0.30 \pm 0.06$	$+0.47 \pm 0.10$

that accounts for the formal geoid error plus a GIA correction error of the same order of the correction itself. This is done by quadratically combining the errors.

#### 4.3. Contribution to sea level change

From the above GRACE-based volume changes (leakage plus GIA corrected), we estimate the ice sheet contribution to sea level. We obtain values of  $+0.30 \pm 0.06$  mm/yr,  $-0.19 \pm 0.07$  mm/yr and  $+0.36 \pm 0.04$  mm/yr for West Antarctica, East Antarctica and Greenland, respectively.

Table 1 summarizes the above water volume change with associated uncertainties and corresponding contributions to sea level for the different studied regions.

## 5. Discussion

Recently, Velicogna and Wahr (2005) used monthly geoids released by the GRACE project between April/May 2002 and July 2004 to estimate the mass balance of the Greenland ice sheet. They find that during this time interval, Greenland lost mass, by an amount of  $87 \pm 23$  cu km/yr (equivalent water volume), or of  $82 \pm 28$  cu km/yr after correcting for GIA (using the ICE-5G ice load model). In terms of sea level rise, this corresponds to  $0.23 \pm 0.06$  mm/yr. Some difference is noticed with our results, but in view of the difference between the geoid solutions and the periods of analysis, this is not surprising, considering the possible interannual variability of the Greenland mass balance. In another study (Velicogna and Wahr, 2006), they also estimate the mass balance of the Antarctica ice sheet using GRACE geoid solutions over the period April 2002 to August 2005. They find that over this period the mass of the Antarctica ice sheet decreased significantly, by  $152 \pm 80$  ice cu km/yr, contributing to  $+0.4$  mm/yr sea level rise. This is significantly more than the values reported in the present study, which translated in terms of sea level change correspond to  $+0.14 \pm 0.09$  mm/yr for the sum of the West and East Antarctica contributions. The reason for this difference is unclear but seems to arise from the GIA correction. Further investigation is needed to clarify this difference. It is encouraging that

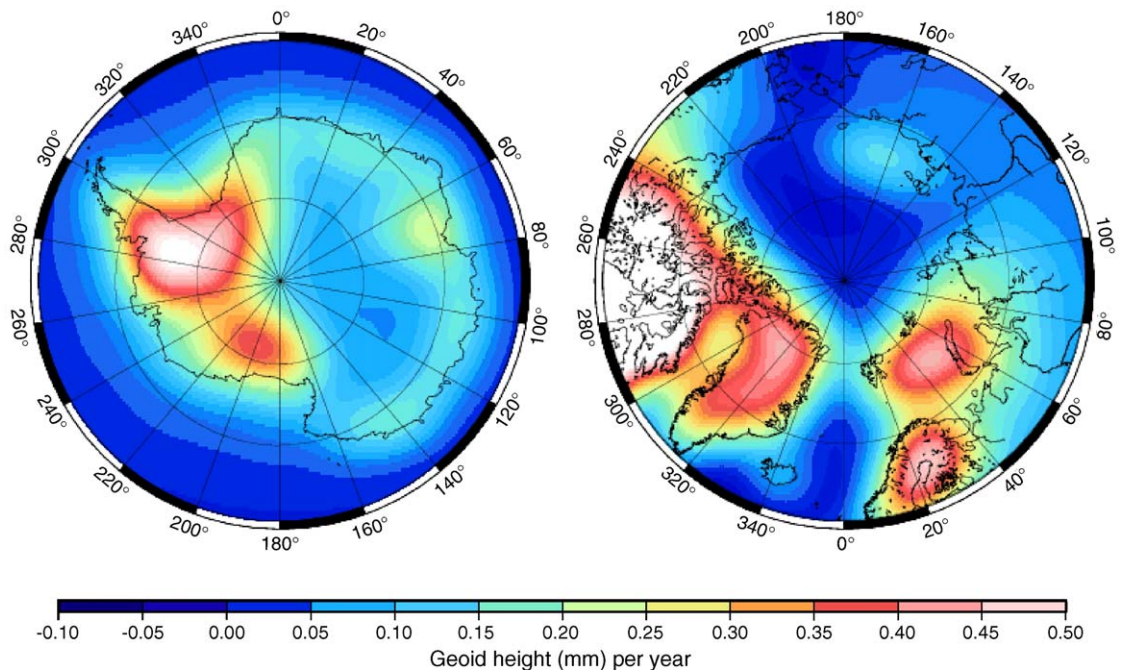


Fig. 6. Maps of GIA-induced geoid rates over Greenland (using the ICE-4G ice load model) and Antarctica (using the IJ05-average mantle — ice load model). Units are in mm/yr geoid rates.

these results are, none-the-less, compatible in sign, since a different time span and barotropic ocean model are assumed in this analysis.

The recent study by [Rignot and Kanagaratnam \(2006\)](#) provides Greenland mass loss of  $91 \pm 32$  ice cu km/yr,  $138 \pm 31$  ice cu km/yr and  $224 \pm 41$  ice cu km/yr in 1996, 2000 and 2005 respectively (or  $82 \pm 29$  cu km/yr,  $124 \pm 28$  cu km/yr and  $202 \pm 37$  cu km/yr water volume change), with associated sea level rise contributions of  $0.23 \pm 0.08$  mm/yr,  $0.35 \pm 0.08$  mm/yr and  $0.57 \pm 0.1$  mm/yr. Our mean Greenland volume trend (expressed in equivalent water volume and GIA corrected) of  $-129 \pm 15$  cu km/yr (associated sea level rise of  $0.36 \pm 0.04$  mm/yr), over the July 2002–March 2005 time span, agrees well with the above results.

Recently, [Davis et al. \(2005\)](#) have analysed satellite radar altimetry measurements over 1992–2003 and find ice mass increase over East Antarctica, of  $45 \pm 7$  cu km/yr of water, equivalent to a sea level decrease of  $-0.12 \pm 0.02$  mm/yr. Besides, their map of elevation change over in the Amundsen sea sector (West Antarctica) shows significant surface elevation decrease. [Zwally et al. \(2005\)](#)'s estimate of East Antarctica mass increase ( $14.5 \pm 10$  cu km/yr water volume change), is less than that of [Davis et al. \(2005\)](#) but it agrees with a slight mass gain in the East.

Qualitatively, the results reported here using the GRGS-EIGEN-GL04 geoid solutions compare well with these independent measurements. In particular there is some striking agreement between the regional distribution of the ice mass loss/gain reported by [Davis et al. \(2005\)](#) over West/East Antarctica and that of [Fig. 1](#) of the present study. Even though the numerical values presented here are still uncertain because of geoid solutions errors, the GIA correction, as well as the very short time span of analysis, results are in general agreement with several recent observations that suggest that the East Antarctica ice sheets is slightly gaining mass while the West Antarctica region is losing mass, with the whole continent being not far from balance (see for example [Remy and Frezzotti, in press](#), for a review). This is what the GRACE observations indeed suggest, with a slightly positive net contribution to sea level from Antarctica, amounting  $0.11 \pm 0.09$  mm/yr. For Greenland, the results of the present study suggest that this ice sheet is currently losing mass and contributes to  $0.36 \pm 0.04$  mm/yr sea level rise. The total ice sheet contribution to sea level based on this study is on the order of  $\sim 0.5$  mm/yr between July 2002 and March 2005. It is worth mentioning that such an amount would explain about 70% of the 0.7 mm/yr sea level rate residual (observed sea level rise corrected for thermal

expansion and mountain glaciers contributions). If this sourcing is correct, an important upper bound could be placed on the highly contentious anthropogenic component at  $\sim 0.2$  mm/yr.

The GRACE data time series is still very short and these results must be considered as preliminary since we cannot exclude that the apparent trends discussed in this study only reflect interannual fluctuations. In the future, effects of residual atmospheric errors on regional estimates of ice mass variations should be investigated. Increasing the length of the GRACE data time series will allow us to provide better constraints on the ice sheet mass balance.

## References

- Biancale R., Lemoine, J.-M., Balmino, G., Loyer, S., Bruisma, S., Perosanz, F., Marty J.-C., 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.
- Box, J.E., Bromwich, D.H., Bai, L.-S., 2004. Greenland ice sheet surface mass balance 1991–2000: application of polar MM5 mesoscale model and in situ data. *J. Geophys. Res.* 109, D16105. doi:10.1029/2003JD004451.
- Carrere, 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), 8.1–8.4.
- Cazenave, A., Nerem, R.S., 2004. Present-day sea level change: observations and causes. *Rev. Geophys.* 42, RG3001. doi:10.1029/2003RG000139.
- Chambers, D.P., Wahr, J., Nerem, R.S., 2004. Preliminary observations of global ocean mass variations with GRACE. *Geophys. Res. Lett.* 31, L13310. doi:10.1029/2004GL020461.
- Chao, B.F., 2005. On inversion for mass distribution from global (time-variable) gravity field. *J. Geodyn.* 39, 223–230. doi:10.1016/j.jog.2004.11.001.
- Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nuan, M.T., Qin, D., Woodworth, P.L., 2001. Changes in sea level. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 881 pp.
- Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X., 2004. Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. *J. Climate* 17 (13), 2609–2625.
- Davis, et al., 2005. Snowfall-driven growth in East Antarctica ice sheet mitigates recent sea level rise. *Science* 308, 1898–1907.
- Dietrich, R., Rulke, A., Scheinert, M., 2005. Present-day vertical crustal deformations in west Greenland from repeated GPS observations. *Geophys. J. Int.* 163, 865–874.
- Döll, P., Kaspar, F., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.* 270, 105–134.
- Dyurgerov, M., Meier, M.F., 2005. *Glaciers and Changing Earth System: A 2004 Snapshot*. INSTAAR, Boulder.
- Ishii, M., Kimoto, M., Sakamoto, K., Iwasaki, S.I., 2006. Steric sea level changes estimated from historical ocean subsurface temperature and salinity analyses. *J. Oceanogr.* 62, 155–170.

- Ivins, E.R., James, T.S., 2005. Antarctic glacial isostatic adjustment: a new assessment. *Antarct. Sci.* 17 (4), 541–553.
- Johannessen, O.M., Khvorostovsky, K., Miles, M.W., Bobylev, L.P., 2005. Recent ice sheet growth in the interior of Greenland. *Science* 310, 1013–1016.
- Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., Yungel, J., 2000. Greenland ice sheet: high-elevation balance and peripheral thinning. *Science* 289, 428–430.
- Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Yungel, J., 2005. Greenland ice sheet: increased coastal thinning. *Geophys. Res. Lett.* 31, L24402. doi:10.1029/2004GL021533.
- Leuliette, E.W., Nerem, R.S., Mitchum, G.T., 2004. Calibration of TOPEX/Poseidon and Jason Altimeter data to construct a continuous record of mean sea level change. *Mar. Geod.* 27 (1–2), 79–94.
- Levitus, S., Antonov, J.I., Boyer, T.P., 2005. Warming of the world ocean, 1955–2003. *Geophys. Res. Lett.* 32, L02604. doi:10.1029/2004GL021592.
- Llubes, M., Lemoine J.M., Remy F., (submitted for publication). Antarctica seasonal mass variations detected by GRACE. *Earth Planet. Sci. Lett.*
- Lombard, A., Cazenave, A., Guinehut, S., Le Traon, P.-Y., Cabanes, C., (in press). Perspectives on present-day sea level change. *Ocean Dyn.* doi:10.1007/S10236-005-0046-X.
- Peltier, W.R., 2001. Global Glacial Isostatic Adjustment and Modern Instrumental Records of Relative Sea Level History. In: Douglas, B.C., Kearney, M.S., Leatherman, S.P. (Eds.), *Sea Level Rise: History and Consequences*, vol. 75. Academic Press, San Diego, pp. 65–95.
- Peltier, W.R., 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.
- Ramillien, G., Cazenave, A., Brunau, O., 2004. Global time-variations of hydrological signals from GRACE satellite gravimetry. *Geophys. J. Int.* 158, 813–826.
- Ramillien, G., Frappart, F., Cazenave, A., Güntner, A., 2005. Time variations of the land water storage from an inversion of 2 years of GRACE geoids. *Earth Planet. Sci. Lett.* 235, 283–301.
- Remy, F., Frezzotti, M., (in press). Antarctica ice sheet mass balance. *Geosciences Comptes rendus*.
- Rignot, E., Kanagaratnam, P., 2006. Changes in the velocity structure of the Greenland ice sheet. *Science* 311, 986–990.
- Rignot, E., Thomas, R., 2002. Mass balance of polar ice sheets. *Science* 297, 1502–1506.
- Schmidt, R., Flechtner, F., Reigber, Ch., Schwintzer, P., Günter, A., Doll, P., Ramillien, G., Cazenave, A., Petrovic, S., Jochman, H., Wunsch, J., 2006. GRACE observations of changes in continental water storage. *Glob. Planet. Change* 50/1–2, 112–126. doi:10.1016/j.gloplacha.2004.11.018.
- Tamisiea, M. E., Mitrovica, J. X., Nerem, R. S., Leuliette, E. W., Milne, G. A., (in press). Correcting satellite-derived estimates of global mean sea level change for glacial isostatic adjustment. *Geophys. J. Int.*
- Tapley, B.D., 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.D., Bettadpur, S., Ries, J.C., Thompson, P.F., Watkins, M., 2004b. GRACE measurements of mass variability in the Earth system. *Science* 305, 503–505.
- Thomas, R.H., 2004. Greenland : recent mass balance observations, in mass balance of the cryosphere. In: Bamber, J.L., Payne, A.J. (Eds.), *Observations and Modelling of Contemporary and Future Changes*. Cambridge University Press, Cambridge.
- Thomas, R., Rignot, E., Casassa, G., Kanagaratnam, P., Acuna, C., Akins, T., Brecher, H., Frederick, E., Gogineni, P., Krabill, W., Manizade, S., Ramamoorthy, H., Rivera, A., Russell, R., Sonntag, J., Swift, R., Yungel, J., Zwally, J., 2004. Accelerated sea level rise from West Antarctica. *Science* 306, 255–258.
- Velicogna, I., Wahr, J., 2005. Greenland mass balance from GRACE. *Geophys. Res. Lett.* 32, L18505. doi:10.1029/2005GL023955.
- Velicogna, I., Wahr, J., 2006. Measurements of time-variable gravity show mass loss in Antarctica. *Science Express*. doi:10.1126/science.1123785 (2 March).
- Wahr, J., Molenaar, M., Bryan, F., 1998. Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res.* 103 (B12), 30205–30229.
- Wahr, J., Swenson, S., Zlotnicki, V., Velicogna, I., 2004. Time-variable gravity from GRACE: first results. *Geophys. Res. Lett.* 31, L11501. doi:10.1029/2004GL019779.
- Wahr, J., Swenson, S., Velicogna, I., 2006. Accuracy of GRACE mass estimates. *Geophys. Res. Lett.* 33, L06401. doi:10.1029/2005GL025305.
- Willis, J.K., Roemmich, D., Comuelle, B., 2004. Interannual variability in upper-ocean heat content, temperature and thermosteric expansion on global scales. *J. Geophys. Res.* 109 (C12036). doi:10.1029/2003JC002260.
- Zwally, H.J., Giovinetto, M.B., Li, J., Cornejo, H.G., Beckley, M.A., Brenner, A.C., Saba, J.L., Yi, D., 2005. Mass changes of the Greenland and Antarctica ice sheets and shelves and contributions to sea level rise: 1992–2002. *J. Glaciol.* 51, 509–524.