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Mass balance and mass loss acceleration of the Greenland ice sheet (2002 – 2011) from GRACE gravity data

Research article

G. Joodaki*, H. Nahavandchi

Norwegian University of Science and Technology, Division of Geomatics, N-7491 Trondheim, Norway

Abstract:

We examine the magnitude and acceleration of the Greenland ice sheet mass loss between 2002 and 2011. We use monthly observations of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission. The Greenland mass loss during this time period is not a constant, but accelerating with time. We have used a quadratic trend in addition to a linear trend, which is usually applied to the GRACE monthly time series of ice mass changes, to show that it better represents GRACE observations. Results of computations provide a mass decrease of -166±20 Gigatonne per year (Gt/yr) by using a linear trend and -111±21 Gt/yr by fitting a quadratic trend to the monthly time series. Quadratic fitting shows that the mass loss increases from -121 Gt/yr in 2002 – 2003 to -210 Gt/yr in 2006 – 2007 and -271 Gt/yr in 2010 – 2011 with an acceleration of -32±6 Gt/yr^2 in 2002 – 2011. This implies that the Greenland ice sheet contribution to sea level rise becomes larger with time. Contrary to recent studies, we use a non-isotropic filter whose degree of smoothing corresponds to a Gaussian filter with a radius of 340 km. Stripping effects in the GRACE data, C_{20} effect, and leakage effects are applied.

Keywords:

Greenland • GRACE gravity satellites • Mass loss • Acceleration • non-isotropic filter

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1. Introduction

Earth's gravity field has been explored from the GRACE satellite gravity mission. GRACE is a satellite mission jointly implemented by the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR) (Tapley et al. 2004a). In addition to the mapping of the Earth's static gravity field, GRACE also provides temporal variations of Earth's gravity field. GRACE can resolve temporal variations in gravity at length scales of a few hundred kilometers and with a period of around one month. Changes in the gravity field caused by the redistribution of mass within the Earth and on or above the Earth's surface can be detected by GRACE and its global coverage enables us to map the gravity field over large areas, like Greenland (see e.g. Wahr et al. 1998). Several research groups have focused their studies to use GRACE data for estimating Greenland rate of ice mass variability, such as Luthcke et al. (2006) that used raw GRACE KBRR (K-Band Range and Range rate) data; Chen et al. (2006) used the CSR monthly solutions Release 01 (RL01) during 2002 – 2005; Ramillien et al. (2006) used the same period as Chen et al. (2006) but with the GRGS/CNES GRACE solutions; Velicogna and Wahr (2006a) used the CSR monthly solutions RL01 during 2002 to 2006; Wouters et al. (2008) used the CSR RL04 monthly solutions from 2003 to 2008; Baur et al. (2009) used monthly GRACE solutions RL04 provided by GRACE processing centers of CSR, GFZ (German Research Center for Geosciences) and JPL (Jet Propulsion Laboratories) for the period 2002 to 2008, and Velicogna (2009) used the CSR RL04 monthly solutions between 2002 and 2009. Note that all of the results reported above are based on isotropic filters. Joodaki and Nahavandchi (2012) ap-

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*E-mail: gholamreza.joodaki@ntnu.no; Tel.: +47-7359-4715; Fax: 47-7359-7021 plied a non-isotropic filter to CSR, GFZ and JPL monthly solutions RL04.

Velicogna (2009) estimated an increase in mass loss from Greenland ice sheet, i.e. it was shown that mass loss is accelerating. However, filtering procedure and removal of periodic variations are different from our study. The observation period is also different. Decorrelating kernels in the filtering approach used in this study are not axisymmetric (isotropic) and they tend to exhibit negative sidelobes in north-south direction with a shape depending on the geographical positions. The GRACE noise also manifests itself as near north-south "stripes" and it has a non-isotropic nature.

Other satellite based sensors are also used to study Greenland ice mass variability. Some examples are Abdalati et al. (2001), Rignot et al. (2004), Rignot and Kanagaratnam (2006) and Joughin et al. (2010) that used Synthetic Aperture Radar (SAR) imaging to reveal an acceleration of a large number of outlet glaciers in Greenland, Slobbe et al. (2008), Howat et al. (2008), Pritchard et al. (2009) and Sørensen et al. (2011) that used laser altimetry and Sørensen et al. (2010) that used satellite laser, radar and gravity measurements to study the Greenland ice mass variability.

In this paper, we present an analysis of trend in Greenland ice mass variability and its rate of change based on monthly GRACE solutions provided by CSR during April 2002 to April 2011. The CSR RL05 Level-2 data products have been recently available for the data span January 2004 through December 2010 which did not cover the study period therefore the latest release RL04 (at the time of this study) is used with improved geophysical signal models and data processing techniques. This release has smallest error among other releases (Bettadpur 2007). Unlike other studies, a filtering technique based on non-isotropic filter is applied (see also Joodaki and Nahavandchi 2012). We examine different ways of fitting a regression through the monthly time series of ice mass change data. Regression of linear and quadratic forms are compared and concluded on the best statistical representation of the ice mass data.

1.1. Data and Methodology

The GRACE twin satellites launched in March 2002 measures Earth gravity changes with unprecedented accuracy. GRACE tracks the changes in the distance between its twin satellites and combines these measurements with data from on-board Global Positioning System (GPS) receivers and accelerometers. Monthly GRACE gravity field solutions are then determined from these data. Solutions consist of monthly spherical harmonic coefficients of the Earth's gravity field. Each monthly field consists of fully normalized (Stokes) coefficients, C_{lm} and S_{lm}, up to degree and order (l, m). We use monthly GRACE gravity coefficients up to degree and order 60 generated at the CSR at the University of Texas (Tapley et al. 2004b). This study is based on 105 monthly models between April 2002 and April 2011. Wahr et al. (1998) introduces a method to estimate monthly local changes in surface mass, using the static monthly spherical harmonic coefficients. The mass changes in this method (ibid) are assumed in a very thin layer of water concentrated at the surface with a variable thickness. This assumption is not far from reality as changes in water storage in hydrologic reservoirs, by moving ocean, atmospheric and cryospheric masses, and by exchange among these reservoirs causes monthly changes in gravity signals (Chambers 2007). The vertical extent of the water is much smaller than the horizontal scales of the changes. It is called equivalent water thickness. Mass variations are modeled as surface density variations $\Delta\sigma$(the unit of $\Delta\sigma$ is mass/surface area) in a spherical layer. One then can estimate monthly local changes in surface mass density using monthly spherical harmonic coefficients of the Earth's gravity field (Wahr et al. 1998):

$$\Delta\sigma\left(\phi,\lambda\right) = \frac{a\rho_{\mathrm{ave}}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\bar{P}_{lm}\left(\sin\phi\right)\left[\Delta C_{lm}\cos m\lambda+\Delta S_{lm}\sin m\lambda\right] \tag{1}$$

where ϕ and λ are the spherical latitude and longitude of the point of interest, a is the radius of the Earth (a = 6377 km in this study), ρ_{ave} is the average mass-density of the solid Earth (assumed throughout this paper to be 5517 kg/m^3), k_l is the Love number of degree l which is given in Wahr et al. (1998), $\bar{P}_{lm}$ is the normalized associated Legendre function of the first kind, and ΔC_{lm} and ΔS_{lm} are time-variable components of the GRACE observed Stokes coefficients for some month of degree and order (l, m) or as changes relative to the mean of the monthly solutions. It should be stated here that $\Delta\sigma/\rho_{\mathrm{w}}$ transforms surface mass-densities to equivalent water thickness values, where ρ_{w} is the mass-density of freshwater. There are several correction terms and contaminating factors which must be applied before the ice mass loss estimates can be interpreted.

Due to the orbital geometry of GRACE, and nature of the measurement technique, the monthly Stokes coefficients are contaminated with short-wavelength noise. The noise is significant when one is interested in signals of geographical extension of a few hundreds km and/or using the higher degree coefficients. The GRACE noise structure mainly manifests itself as near north-south "stripes" and it has a non-isotropic nature. Convolving against an isotropic Gaussian smoothing kernel, and recently probabilistic decorrelation methods in GRACE solutions in conjunction with an additional smoothing are among the methods used to identify and remove error correlation (noises) in the GRACE monthly spherical harmonic coefficients. The latter methods result in decorrelation kernels that are not isotropic. We used Kusche et al. (2009) non-isotropic decorrelation and smoothing technique to de-stripe monthly GRACE RL04 gravity models. The non-isotropic filter was also used by Joodaki and Nahavandchi (2012).

Due to the GRACE orbit geometry and the separation length between its twin satellites, the monthly GRACE C_{20} coefficients cannot be well determined (Tapley et al. 2004b). The GRACE C_{20} estimates also are well-known to be affected by significant long-period tidal aliases. An alternative which improves the estimation of mass variations from GRACE is to replace the monthly GRACE C_{20} coefficient by their estimates from Satellite Laser Ranging (SLR) (Chen et al. 2005). The SLR time series are also more precise, with about a third of the noise of the GRACE time series. In this study, we replace GRACE C_{20} coefficient with monthly SLR estimates which are obtained from the analysis of SLR data to five geodetic satellites: LAGEOS-1 and 2, Starlette, Stella and Ajisai. These estimates are provided from the CSR GRACE Science Data System (TN05) (Cheng and Tapley, 2004).

Leakages from other geophysical signals besides the ice mass loss are an error source which should be accounted for a reliable estimate of secular mass changes over Greenland. Leakages are divided into leakage in and leakage out effects. On the one hand, mass change at a place outside Greenland propagates into a signal spreading over Greenland and has an impact on the Greenland mass-change estimates. On the other hand, mass change over Greenland propagates into a signal spreading over outside the Greenland area. The leakage out signal has to be restored back into the region of interest. The leakage in signal has to be reduced from the region of interest. We used the model as described by Joodaki and Nahavandchi (2012) to estimate the leakage effects. In this model, only GRACE data is used to delineate the leakage effects. The model calculates spherical harmonic coefficients, associated with leakage effects, from the surface mass densities on the areas concerned. The GRACE data alone is used to calculate the surface mass densities. The sources generating leakage in signals could be from all over the world, however the impact reduces with increasing distances following the Newton's law of gravitation. The strongest signals on Greenland are caused by Alaska, Fennoscandia and the Canadian Shield. These three sources are used in this study to determine the leakage effects which were also used in Baur et al. (2009) investigations.

The degree-0 Stokes coefficient in Equation (1) is assumed constant and is not used in this investigation. It is proportional to the total mass of the Earth and atmosphere. The geocenter motion represented by variations in the degree-1 Stokes coefficients cannot be derived from the GRACE data. We have not applied these variations in our monthly models, but it is recognized that neglecting the geocenter motion might introduce an error in the rate of Greenland ice mass variability (Chambers et al. 2004 and Chen et al. 2005).

We have not applied, in our estimation of ice mass change rates, contaminating factors caused by the effects of variations in atmospheric mass, and the solid Earth contribution from high-latitude Post Glacial Rebound (PGR). The atmospheric effects are negligible for Greenland on the long term trend (Velicogna and Wahr 2006a, b). We also chose not to apply the correction for the PGR signal, considering the total uncertainty in the PGR estimations (Velicogna and Wahr 2006a, b). It is left to others to choose their preferred PGR model. Nevertheless, it should be noted that the PGR signal for the entire Greenland is estimated to -7.4 Gigaton per year (Gt/yr) with a standard deviation of ±19 Gt/yr (Velicogna and Wahr 2006b) and this value or other preferred PGR model can easily be applied to the ice-mass estimates by readers. When comparing to the ice-mass estimates, the PGR signal is more than one order of magnitude smaller.

2. Numerical investigations

We obtain the time series for Greenland ice mass change and the secular trend in ice mass rate, calculated from GRACE level 2 RL04 monthly solutions generated at CSR processing centers from April 2002 to April 2011. The maximum degree of the expansion for the CSR spherical harmonic coefficients is 60. This spatial resolution may not be enough fine to isolate the source of the ice mass variability but it is the maximum resolution available by CSR model and enough to show the Greenland ice sheet mass loss. Unphysical striping error pattern (noises) in monthly solutions of the GRACE is decorrelated/filtered in the corresponding Gaussian radius of 340 km (see Kusche et al. 2009, Joodaki and Nahavandchi 2012). We calculated potential leakage effects and applied them in monthly total mass change estimations. The average leakage in and leakage out effects for CSR monthly gravity solutions and smoothing degree of corresponding Gaussian radius of 340 km is estimated to 7.7 Gt and 17 Gt, respectively. Finally, GRACE C_{20} coefficients were replaced by the monthly SLR estimates for C_{20} to complete the data correction step.

The time-mean of the GRACE Stokes coefficients from April 2002 to April 2011 is calculated and the monthly gravity field residuals ΔC_{lm} and ΔS_{lm} are determined by removing the time-mean average of the coefficients from monthly Stokes spherical harmonics. The gravity field residuals obtained by the GRACE are then converted into surface mass variations using Equation 1. This process is performed on a $1^\circ \times 1^\circ$ grid, where we estimate monthly mass variability over Greenland (see Chen et al. 2006; Joodaki and Nahavandchi 2012). Then we form an estimate of total mass change for each month by summing over grid elements with cosine latitude weighting. Figure 1 shows the time series for Greenland ice mass changes.

As it can be seen from Figure 1, the ice mass change shows seasonal changes superimposed on long-period variability. The objective of this study is to estimate the long term trend in Greenland ice mass variability; therefore, we examine a process to remove from time series of ice mass changes, the periodic variations. This is to reduce as much as possible the contamination of the long term trend by periodic variations. To detect the secular trend and periodic variations in the monthly mass anomalies, a general expression of the following form is used:

$$f(\phi, \lambda, \ t) = A + Bt + \sum_i C_i \cos(\omega_i t) + D_i \sin(\omega_i t) + \varepsilon \quad (2)$$

where f is the value of the ice mass anomaly at a selected location $(\varphi, \ \lambda)$ and time t, that is approximated by a static value A, and its secular (B) and periodic (with amplitude C_i and D_i of typical angular frequencies ωi) variations. The variable ε characterizes noise and un-modeled effects. In our estimation of the secular trend, we simultaneously fit periodic and secular terms to the time series of ice mass changes. A bias term, trend and four annual and semi-annual terms as well as seasonal variations are considered. The periodic variations terms of the ice mass change have then been removed so that the long term variations would be more evident. As it is obvious from Equation 2, we fit a linear trend, as done in most prior studies. The average value of -166±20 Gt/yr between 2002 and 2011 is obtained for the Greenland ice sheet. This corresponds to a 0.46±0.06 mm/yr sea level rise. The uncertainty in our estimate is calculated by taking the root sum squares of the errors in the least squares adjustment of the mathematical model which is used to detect the secular trend and periodic variations in time series of ice mass changes, the leakage effects and the gravity field error. In estimation of these errors, the PGR effects are not applied.

One objective of this study was to consider higher order regression models instead of a linear trend. This is to investigate whether a curved line will better fit to the GRACE time series of ice mass loss of Greenland than a linear regression. We therefore fit a quadratic trend to the time series of ice mass changes. The computation process is the same as for the linear trend. In Equation 2, we replace the linear trend term by a quadratic form. The least squares estimate for the acceleration in Greenland ice sheet mass loss is -32±6 Gt/yr^2 in 2002 – 2011. This corresponds to 0.09±0.02 mm/yr^2 of sea level rise from Greenland ice mass loss acceleration. For the period 2002-2011, we obtain a trend of -111±21 Gt/yr for Greenland ice sheet using a quadratic form. The uncertainties in the quadratic regression are calculated the same as in the linear trend model.

To investigate which of the two linear or quadratic models best fits the time series of ice mass changes, we used a goodness of fit statistic. Statistically speaking, it is more appropriate to compare two fit results rather than testing whether a particular fit result is good. There are statistics that can be used to compare the fit results to a dataset. R-square (R^2) and adjusted R-square (R^2_{Adj}) are two of the statistics. These are indicators of how successful the fit is in explaining the variation of the data. R^2 can be calculated from $R^2 = 1 - SSE/SST$ where SSE is summed square of residuals and SST is the sum, over all observations, of the squared difference of each observation from the mean. R-square can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model. For example, an R-square value of 0 indicates that the proposed model does not improve prediction over the mean and a value of 0.90 means that the fit explains 90% of the total variation in the data about the mean. There are situations that the number of model parameters is increased, and then R-square will increase although the fit is not improved in practice. To avoid these situations we use degree of freedom adjusted R-square. Adjusted R^2 (R^2_{Adj}) is used to compensate for the addition of parameters to the model. We use R^2_{Adj} to determine which of the two models best fits the data. Unlike R-square, the R^2_{Adj} increases only if the new term improves the model more than would be expected by chance. R^2_{Adj} is defined as $R^2_{Adj} = 1 - \left[\left(1 - R^2\right)(N-1)/(N-M-1)\right]$, where N is the number of observations and M is the number of unknowns in the model. R^2_{Adj} can take any value less than or equal to 1, with a value closer to 1 indicating a better fit.

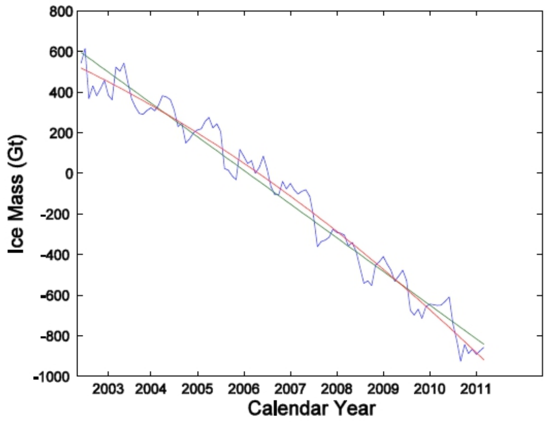

Figure 1. GRACE estimation of time series of Greenland ice mass changes in Gigatone for the period from April 2002 to April 2011(blue line). The best fitting linear trend is shown as green line, and the best fitting quadratic trend is depicted as red line.

For Greenland we find that R^2_{Adj} is larger when quadratic form is used. This means that the time series of ice mass changes are better modeled by an increasing rate of ice mass loss, i.e. including acceleration term, than with a constant ice mass loss. R^2_{Adj} is calculated to 0.975 for quadratic trend. This value is 3% larger than for the linear trend.

3. Discussions and conclusions

The GRACE twin satellites have been providing comprehensive survey of the Earth's gravity field over more than 10 years. It offers an excellent tool to study the entire Greenland ice sheet. The monthly GRACE gravity field solutions allow regional estimation of Greenland ice mass balance free from the issue of incomplete sampling and other limitations that are present in competing techniques. Furthermore, to obtain the mass variability, the process is less ambiguous using GRACE data as the relationship between gravity and mass variability follows directly from Newton's law.

Our monthly GRACE model of time variable gravity measurements for 105 months during the period April 2002 – April 2011 shows an acceleration of the Greenland ice sheet mass loss. Several other studies also pointed out that the Greenland ice sheet mass loses is accelerating. However, the ice mass estimates and acceleration are not all in agreement and differ significantly (see Table 1).

Joodaki and Nahavandchi (2012) obtained an ice mass decrease of -163 ±20 Gt/yr. Baur et al. (2009a) estimated an average value of -162±11 Gt/yr, Velicogna (2009) estimated a decrease of the Greenland ice mass of -230±33 Gt/yr, another estimate by the same

Table 1. Ice mass change and mass loss acceleration of the Greenland ice sheet using different GRACE data time span and methods. Where applicable, the ice mass change unit is converted from km^3/yr to Gt/yr, by multiplying an ice density of 917 kg/m^3.

Authors	Time span	Ice Mass change	Mass loss acceleration
Ramillien et al. (2006)	2002-2005	-109±9 Gt/yr	–
Chen et al. (2006)	2002-2005	-219 ± 21 Gt/yr	–
Lutchke et al. (2006)	2003-2005	-101 ± 16 Gt/yr	–
Velicogna and Wahr (2006)	2002-2006	-227±33 Gt/yr	–
Wouters et al. (2008)	2003-2008	-179±25 Gt/yr	–
Baur et al. (2009)	2002-2008	-162±11 Gt/yr	–
Velicogna (2009)	2002-2009	-230±33 Gt/yr	-30 ± 11 Gt/yr^2
Joodaki and Nahavandchi (2012)	2002-2010	– 163 ±20 Gt/yr	–
Current study	2002-2011	-166±20 Gt/yr	-32±6 Gt/yr^2

author amounts to -227±33 Gt/yr (Velicogna and Wahr, 2006a), Wouters et al. (2008) estimated a value of -179±25 Gt/yr, Luthcke et al. (2006 estimate was -101±16 Gt/yr, Chen et al. (2006) computed a decrease of ice mass of -219±21 Gt/yr for the Greenland, Ramillien et al. (2006) estimated a value of -109±9 Gt/yr mass loss for the Greenland ice sheet. The large differences in the estimates can partly be attributed to the different observation periods used, combined with the large variability in Greenland's mass balance, but they are mainly due to the different methods used and corrections applied. Besides differences introduced by the different groups processing the raw data, they can be caused by truncating GRACE monthly coefficients differently, using different filters and different smoothing radii, and from failing to restore power lost by smoothing. The results presented in this study might help to settle and resolve doubts in these different GRACE estimates of the Greenland ice mass loss. In the estimates mentioned above, a linear trend fit was used. The acceleration term used in this study shows that different GRACE observation periods give different mass loss estimates. The longer the period of study is the more mass-loss estimate might be resulted. During the 9-year period of this study, we obtained ice mass loss estimates of -121 Gt/yr in 2002 – 2003, -167 Gt/yr in 2004 – 2005, -210 Gt/yr in 2006 – 2007, -189 Gt/yr in 2008 – 2009, and -271 Gt/yr in 2010 – 2011. As mentioned above, there are other parameters which affect the mass loss estimates in addition to the observation period. The acceleration estimated here is tested statistically with a significance of around 98%.

Important features in our computations are: 1) GRACE level 2 release 4 datasets from CSR is used to compute the Greenland mass changes, 2) non-isotropic filter in 340 km corresponding radius is used to decorrelate high frequency GRACE measurements provided by high degree terms and order of the Stokes's coefficients, 3) leakage effects are estimated and applied, 4) un-weighted least squares method is used to estimate secular trends and periodic variations for the Greenland mass changes, and 5) A linear trend and a quadratic form are used to fit to the GRACE time series of ice mass changes. Note that our estimated values are free of any PGR corrections. PGR signals are more than one order of magnitude smaller than ice mass loss signals.

The secular trend error estimates for both linear and quadratic forms take into account the residuals between the recovered mass-variation time series and the least-squares fit to this series, the leakage effects and the gravity field solution error.

The acceleration term estimated in this study emphasizes the need for continuous observation of Greenland ice sheet and extending observation time in order to extract time series of ice mass changes by GRACE and future gravity missions.

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