GRACE data viser at issmeltingen på Grønland sprer seg til nordvestkysten

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Hossein Nahavandchi and Gholamreza Joodaki: Greenland ice-melt spread into Northwest Coast revealed by GRACE

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We examine the extent and magnitude of Greenland ice sheet surface melting between 2002 and 2010. We show that the well documented Greenland ice mass loss in the southern region spread to northwest Greenland in the period from 2007 to 2010. We use Gravity Recovery and Climate Experiment (GRACE) satellite data to estimate ice mass variability over time in Greenland. Monthly GRACE level 2 Release-04 (RL04) data from Center for Space Research (CSR) are used for the period April 2002 to December 2010. In contrast to other recent studies, our method employs 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 taken into consideration in the computations.

Key words: Greenland, Ice mass loss, Ice-melt spread, GRACE gravity satellites

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1. Introduction

The GRACE satellite gravity mission has been providing valuable information regarding Earth's gravity field. GRACE not only maps the Earth's static gravity field but it also measures temporal variation in the Earth's gravity field to a scale of several hundred kilometers and with a period of around one month. GRACE detects changes in the gravity field caused by redistribution of mass within the Earth and on or above the Earth's surface. Due to its global coverage, GRACE provides an excellent tool for mapping the gravity field over large areas such as Greenland. In recent years, several research groups have used GRACE data to estimate the rate of ice mass change over Greenland.

Several studies indicate that the Greenland ice sheet has been losing mass at a significant rate over the last decade. Ice mass loss estimates from GRACE are reported by Luthcke et al. (2006) using raw GRACE KBRR (K-Band Range and Range rate) data; Chen et al. (2006) using the CSR monthly solutions RL01 from 2002-2005; Ramillien et al. (2006) using the same period as Chen et al. (2006) but using the GRGS/CNES GRACE solutions; Velicogna and Wahr (2006a) using the CSR monthly solutions Release 01 (RL01) from 2002 to 2006; Wouters et al. (2008) using the CSR RL04 monthly solutions from 2003 to 2008; Baur et al. (2009) using monthly GRACE solutions RL04 provided by GRACE processing centers of CSR, GFZ (German Research Center for Geosciences) and JPL (Jet Propulsion Laboratories) for 2002 to 2008, and Velicogna (2009) using the CSR RL04 monthly solutions from 2002 to 2009. Note that all of the results reported above are based on isotropic filters.

Other satellite based sensors can also be used to study Greenland ice mass changes. Abdalati et al. (2001), Rignot et al. (2004), Rignot and Kanagaratnam (2006) and Joughin et al. (2010) used Synthetic Aperture Radar (SAR) imaging to reveal accelerated mass change in 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) used laser altimetry to study the mass balance of Greenland. Sørensen et al. (2010) used satellite laser, radar and gravity measurements to study Greenland ice mass change.

In this study we estimate Greenland ice mass change and ice-melt spread based on monthly GRACE solutions provided by CSR from April 2002 to December 2010. The latest release RL04 is used along with improved geophysical signal models and data processing techniques. This release has the smallest error compared to other releases (Bettadpur 2007). Due to the presence of noise in the provided spherical harmonic coefficients of the GRACE data, a filtering technique based on non-isotropic filter is applied (See Joodaki and Nahavandchi 2012).

2. Surface mass change estimation from GRACE

The GRACE twin satellites were launched in March 2002 and are jointly implemented by the US National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) (Tapley et al. 2004a). GRACE measures Earth gravity changes with unprecedented accuracy by tracking changes in the distance between the two satellites and combining these measurements with data from on-board accelerometers and Global Positioning System (GPS) receivers. GRACE data are used to determine monthly spherical harmonic coefficients of the Earth's gravity field. Each field consists of gravity field normalized (Stokes) coefficients, C_{lm} and S_{lm}, up to degree and order (l, m) 60 in CSR products (Tapley et al. 2004b). Using the static 30-day fully normalized spherical harmonic coefficients, one can estimate monthly local changes in surface mass (Wahr et al. 1998). The mass changes can be assumed to be located in a very thin layer of water concentrated at the surface and with variable thickness. This assumption is not far from reality. Changes in water storage in hydrologic reservoirs, by moving ocean, atmospheric and cryospheric masses, and by exchange among these reservoirs has been shown to cause monthly changes in gravity signals (Chambers 2007). The vertical extent of the water is much smaller than the horizontal scale of the changes and 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.

Having obtained monthly spherical harmonic coefficients of the Earth's gravity field, one can estimate monthly local changes in surface mass density (Wahr et al. 1998):

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

where φ and λ are the spherical latitude and longitude of the point of interest, a is the major semi axis of a reference ellipsoid and $\bar{P}_{lm}$ is the normalized associated Legendre function of the first kind. ρ_{ave} is the average mass-density of the solid Earth (assumed throughout this paper to be 5517 kg/m^3), 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, and k_l is the Love number of degree l which is given in Wahr et al. (1998). It should be stated here that $\Delta\sigma/\rho_w$ transforms surface mass-densities to equivalent water thickness values, where ρ_w is the mass-density of freshwater (=1000 kg/m^3 in this study).

Crucial for a reliable estimate of secular mass changes from GRACE monthly solutions is the ability to correct for systematic errors in the surface mass density computation as discussed below.

Due to the nature of the measurement technique in GRACE and mission geometry, the monthly spherical harmonic coefficients are contaminated by short-wavelength noise. The noise is significant when one is interested in signals extending geographically a few hundred km or when using higher degree coefficients (short-wavelengths). Non-isotropic filters are used in this study since the GRACE noise structure mainly manifests itself as near north-south "stripes" and has a non-isotropic nature. We use the Kusche et al. (2009) decorrelation and smoothing method to correct monthly GRACE RL04 gravity models, as did Joodaki and Nahavandchi (2012).

Due to the GRACE orbit geometry and the separation length between its satellites, the lowest-degree zonal harmonics, C_{20} (or in another format as J_2) cannot be satisfactorily determined from the GRACE data (Tapley et al. 2004b). The C_{20} estimates from GRACE also are well-known to be affected by significant long-period tidal aliases. Replacement of the GRACE C_{20} coefficient by its estimate from Satellite Laser Ranging (SLR) improves the estimation of mass variations from GRACE (Chen et al. 2005). The SLR time series are also more precise, with about a third of the noise of the GRACE time series. Therefore, the monthly SLR estimates for C_{20} coefficient are used to replace the estimates from GRACE in this study. The SLR time series for C_{20} coefficient are taken from J. Ries (personal communication, 2010).

For a reliable estimate of secular mass changes over Greenland one needs to correct for leakage effects. On the one hand, mass change located 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 areas outside Greenland. These are called leakage in and leakage out effects, respectively. 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 use results from Joodaki and Nahavandchi (2012) to estimate leakage effects. In this approach, we use only GRACE results to delineate the leakage effects rather than additional information from sources such as remote sensing or global hydrological models. The procedure is to calculate the spherical harmonic coefficients associated with leakage effects, on the areas concerned, from the surface mass density derived from GRACE data alone. The sources generating leakage in signals could be from all over the world; however, the impact declines with increasing distance. This is because leaking signals follow Newton's law of gravitation. The strongest signals on Greenland are caused by Alaska, Fennoscandia and the Canadian Shield. These three sources are also used in investigations by Baur et al. (2009).

In the estimation for ice mass change rates in this study, contaminating factors like the effects of variation in atmospheric mass and the solid Earth contribution from high-latitude Post Glacial Rebound (PGR) are not applied. 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 stated here that the PGR signal for the entire Greenland is computed to about –7.4 Gigaton per year (Gt/yr) with standard deviation of ±19 Gt/yr (Velicogna and Wahr 2006b). When compared to the ice-mass estimates, the PGR signal is more than one order of magnitude smaller.

3. Numerical investigations

We estimate the secular trend in Greenland ice mass rate using more than 8 years of GRACE level 2 RL04 data. Monthly GRACE solutions by CSR processing centers are used for the period April 2002 to December 2010. The maximum degree of expansion for the CSR in this study 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 the CSR model and enough to show the Greenland ice sheet mass loss. As mentioned in section 2, monthly solutions of GRACE when computing ice mass rates include a non-physical striping error pattern which can be considered noise and must be decorrelated/filtered. It has been filtered in the corresponding Gaussian radius of 340 km (see Joodaki and Nahavandchi 2012). The monthly SLR estimates for the C_{20} coefficient are used to replace the estimates from GRACE to complete the data edition step. Leakage effects are corrected for in the estimation of total mass change for each month. The average leakage in and leakage out effects for CSR monthly gravity solutions and smoothing degree of corresponding Gaussian radius of 340 km are estimated at 7.7 Gt and 17 Gt, respectively.

We convert the gravity field residuals observed by GRACE into surface mass using Equation (1).To do this, the time-mean of the GRACE Stokes coefficients from April 2002 to December 2010 is calculated and the monthly coefficients anomalies ΔC_{lm} and ΔS_{lm} are determined by removing the mean from monthly Stokes spherical coefficients. On a 1° x 1° grid, we estimate monthly mass variability over Greenland using Eq. (1) (see Chen et al. 2006; Joodaki and Nahavandchi 2012). To detect the secular trend and periodic variations in the monthly mass anomalies, a general expression of the following form can be used:

$$f(\varphi,\lambda,\ t) = A + Bt + \sum_i C_i \cos(\omega_i t) + D_i \sin(\omega_i t) + \varepsilon \tag{2}$$

The value of the considered functional f (the ice mass anomaly, here) at a selected location (φ, λ) and time t is approximated by a static value A, and its secular (B) and periodic (with amplitude C_i and D_i of typical angular frequencies ω_i) variations. The variable ε characterizes noise and unmodeled effects. To detect the secular trend, we have simultaneously fit periodic and secular terms to the results (a bias, trend and four annual and semiannual terms as well as seasonal variations). These terms are applied to a time series of grids from which Figure 1 is derived. The seasonal terms of the ice mass loss variations have been removed to make the long term variations more evident. The average value of –162±20 Gt/yr between 2002 and 2010 is estimated for the Greenland ice-mass change using CSR monthly solutions. This estimate is –151±20 Gt/yr between 2002 and 2007. These results are reached by application of a non-isotropic filter whose degree of smoothing corresponds to a Gaussian filter with a radius of 340 km. These annual mass loss estimates of the Greenland ice sheet agree well with several other studies of the Greenland ice sheet mass balance using different remote-sensing techniques. However, it should be noted that each study is characterized by its observation period, individual analysis method and monthly gravity solutions. Therefore, it would be very difficult to compare different GRACE studies objectively. Previously published estimates of the Greenland ice mass loss range from -101 Gt/yr to –240 Gt/yr (see e.g. Velicogna 2009 and Sørensen et al. 2011). The secular trend error estimates for both periods above take into account errors of the least squares adjustments of the mathematical model used to detect the secular trend and periodic variations in the monthly mass anomalies, the leakage effects and the gravity field error. Table 1 shows the bias, trend and annual terms for the period 2002-2010. The error estimates in Table 1 are only derived from residuals between the recovered mass-variation time series and the least-squares fit to this series; they do not account for the uncertainties of leakage effects and GRACE gravity field errors.

Table 1. Summary statistics for the model estimation of the Greenland secular trend.

	Bias (Gt)	Trend(Gt/yr)	Annual Cos-term (Gt)	Annual Sin-term (Gt)
2002-2010	601±13	–162±3	35±7	-57±9

We decided to calculate the resulting secular trends in Greenland ice mass in two different periods to see whether the extent and magnitude of ice mass melting is constant, accelerating or decelerating. Figure 1 shows the secular trends in the Greenland ice mass variability represented as equivalent water thickness change averaged between April 2002 and December 2007, and between April 2002 and December 2010. These two figures illustrate areas in which Greenland lost mass at different rates during the study period. It is obvious that the ice mass loss has been significant along the northwest coast of Greenland. A large area experienced losses of 6 to 10 centimeters per year (blue). Losses were highest over southeastern Greenland. The interior parts of Greenland shows less negative trend and the northern and northeastern parts show the least negative trends.

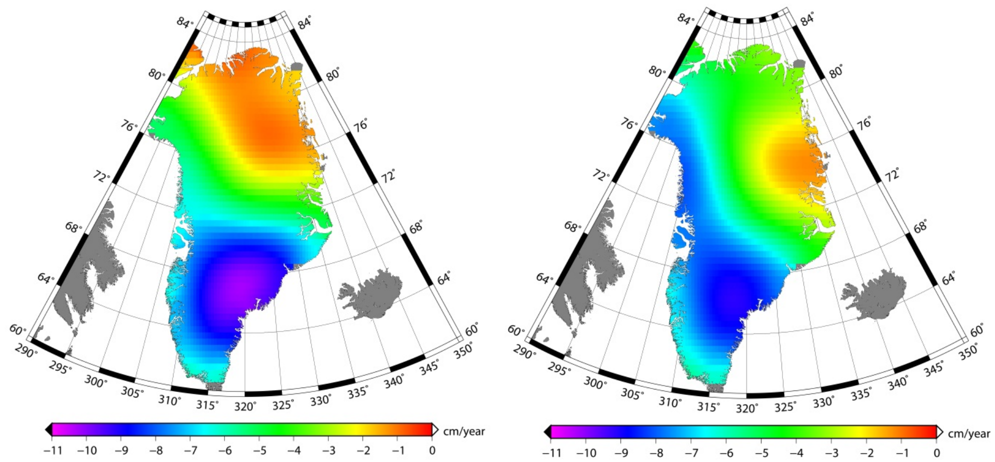

Figure 1. GRACE model estimation of the Greenland Ice mass loss rate in units of equivalent water height change per year, cm/year. The left figure is the averaged rate from April 2002 to December 2007 and the right figure is the averaged rate from April 2002 to December 2010.

4. Discussions and conclusions

The GRACE twin satellites have been providing a continuous record of the Earth's gravity field for more than 9 years, offering an excellent tool to study mass changes over large areas. The Earth's gravity field is a product of its mass distribution. The mass distribution is constantly changing. GRACE tracks changes in Earth's gravity field due to changes in Earth's mass distribution. This includes changes in ice of the Greenland ice sheet. Mass loss over Greenland is reported in several studies consistent with increased global warming in recent years, and indicates that Greenland is a major contributor to recent global sea level rise.

The monthly GRACE gravity field solutions allow regional estimation of Greenland ice mass balance. In contrast to some other techniques, GRACE measures Greenland mass variability over the entire ice sheet. Furthermore, the process to obtain this mass variability is less ambiguous for GRACE because the relationship between gravity and mass variability follows directly from Newton's law.

Our model shows that rapid mass loss of the Greenland icecap spread from southern portions to northwest Greenland coast in 2007-2010. From 2002 to 2010, the ice loss rate doubled (see also Velicogna 2009). The summers of 2003, 2005, 2007 and 2008 are observed to be among the warmest years since 1961. Our model reveals large mass loss in these years, indicating strong correlation between summer temperature and the ice loss observed by GRACE.

Important elements in our computations are that: 1) GRACE level 2 release 4 datasets from CSR are 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 and 4) unweighted least squares method is used to estimate secular trends and periodic variations for the Greenland 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.

Accelerations and decelerations of ice mass loss are apparent from the GRACE data. As mentioned, the results of this study shows a northward movement of ice mass loss along the west side of the Greenland ice sheet while at the same time we observe rapid ice melting in southeast Greenland in 2005 and 2007, followed by a moderate deceleration in 2006 and 2008 (see also Joodaki and Nahavandchi 2012). However, the deceleration is weak. Southeast Greenland is still losing mass at a high rate and continuing to contribute to global sea level rise.

The low resolution of GRACE, 250 kilometers, is not enough fine to isolate the source of ice mass variability. However, the results of this study show that the Greenland ice sheet is losing mass nearer to the ice sheet margins than in the interior portions. The ice mass loss has been very dramatic along the northwest coast of Greenland. The long term assessment of the Greenland ice mass sheet variability and its contribution to sea level rise is important for future forecasting of global sea level rise.

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