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GRACE-derived ice-mass loss spread over Greenland

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Abstract: The Gravity Recovery and Climate Experiment (GRACE) monthly satellite data is used to examine the extent and magnitude of Greenland ice sheet melting for 2003-2012. 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 and 2010 to 2012 by estimating ice mass variability over time in Greenland. The ice-mass melting is estimated to –183±11 Gt/yr. This estimation means that Greenland is still losing much more ice than gained, and continuing to contribute to global sea level rise in a warming world. Unlike other recent studies, our method employs a non-isotropic filter. A non-isotropic filter is used to decorrelate the GRACE data, since the GRACE noise structure has a non-isotropic nature.

Keywords: GRACE gravity satellites; Greenland; Ice mass loss; Ice-melt spread

1 Introduction

The satellite gravity mission has been providing valuable information regarding the Earth's gravity field. The Gravity Recovery and Climate Experiment (GRACE) twin satellites were launched in March 2002 and are jointly implemented by the US National Aeronautics and Space Administration (NASA) and the German Aero-space Center (DLR) (Tapley et al. 2004a). GRACE measures the 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. The GRACE mission not only maps the Earth's static gravity field, but it also measures temporal variations in the Earth's gravity field to a scale of several hundred kilometers and with a period of around one month. GRACE provides a comprehensive map of the gravity field over large areas, such as Greenland due to its global coverage.

Several studies have indicated that the Greenland ice sheet has been losing mass at a significant rate over the last several years (e.g. Velicogna and Wahr 2013). However, few attempts have been made to document the spatial changes of the Greenland ice-mass loss and its spread to other geographical areas. The first attempt was made by Khan et al. (2010). They used GRACE and GPS data to show the ice mass loss spread into northwest Greenland between 2007 and 2009. They smoothed monthly GRACE level 2 Release-04 (RL04) data from the Center for Space Research (CSR) with an isotropic Gaussian filter with a 250 km half-width. Joodaki and Nahavandchi (2012) used a non-isotropic filter and CSR GRACE data to document the ice mass loss spread between 2007 and 2010. GRACE level 2 RL04 data was used in the computations. There is a good agreement between Khan et al. (2010) and Joodaki's and Nahavandchi's (2012) results.

In this paper, we examine the Greenland ice mass change and ice melt spread based on monthly GRACE solutions. The latest GRACE release, Release-05 (RL05) field is used. The main difference between RL05 and the previous release of the GRACE solution, RL04, is an improved atmospheric and ocean de-aliasing product that provides a more accurate correction for sub-monthly mass variability from the atmosphere and the ocean (Bettadpur et al. 2012). Due to the presence of non-isotopic noise structure in the real, unconstrained GRACE gravity field solutions, a filtering technique based on a non-isotropic filter is applied (See e.g. Joodaki and Nahavandchi 2012). We compare the ice mass change and spread in different years and discuss the impact of our results on the ice mass loss spread within different regions in Greenland. This sort of analysis is possible now that enough years of GRACE data have been accumulated.

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2 Data and Methodology

We use RL05 GRACE gravity field solutions data from CSR at the University of Texas (Tapley et al. 2004b) . We estimate the Greenland mass variability. GRACE gravity field monthly solutions are released in terms of fully normalized spherical harmonic coefficients of the Earth's gravity field. Each gravity solution consists of gravity field normalized (Stokes) coefficients, C_{lm} and S_{lm}, in this study, up to degree and order *(l, m)* 60 in CSR products. GRACE errors are larger at short wavelengths than at long wavelengths. This is because the GRACE satellites are approximately 450 km above the Earth's surface, and they are relatively insensitive to high-frequency terms in the gravity field, which decay with altitude more quickly than low-frequency terms. The CSR truncates its gravity field solutions to maximum degree of 60 to avoid high frequency noise, typically corresponding to scales of a few hundred kilometers and larger. Using the static monthly 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 oceans, atmospheric and cryospheric masses, and by exchange among these reservoirs have 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 can be modeled as surface density variations $\Delta\sigma$ (the unit of $\Delta\sigma$ is mass/surface area) in a spherical layer.

Vertically integrated mass changes are approximated by surface mass densities. Having obtained monthly Stokes coefficients of the Earth's gravity field, one can estimate monthly local changes in surface mass density (Wahr et al. 1998):

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

where φ and λ are the spherical latitude and longitude of the point of interest, a is the semi-major 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 load Love number of degree l which is given in Wahr et al. (1998). It should be stated here that $\Delta\sigma/\rho_w$ is the change in surface mass expressed in equivalent water thickness values, where ρ_w is the mass-density of freshwater (=1000 kg/m^3 in this study). The equivalent water thickness is of great importance in visualizing secular trends and spatial-temporal variations in land and ocean hydrologic mass balances.

Due to the nature of the measurement technique in GRACE and its mission geometry, the monthly spherical harmonic coefficients are contaminated by short-wavelength noise. The errors in the GRACE gravity field solutions increase rapidly with increasing degree. This means that the noise is significant when one is interested in signals extending geographically a few hundred km or when using higher degree GRACE-derived coefficients (short-wavelengths). The errors are also correlated between degrees in such a way as to produce north/south–trending stripes when converted into the spatial domain. Various post processing methods have been used to suppress these noises which contaminate the final maps of monthly mass anomalies (See e.g. Swenson and Wahr 2006). A common procedure is to use isotropic filters. After filtering, monthly spherical harmonic coefficients are converted to maps of equivalent water height. And then finally, to suppress any remaining noise in the maps of mass anomalies, one convolves the solutions with a Gaussian smoothing kernel with some hundred km half-width radius. This common procedure and other methods include Gaussian smoothing that is reported by Wahr et al. (1998); destriping by Swenson and Wahr (2006); fitting mascons to the Stokes coefficients by Tiwari et al. (2009); convolving with an averaging function by Swenson and Wahr (2002), and using empirical orthogonal functions to reduce the errors in monthly solutions by Wouters and Scharma (2007). In this study, we use non-isotropic filters, 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 RL05 gravity models, as done in Joodaki and Nahavandchi (2012). The filtered gravity coefficients are archived by the International Centre for Global Earth Models (ICGEM) and are publicly available at http://icgem.gfz-potsdam.de/ICGEM/. We used a DDK5 filter which corresponds to a Gaussian filter with a radius of 180 km. The use of a smaller corresponding Gaussian radius results in noisier monthly time series, but improves the characteristics of our sensitivity kernel.

Due to the GRACE orbit geometry and the separation length between its satellites, and significant long-period tidal aliases, the lowest-degree zonal harmonics, C_{20} estimates from GRACE (or in another format as J_{20}) were suggested to be replaced by its estimate from Satellite Laser Ranging (SLR) (see Tapley et al. 2004b; Chen et al. 2005) for the CSR GRACE data releases. Therefore, we replace the GRACE results for the C_{20} with those obtained from SLR. The SLR results are more precise, with less noise than the GRACE results. The SLR coefficients are taken from J. Ries (personal communication, 2010). We also include degree-one coefficients computed as described by Swenson et al. (2008).

Leakage effects are significant error sources for the computation of mass variations from the GRACE gravity solutions. For a reliable estimate of secular mass changes over Greenland, one needs to correct for leakage effects. The leakage effect originates, for example, from limited spatial resolution and imperfect reduction of satellite measurement errors (Swenson et al. 2003). Leakage effects degrade the computations over Greenland in two different ways. The gravity signals propagate from the areas around Greenland into a signal spreading over Greenland and hence have an impact on the mass change computations over Greenland (leakage-in). On the other hand, the depletion of signal from Greenland out to the same areas affects mass change computations over Greenland (leakage-out). 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 results are similar to the Baur et al. (2009) solution. The corrections for leakage-in and leakage-out effects are performed by algebraic calculations and their values are estimated to 7±2 and 17±2 Gt/yr.

The GRACE-derived secular trends in mass changes are superposed by the continuing viscoelastic response of the Earth's crust and upper mantle due to the Post Glacial Rebound (PGR). If not corrected, the PGR contamination will manifest as an apparent ice-mass change and hence degrade the computations. Unfortunately, the PGR signal and its correction have been a case of discussion for the GRACE community. This is due to the total uncertainty in the PGR estimations due to the PGR model-dependency on assumptions of the ice-load history and mantle viscosity (see e.g. Velicogna and Wahr 2006a, b). In Antarctica, the PGR contribution is important as it is a major part of the GRACE signal (Velicogna and Wahr 2006b). In Greenland, the PGR signal is less significant as the average PGR gravity signal is 2-3 times smaller than the GRACE gravity signal and the ice sheet area is 7 times smaller. In this study, we correct our GRACE Stokes coefficients using the PGR model based on the ICE5G ice load history (Peltier 2004). The PGR signal for Greenland is computed to about −2 Gt/yr. with a standard deviation of ±21 Gt/yr. The large uncertainty comes from considering a range of viscosity profiles.

In the estimation for ice mass change rates, the effects of variation in atmospheric mass are not applied. Atmospheric effects are negligible for Greenland on the long term trend (Velicogna and Wahr 2006a, b).

In the ice mass change studies, the objective is to estimate the long term trend in mass changes, and the time series show a short-term period seasonal variability superimposed on a longer term variability. We therefore emphasize the long-term response of the ice sheet by keeping the static value and the secular trend. A general expression of the following form can be used:

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

Functional f is the ice mass anomaly at a selected location φ and λ 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 ω_i) variations. The variable ε characterizes noise and un-modeled effects.

3 Results

The recent release of GRACE gravity solutions is used, and we calculate the time series of the Greenland ice mass using 9 years of GRACE level 2 RL05 fields. Monthly GRACE solutions by the CSR processing center are used for the period from January 2003 to December 2012. The maximum degree of expansion for the CSR solution is 60. We make all the corrections described above. Unphysical stripping error pattern in monthly solutions of GRACE are decorrelated/filtered. It has been filtered in the corresponding Gaussian radius of 180 km. We have replaced the GRACE CSR C_{20} coefficients with those obtained from SLR. Leakage effects are corrected for in the estimation of total mass change for each month. The average leakage in and leakage out effects for monthly gravity solutions are estimated.

Using Eq. 1, we convert the gravity field residuals observed by GRACE into equivalent water thickness (height) values. To determine ΔC_{lm} and ΔS_{lm} in Eq. 1, we calculate the time-mean of the GRACE Stokes coefficients and remove the mean from monthly Stokes spherical coefficients. We then estimate monthly mass variability over Greenland using Eq. 1 on a 1°x 1°grid (see Chen et al. 2006; Joodaki and Nahavandchi 2012). Using Eq. 1 and after applying all the above corrections, one can obtain the time series for the Greenland ice mass changes from the GRACE monthly mass solutions.

We apply a bias, trend and four annual and semiannual terms using Eq. 2 to finally detect a secular trend. These terms are applied to a time series of grids from which Fig. 1 is derived. Although the main focus of this study is to investigate the geographical ice mass loss spread across Greenland, we also estimate the average value of the Greenland ice mass change over the entire period. The average value of –183±11 Gt/yr between 2003 and 2012 is estimated. This annual mass loss estimate of the Greenland ice sheet helps reconcile several other studies of the Greenland ice sheet mass balance from different remote-sensing techniques. Previously published estimates of the Greenland ice mass loss range from –101 Gt/yr to –240 Gt/yr (see e.g. Velicogna 2009 and Sřrensen et al. 2011). However, it should be noted that each study is characterized by its observation period, individual analysis method, error analysis methods and monthly gravity solutions. When systematic errors are accounted for, and a consistent set of corrections and the same time span are used, different post processing methods produce consistent results (see e.g. Shepherd et al. 2012). The secular trend error estimate takes into account errors of the least squares adjustments in Eq. 2, the leakage effects and the gravity field error.

In an attempt to study the geographical spread of ice mass budget, we decided to calculate the secular trends in three different periods. The analysis aimed to see whether the extent of ice mass melting is constant or changing (spreading). Figure 1 (top) shows the secular trends in the Greenland ice mass variability represented as equivalent water thickness change averaged between January 2003 and December 2007, (middle) between January 2003 and December 2010, and (bottom) between January 2003 and December 2012. These three figures illustrate areas in which Greenland lost mass at different rates during the study period. The mass loss along the southeast coast was expected as it was indicated in previously published studies (See e.g. Velicogna and Wahr 2006; Khan et al. 2010; Velicogna et al. 2014). However, in recent years, the situa-

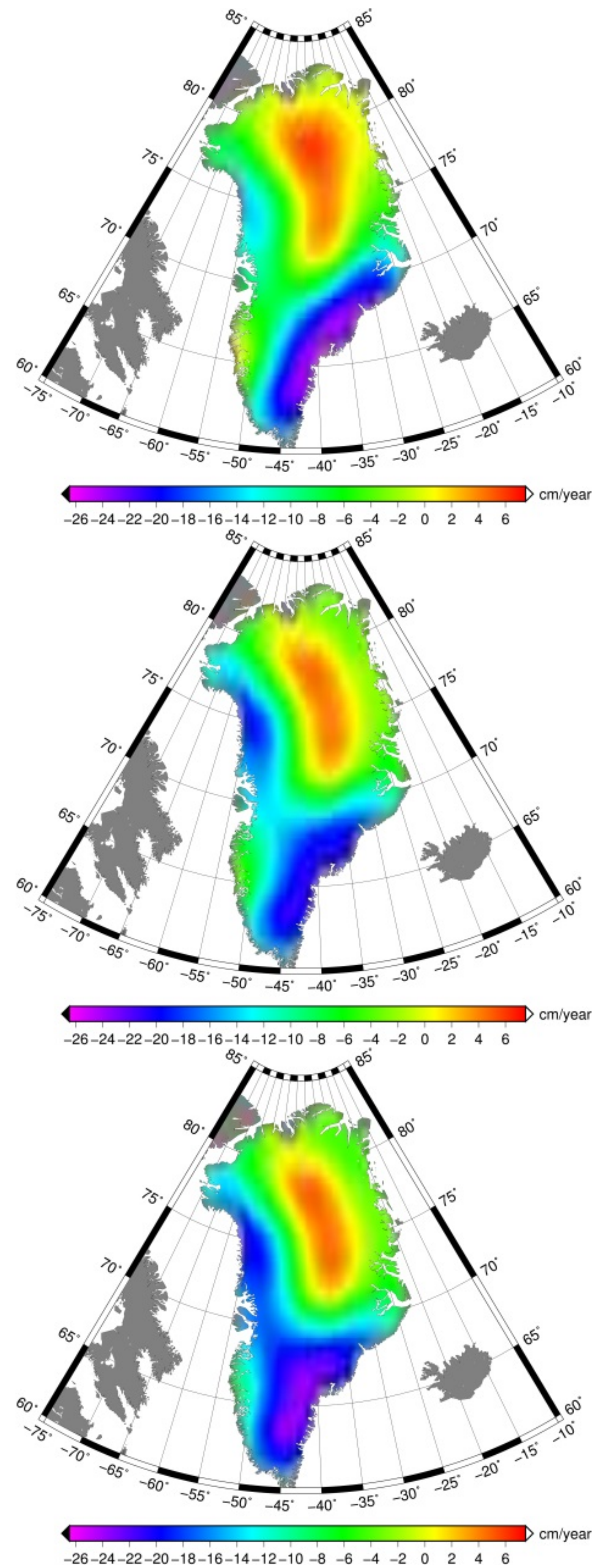

Figure 1: GRACE model estimation of the Greenland ice mass loss rate in units of equivalent water thickness change per year, cm/year. The figures are (top) the averaged rate from January 2003 to December 2007, (middle) from January 2003 to December 2010, and (bottom) January 2003 to December 2012.

Table 1: The Greenland mass balance from GRACE monthly gravity field solutions provided by CSR. Smoothing radius of 180 km is used for these computations. The numbers in columns 2-6 are the average values of the total mass with respect to 2003-2012 mean. A-M-J is the April-May-June total mass and A-S-O is August-September-October total mass. Total masses are in Gt.

	A-M-J	A-S-O	Summer Loss	Winter Gain	Net
2003	823	565	−258	–	–
2004	690	502	−188	125	−63
2005	622	301	−321	120	−201
2006	390	204	−186	89	−97
2007	271	23	−248	67	−181
2008	68	−103	−171	45	−126
2009	−75	−302	−227	28	−199
2010	−282	−625	−343	20	−323
2011	−591	−783	−192	34	−158
2012	−763	−923	−160	20	−140

tion across Greenland continued to evolve. Figure 1 shows that the ice mass loss has been significant along the northwest coast of Greenland from 2007 to 2012. A large area experienced losses of 15 to 20 centimeters per year (blue). Losses were highest over southeastern Greenland. The interior parts of Greenland show less negative trends and the northern and northeastern parts show the least negative trends.

Several studies showed that there is a strong correlation between summer/winter temperature and the ice loss/gain observed by GRACE (see e.g. Wouters et al., 2008). The difference between the April-May-June and August-September-October mean mass over Greenland is calculated in Table 1. April-May-June (A-M-J) manifests the beginning of the melt season while August-September-October (A-S-O) indicates the end of the melt season. In Table 1, average values of the total mass with respect to the 2003-2012 mean are given for A-M-J and A-S-O. Winter gain, summer loss and net balance are also listed. The summer loss is calculated from the comparison of the A-S-O average value with respect to the A-M-J value at the same year and the winter loss is calculated from the comparison of the A-S-O average value in the preceding year with the A-M-J value in the next year. The summer ice loss values are different over the years, with a maximum in 2010 in which -343 Gt was lost. The summer ice mass losses are somehow compensated by ice mass increases in the preceding winter seasons. Similar trends with different magnitudes are observed for 2005, 2007 and 2009 with -321 Gt, -248 Gt and -227 Gt ice mass losses during summer. Largest winter ice mass increase is observed for 2004 (125 Gt). It compensates the mass loss in the coming summer (see also Wouters et al., 2008). In the winter 2009-2010, the total Greenland ice mass gain was calculated only 20 Gt, and with ice mass loss -343 Gt, resulting in a net mass loss of -323 Gt for the whole 2009-2010, which is the largest net mass loss. The net balance for 2003-2004 is the smallest net mass loss of -63 Gt.

4 Conclusions

The analysis described here demonstrates that GRACE measurements of time variable gravity have been offering an excellent tool to study mass changes over large areas. Published Greenland ice melting spread shows that the northwest ice sheet margin has been losing mass since 2007. In addition, southeast Greenland still appears to be losing ice mass at a higher rate than before. Our model shows that the rapid mass loss of the Greenland icecap is not constant spatially and spread from southern portions to the northwest Greenland coast in 2007-2012. From 2003 to 2012, the ice loss rate more than doubled (see also Velicogna 2009). The summers of 2010, 2005, and 2003 are observed to be among the warmest years since 1880. Actually, they are among 10 warmest years. The top 10 warmest years are archived by the NOAA National Climatic Data Center and are publicly available at http://www.ncdc.noaa.gov/sotc/global/2014/13. Our model reveals large mass losses in these years, indicating strong correlation between summer temperature and the ice loss observed by GRACE.

Accelerations and decelerations of ice mass loss are apparent from our GRACE results. The results of this study show 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. 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, with smallest spatial scale of 330 km for maximum degree and order 60 for CSR data in this study is not fine enough 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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