Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet

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Using time-variable gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) satellite mission, we estimate ice mass changes over Greenland during the period April 2002 to November 2005. After correcting for effects of spatial filtering and limited resolution of GRACE data, estimated total ice melting rate over Greenland is – 239 ± 23 km^3/year, mostly from East Greenland. This estimate agrees remarkably well with a recent assessment of – 224 ± 41 km^3/year, based on satellite radar interferometry data. GRACE estimates in southeast Greenland suggest accelerated melting since the summer of 2004, consistent with the latest remote sensing measurements.

Greenland is the location of the second largest ice cap on Earth, and contains about 2.5 million cubic kilometers (km^3) or 10% of total global ice mass (Fig. 1). Complete melting of the Greenland cap would raise global mean sea level by about 6.5 m. Repeat-pass airborne laser altimetry measurements indicate that Greenland lost ice at a significant rate (– 80 ± 12 km^3/year) during the period 1997 to 2003 (*1*). Most of the estimated loss comes from the periphery, while the interior appears to be in balance. A more recent study (*2*) based on satellite interferometry suggests that ice loss is accelerating in recent years and is near – 224 ± 41 km^3/year in 2005, significantly larger than the estimate (– 80 ± 12 km^3/year) from airborne laser altimetry measurements (between 1997 and 2003), and also significantly larger than the estimate (– 91 ± 31 km^3/year) from satellite interferometry observations in 1996 (*2*). Acceleration of mass loss over Greenland, if confirmed, would be consistent with proposed increased global warming in recent years, and would indicate additional polar ice sheet contributions to global sea level rise (3).

Here, we use satellite gravity measurements to estimate mass change over Greenland. Since its launch in March 2002, the NASA-DLR Gravity Recovery and Climate Experiment (GRACE) has been providing measurements of Earth's gravity field at roughly monthly intervals (*4,5*). After atmospheric and oceanic contributions are removed (through the GRACE dealiasing process) (*6*), monthly gravity field variations mainly reflect changes in terrestrial water storage, snow/ice mass of polar ice sheets, and mountain glaciers. GRACE data have been successfully used to determine seasonal terrestrial water storage change in major river basins (*7-9*) and seasonal non-steric global mean sea level change (*10,11*). In order to use GRACE to study trends in glacial ice mass in polar regions, one must also consider changes that arise from Post Glacial Rebound (PGR), the delayed response of the crust and mantle to past glacial loads (*12*). Since PGR effects are present within the same geographical regions as current deglaciation, a PGR model is required to separate the effects. Based on the ICE5G model *(12),* average PGR effects over all of Greenland are estimated to be small (*13*).

As longer GRACE time series become available, studies of long-term ice mass change in polar ice sheets become possible (*13-17*). Previous studies mainly focus on continental scales, and have been limited by the spatial resolution of GRACE gravity fields. It is possible to improve the spatial resolution of GRACE estimates somewhat by assuming that surface load variations in the oceans are much smaller than those on land, especially at long periods (*16,18*). To improve resolution beyond this, we resort to numerical simulations to assign mass changes to regions suggested by remote sensing or other observations. We use 40 monthly GRACE gravity fields over a 3.5-year period from April 2002 to November 2005. These are the release 01 GRACE solutions provided by the Center for Space Research, University of Texas at Austin (*6*). Using a 2-step optimized filtering technique developed in a recent study (*16*) we fit linear trends to estimate ice mass rates over the entire Greenland ice sheet. The optimized filtering technique is designed to maximize the signal-to-noise ratio (*18*) in GRACE mass change fields. A separate regional estimate for East Greenland is of particular interest because satellite radar interferometry measurements show significant loss.

A global gridded (1° x 1°) surface mass change field is estimated from each of the 40 GRACE gravity solutions. At each grid point we estimate from the time series of mass change a linear trend using unweighted least squares, after first subtracting least squares seasonal (annual and semiannual) signals. Figure 2a shows GRACE surface mass rates over Greenland and surrounding regions. Prominent negative trends (~ – 3 to -4 cm/year of equivalent water height change) are observed over much of Greenland. Spatial leakage effects are also evident, due to filtering applied to suppress the noise in high degree and order spherical harmonics. Two other prominent features are positive rates (mass accumulation) near Hudson Bay and Scandinavia. In these two regions a strong PGR signal is predicted by models (*12*). Figure 2 shows two regions of mass loss in eastern Greenland. One is in the southeast where active ice flow and related ice loss are observed by remote sensing and satellite radar altimetry (*1,2*), and the other is along the coast in the northeast. As we show below, the region of loss in the northeast can be accounted for by a combination of northeast Greenland loss and additional loss from Svalbard, which shifts the center of the region slightly off the Greenland coast, into the oceans.

We select two grid points (A and B, marked in Fig. 2a), near centers of the mass loss features, and show the associated time series in Fig. 3. The red lines are linear trends from unweighted least square fits. The GRACE time series for both points A and B show negative trends on the order of – 4 to 5 cm/year) superimposed on seasonal variations. At point A, the later portion of the time series shows an increased rate of ~ – 7.24 cm/year, compared to about – 1.03 cm/year for the first 2 years (up to July 2004). The rate for the entire 3.5-year period is – 4.59 ± 0.39 cm/year. Although these rates need to be adjusted for effects of spatial filtering, it is clear that GRACE has observed accelerated ice mass loss in southeast Greenland in recent years, consistent with recent assessments (*1*) from satellite interferometry measurements.

Figure 2a suggests that limited spatial resolution of GRACE estimates causes a large portion of variance to be spread into the surrounding oceans, even though the actual source location is likely on the continent. Similarly, PGR effects from nearby regions such as Hudson Bay may contribute to variations over Greenland. Numerical simulations can help identify probable mass change sources that are consistent with GRACE observations. These experiments (see SOM Text and Fig. S1) consist of proposing probable geographical regions as sources of mass change, applying processing steps replicating the limited spatial resolution of GRACE data, and comparing predictions with GRACE observations.

Figure 2b is the predicted gravity data, which shows a good match with the GRACE observations in Fig. 2a, both over Greenland and in surrounding regions, including the oceans. To assign an uncertainty to this figure, we scale up errors assigned to linear rates determined from GRACE. The contribution of GRACE measurement error to uncertainty is small, since the rate is estimated from over 3.5 years of observations. Therefore, the estimate for Greenland is – 239 ± 23 km^3/year. This figure agrees well with a recent estimate of – 224 ± 41 km^3/year from satellite radar interferometry (*2*), and is significantly larger than earlier assessments, around – 80 to -90 km^3/year from remote sensing, satellite interferometry, and the first 2 years of GRACE data.

Most of the – 239 ± 23 km^3/year simulated loss comes from east Greenland, with about – 90 km^3/year from the glacier complex in southeast Greenland (blue shaded area in Fig. S1), consistent with recent satellite interferometry observations (*2*). Approximately – 74 km^3/year is assigned to northeast Greenland, where satellite interferometry observations suggest negligible ice mass change. However, Fig. 2a suggests that the loss may come from latitudes above 80°N, within the area marked by the black box on Fig. 1, containing glaciers separate from the main Greenland ice sheet, that were excluded from recent interferometry estimates (*2*). Therefore, it is possible that mass loss in this region has been observed by GRACE, but is omitted from the interferometry estimates. The 'dipole' feature of Greenland mass loss is also suggested by a recent study (*17*).

The numerical simulation also shows that GRACE observations are consistent with significant mass loss (~ – 75 km^3/year) over Svalbard, where remote sensing estimates are lacking. However, a recent study (*19*), based upon gravity and surface deformation observations in Svalbard, suggests significant present-day glacial melting in the region. Absolute gravity measurements indicate a melting rate of ~ – 50 km3/year, while surface deformation data suggest a rate of ~ – 25 km3/year. The substantial variability among surface deformation, surface gravity, and our GRACE estimate of Svalbard melting can be attributed to many factors, but all suggest that significant glacial melting is taking place, another strong indication of Arctic warming.

To this point we have neglected PGR effects in the immediate area of Greenland and surrounding regions (circled by white line on Figs. 2a,b). This assumption appears to be supported by the estimated total PGR contribution (~ – 5 km^3/year) over Greenland in a recent study (*13*), based on the ICE5G model (*12*). Different PGR models may show large discrepancy in modeling Greenland surface deformation effect, which is largely controlled by the ice history and the solid Earth properties (e.g., mantle viscosity and crust thickness) in that region, especially over the Hudson Bay and Scandanavia, two prominent PGR active areas. It is possible that the ICE5G PGR model (*13*) may under estimate the PGR contribution to GRACE-observed ice mass loss over Greenland. However, the uncertainty of the estimated PGR contribution will not likely account for a significant portion of the – 239 ± 23 km^3/year ice mass loss observed by GRACE. If we adopt this ICE5G based PGR contribution of mass rate over Greenland (~ – 5 km^3/year, with uncertainty at 100% of the signal, i.e., ± 5 km^3/year), then our GRACE estimate of Greenland ice mass rate is ~ – 234 ± 24 km^3/year.

The current GRACE estimate is significantly larger than an earlier estimate (– 82 ± 28 km^3/year), based on just the first 2-year of data (*13*). The difference is attributed both to increased melting in the most recent 1.5-year period and to improved filtering and estimation techniques (including use of numerical simulations), and the later may have played a more important role. Increased recent melting may represent simple interannual variability or accelerated melting driven by steady Arctic warming (*20*). Despite remarkable agreement between our GRACE estimate and recent radar interferometry estimates (*2*), quantification of Greenland ice mass balance remains a challenge. For example, another study (*21*) based on 10 years of radar altimetry data during the period 1992 – 2002, suggests a small mass gain for Greenland (~ 11 ± 3 km^3/year) (*2*), opposite in sign to the more recent estimate (2) . On the other hand, thermo-mechanical ice models forced by general circulation model climate scenarios predict significant Greenland ice loss in the 21th century (*22*).

The numerical simulation approach used in this study is useful in interpreting GRACE time-variable gravity fields. It contrasts with the basin kernel function approach (*13,15*) where the focus is on a continent-wide average. Numerical simulations are useful in quantifying spatial leakage of variance, and in testing hypotheses concerning possible regional contributors to change, such as the glacier complex in southeast Greenland or Svalbard. Many error sources may affect our GRACE estimates, which include the remaining GRACE measurement error (after spatial smoothing), uncertainty in the background geophysical models used in GRACE (e.g., the uncorrected ocean pole effect in the release-01 GRACE data and errors in the atmospheric and ocean models over Greenland and surrounding regions), unquantified other leakage effects, and etc.

The conclusion that ice loss has accelerated in recent years is independent of uncertainty in PGR effects, since, regardless of magnitude, PGR should contribute a constant rate to time series of any length. GRACE clearly detects a rate change in the most recent period, suggesting a contribution of about 0.54 mm/year to global sea level rise, well above earlier assessments (*23*). Time series are still relatively short, and an understanding of interannual variation in ice mass rates is lacking for Greenland. Without question, the extension of the GRACE mission beyond 2010, or development of a follow-on mission, will contribute fundamentally to separating contributions of ice mass change from other geophysical signals (such as PGR) that contribute to the observations.

References and Notes

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Figure Captions

Figure 1 The Greenland ice sheet is the 2nd largest ice cap on Earth, and contains ~ 2.5 million cubic kilometers or 10% of total global ice mass.

Figure 2 a). GRACE long-term mass rates over Greenland and surrounding regions during the period April 2002 to November 2005 determined from mass change time series on a 1-degree grid. **b).** Simulated long-term mass rates over Greenland and surrounding regions from the experiment as described in SOM text and Fig. S1.

Figure 3. GRACE mass changes at points A and B in East Greenland, marked on Fig. 2. The red straight lines are long-term linear rates estimated from unweighted least squares fit.


Lincoln Sea
CANADA
Wandel Sea
Greenland Sea
Greenland
Baffin Bay
Denmark Strait
ICELAND
ATLANTIC OCEAN
80°
75°
70°
60°
60°
10°
20°
30°
40°
50°

Figure 1

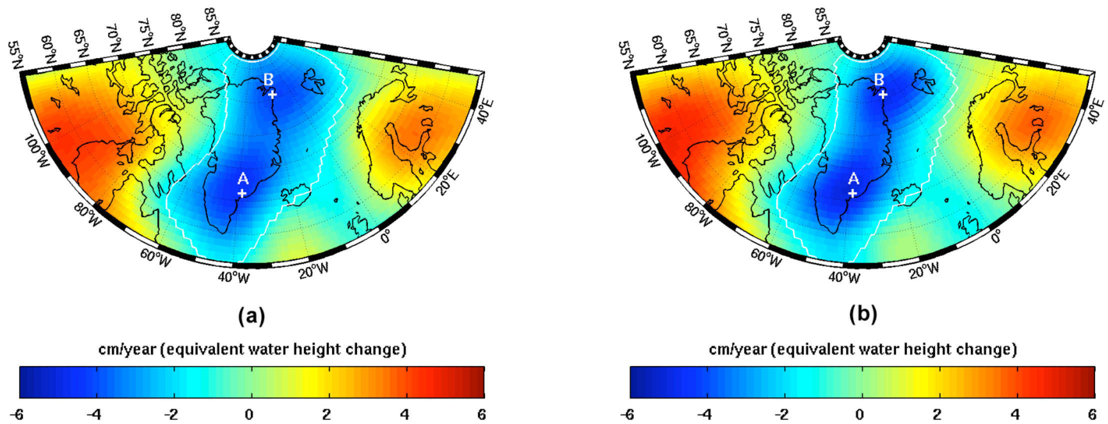

Figure 2

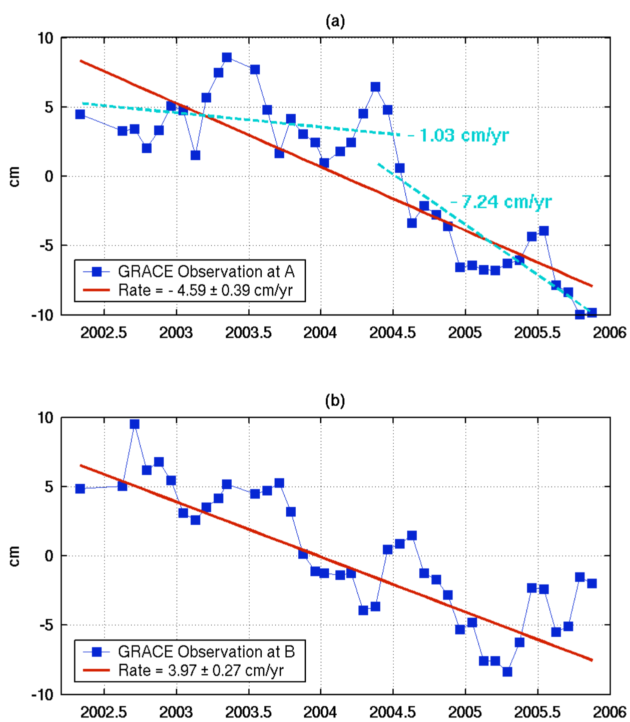

Figure 3

Supporting Online Materials

Numerical Simulations of GRACE Observed Greenland Mass Rates

These numerical simulation experiments consist of proposing geographical regions that are probable sources of mass change, applying processing steps that replicate the limited spatial resolution of GRACE data, and comparing predictions with GRACE measurements. The experiments do not alter the fundamental limitation of GRACE to resolve small features, but, instead provide an interpretive tool.

The first step in the numerical experiments is to form an approximate estimate of the total mass rates, within the area circled by the white line in Fig. 2a, by summing over grid elements with cosine latitude weighting. The resulting mass rate is about – 190 ± 18 km^3/year. The criterion for selecting the predefined area is to cover as much of the variance and leaked variance from Greenland as possible while, at the time, minimize leakage effects from surrounding regions (16). Second, we assign geographical locations of the predetermined total Greenland mass loss (e.g., – 190 ± 18 km^3/year) to 1° x 1° grid cells near the centroids of the principal features in Fig. 2, using published catchment basin analysis from remote sensing data (*2*). Third, we repeat the first two steps for surrounding regions, including the prominent increases in the Hudson Bay area and Scandanavia where PGR may contaminate estimates for Greenland. Fourth, we convert the grid of mass rates into spherical harmonics, and subject these to the same data processing procedures as GRACE data (e.g., the removal of degree-1 spherical harmonics that are not in GRACE data and the use of the same 2-step optimized spatial smoothing). Finally, we compare the predictions from the above numerical simulations with GRACE observations in Fig. 2. Repeated adjustments of both locations and magnitudes of mass rates result in a mass rate distribution (illustrated in Fig. S1) that provides a reasonable match to the shape and amplitude of features in Fig. 2a, and agrees with the summed rates (i.e., – 190 km^3/year) in the region circled by white in Fig. 2a.

Figure S1 shows the simulation scheme of a particular experiment, in which a total of – 239 km^3/year evenly distributed over the shaded areas in East Greenland. Of this, – 90 km^3/year is evenly distributed in the blue area (i.e., the location of the Southeast Glacier), – 75 km^3/year in the light blue area, and – 74 km^3/year in the orange area, and – 75 km^3/year over Svalbard island (magenta area). The colors in Fig. S1 are only used to distinguish different simulated areas and do not represent the magnitudes of simulated mass loss. To appropriately replicate the two prominent mass increases in Hudson Bay and Scandanavia, presumably from PGR contribution, and quantify potential leakage effects on Greenland mass change, we place two positive anomalies of + 470 and + 130 km^3/year, evenly distributed in these two regions. These two positive anomalies (+ 470 and + 130 km^3/year) are chosen, after extensive numerical experiments, from comparison between simulated results and GRACE observations (Fig. 2a), using the same procedures described for estimating mass changes over Greenland. To further consider possible leakage effects from residual oceanic signal or noise, we also model the mass changes in a few small regions over the ocean (marked as a, b, c, and d) as described in the caption.

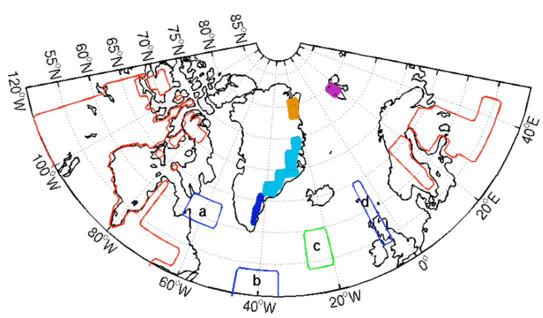

Figure S1. Illustration of simulated areas (shaded areas) of mass changes over east and north Greenland and Svalbard island (northeast to Greenland). – 90 km^3/year is evenly distributed over the dark blue area (Southeast Glacier), – 75 km^3/year over the light blue area, and – 74 km^3/year over the orange area, and – 75 km^3/year over Svalbard island (magenta area). To simulate leakage effects from the two prominent mass increase regions (circled by red lines) in Hudson Bay and Scandanavia, presumably from PGR contribution, we place two positive anomalies of +470 and + 130 km^3/year, evenly distributed in these two regions, respectively. To further consider possible leakage effects from residual oceanic signal or noise, we select 4 regions (circled by blue or green lines), to construct some best-match (to GRACE shown in Figure 1) anomalies of – 40 km^3/year in region (a), – 90 km^3/year in region (b), + 40 km^3/year in region (c), and – 50 km^3/year in region (d).