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Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet

J. L. Chen,[1]* C. R. Wilson,[1,2] B. D. Tapley[1]

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 the effects of spatial filtering and limited resolution of GRACE data, the estimated total ice melting rate over Greenland is –239 ± 23 cubic kilometers per year, mostly from East Greenland. This estimate agrees remarkably well with a recent assessment of –224 ± 41 cubic kilometers per 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 the 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, whereas the interior appears to be in balance. A more recent study (*2*) based on satellite interferometry suggested that ice loss has been accelerating in recent years and was 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*).

We used satellite gravity measurements to estimate mass change over Greenland. Since its launch in March 2002, the NASA–German Aerospace Center 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 nonsteric global mean sea level change (*10*, *11*). To use GRACE to study trends in glacial ice mass in polar regions, one must also consider changes that arise from postglacial rebound (PGR), the delayed response of the crust and mantle to past glacial loads (*12*). Because 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 focused mainly 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 resorted to numerical simulations to assign mass changes to regions suggested by remote sensing or other observations. We used 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 two-step optimized filtering technique developed in a recent study (*16*), we fitted 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° by 1°) surface mass change field is estimated from each of the 40 GRACE gravity solutions. At each grid point, we estimated 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 (about –3 to –4 cm/year of equivalent water height change) are observed over much of Greenland. Spatial leakage effects are also evident, because of filtering applied to suppress the noise in high-degree and high-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 selected two grid points (A and B, marked in Fig. 2A), near centers of the mass loss features, and showed 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 about –7.24 cm/year, compared with 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

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

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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.

The predicted gravity data (Fig. 2B) 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 scaled up errors assigned to linear rates determined from GRACE. The contribution of GRACE measurement error to uncertainty was small, because the rate was 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, about –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 southeast Greenland glaciers (blue shaded area in fig. S1), consistent with recent satellite interferometry observations (*2*). About –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 was also suggested by a recent study (*17*).

The numerical simulation also shows that GRACE observations are consistent with significant mass loss (about –75 km^3/year) over Svalbard, where remote sensing estimates are lacking. However, a recent study (*19*), based on gravity and surface deformation observations in Svalbard, suggests significant present-day glacial melting in the region. Absolute gravity measurements indicate a melting rate of about –50 km^3/year, whereas surface deformation data suggest a rate of about –25 km^3/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 the white line in Fig. 2, A and B). This assumption appears to be supported by the estimated total PGR contribution (about –5 km^3/year) over Greenland in a recent study (*13*), based on the ICE5G model (*12*). Different PGR models may show large discrepancies in modeling the Greenland surface deformation effect, which is largely controlled by the ice history and the solid Earth properties (e.g.,

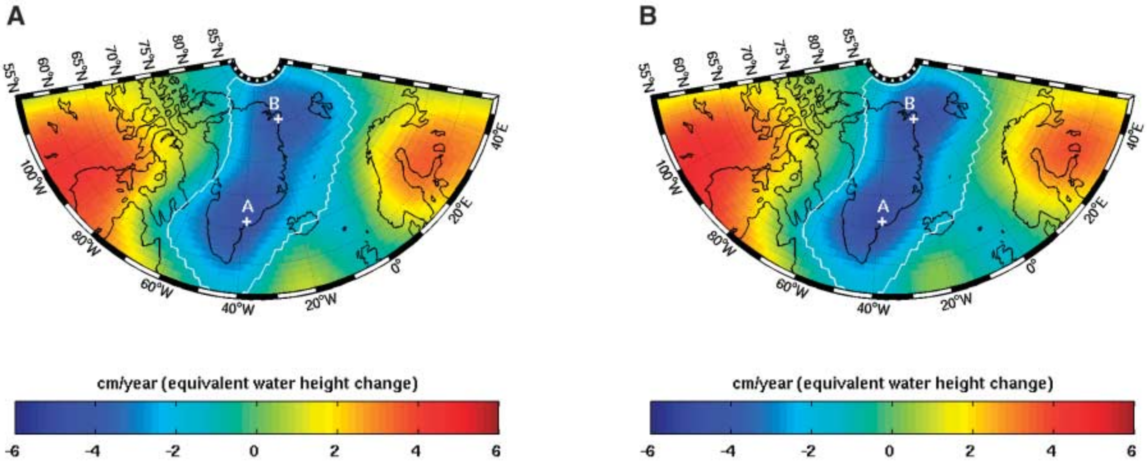

Fig. 2. (**A**) GRACE long-term mass rates over Greenland and surrounding regions during the period April 2002 to November 2005, determined from mass change time series on a 1° grid. (**B**) Simulated long-term mass rates over Greenland and surrounding regions from the experiment as described in SOM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

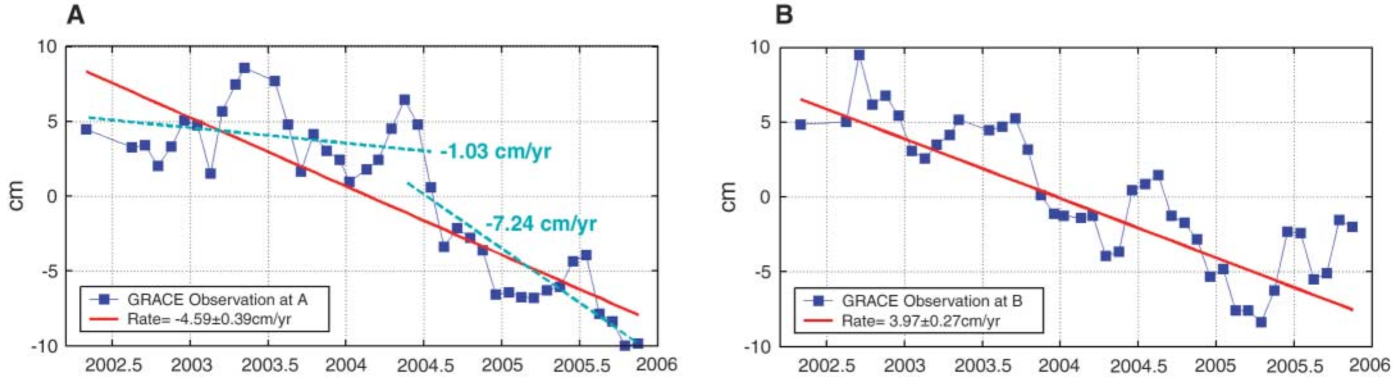

Fig. 3. (**A** and **B**) GRACE mass changes at points A and B in East Greenland, marked on Fig. 2. The straight red lines are long-term linear rates estimated from unweighted least squares fit.

mantle viscosity and crust thickness) in that region, especially over the Hudson Bay and Scandinavia, two prominent PGR active areas. It is possible that the ICE5G PGR model (*13*) may underestimate 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 (about –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 about –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 years 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 latter 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 close 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 to 2002 suggests a small mass gain for Greenland ($\sim$11 ± 3 km^3/year) (*2*), opposite in sign to the more recent estimate (*2*). On the other hand, thermomechanical ice models forced by general circulation model climate scenarios predict significant Greenland ice loss in the 21st 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*), in which 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 Southeast Glacier 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), and unquantified other leakage effects.

The conclusion that ice loss has accelerated in recent years is independent of uncertainty in PGR effects, because, 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 the development of a follow-up mission, will contribute fundamentally to separating contributions of ice mass change from other geophysical signals (such as PGR) that contribute to the observations.

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Type, Density, and Location of Immune Cells Within Human Colorectal Tumors Predict Clinical Outcome

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The role of the adaptive immune response in controlling the growth and recurrence of human tumors has been controversial. We characterized the tumor-infiltrating immune cells in large cohorts of human colorectal cancers by gene expression profiling and in situ immunohistochemical staining. Collectively, the immunological data (the type, density, and location of immune cells within the tumor samples) were found to be a better predictor of patient survival than the histopathological methods currently used to stage colorectal cancer. The results were validated in two additional patient populations. These data support the hypothesis that the adaptive immune response influences the behavior of human tumors. In situ analysis of tumor-infiltrating immune cells may therefore be a valuable prognostic tool in the treatment of colorectal cancer and possibly other malignancies.

Tumors in mice and humans often contain infiltrates of immune cells. Experiments with immune-deficient mice have provided data supporting the role of adaptive immunity in cancer immunosurveillance (*1*–*4*). Tumor cells can express antigens and become targets for a T cell–mediated adaptive immune response (*5*, *6*). The differentiation of naïve CD4$^+$ T cells into T helper type 1 (T$_H$1) cells producing interferon gamma (IFN-γ) promotes CD8 T cell–mediated adaptive immunity (*7*). In mice, immune cells appear to prevent the development of tumors and inhibit tumor progression (*1*, *3*, *4*). Anti-tumor immunity also leads to immunoediting, a process favoring the eventual outgrowth of tumor cells with reduced immunogenicity (*3*).