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LETTERS

Acceleration of Greenland ice mass loss in spring 2004

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In 2001 the Intergovernmental Panel on Climate Change projected the contribution to sea level rise from the Greenland ice sheet to be between −0.02 and +0.09 m from 1990 to 2100 (ref. 1). However, recent work[2–4] has suggested that the ice sheet responds more quickly to climate perturbations than previously thought, particularly near the coast. Here we use a satellite gravity survey by the Gravity Recovery and Climate Experiment (GRACE) conducted from April 2002 to April 2006 to provide an independent estimate of the contribution of Greenland ice mass loss to sea level change. We detect an ice mass loss of 248 ± 36 km^3 yr^{-1}, equivalent to a global sea level rise of 0.5 ± 0.1 mm yr^{-1}. The rate of ice loss increased by 250 per cent between the periods April 2002 to April 2004 and May 2004 to April 2006, almost entirely due to accelerated rates of ice loss in southern Greenland; the rate of mass loss in north Greenland was almost constant. Continued monitoring will be needed to identify any future changes in the rate of ice loss in Greenland.

The Greenland mass balance in a warming climate is a competition between increased precipitation caused by greater oceanic evaporation, and a combination of increased melting at the ice sheet surface and increased glacial discharge at the coasts. All these trends have been confirmed in recent studies. Regional climate models, supported by *in situ* observations, suggest that both accumulation and melting have increased during the past decade, with melting increasing faster than accumulation[5]. These surface mass balance estimates are consistent with radar altimeter measurements during 1992–2003 that show interior growth[6,7], and with laser altimeter observations that show thinning in the 1990s at low elevations[8] where increased melting is probably more important than increased accumulation. Laser altimeter and satellite radar imaging observations over the last decade have shown accelerated glacial mass loss at the ice sheet margins[2–4,9,10].

Here we estimated changes in Greenland mass using an independent technique based on data from the GRACE satellite mission. GRACE, launched in March 2002 by NASA and Deutsches Zentrum für Luft- und Raumfahrt, is mapping the Earth's gravity field every month during its 8–9-year lifetime[11]. In a previous study a Greenland mass loss of 82 ± 22 km^3 yr^{-1} was estimated using monthly GRACE gravity solutions for the period April 2002–July 2004[12]. Here, we extended that analysis to include solutions to the end of April 2006. GRACE provides a comprehensive survey of the entire ice sheet, free from the issue of incomplete spatial sampling and other limitations that characterize competing techniques. The primary limitations of GRACE are that it cannot provide spatial resolution finer than a few hundred kilometres, and that it is particularly sensitive to post-glacial rebound (PGR, the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years).

Each GRACE monthly gravity solution consists of spherical harmonic (Stokes) coefficients C_{lm} and S_{lm}, to degree l and order m both ≤120. Here, we used CSR Release 1 (http://podaac-www.jpl.nasa.gov/grace/) solutions for 42 months between April 2002 and April 2006. The C_{20} coefficients show large variability, so we replaced them with values derived from satellite laser ranging[13]. We used the Stokes coefficients to estimate monthly mass changes of the entire Greenland ice sheet, and of South and North Greenland separately (defined here as the regions south and north of 73.25°). We constructed an averaging function for each region using a method that minimizes the combined measurement error and signal leakage (Fig. 1)[14]. GRACE does not recover $l = 1$ Stokes coefficients (representing displacements of the Earth's centre of mass), so we removed those coefficients from the averaging function. We convolved the GRACE Stokes coefficients with these averaging functions to obtain monthly mass change estimates. We simultaneously fitted a trend and annually and semiannually varying terms to each time series.

Before the trends can be interpreted as mass loss estimates, they must be scaled and corrected for contamination from other geophysical signals, and uncertainty estimates must be derived. Procedures for scaling and for estimating uncertainties are described below. For sources of contamination we considered changes in the distribution of (1) continental water storage outside Greenland, (2) water in the ocean, (3) atmospheric mass, and (4) the PGR signal in the solid Earth. Contamination from (3) and (4) comes mostly from mass variability directly above (3) or below (4) the ice sheet. Leakage from (1) and (2) occurs because our averaging functions extended outside Greenland. This latter leakage is increased because our omission of $l = 1$ terms caused the averaging functions to have small-amplitude tails extending around the globe.

To estimate the leakage from (1) and (2), we used global land water storage output from the Global Land Data Assimilation System model[15], and sea floor pressure fields from a baroclinic ocean

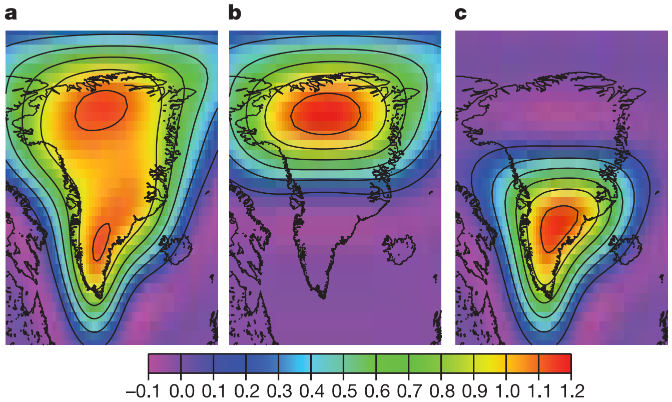

Figure 1 | **Averaging functions.** Shown are the (unscaled, dimensionless) averaging functions used to estimate the change in total Greenland mass (**a**), and in the mass of North (**b**) and South Greenland (**c**) separately.

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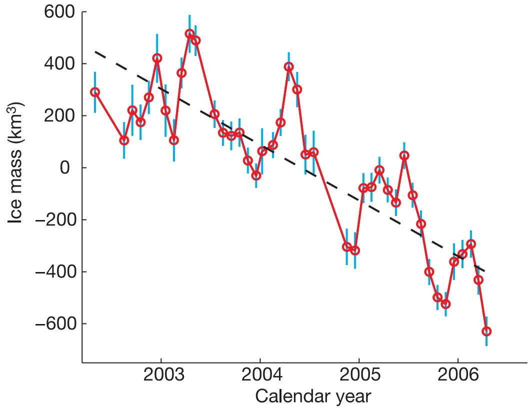

Figure 2 | Greenland GRACE monthly mass solutions. Shown is the GRACE solution for the entire Greenland ice sheet, for April 2002 to April 2006, after scaling the results and removing the mean. The blue error bars include only the contributions from uncertainties in the GRACE gravity fields, and represent 68.3% confidence intervals[18]. Also shown is the best-fitting linear trend (dotted line). The results shown here have not been corrected for PGR or for the effects of hydrological or oceanic leakage.

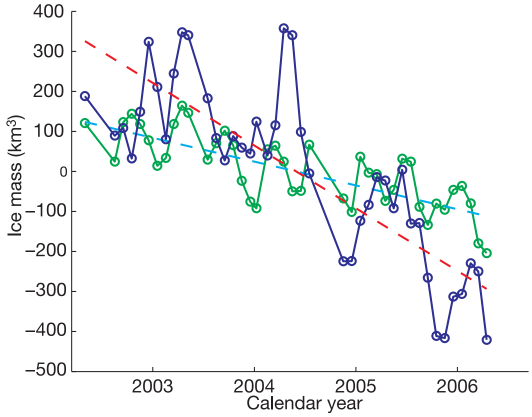

Figure 3 | North and south Greenland GRACE monthly mass solutions. This is shown as in Fig. 2, but for South Greenland (blue monthly values with the best-fitting trend shown as a red dotted line) and North Greenland (green monthly values with the best-fitting trend shown as a cyan dotted line) separately.

model[16] forced by atmospheric winds and pressure. We added a uniform layer to the global ocean at every time step to conserve the total land + ocean mass. We convolved monthly surface mass estimates from these models with our Greenland averaging functions, and fitted a trend and annually and semiannually varying terms to the results. We used the trend as our estimate of hydrological + oceanographic leakage. Because long-period variability is difficult to model, we adopt a conservative uncertainty estimate equal to ± the leakage estimate itself.

Figure 2 shows the monthly (scaled) GRACE estimates for all Greenland, before removing the hydrological and oceanographic leakage. There is a clear decrease in mass during this 4-year period. Interpreting the trend as due entirely to a change in ice, and subtracting the leakage trend, we inferred an ice volume decrease of $240 \pm 12\,\mathrm{km}^3\,\mathrm{yr}^{-1}$. The trend obtained without removing the leakage is $224 \pm 8\,\mathrm{km}^3\,\mathrm{yr}^{-1}$. The ±12 uncertainty is the root sum square (RSS) of the ±8 gravity field error and the uncertainty in the leakage estimate.

Contamination from the atmosphere and from PGR must be evaluated separately. The GRACE project uses meteorological fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) to remove atmospheric effects from the raw data before constructing gravity fields. We evaluated the probable effects of errors in the meteorological fields by comparing ECMWF pressure fields with pressure observations from stations in the World Meteorological Organization catalogue and from Greenland automatic weather stations[17]. The variance of atmospheric errors is less than 3% of the GRACE variance, implying a negligible contribution to the trend uncertainty.

The PGR signal is indistinguishable from a linear trend in ice mass, and must be independently modelled and removed (see below). We obtained a PGR contribution to the GRACE estimate of total Greenland ice decrease of $-8 \pm 21\,\mathrm{km}^3\,\mathrm{yr}^{-1}$. When this PGR contribution was subtracted from the GRACE-minus-leakage trend, we obtained $248 \pm 36\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ as our final estimate of the decrease in total Greenland ice during April 2002–April 2006. The uncertainty is the RSS of the uncertainties in the GRACE fit, in the hydrology + ocean leakage, and in the PGR contribution, with an additional overall 5% error from the uncertainty in the scaling factor. This rate of ice loss corresponds to $0.5 \pm 0.1\,\mathrm{mm}\,\mathrm{yr}^{-1}$ of global sea level rise.

Figure 3 shows the monthly GRACE results after applying the same analysis to North and South Greenland separately. A mass loss is clearly evident in each region, but the South Greenland trend is especially notable. After correcting for the effects of contamination from hydrological, oceanographic, and PGR signals, we obtained ice losses of $161 \pm 24\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ and $83 \pm 18\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ for South and North Greenland respectively, during April 2002–April 2006. The mass loss in the south was twice that in the north during these four years. Our results show a significant increase in the rate of Greenland mass loss, starting in spring 2004. A fit to the GRACE results for all Greenland before and after April 2004 yielded ice loss trends of $104 \pm 54\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ during April 2002–April 2004, and $342 \pm 66\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ during May 2004–April 2006.

This corresponds to a 250% increase in the ice loss rate after April 2004. The acceleration occurred mostly in the south. There, the ice loss rate increased from $20 \pm 26\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ during April 2002–April 2004 to $246 \pm 36\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ during May 2004–April 2006. For North Greenland the ice loss rate was about the same during April 2002–April 2004 ($80 \pm 28\,\mathrm{km}^3\,\mathrm{yr}^{-1}$) as during May 2004–April 2006 ($90 \pm 28\,\mathrm{km}^3\,\mathrm{yr}^{-1}$). Changes in mass loss rates are evident in Fig. 4, which shows best-fitting trends for moving two-year data spans, each obtained by simultaneously solving for a trend and annually and semi-annually varying terms. Figure 4 shows that the South Greenland trends increase as the two-year period passes through spring 2004. The North Greenland trends are relatively constant over this time period.

Because only four years of data are available at present, GRACE is not yet able to tell us whether the 250% increase in the Greenland trend is a true long-term increase in ice loss such as might be caused by accelerated glacial discharge, or is an interannual variation in accumulation or melting. However, the timing of the GRACE acceleration is consistent with the dramatic 2004 acceleration of the Kangerdlugssuaq and Helheim glaciers in southeast Greenland that was detected using satellite radar observations[4]. Furthermore, independent estimates of Greenland surface mass balance variability through the end of 2004 (ref. 5) show no evidence of accelerated surface mass loss with the timing and amplitude of the GRACE results. The implication is that the increased mass loss rate inferred from GRACE probably reflects accelerated flow of glacial ice into the ocean from South Greenland, and suggests that this increased flow is probably the dominant mechanism at present in controlling the overall mass balance of the ice sheet. This mass loss component does not figure into traditional surface mass balance estimates, and is difficult to recover with a radar altimeter given the large altimetry footprint.

Our numerical results are consistent with recent remote sensing estimates that indicate the total Greenland mass loss more than doubled between 1996 and 2005, from $90\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ to $220\,\mathrm{km}^3\,\mathrm{yr}^{-1}$ (ref. 2). The GRACE results provide a completely independent measurement that recovers both the glacial discharge and the surface mass balance component in a single observational result, and allow us to identify the timing of this accelerated mass loss and the region

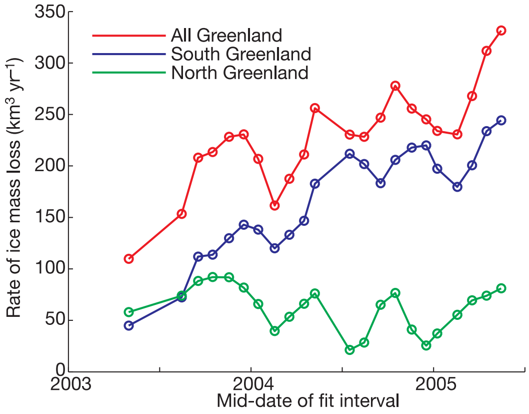

Figure 4 | The best-fitting mass loss trends for each region, as determined for moving two-year data spans. The dates on the *x* axis indicate the mid-times of each two-year period.

(South Greenland) from which it originated. Mass loss in North Greenland was relatively constant during this time period. There are, however, indications based on radar interferometric surveys that the glacial accelerations already occurring in southern Greenland may be in the process of spreading into regions further north[2]. Continued monitoring with GRACE will help identify any future increase in the rate of ice loss in this region.

METHODS

Scaling. Our optimal averaging functions (Fig. 1) have values less than 1.0 over most of their respective regions, and extend outside those regions. They thus give results that are biased low. To recover unbiased mass estimates for all Greenland we scaled its averaging function so that when applied to a uniform 1-cm ice change over all regions within a few hundred kilometres of the Greenland coast, but zero in the interior, it returns an average Greenland value of 1 cm. We obtained a scaling factor of ~2. This choice of mass distribution is motivated by laser altimeter data suggesting that the largest Greenland mass changes are concentrated at the edges[10]. If, instead, we had scaled the averaging function to reproduce the mass from 1 cm of ice spread evenly over all Greenland, the scale factor would be reduced by 5%. This 5% difference is included in our overall uncertainty estimates. To determine scaling factors for South and North Greenland is more complicated because the South Greenland averaging function extends slightly over North Greenland, and vice versa. We applied each averaging function to a uniform mass change over each region individually, and used the four resulting values to determine the linear combination of South and North Greenland results that correctly recovers the mass in each region. Again, these scaling factors have a 5% uncertainty, which we included in our overall uncertainty estimates.

Gravity field uncertainties. We estimated 1σ uncertainties caused by errors in the gravity fields, by convolving our averaging functions with uncertainty estimates for the GRACE Stokes coefficients[18]. The uncertainties in each Stokes coefficient were obtained by assuming that the scatter of the 42 monthly values about their best-fitting annual cycle is due entirely to errors, with no contributions from real geophysical signals. This is certainly not true and led to overestimated errors. The convolution with an averaging function assumes that the errors in different Stokes coefficients are uncorrelated. This assumption is not true either, and led to error estimates for the mass results that oversimplify their spatial pattern. The scatter of the non-annually varying mass estimates shows larger amplitudes at high northern latitudes than were expected from our error estimates[18,19]. This could be due either to non-annually varying geophysical signals, or to error correlations between Stokes coefficients. Comparable results derived from hydrological and oceanographic models show enough similarity with GRACE to suggest that the increased GRACE scatter at high latitudes probably reflects contributions from real geophysical signals, rather than increased errors there[18].

Post-glacial rebound. The two main sources of PGR model error are the ice history and the Earth's viscosity profile. We used two Greenland ice history models: ICE-5G[20] and GREEN1[21]. For ice loading outside Greenland we use both ICE-5G and ICE-3G[22]. We convolved these ice histories with viscoelastic Green's functions for an incompressible Earth[12], constructed using a wide range of plausible two-layer viscosity profiles. We computed a set of Stokes coefficient trends for each Green's function and each ice model, and convolved those trends with the GRACE Greenland averaging functions. We obtained a range of possible PGR contributions to the GRACE mass trends. For our preferred PGR contribution we used results based on ICE-5G and the VM2 viscosity profile adopted for the construction of ICE-5G (ref. 20). We used the range of values determined from all other viscosity profiles and ice models as our PGR uncertainty estimate.

We concluded that the PGR signal causes an apparent Greenland ice decrease of -8 ± 21 km^3 yr^{-1}. About half this uncertainty comes from not knowing the viscosity profile, and half comes from the uncertainty in the ice model. The relatively small preferred value (-8 km^3 yr^{-1}) may seem incompatible with the expectation that the Earth beneath Greenland should be rebounding upward at a significant rate owing to the Holocene removal of Greenland ice. But Greenland lies outside the forebulge of the Pleistocene ice sheet in northern Canada, and so there is subsidence caused by the removal of that ice sheet. The -8 km^3 yr^{-1} value comes from the near-cancellation of ~25 km^3 yr^{-1} signals caused by the Greenland and non-Greenland ice histories. The degree of this cancellation is different in North and South Greenland, where the preferred values are -9 km^3 yr^{-1} and $+5$ km^3 yr^{-1}, respectively.

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