Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations

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Mass changes of the Greenland ice sheet resolved by drainage system (DS) regions are derived from a local mass concentration analysis of the GRACE mission gravity observations. During 2003-2005, the ice sheet lost 101±16 Gt/yr with a gain of 54 Gt/yr above 2000 m and a loss of 155 Gt/yr at lower elevations. The lower elevations show a large seasonal cycle with mass losses during summer melting followed by gains from fall through spring. The overall rate of loss reflects a considerable change in trend (-113 ± 17 Gt/yr) from a near balance of the 1990’s, but is smaller than some other recent estimates.

Mass changes of the Greenland ice sheet are of considerable interest because of their sensitivity to climate change and the potential for an increasing contribution of Greenland ice loss to rising sea level. Observations and models have shown that in recent years Greenland has experienced significantly increased melt (1), thinning at the margins (2–4), and significantly increased discharge from many outlet glaciers (5). At the same time the ice sheet has been growing in its interior (3, 4, 6).

These recent changes in the Greenland ice sheet and the wide range of mass-balance estimates (7) highlight the importance of methods for directly observing variations in ice sheet mass. Moreover, the fact that some regions are shedding mass dramatically while others are not (2–5), indicates a clear need for measurements with a spatial resolution that allows assessment of the behavior of individual drainage systems (DS). The local mass concentration analysis presented here provides an assessment of mass balance of individual Greenland DS regions sub-divided by elevation as well as the overall ice sheet mass balance.

Direct measurements of mass change have been enabled by the NASA/DLR Gravity Recovery and Climate Experiment (GRACE) mission (8). Since its launch in March of 2002, GRACE has been acquiring ultra-precise (0.1 µm/sec) inter-satellite K-band range and range-rate (KBRR) measurements taken between two satellites in polar orbit approximately 200 km apart. The changes in range-rate sensed between these satellites provide a direct mapping of static and time-variable gravity.

Recent GRACE-based mass balance estimates of Antarctica (9) and Greenland (10, 11) have been derived from the monthly spherical-harmonic gravity fields produced by the GRACE project. While these solutions represent an important advance in using gravity measurements to assess ice sheet mass balance they are limited in their temporal and spatial resolution. For example, the recent results presented in (11) show sizable mass loss spread over the entire Greenland continent in contrast with recent studies that indicate loss concentrated on the margins (2–5) and growth in the interior (3, 4, 6). However, the fundamental measurements being made by GRACE contain far more information than is currently being exploited by techniques that rely on these monthly spherical-harmonic fields. Close examination of the KBRR measurements reveals coherent mass variation signals at better than 400 km full wavelength spatial and 10-day temporal resolution at the mid-latitudes (12), and still better resolution at high latitudes.

Our approach to estimating ice-sheet mass changes follows a strategy of preserving the gravity information contained within the GRACE KBRR observations. This is accomplished through an innovative processing of the GRACE inter-satellite range-rate measurements (13) and the parameterization of local mass variations as mass concentrations (mascons). Mascons are estimated from short arc solutions of GRACE KBRR data exclusively within a local area of interest (12). The regional solution exploits the fact that the signal from a mass concentration observed in the GRACE KBRR data is centered over the mass concentration and is spatially limited in extent. The mathematical formulation of mascon parameters, the details of the local
mascon approach, and the results of a simulation which validate the method are provided in the supporting online material (14). The results of the simulations show that the mascon approach is capable of recovering the spatial distribution and magnitude of realistic and complex ice mass change signal to better than 90% (14).

For our ice sheet analysis, a mascon parameter corresponds to a surplus or deficit of mass in an irregularly shaped DS region (Fig. 1) defined by surface slopes and climatology (15) and sub-divided into surface elevation above and below 2000 m. Exterior regions (as outlined in Fig. 1) as well as daily baseline state parameters are estimated to account for mass variations occurring outside our Greenland DS regions of interest (14). The mascon estimates are relative to models of both static and time varying gravity effects (e.g. tides and atmospheric mass redistribution) in order to isolate ice mass change (14).

We derive mascon solutions from GRACE KBRR data for each drainage system region (Fig. 1) every 10-days from July 2003 through July 2005. A summary of the resultant mascon solutions is presented in Table 1. The individual elevation dependent mascon solution time series can be summed over each 10-day interval to produce time series for the six overall DS (Fig. 2), and time series for regions above and below 2000 m elevation (Fig. 3). The results summarized in Table 1 and Fig. 2 and 3 represent the total observed mass variation including the trends from Glacial Isostatic Adjustment (GIA). Included separately in Table 1 is the computed GIA trend from ICE-5G using a 90 km lithosphere and VM2 viscosity model (16).

Fig. 2 shows the northern DS-1 and 2, and the southwest DS-5 are nearly in mass balance considering the associated error bars and the GIA noted in Table 1. DS-3, 4 and 6 all exhibit significant mass loss with DS-4, the southeast, dominating the overall mass loss. Fig. 3 presents our mascon time series for the regions above and below 2000 m elevation. For the two years (July 2003 – July 2005) our solutions (Fig. 3) show a moderate growth of 54 ± 12 Gt/yr for the high elevation Greenland interior with a significant loss of 155 ± 26 Gt/yr occurring in the low elevation coastal regions. Therefore, we obtain a total Greenland trend of −101 ± 16 Gt/yr. These trends have been corrected for GIA and scaled by 1.1 to account for potential signal loss as determined in the simulation analysis (14). Treatment of the associated errors is discussed in (14). The mass loss is dominated by loss in the eastern low elevation coastal regions and the southeast DS-4. Our overall Greenland mass trend of −101 ± 16 Gt/yr is consistent with the GRACE based analysis by (17) which determined a trend of −118 ± 14 Gt/yr for the time period of July 2002 – March 2005. However, these overall trends are nearly a factor of two smaller than the recent GRACE based trend determined in (11). The results presented in (11) show significant mass loss over the entire continent and therefore are difficult to reconcile with known mass loss concentrated in the low elevation coastal regions and gain in the interior.

The high elevation interior region solutions show little annual cycle with an overall amplitude of 13 ± 9 Gt, while in contrast the low elevation coastal region solutions resolve a significant annual cycle with an amplitude of 150 ± 27 Gt (Table 1 and Fig. 3). The low elevation coastal region annual cycle exhibits significant mass shedding beginning in May-June and ending in October corresponding to summer melt (Fig. 3). The largest annual cycle is found in the southwest DS-5. A nearly semiannual signal most noticeable in DS-2 is an artifact caused by mismodeled ocean tides (14).

The temporal and spatial resolution of the GRACE mascon solutions provides important insights into the ice sheet behavior and the quality of the mascon solutions. The moderate growth of the high elevation interior ice sheet with significant mass shedding of the low elevation coastal regions is consistent with other recent studies (1–6). In addition the solutions exhibit a relatively small annual cycle for the high-elevation interior ice sheet consistent with the low temperatures, negligible melting, and small seasonal variation in precipitation. The low elevations show a large annual cycle with the largest in the southwest DS-5. These results are consistent with warm summer temperatures of the coastal regions in general, and combined with shallow slopes for DS-5 in particular, leading to the most extensive summer melt (18). Therefore, our mascon time series for the low elevations exhibit seasonal characteristics that are very consistent with the well-known net ablation during summer melt followed by growth during winter, as shown for example by radar altimeter data (3) and surface mass balance models (19).

Comparison of our 2003-2005 ice mass trends by DS in Table 2 to the 1992-2002 trends computed from satellite radar and airborne laser altimetry (3) provide insights into the evolution of the ice sheet. The changes of the trends with time of the two most northerly DS-1 and 2 are not significantly different from zero, which is consistent with the lack of glacier acceleration (5) or detected icequakes (20) reported for those areas. DS-3 in the east appears to have changed by −20 GT/yr from a slightly negative balance (−5 GT/yr) to a significantly negative overall balance of −25 GT/yr with very large mass shedding in the low elevation coastal region and growth at high elevations (Table 1). While DS-3 had one accelerating glacier (5) and icequakes in two glaciers (20), it has also had a large average annual mass input of 42 GT/yr (3) and is therefore very sensitive to interannual variations or trends in precipitation and ice accumulation. Our largest observed change (−61 GT/yr) occurred in DS-4 in the southeast, while the other significant negative change occurred in DS-6 in the west (−32 GT/yr), consistent with glacier accelerations (5) and increases in icequakes (20) in
that system. In particular, the acceleration of three glaciers in DS-4 indicated an increase in the rate of loss in 2005 compared to 1996 of -56 GT/yr (5), which is comparable to our change of -61 GT/yr. In DS-5 and 6, the change from glacier accelerations was -25 GT/yr (5), which compares well with our total change of -37 GT/yr that includes changes in surface balance as well as changes in glacier discharge. While the extent to which meaningful conclusions can be drawn from a 2-year time series is limited, due to the influence of interannual variations, the consistency of our results with all other indications of accelerating mass loss (1, 4, 5, 19) strongly supports our interpretation that a significant change in the Greenland mass balance has occurred primarily in DS 3, 4, and 6.

The high temporal resolution of the mascon solutions provides unprecedented observation of mass change events and provides the opportunity to apply filtering techniques to reduce the solution noise. By reliably resolving ice mass change observations into ice sheet drainage system scales sub-divided by surface elevation, the mascon solutions provide the ability to separate the areas of rapid loss (e.g. the southeast system 4 and the low elevation coastal regions, Fig. 2 and 3) from areas of slower loss or even gain (e.g. high elevation interior regions). The mascon solutions provide a better basis for comparison to passive microwave-derived melt data (18) and surface mass balance models (19), and facilitate the comparison to flux-based methods (5) and altimetric methods (2–4, 6, 21) that examine individual drainage basins.

Our GRACE mascon solutions provide a direct measure of mass changes on the scale of DS sub-divided into regions above and below 2000 m surface elevation. In contrast with other recent gravity based mass balance estimates (10, 11, 17) our mascon solutions exhibit significantly improved spatial resolution delineating high elevation interior region growth and significant mass loss for the low elevation coastal regions. In addition the mascon solutions show improved temporal resolution delineating the large seasonal cycle for the low elevation coastal regions, observing the summer melt and winter growth cycles. Our finding of an overall mass loss of 101 ± 16 GT/yr for 2003 to 2005 is consistent with the finding of near balance during the 1990’s (3) and with the recent results on increased melt rates (1), acceleration of outlet glaciers (5, 20), and the increasingly negative surface balance in recent years (22). The Greenland mass loss contributes 0.28 ± 0.04 mm/yr to global sea level rise which is nearly 10% of the 3 mm/yr rate recently observed by satellite altimeters (23). The observed change from the 1990’s of -113 ± 17 GT/yr represents a change from a small growth of about 2% of the annual mass input to a loss of about 20%, which is a significant change over a period of less than 10 years (24). This result is in very good agreement with the change in trend of -117 GT/yr from 1996 to 2005 determined from radar interferometry (5). During the 1990’s the observed thinning at the margins and the growth inland were both expected responses to climate warming. Our new results suggest that the processes of significant ice depletion at the margins, through melting and glacier acceleration, are beginning to dominate the interior growth as climate warming has continued.

References and Notes

7. For mass balance within the 1992-2002 time period the following estimates have been published: +11 ± 3 GT/yr for 1992-2002 (3), -46 GT/yr for 1993/4 – 1998/9 (21), -72 ± 11 GT/yr for 1997-2003 (2) and -83 ± 29 and -127 ± 29 GT/yr for 1996 and 2000 respectively (5). If the correction for firn compaction used in the radar altimeter analysis (3) is applied to the airborne altimeter estimates (2, 21), the difference between the two approaches is reduced by approximately 23 GT/yr as reflected by revised airborne values of -4 to – 50 GT/yr for 1993 to 1999 (4).
14. Materials and methods are available as supporting material on Science Online.
24. For the 1990’s, we use the small 11 GT/yr mass gain from (3) and note that the negative balances discussed in (7) would give either significantly less negative changes than 113 Gt/yr or would give positive changes in contradiction to the evidence for increases in melt and glacier accelerations. Also, our 113 ± 17 Gt/yr is in good agreement with the change in mass flux of 117 Gt/yr from 1996 to 2005 from radar interferometry (5).
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Supporting Online Material

www.sciencemag.org/cgi/content/full/1130776/DC1

Materials and Methods

Fig S1

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Include this information when citing this paper

**Figure 1.** Greenland drainage system (DS) mascon regions: regions above 2000 m elevation labeled “a” and those below labeled “b”. Exterior region mascons outside of Greenland are also shown outlined in red.

**Figure 2.** Greenland drainage systems two-year (July 2003 – July 2005) mascon time series (summing regions above and below 2000 m elevation for each system) derived from GRACE KBRR data: 10-day estimates (blue dots with error bars), Gaussian 1-d filter with 30-day window applied to 10-day estimates (green line), trend (red line) recovered from simultaneous estimation of bias, trend, annual and semi-annual sinusoid. Trends have not been corrected for GIA.

**Figure 3.** Time series computed from the sum of mascon region solutions above and below 2000 m elevation: 10-day estimates (blue dots with error bars), Gaussian 1-d filter with 30-day window applied to 10-day estimates (green line), trend (red line) recovered from simultaneous estimation of bias, trend, annual and semi-annual sinusoid. Trends have not been corrected for GIA.
### Table 1. Summary of Greenland drainage system mascon solutions above and below 2000 m elevation (July 2003 – July 2005).

<table>
<thead>
<tr>
<th>Drainage System</th>
<th>Observed Mass Change</th>
<th>GIA* GT / yr</th>
<th>Annual Amp. GT</th>
</tr>
</thead>
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<tr>
<td></td>
<td>&gt; 2000 m</td>
<td>&lt; 2000 m</td>
<td>&gt; 2000 m</td>
</tr>
<tr>
<td>1</td>
<td>13 ± 2</td>
<td>-4 ± 4</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>40 ± 2</td>
<td>-32 ± 2</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>50 ± 3</td>
<td>-75 ± 2</td>
<td>-1</td>
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<tr>
<td>4</td>
<td>-38 ± 11</td>
<td>-33 ± 3</td>
<td>-1</td>
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<tr>
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</tr>
<tr>
<td>6</td>
<td>-27 ± 3</td>
<td>6 ± 5</td>
<td>-1</td>
</tr>
<tr>
<td>Greenland</td>
<td>41 ± 8</td>
<td>-140 ± 24</td>
<td>-8</td>
</tr>
</tbody>
</table>

*GIA: ICE-5G, 90 km lithosphere and VM2 viscosity model (16)

### Table 2. Comparison of mascon derived trends with previous values determined from satellite and airborne altimetry (3).

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>8 ± 5</td>
<td>1.6 ± 0.3</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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<td>-4.9 ± 2.0</td>
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<tr>
<td>4</td>
<td>-77 ± 11</td>
<td>-15.7 ± 1.2</td>
<td>-61 ± 11</td>
</tr>
<tr>
<td>5</td>
<td>7 ± 13</td>
<td>11.4 ± 0.8</td>
<td>-5 ± 13</td>
</tr>
<tr>
<td>6</td>
<td>-22 ± 7</td>
<td>10.5 ± 0.5</td>
<td>-32 ± 7</td>
</tr>
<tr>
<td>Greenland</td>
<td>-101 ± 16</td>
<td>11.7 ± 2.5</td>
<td>-113 ± 17</td>
</tr>
</tbody>
</table>

*Corrected for GIA and potential signal loss (~9%) as determined from simulation analysis (14). Errors computed as in (14) along with assuming 100% error in GIA.
Regions above 2000 m

Trend: 41 +/- 8 Gt/yr

Regions below 2000 m

Trend: -140 +/- 24 Gt/yr