Mass change of the Greenland ice sheet from GRACE, ICESat and GPS

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Motivation

Numerous studies have been conducted to investigate the mass balance in Greenland. Most of these studies, however, used only a certain space technique, while studies based on combined processing of multiple remote-sensing data are relatively rare. Moreover, aside from GPS sites installed mostly along the coast of Greenland, \textit{in situ} measurements are not available.

We address this issue by estimating the total mass change of the Greenland ice sheet based on a joint processing of the GRACE satellite gravity data, the ICESat satellite laser measurements, the GPS observations, while involving also the surface mass balance model. This model provides the information about the snow accumulation and ice discharge.
Method

We investigate the mass changes of the Greenland ice sheet based on combining GRACE, ICESat, surface mass balance model and GPS observations between September 2003 and October 2009.

The forward modelling technique is applied to process the GRACE data in order to partially mitigate ocean-land leakage effect.

The ICESat data processing strategy involves the repeat-tracks least-squares plane fitting method with slope correction.

The surface mass and firn ice elevation changes were estimated from the RACMO2.3 and IMAU-FDM models.

The GIA trend was estimated from GPS time series of vertical motions.
Large differences exist in published estimates of the mass balance change of the Greenland ice sheet, with a range of values from -280 to -80 Gt/yr (Table 1). Even within the same observation periods and using the same data, these differences could still be significant. Slobbe et al. (2009), for instance, used the GRACE data from different data processing centers. According to their results, mass change rates of the Greenland ice sheet were $-218 \pm 18$ Gt/yr (from CSR), while only $-168 \pm 05$ Gt/yr (from GFZ) during the period of 2002.04-2007.06. This large disagreement is mainly due to uncertainties of forward models (e.g. snow accumulation model for surface mass balance, and firn compaction and surface density models for altimetry) that are indispensable to simulate some processes that are unmeasured or unknown for these observations. Moreover, the glacial isostatic adjustment (GIA) has to be taken into consideration when estimating ice sheet mass changes. Studies confirmed that GRACE estimates of the Greenland ice sheet mass change are greatly affected by the use of different GIA models. Due to a lack of climatological and geophysical data to constrain the glacial history and Earth’s viscoelastic structure, GIA models are still affected by large uncertainties.
# Studies of Greenland Ice Sheet Mass Balance

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<td>-82±28 km³/yr</td>
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<td>SMB+ID</td>
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<td>Rignot et al. (2006)</td>
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<td>Ewert et al. (2012)</td>
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<td>2003.08-2008.03</td>
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Data

**GRACE** Level 2 monthly spherical harmonic coefficients of the ITSG-GRACE2016 prepared by the Institute of Geodesy in Graz (ITSG). These coefficients are compiled with a spectral resolution complete to the spherical harmonic degree of 60. The ITSG-GRACE2016 is the latest GRACE-only gravity model that provide unconstrained monthly and Kalman-smoothed daily solutions.

**ICESat** data over 15 observation campaigns of ~35 days between 2003 and 2009 to estimate changes of ice and snow elevations in Greenland. For this purpose, we first converted the measured ICESat elevations (that are referenced with respect to the Topex/Poseidon ellipsoid and the EGM96 geoid) to the WGS84 ellipsoid elevations. The GLA14 data releases are provided with control indicators and corrections to illustrate data acquisition and to correct elevation data. In order to ensure the data accuracy and to improve the data quality, we selected the ICESat elevation data based on checking a quality index and applying a number of necessary corrections (such as the saturation elevation correction).
**Data**

**RACMO2.3 and IMAU-FDM:** In order to separate the contribution of ice sheets mass changes from elevation changes that involve ice and snow mass changes and GIA, we used the monthly mean of surface mass balance from the Regional Atmospheric Climate Model (RACMO2.3) that is prepared by the Institute for Marine and Atmospheric research Utrecht over the period from 1958 to 2016. The surface mass balance is basically defined as the sum of accumulations of snow, rain from which the surface ablation (erosion and sublimation, runoff, wind and snow) is subtracted. In the 1990s, the Royal Netherlands Meteorological Institute cooperated with the Danish Institute of Meteorology to develop the research model RACMO based on the High Resolution Finite Area Model (HIRLAM).

**GPS** tracking time series for one station per day provided the NASA Jet Propulsion Laboratory and the Scripps Orbit and Permanent Array Center.

**GIA** model of Geruo et al. (2013) to correct the GRACE estimates. This model was compiled based on the ICE-5G deglaciation history, VM2 viscosity profile and the PREM-based elastic structure.
Figure 1 Seasonal mass changes derived from the ITSG-GRACE2016 data between September 2003 and October 2009: (a) annual amplitude, (b) semi-annual amplitude, (c) annual phase, and (d) semi-annual phase.
Results - GRACE

Figure 2 Seasonal mass variations obtained from processing GRACE data and estimated by applying the forward modelling technique between September 2003 and October 2009. The values represent monthly averages.
Results of GRACE

Figure 3 Mass change rates derived from ITSG-GRACE2016 data between September 2003 and October 2009: (a) GRACE apparent mass rate before correcting for the ocean-land leakage effect, (b) the forward modeled mass rate after correcting for the ocean-land leakage effect, and (c) the mass rate from the GRACE RL05 mascon solution.
Results of ICESat

Figure 5 Elevations and elevation changes of the Greenland ice sheet from the ICESat data
Figure 6 Estimates of (a) the mean surface mass balance from RACMO2.3, (b) the surface density from IMAU-FDM, and (c) the firn ice height rates from IMAU-FDM between 2003 and 2009.
Results of ice discharge

Figure 7 Ice discharge rate from the GRACE and surface mass balance between 2003 and 2009.
Results of GPS

Figure 8 Vertical crustal deformation rates derived from GPS.
Results of GIA

Figure 9 GIA in Greenland according to Geruo et al. (2013)

Figure 10 Vertical crustal deformations due to GIA derived from GRACE, ICESat and the surface mass balance estimated from the RACMO2.3 and IMAU-FDM models.
Conclusions

- The total mass budget of the Greenland ice sheet is characterized by seasonal maxima in May and minima in October. The annual mass accumulation of the Greenland ice sheet over the investigated period is far too small to offset the mass loss caused by snow and ice melting.
- The mass change rate of the Greenland ice sheet estimated from GRACE data (by applying the forward modelling technique) was $-217.88\pm4.48$ Gt/yr for 6 years (between September 2003 and October 2009).
- A similar result of $-237.94$ km$^3$/yr over the same period was confirmed based on processing the ICESat data.
Conclusions

- We found significant differences between GPS vertical crustal motions and the vertical deformations due to GIA estimated from a combined processing of GRACE, ICESat and incorporating the surface mass balance estimated from the RACMO2.3 and IMAU-FDM models. Whereas the former are only positive, the latter are positive as well as negative. Both these estimates also differ when compared with the GIA model predicted using ice load history and geophysical models.
Conclusions

From GRACE the total mass of the Greenland ice sheet between August 2002 and December 2016 decreased at an annual rate of -267.77±8.68 Gt.
Thank You