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Acceleration of the Greenland ice sheet mass loss as observed by GRACE: Confidence and sensitivity

P.L. Svendsen*, O.B. Andersen, A.A. Nielsen

DTU Space, Technical University of Denmark, Kgs. Lyngby, Denmark

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ABSTRACT

We examine the scale and spatial distribution of the mass change acceleration in Greenland and its statistical significance, using processed gravimetric data from the GRACE mission for the period 2002–2011. Three different data products – the CNES/GRGS, DMT-1b and GGFC GRACE solutions – have been used, all revealing an accelerating mass loss in Greenland, though with significant local differences between the three datasets. Compensating for leakage effects, we obtain acceleration values of $-18.6\ \mathrm{Gt/yr^2}$ for CNES/GRGS, $-8.8\ \mathrm{Gt/yr^2}$ for DMT-1b, and $-14.8\ \mathrm{Gt/yr^2}$ for GGFC.

We find considerable mass loss acceleration in the Canadian Arctic Archipelago, some of which will leak into the values for Greenland, depending on the approach used, and for our computations the leakage has been estimated at up to $-4.7\ \mathrm{Gt/yr^2}$.

The length of the time series of the GRACE data makes a huge difference in establishing an acceleration of the data. For both 10-day and monthly GRACE solutions, an observed acceleration on the order of $10-20\ \mathrm{Gt/yr^2}$ is shown to require more than 5 yrs of data to establish with statistical significance.

In order to provide an independent evaluation, ICESat laser altimetry data have been smoothed to match the resolution of the GRACE solutions. This gives us an estimated upper bound for the acceleration of about $-29.7\ \mathrm{Gt/yr^2}$ for the period 2003–2009, consistent with the acceleration values and corresponding confidence intervals found with GRACE data.

1. Introduction

In recent years, the mass loss of the Greenland Ice Sheet (GrIS) has been analysed in a variety of ways, including altimetry, gravimetry and mass budget calculations, establishing a continuing decrease in the ice mass, with a number of studies finding an acceleration in the mass loss, such as Rignot et al. (2008), or in glacial retreat, e.g. Howat and Eddy (2011).

Determination of acceleration in GRACE (Gravity Recovery and Climate Experiment) time series has been examined in previous studies using piecewise line fits (Chen et al., 2006), as well as line fits through a differenced time series for the entire ice sheet (Rignot et al., 2011). As noted by Wouters et al. (2008), the GRACE solutions contain enough data to allow regional estimation of trends, though assessing the mass loss to be dominated by summer events rather than a linear trend. We examine pointwise trend fits, though such trends should only be considered qualitatively.

The mass loss, previously mostly limited to the southeast part, has been spreading to northwest Greenland in recent years, as confirmed using GRACE and GPS data (Khan et al., 2010), Gardner et al. (2011) have also found a rapidly increasing mass loss in the Canadian Arctic Archipelago (CAA) for the period 2004–2009, using both surface mass budget/discharge, GRACE and ICESat data.

While the GRACE mission provides a unique set of gravity data, the measurements need considerable processing to yield usable mass change data. Slobbe et al. (2009) compared four different GRACE solutions, obtaining mass change rates varying by almost a factor of two (between -128 and $-218\ \mathrm{Gt/yr}$) for the period 2002–2007. Sørensen and Forsberg (2010) also found substantial differences in Greenland mass change rates (between -67 and $-189\ \mathrm{Gt/yr}$ for 2002–2008) depending on the GRACE solution used.

Velicogna (2009) fitted a quadratic trend to the GRACE data for Greenland (April 2002–February 2009), using a 13-month moving average and an F-test to conclude that it provides a better fit than a simple linear trend, and obtaining an acceleration for this period of $-30 \pm 11\ \mathrm{Gt/yr^2}$.

We examine the variation in this mass loss acceleration within Greenland, with uncertainty estimation for both local and overall trends for three different datasets, with an additional three for reference. Since the time series for the GRACE data are relatively short for the purposes of determining secular trends, we have estimated a development of the size of the confidence intervals

* Corresponding author. Tel.: +45 45259742.
E-mail address: plsv@space.dtu.dk (P.L. Svendsen).

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with increasing length of the observation period in order to determine the length of GRACE time series required to establish the presence of an acceleration.

2. Data

We consider three different GRACE data products, each giving mass changes as equivalent water height (EWH).

The CNES/GRGS (Groupe de Recherche de Géodésie Spatiale) 10-day solutions (release 02) used are $1^\circ \times 1^\circ$ grids based on spherical harmonics up to degree and order 50. They are stabilised (constrained) towards a time-variant mean field, EIGEN-GRGS.RL02.MEAN-FIELD (Bruinsma et al., 2010) and span from August 2002 to August 2011. A total of twenty 10-day solutions are missing, mostly at the beginning and end of the time series.

The DMT-1b monthly solutions from Delft Institute for Earth-Oriented Space research (DEOS) are $0.5^\circ \times 0.5^\circ$ grids, based on spherical harmonics up to degree and order 120. The timespan covered is from February 2003 to November 2010. While their temporal resolution is lower than the CNES/GRGS solution, their spatial resolution is considerably higher. The DMT-1b solutions are given as deviations from the mean field EIGEN-GL04C, and smoothed by post-processing using a Wiener filter (Ditmar et al., 2011). One monthly solution (June 2003) is missing.

The monthly solutions from Global Geophysical Fluids Center (GGFC) are $1^\circ \times 1^\circ$ grids, truncated at degree 60 and covering from April 2002 to September 2011. They are derived from the CSR RL04 solutions, and have decorrelation/destriping and 500 km Gaussian smoothing applied, consequently yielding generally smaller signals than the other solutions (Swenson and Wahr, 2006). Five monthly solutions are missing from the GGFC (June/July 2002, June 2003, and January/June 2011); they have been downloaded from http://www.csr.utexas.edu/research/ggfc/dataresources.html.

In order to test the effect of smoothing and processing of the GRACE data on establishing mass loss acceleration, three additional models were included in the analysis. These models were release 4 of the Center for Space Research (CSR) and GeoForschungsZentrum Potsdam (GFZ) for the period 2003–2011 (downloaded from (http://podaac.jpl.nasa.gov/grace) as well as the ITG-GRACE 2010 for the slightly shorter period 2003–2009. As the GGFC is basically a decorrelated version of the CSR solution, this gives a total of five independent models which were submitted to a common or identical computation of mass change for Greenland. Monthly solutions were used to compute EWH mass changes using the method by Andersen et al. (2005) and applying a Gaussian smoothing of 500 km. Gravity coefficients for degree and order 2–50 were used fora each model, as GRACE does not recover spherical harmonic coefficients 0 and 1. Furthermore the C_{20} time series was substituted by more accurate time series derived from satellite laser ranging (Cheng and Tapley, 2004). For consistency, the following monthly solutions have been set to be missing for all solutions: June/July 2002, June 2003, and January/June 2011.

3. Model

Our model is a simple ordinary least squares (OLS) regression model. Since we are testing for the presence of an acceleration, the predictors in the model include a constant term, time, and time squared (the latter normalised by 1/2). Also included, based on results from spectral analysis of the CNES/GRGS data, are harmonic oscillations of 1/1-, 1/2- and 1/3-yr wavelengths; the subannual frequencies are due to the somewhat sawtooth-shaped waveform of the annual signal, as the ice level each year takes

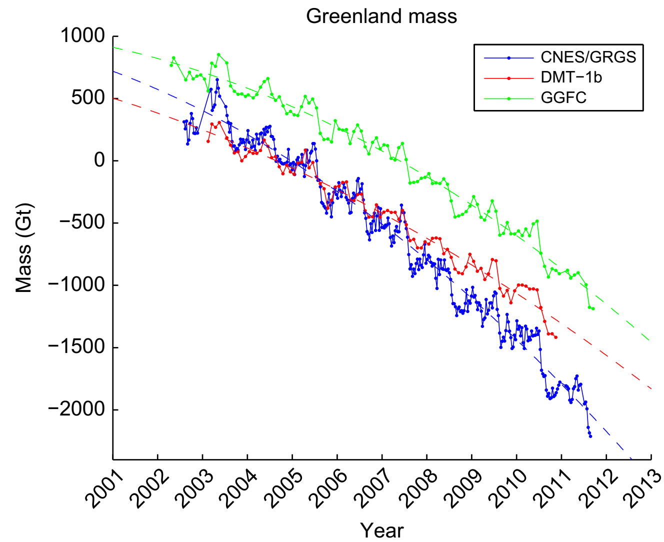

Fig. 1. Time series and OLS model fits for the Greenland mass for each of the GRACE solutions used (400 km mask extension applied); the mass values are relative to an arbitrary zero level. Only the nonseasonal (polynomial) parts of the model are shown.

more time to build up than to melt, which is also visible to some extent in Fig. 1. Velicogna (2009) also uses a quadratic model to examine the acceleration of the ice sheet, though with a smoothing procedure to filter out seasonal variation, then fits a quadratic trend; this should take into account the variability of the seasonal amplitude. However, variation in the seasonal amplitude and phase will still show up in the residuals from an OLS model, and we find that an OLS model with the three harmonic oscillations to provides a very good fit to the GRACE solutions used.

3.1. Parameter dispersion

Considering each pixel's EWH time series as a column vector $\boldsymbol{y}$, we can build a predictor matrix $\mathbf{X}$ containing the desired functions of time. For such an OLS model

$$\boldsymbol{y} = \mathbf{X}\boldsymbol{\theta} + \boldsymbol{e} \tag{1}$$

we can determine a dispersion matrix of the estimated coefficients $\hat{\boldsymbol{\theta}}$, $D(\hat{\boldsymbol{\theta}})$. This is given by the predictor and the mean squared error ($\hat{\sigma}^2 = \hat{\boldsymbol{e}}^{\mathsf{T}}\hat{\boldsymbol{e}}/(N-p)$) of the fit relative to the input data

$$D(\hat{\boldsymbol{\theta}}) = \hat{\sigma}^2 (\mathbf{X}^{\mathsf{T}}\mathbf{X})^{-1} \tag{2}$$

Then, using the diagonal elements $\hat{\sigma}^2_{\theta_i} = D(\hat{\boldsymbol{\theta}})_{i,i}$ (i.e., the parameter variances), we can obtain a test statistic

$$z_i = \frac{\hat{\theta}_i - c_i}{\hat{\sigma}_{\theta_i}} \tag{3}$$

to test for equality of the coefficient $\hat{\theta}_i$ with a constant c_i. Assuming the residuals to be normally distributed and independent, z_i will then follow a t-distribution with $(N-p)$ degrees of freedom, where N is the number of data points in the time series, and p the number of parametres. The assumption about the residuals is key to the validity of the coefficient confidence intervals; if data uncertainties are not present as Gaussian noise of appropriate variance, the confidence intervals will generally not reflect the true sensitivity of the model.