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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 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.

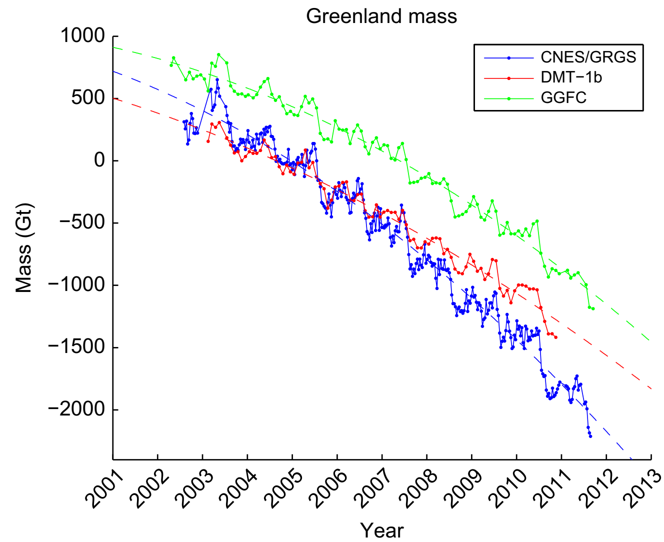

Fig. 1. Time series and OLS model fits for the Greenland mass for each of the GRACE solutions used (400 km mask extension applied); the mass values are relative to an arbitrary zero level. Only the nonseasonal (polynomial) parts of the model are shown.

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.

4. Results

4.1. Mass trends for the entire Greenland ice sheet

Fitting to the area-integrated EWH values within the Greenland mask (as opposed to the pointwise data), all three GRACE solutions show an overall acceleration in the ice mass loss. The best-fit mass acceleration values for Greenland within a mask extended 400 km from the coast are shown in Table 1.

The OLS model provides a good fit to the Greenland mean EWH for all three datasets; all have $R^2 > 0.98$, and all have root mean squared errors (RMSE) of less than 80 Gt (or 2 cm EWH). Rignot et al. (2011) obtain a GRACE mass loss acceleration for Greenland of 17.0 ± 8 Gt/yr^2, with an additional estimate from the mass budget method of 19.3 ± 4 Gt/yr^2 (i.e., estimated from weather and glacial movement).

The DMT-1b solution yields a smaller RMSE than the other two solutions, though the coefficient of determination R^2 is the smallest of the three. This suggests that although the model provides a closer fit in absolute terms, it also generally exhibits less variation to explain. The differences between the GRACE products may be due to differences in the way the solutions are constrained; the Greenland mass values from DMT-1b are less prone to large, sudden jumps.

The CNES/GRGS and the GGFC solutions have roughly the same time span, and the acceleration integrated over Greenland are very similar and within the confidence intervals estimated. The DMT-1b solution provides a somewhat lower estimate due to the fact that data are missing for 2002 and 2011 and thus the time span is shorter; also, this solution sees a very large slowdown of the melting in Southeast Greenland, cf. Fig. 3. If the southeastern part of Greenland is not considered the three solutions agree to better than ± 3 Gt/yr^2 in acceleration.

The confidence intervals given in Table 1 are determined from the residuals of the model fit to the input data. Since the data products are very smooth, these errors may be artificially low. As an alternative, one could decide on a fixed estimate for $\hat{\sigma}^2$ if specific knowledge is available regarding the uncertainties in the data.

Because of the smoothness of the data, and because the mass loss is largely focused in coastal areas, the relevant mass changes affect pixel time series some distance outside Greenland, and a spatially extended mask must be applied when determining the total mass loss. In our investigation we used a spatial mask extension of half the maximum wavelength represented in each model (cf. Slobbe et al., 2009). Consequently the spatial mask extensions were 400 km for GRGS, 330 km for GGFC and 170 km for the DMT-1b model.

Note that we have not corrected the trends for glacial isostatic adjustment (GIA), which in Greenland may appear in the mass change rate as up to 1–2 cm/yr of water equivalent, mostly present in the northernmost part of Greenland, per the model by (Paulson et al., 2007). However, for the short time span considered, this rate may be considered constant, allowing us to consider the acceleration without correcting for GIA. Velicogna (2009) also concluded that a change in the rate of the ice mass loss on this time scale would not be affected by GIA.

Change in the rate of ice mass loss might also be contaminated by leakage from change in mass loss rates from other geophysical signals. Velicogna (2009) estimated the contribution from a combination of the GLDAS land hydrology and ECCO general circulation model (Lee et al., 2002). In both cases it was found that the predicted oceanic and hydrological leakage is negligible.

The most notable leakage problem will be leakage from recently observed mass loss acceleration in the CAA region, as described by Gardner et al. (2011). A simulation was performed to study the impact of this mass loss. In this simulation, the observed mass acceleration of approximately -20 Gt/yr^2 by Gardner et al. (2011) was added to the northern CAA region and a spherical harmonic expansion to degree and order 50 was performed. Subsequently the contribution to this signal under the 400 km extended Greenland mask were computed. This gave a leakage of -4.7 Gt/yr^2 for the 400 km mask, -3.0 Gt/yr^2 for the 330 km GGFC mask and -1.2 Gt/yr^2 for the 170 km DMT-1b mask. Subsequently our estimates should be corrected for this contribution; the corrected acceleration values in Table 1 will thus be -18.6 Gt/yr^2 for the CNES/GRGS solutions, -8.8 Gt/yr^2 for DMT-1b, and -14.8 Gt/yr^2 for GGFC.

Table 2 confirms that all commonly used GRACE solutions show a clear acceleration of mass loss on Greenland. The CSR and GFZ both confirm an acceleration of the same magnitude as the original CNES/GRGS solutions as well as the CNES/GRGS solution processed using common or identical processing to the two other GRACE solutions. It is also notable that the CSR solution shows higher acceleration than the GGFC solution based on the same Release 4 CSR data, but decorrelated to remove the north-south striping in GRACE (Chen et al., 2006). The results found here are in agreement with the fact that this decorrelation removes part of the signal (Swenson and Wahr, 2006). Contrary to this both the DMT and the CNES/GRGS solutions computed using identical processing shows less acceleration. This can largely be explained by the fact that the manually processed solution is smoother and

Table 2
Acceleration values with 95% confidence intervals for all six models. In this case, the solutions have been processed in a common way—truncated at degree and order 50, smoothed with a 500 km Gaussian filter and computed with 400 km Greenland mask extension. Note that the GGFC solution thus becomes equal to the CSR product on which it is based.

GRACE product	Time span	d/o	Smoothing (km)	Acceleration (Gt/yr^2)	RMSE (Gt)
CSR (GGFC)	2003–2011	50	500	-22.1 ± 4.3	66.9
GFZ	2003–2011	50	500	-21.3 ± 3.9	59.1
CNES/GRGS	2002–2011	50	500	-18.9 ± 1.7	48.3
ITG	2002–2009	50	500	-12.8 ± 4.8	41.7
DMT	2003–2010	50	500	-14.2 ± 4.9	54.1

Table 1
Acceleration values with 95% confidence intervals, root mean squared error (RMSE, $\hat{\sigma}$), and coefficient of determination for OLS fits to the total Greenland mass level. The values are given for mask extensions calculated for the maximum degree and order of each individual dataset; as described in the text, the values include a leakage from the Canadian Arctic Archipelago, estimated as up to approximately -4.7 Gt/yr^2 for the largest extension. The acceleration value with this estimated leakage removed is also shown. Processing notes: (1) inversion, (2) optimal (Wiener) filtering, and (3) decorrelation and 500 km Gaussian smoothing.

GRACE product	Time span	Resolution	Proc.	Acc. (Gt/yr^2)	Acc. (no CAA) (Gt/yr^2)	RMSE (Gt)	R^2
CNES/GRGS	2002–2011	d/o 50	(1)	-23.3 ± 2.9	-18.6	76.6	0.9885
DMT-1b	2003–2010	d/o 120	(2)	-10.0 ± 3.8	-8.8	41.7	0.9856
GGFC	2002–2011	d/o 60	(3)	-17.8 ± 3.1	-14.8	51.3	0.9898

hence will be more contaminated by leakage from CAA as described previously.

The RMSE values of Table 2 show a slightly different picture compared to Table 1; for example, the CSR solution (on which the GGFC is based) now has the largest RMSE of all. Large values of the RMSE appear to be associated with large acceleration, and may thus be a reflection of a larger underlying signal variation in the GRACE solution, rather than a poorer model fit as such.

The DMT and ITG models (Mayer-Gürr et al., 2005) only cover the first 7 and 6 yrs of the time period, respectively. Both show accelerations that are roughly 8 Gt/yr^2 smaller than the longer periods except for the models computed over longer timeseries. This seems to agree well with the fact that Greenland experienced record-breaking summer melting during 2010 and 2011 which is not fully accounted for in this shorter time series.

4.2. Spatial distribution of trends

Applying the OLS model to the individual time series (i.e., each pixel), we can obtain an estimate for the EWH acceleration in each particular point. Since the datasets are spatially very smooth, the mass loss from any actual point will be smeared out across numerous pixels, but we may obtain a qualitative value for the acceleration. The best-fit local accelerations for the individual data products are shown in Figs. 2–4.

Regressions on the individual pixels of the datasets generally show highly statistically significant results, with p-values for zero acceleration down to the order of 10^{-81} (CNES/GRGS), 10^{-5} (DMT-1b) and 10^{-33} (GGFC) within the Greenland mask. The particularly low values for the CNES/GRGS and GGFC data are likely due to the processing, with any signals constrained and/or smoothed to lie closely around the mean field.

The three solutions agree on a clear accelerated mass loss in the northwestern part of Greenland and all GRACE solutions agree that the major acceleration is found around the Melville Bay/Thule region where several huge glaciers are found. The CNES/GRGS solution also identifies a secondary maximum in the Disko Bay right on the Jakobshavn Glacier. It is interesting that this maximum is not seen in the CNES/GRGS data if the timespan is limited to the time period for the DMT-1b solution. By excluding or including CNES/GRGS GRACE data for 2011, it is generally revealed that the acceleration computed for the 2002–2010 period is continued in 2011, but with an increased acceleration around the Jakobshavn Glacier.

The DMT-1b solution clearly stands out from the other two solutions in Southeast Greenland. Both the CNES/GRGS and the GGFC solutions show a positive acceleration in the eastern Greenland corresponding to a slowdown in the melting, but neither of the two solutions show the huge signal that is found in the DMT-1b solution.

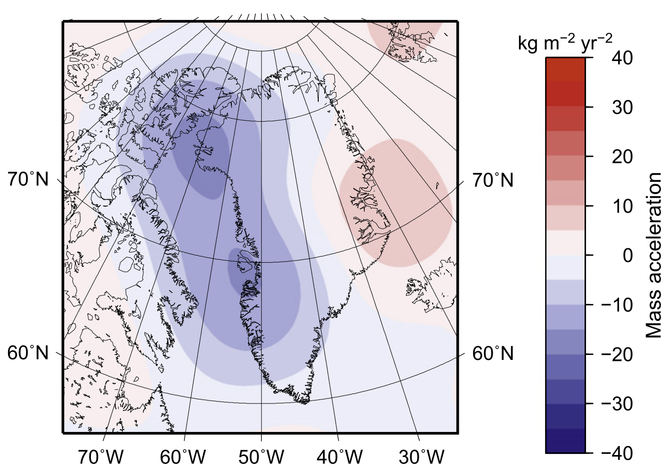

Fig. 2. Acceleration in the CNES/GRGS model over Greenland (July 2002–August 2011).

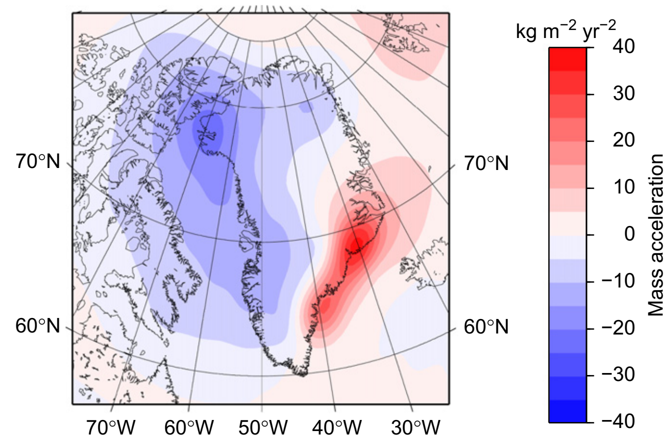

Fig. 3. Acceleration in the DMT-1b model over Greenland (February 2003–November 2010). Note the apparent strongly positive acceleration (slowing mass loss) in SE Greenland, which is not present in the CNES/GRGS and GGFC solutions.

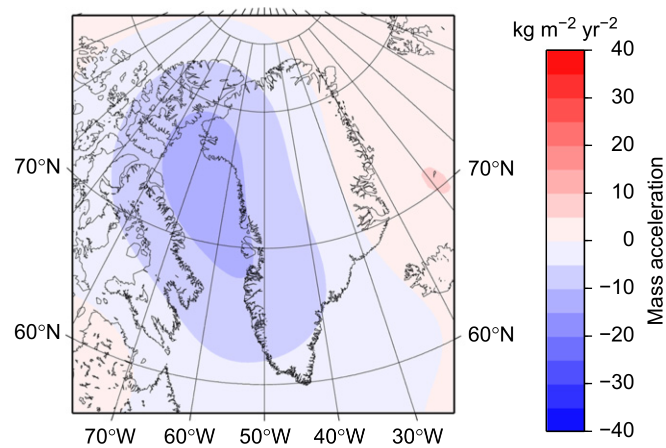

Fig. 4. Acceleration in the GGFC model over Greenland (April 2002–September 2011).

The maximum in the DMT-1b solution is neatly located close to the Kangerdlugssuaq glacier around 68.5°N and 30.5°W, with a secondary maximum close to the Helheim glacier at 66.5°N and 37°W, which could support the physical nature of such a signal. Moreover, the DMT-1b solution is given up to degree and order 120, whereas the CNES/GRGS and GGFC are only given up to degree/order 50 and 60, respectively, and thus this model should be able to resolve much finer spatial signal. The six GRACE solutions processed as similarly as possible were studied to determine the effect of the processing (smoothing/inversion) on the result. Most GRACE solutions show a deceleration over southeast Greenland. However, for identical processing, the DMT solution clearly shows a much larger deceleration than any other solution.

In order to investigate this in more detail, Fig. 5 shows the time series of EWH development for the Kangerdlugssuaq glacier for the CNES/GRGS and DMT-1b solutions. The two models agree on the magnitude and rate of melting. However, a larger acceleration of the melting was seen during the 2005–2007 period and a corresponding deceleration in the 2007–2010 period is seen for the DMT-1b solution giving rise to a much larger overall positive acceleration for the 2002–2010 period. The huge acceleration of the melting during the first period have also been confirmed by GPS-observed uplift close to the two glaciers (Khan et al., 2010).

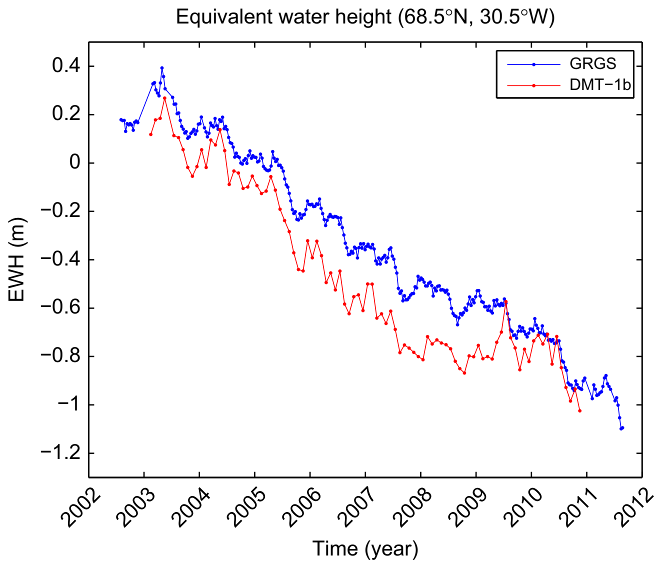

Fig. 5. EWH development for a point in southeast Greenland, where the DMT-1b model shows a large positive acceleration (see Fig. 3). It is clear that the positive acceleration is due to relatively low values in the period 2005–2009.

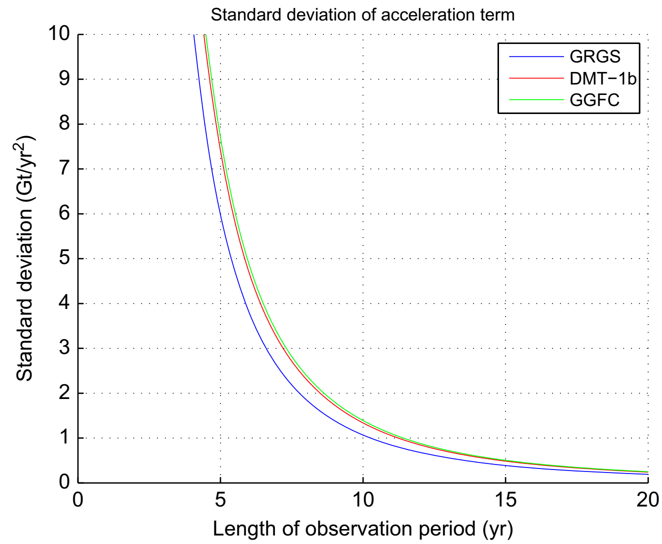

Fig. 6. Theoretical development of the standard deviation of the acceleration term with increasing time series length, taking into account the interval length and determined RMSE for each dataset.

4.3. Confidence intervals

The standard deviations of the acceleration terms are very much dependent on location, with larger dispersion generally occurring in areas containing any kind of signal (secular or seasonal variation). With the DMT-1b data, we obtain standard deviations of below 1 mm/yr^2 in the centre of the ice sheet to more than 4 mm/yr^2 in the southeast. In the southeast, a considerable seasonal signal is present, and the larger error is likely to be a reflection of the variations in seasonal changes.

The model RMS errors variy considerably for the local fits, with values of about 1.5 mm in central Greenland to 6 mm (CNES/GRGS) or 10 mm (DMT-1b) in the southeast, reflecting the spatially more well-defined phenomena in the DMT-1b solutions.

As the length of the GRACE time series increases, the acceleration term can be determined with improving precision. As Fig. 6 shows, the uncertainty is very similar for all three solutions, with slightly smaller confidence intervals for the CNES/GRGS solutions.

The standard deviations in Fig. 6 have been computed analytically, though (for ease of computation) without seasonal terms in the model, which we have empirically found to have a very small influence on the scale of these values.

The DMT-1b solutions yield a wider confidence interval for the total Greenland acceleration than the other two solutions, due to the time series being somewhat shorter than the other two (since the RMSE is virtually equal to that of the also monthly GGFC data).

Since the number of observations in each case is large compared to the number of model parameters, a $t(N-p)$ distribution will be approximately normal. Thus, the acceleration can be considered statistically significantly different from 0 when the term is more than 2–3 standard deviations from 0, assuming the RMSE to be an appropriate estimate of the uncertainty in the data.

The length of the time series of the GRACE data makes a huge difference in establishing the presence of an acceleration in the data. For example the monthly DMT-1b and GGFC an observed acceleration on the order of 10–20 Gt/yr^2 requires more than 5 yrs of data to establish. This period may naïvely be considered shorter for the 10-day GRGS data, but it should be noted that the shorter time averaging used for the GRGS data sacrifices some of the spatial resolution (and precision of each data point) of the data.

4.4. Comparison with ICESat results

The laser altimeter onboard ICESat can be used to provide an upper bound on the acceleration in ice mass loss of Greenland. ICESat observes the change in volume of the Greenland ice sheet. The laser pulse reflects from the uppermost surface of the snow, making it difficult to accurately estimate mass change from ICESat. However, assuming the entire volume to be solid ice and using the density of pure ice (917 kg/m^3), volume change from ICESat can be used to estimate an upper bound on the mass change. ICESat laser altimetry data for the 2003–2009 period were provided and prepared as in Sørensen et al. (2011) for comparison with the GRACE data. The estimated ICESat normal point acceleration parameters were then expanded into spherical harmonic functions to degree and order 50 to yield an upper bound on the acceleration of mass-loss of approximately -29.7 Gt/yr^2.

This compares well with the findings using CNES/GRGS and GGFC in this study. ICESat provides very high resolution data and the results by Sørensen et al. (2011) also confirm that the melting is primarily focused along the edges of the Greenland Ice Sheet. Unfortunately, due to the failure of the instrument onboard the satellite, the ICESat data are only available up to 2009.

5. Conclusions

We find a statistically significant acceleration in the Greenland Ice Sheet mass loss with all three data products used. There is variation in best-fit values between the data products and their respective uncertainties. For the CNES/GRGS and GGFC solutions spanning the entire 2002–2011 period, we find an acceleration of -18.6 Gt/yr^2 and -14.8 Gt/yr^2, whereas the DMT-1b solution spanning 2003–2010 gives a lower acceleration of -8.8 Gt/yr^2. These values are lower than the -30 ± 11 Gt/yr^2 by Velicogna (2009), though nearly consistent with the value of -17.0 ± 8 Gt/yr^2 by Rignot et al. (2011).

In addition to the mass loss in Greenland, we find a considerable contribution from the CAA of up to -4.7 Gt/yr^2. This is both apparent when plotting the local best-fit acceleration, and was verified by simulating a mass loss at the CAA and computing the contribution under the Greenland mask. The findings are also supported by Gardner et al. (2011).

Despite local disagreement between the data products, all models agree that the acceleration in mass loss is largely confined to the west-northwestern part of Greenland. For southeast Greenland, the DMT-1b model indicates a significant deceleration which is not found by the two other models.

Establishing the presence of an acceleration on the order of magnitude found in the Greenland Ice Sheet requires more than 5 yrs of data, and we find that the GRACE time series available are now long enough to establish the presence of such an acceleration.

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