GREENLAND ICE SHEET CHANGES FROM SPACE USING LASER, RADAR AND GRAVITY

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ABSTRACT

The Greenland cryosphere is undergoing rapid changes, and these are documented by remote sensing from space. In this paper, an inversion scheme is used to derive mass changes from gravity changes observed by GRACE, and to derive the mean annual mass loss for the Greenland Ice Sheet, which is estimated to be 204 Gt/yr for the period 2002-2010.
NASA's laser altimetry satellite ICESat has provided elevation estimates of the ice sheet since January 2003. In order to be able to compare GRACE and ICESat derived results, the ICESat volume change must be converted into a mass change estimate. Therefore, it is necessary to model the densities and compaction of the firn. We find that data from ASIRAS show great potential for validating the glaciological models used to determine the densities and firn compaction.

Key words: Greenland Ice Sheet; GRACE; ICESat; ASIRAS.

1. INTRODUCTION

The space-based techniques for measuring cryospheric changes are very different in nature, and have different advantages and disadvantages. The large present-day changes of the Greenland Ice Sheet are quantified by the different satellite data sets. Gravity changes observed by the GRACE satellites since 2002 can be used to estimate the total mass loss of the ice sheet [1, 2, 3]. The GRACE observations are sensitive to other mass redistribution signals such as post glacial rebound (PGR), which is still poorly constrained in Greenland. In this paper, we use an inversion scheme to estimate the mean annual mass loss of the Greenland Ice Sheet from GRACE data (2002-2009).
NASA's laser altimetry satellite ICESat has, since the launch in January 2003, provided time tagged and geolocated elevation estimates of the ice sheet. The ICESat laser signal is reflected by the snow surface and thus allowing the estimation of the change in volume of the entire ice sheet. Modeling of the snow/ice densities, and processes such as firn compaction, is a necessity in order to convert the volume change of snow and ice observed by ICESat into a mass change estimate, which can be compared with the GRACE results.
We show that the use of high resolution SAR altimeter data from ASIRAS along the EGIG line (see Figure 1) has great potential for validating and constraining the glaciological models, used to convert volume to mass changes.

2. MASS LOSS OF THE GREENLAND ICE SHEET FROM GRACE

We use a Tychonov generalized inversion method with regularization described in [4], to derive monthly mass variations of the Greenland Ice Sheet from changes in gravity, observed by the GRACE satellites.
The GRACE Level-2 data used, consist of monthly spherical harmonic expansions of the Earth's gravity potential. The monthly solutions are represented by a set of Stokes harmonic coefficients up to degree and order 60 [5], provided by the CSR processing center (Center for Space Research, University of Texas, USA) [6]. The C_{20} coefficients in the monthly GRACE solutions are replaced by coefficients derived from 5 satellite laser ranging (SLR) campaigns [7].
The gravity signal caused by PGR is determined from the ice history ICE-5G(VM2) [8], and is subtracted from the gravity trend derived from the GRACE data.
The time series of mass change is shown in Figure 2. By fitting a linear trend through the entire period (2002-2009) gives a mean annual mass loss of 204 Gt/year.

3. ICESAT DERIVED ELEVATION CHANGES ALONG THE EGIG LINE

The elevation changes of the ice sheet near the EGIG line are derived from the ICESat data. The area is outlined

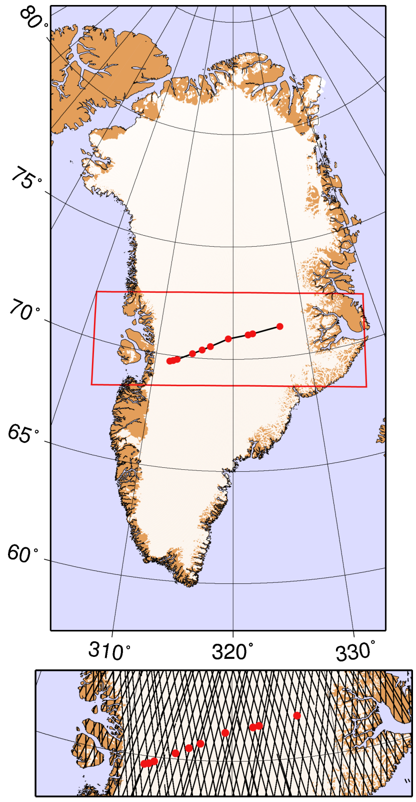

Figure 1. The upper figure shows the EGIG line crossing the Greenland Ice sheet. The lower figure shows the ICESat ground track coverage in the area.

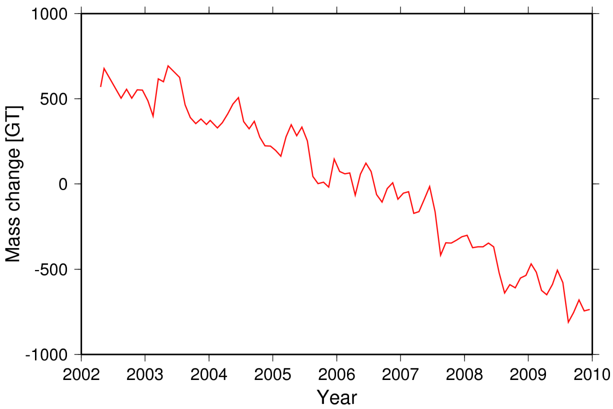

Figure 2. Mass change time series of the Greenland Ice Sheet from the monthly GRACE CSR models.

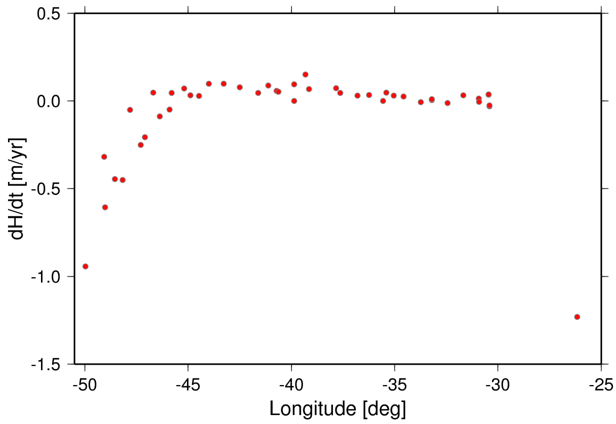

Figure 3. Elevation changes [m/yr] along the EGIG line derived from ICESat data.

in Figure 1. The data used is the GLA12 'Antarctic and Greenland Ice Sheet Altimetry Data' product [9], which was downloaded from National Snow and Ice Data Center. This study is based on the available release 31, 91-day repeat cycle data, spanning the period from October 2003 to March 2008.

Filtering of the data and application of corrections is necessary in order to remove problematic data [10, 11]. The saturation correction is added to the relevant measurements, which are flagged in the data files. We reject problematic data, based on the shape of the return signal, and the number of peaks. Besides these criteria, we have used the data quality flags and warnings given with the data to reject less accurate measurements [12].

Due to problems with the GLAS instrument, ICEsat has measured only 2-3 months (campaigns) every year. The ICESat ground tracks are not exactly repeated, and this makes deriving elevation changes problematic. An observed elevation difference between two (repeat) tracks is a sum of the surface slope, seasonal variations, and a secular trend.

Several method for deriving elevation changes from ICESat data have been published [13, 14, 15]. The elevation changes (dH/dt) presented here, are derived by a method similar to [16, 17] in which the elevation (H) is assumed to be a linear function of time and the surface slope (along-track and cross-track), and a cosine and sine function, describing the seasonal variability. Using this assumption, we estimate dH/dt in 500 m segments along track. The individual ICEsat measurements in each 500 m segment are assigned a weight which ensures that each available ICESat campaign will have equal weight in the dH/dt solution.

Figure 1 shows the ICESat data coverage in the area, and Figure 3 shows the derived elevation changes in a profile crossing the ice sheet, following along the EGIG line. It is seen, that there is a clear thinning of the ice sheet near the ice margins, and that the elevation changes are close to zero in the central parts.

4. DENSITY AND FIRN COMPACTION MODELLING

In order to tie the different observations of the Greenland Ice Sheet together, modelling of snow and firn processes have to be conducted. An observed elevation change of the ice sheet can be related to mass changes by modelling the firn response to climate changes, and the surface density of the ice sheet.

The firn compaction is a function of climate variables such as temperature and accumulation. It is important to determine the elevation changes caused by firn compaction, since it should not contribute to the total mass balance of the ice sheet determined from ICESat data.

Following [18, 19, 20, 21, 22], the annual firn layer thickness (λ) at time after deposition $t = t_0 + t_i$, can be modeled by Eq. 1

$$\lambda(t_0, t) = \begin{cases} \left(\frac{(b(t_0)-r(t_0))\rho_i}{\rho_f(t_0,t)} + r(t_0)\right)\tau & ,b(t_0) \geq r(t_0) \\ b(t_0)\delta(t-t_0)\tau & ,b(t_0) < 0 \end{cases} \quad (1)$$

where b is the surface mass balance, $r(t_0)$ is the amount of refrozen melt water inside the firn layer, ρ_i is the density of ice, ρ_f is the surface firn density, τ is a time constant and δ is the Kronecker delta. The layer thickness is estimated from year to year, to determine the elevation changes of the Greenland Ice Sheet, caused by changes in the surface temperature and precipitation.

Firn compaction modelling is associated with a number of unknowns, and the error analysis is not tangible from the model input. However, an important part of the modelling is to validate the models with airborne measurements such as the ASIRAS flight campaign and connected firn density studies from in-situ measurements.

5. ASIRAS DATA

The ASIRAS instrument [23] is developed as an airborne interferometric SAR altimeter with properties similar to the SIRAL instrument on CryoSat-2. ASIRAS radar data and lidar data was collected in spring 2006 along the EGIG line and snow densities were measured with N-probe [24] at selected sites. A combination of the delay compensated SAR processing and the low flight altitude (approximate 300 m above terrain), allows the radar signal to penetrate up to 15 m into the snow pack. From the radar return signal it is possible to detect layering in the snow pack [25], caused by the seasonal variations in the snow properties.

A local maximum algorithm is used to detect peaks in the ASIRAS echoes, which is related to the annual variation in the snow density. These annual layers can be detected and followed along the EGIG line in the entire dry snow zone, and in some parts of the percolations zone.

Assuming that the snow can be described as a mixture of air and small ice particles, it is possible to calculate

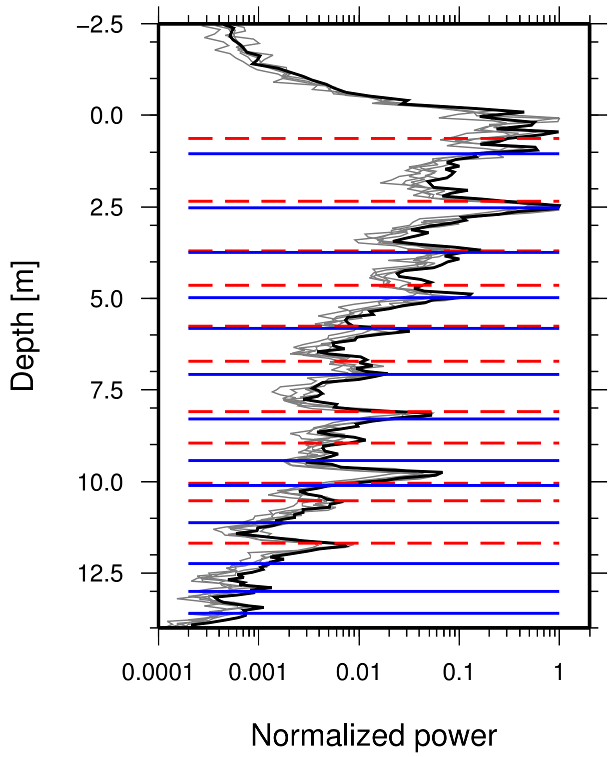

Figure 4. Comparison of different data types at T19. ASIRAS echos (in black and grey), modelled layers (in blue), and high density layers measured by N-Probe (in red).

the permittivity of the snow volume [26], as a function of the density, and hence the refractive index. The apparent depth of a layer can now be converted to true depth using a simple density model for the snow pack. It is now possible to compare the layers derived from the model with the layers detected in ASIRAS data.

An example of typical ASIRAS echoes is shown in Figure 4. The black line shows the echo obtained closest to the T19 site and the grey lines show echoes immediately before and after the closest approach.

6. CONCLUSION AND OUTLOOK

We find a mass loss estimate of the Greenland Ice Sheet of -204 Gt/yr based on GRACE data (2002–2009). In order to compare changes derived from ICESat data with the GRACE results, it is necessary to model firn compaction. Preliminary studies show that the firn compaction is a significant contribution to the total volume change, and therefore it is important to validate the models used.

In order to do so, we use ASIRAS and N-probe data along the EGIG line. We show that in general there are good agreement between ASIRAS data, N-probe data and the snow model west of the Ice Divide, see Figure 4. However, east of the Ice Divide the modelled layers and ASIRAS derived layers deviates, and unfortunately there is no N-probe data in this area to confirm either.

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ECMWF ERA-interim data used in this study have been provided by ECMWF and been obtained from the ECMWF Data Server.
ICESat data was downloaded from the NSIDC web site.
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