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Volume and mass changes of the Greenland ice sheet inferred from ICESat and GRACE

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ABSTRACT

This study examines the recent evolution of the Greenland ice sheet and its six major drainage basins. Based on laser altimetry data acquired by the Ice, Cloud and Land Elevation Satellite (ICESat), covering the period September–November 2003 to February–March 2008, ice surface height changes and their temporal variations were inferred. Our refined repeat track analysis is solely based on ICESat data and is independent of external elevation models, since it accounts for both ice height changes and the local topography. From the high resolution ice height change pattern we infer an overall mean surface height trend of $-0.12 \pm 0.006\,\mathrm{m\,yr^{-1}}$. Furthermore, the largest changes could be identified at coastal margins of the ice sheet, exhibiting rates of more than $-2\,\mathrm{m\,yr^{-1}}$. The total ice volume change of the entire ice sheet amounts to $-205.4 \pm 10.6\,\mathrm{km^3\,yr^{-1}}$. In addition, we assessed mass changes from 78 monthly Gravity Recovery and Climate Experiment (GRACE) solutions. The Release-04 gravity field solutions of GeoForschungsZentrum Potsdam cover the period between August 2002 and June 2009. We applied an adjusted regional integration approach in order to minimize the leakage effects. Attention was paid to an optimized filtering which reduces error effects from different sources. The overall error assessment accounts for GRACE errors as well as for errors due to imperfect model reductions. In particular, errors caused by uncertainties in the glacial isostatic adjustment models could be identified as the largest source of errors. Finally, we determined both seasonal and long-term mass change rates. The latter amounts to an overall ice mass change of $-191.2 \pm 20.9\,\mathrm{Gt\,yr^{-1}}$ corresponding to $0.53 \pm 0.06\,\mathrm{mm\,yr^{-1}}$ equivalent eustatic sea level rise. From the combination of the volume and mass change estimates we determined a mean density of the lost mass to be $930 \pm 11\,\mathrm{kg\,m^{-3}}$. This value supports our applied density assumption $900 \pm 30\,\mathrm{kg\,m^{-3}}$ which was used to perform the volume–mass-conversion of our ICESat results. Hence, mass change estimates from two independent observation techniques were inferred and are generally in good agreement.

1. Introduction

One important topic in the present-day global change debate is the question of how climate change will affect the future sea level change. The global average of sea level rise measured by TOPEX/Poseidon satellite altimetry between 1993 and 2003 is $3.1 \pm 0.7\,\mathrm{mm\,yr^{-1}}$ (IPCC, 2007). For the 21st century, the IPCC (2007) predicted a sea level rise in the range of 0.18–0.59 m with an increasing input from the Greenland ice sheet (GIS). Hence, a sound knowledge of the current evolution of the polar ice sheets, and especially of the GIS, is an essential prerequisite for reliable sea level predictions. Therefore, several recent investigations concentrate on the determination of the present mass balances of the polar ice sheets.

Recent satellite missions allow a comprehensive monitoring of the changing ice sheets and help to improve the estimates of their contribution to global sea level rise. Altogether, there are at least three independent approaches commonly used to determine the mass balance of ice sheets. The first one can be called the *gravity-change approach*, since it utilizes satellite measurements of temporal gravity changes to infer mass changes of the ice sheet. Some of the results yielded by this approach are listed in Table 1. As a second approach, the *mass-budget method*, compares the total accumulation with the total ice mass loss due to melting and discharge through the grounding line. This approach was adopted by e.g. Rignot (2006) (cf. Table 1). The third approach, the *altimetry method*, infers changes of the ice surface elevation from satellite altimetry time series. These elevation changes can be converted into volume changes of the ice sheet as demonstrated by e.g. Slobbe et al. (2009).

The Ice, Cloud and Land Elevation Satellite (ICESat) was the first Earth-orbiting laser altimeter mission in space and provides

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Table 1
GIS mass change trends derived from *altimetry method*†, *mass-budget method*‡ and *gravity-change approach**. The investigations are based on several sensors and cover different periods. For GRACE-derived trends it is indicated whether monthly solutions or the mascon method were utilized.

Author	Method/sensor	GRACE solution	Period	Trend	
				Volume [$km^3\,yr^{-1}$]	Mass [$Gt\,yr^{-1}$]
Krabill et al. (2000)†	Airborne LA		06/94–05/99	−51	
Zwally et al. (2005)†	ERS1/2		04/92–10/02		+11 ± 03
Slobbe et al. (2009)†	ICESat		02/03–04/07		−139 ± 68
Rignot and Kanagaratnam (2006)‡	InSAR		2005	−224 ± 41	
Chen et al. (2006)*	GRACE	CSR	04/02–11/05		−219 ± 21
Ramillien et al. (2006)*	GRACE	CNES	07/02–03/05		−118 ± 14
Luthcke et al. (2006)*	GRACE	Mascon	01/03–12/05		−101 ± 16
Wouters et al. (2008)*	GRACE	CSR	02/03–01/08		−179 ± 25
Velicogna (2009)*	GRACE	CSR	04/02–02/09		−230 ± 33
Slobbe et al. (2009)*	GRACE	CSR	04/02–06/07		−218 ± 18
Slobbe et al. (2009)*	GRACE	GFZ	08/02–06/07		−168 ± 05
Present study†	ICESat		09/03–03/08	−205 ± 11	−185 ± 28
Present study*	GRACE	GFZ	08/02–06/09		−191 ± 21

elevation time series of high resolution along profiles. Based on such a repeated mapping of the ice sheet geometry the *altimetry method* can be applied. Several strategies, like the analysis of crossovers or overlapping footprints (Slobbe et al., 2009) and the repeat track analysis (Thomas et al., 2008) can be utilized for the evaluation of altimetry data. In the present study we make use of the latter approach in order to derive ice elevation changes.

The Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004) provides the opportunity to infer temporal solutions of the Earth's gravity field (e.g. on a monthly basis). Hence, GRACE is suitable to derive the mass balance of the GIS according to the *gravity-change approach*. Within the geoscience community various groups derived mass changes of the GIS utilizing GRACE monthly solutions. Depending on the origin of the GRACE data products, the time period covered and the applied estimation approach the results vary within a range of more than 100 gigatons year^{-1} (Gt yr^{-1}) (cf. Table 1). Our estimated ice mass changes are based on the approach described by Swenson and Wahr (2002) utilizing a regional integration in the spherical harmonics domain and an optimized filtering technique.

In order to compare the results of both techniques the ICESat derived volume changes have to be converted to mass changes. By combining both results (ice volume and mass changes) an effective density of the lost ice mass can be inferred.

2. ICESat: data and methodology

ICESat was the first Earth-orbiting laser altimeter mission in space. Since the launch of the satellite in January 2003, the Geoscience Laser Altimeter System (GLAS) has provided altimetry data with an unprecedented level of accuracy and resolution (Luthcke et al., 2005; Shuman et al., 2006). In contrast to previous radar altimeter missions the footprint is small and varies between 60 and 70 m only. The GLAS operates at a frequency of 40 Hz which leads into a shot-by-shot along-track separation of about 172 m along the track (Luthcke et al., 2005). A detailed overview of the mission and the performance of the GLAS can be found in Schutz et al. (2005) and Abshire et al. (2005). ICESat provides altimetry data between 86° North and South for a wide range of geoscientific research. However, the primary science objective is to focus on the ice sheet mass balances (Zwally et al., 2002).

For our investigation we used the GLAS-12 data product of Release-428 which provides *Antarctic and Greenland Ice Sheet Altimetry Data* and covers the time span from September–November 2003 (2A) to February–March 2008 (3J) with a 91-day repeat orbit. The abbreviations in brackets are the *laser identifiers*, denoting the first and last laser operational period (LOP) of the evaluated time span. Fig. 1(a) shows the spatial distribution of the ICESat elevation profiles over the GIS. It can be seen that the across-track distance between the elevation profiles is a function of latitude. Shortly after each laser started its operation the measurement performance of the GLAS was heavily affected by saturated waveforms due to strong reflectors such as snow and sea ice. Therefore we applied the saturation range correction to all elevations used in this study, as strongly recommended by ICESat data processing center. This correction has been provided together with the GLAS-12 data product since Release-428 (Fricker et al., 2005). In addition, we utilized several quality flags given by the GLAS-12 data set, that indicate the quality of the laser measurements (NSIDC, 2010). All measurements which are subject to larger uncertainties were excluded from the analysis. Recorded elevation profiles during off-nadir operations of the satellite system are also eliminated from the investigation. The remaining data set was corrected for laser campaign biases. These biases have been determined by a crossover minimization approach utilizing ICESat data covering the subglacial Lake Vostok area in Antarctica. Richter et al. (2008) could confirm that in this region the ice surface height is very stable in time. Our obtained campaign bias rate of 2.0 ± 0.6 cm yr^{-1} is equivalent to the value of 2.0 ± 0.9 cm yr^{-1} obtained by Urban and Schutz (2005) and Gunter et al. (2009).

There are several methods to retrieve elevation changes from altimetry data. A short overview of the approaches mainly used can be found in Slobbe et al. (2008). The crossover analysis, a widely used tool in the analysis of radar-altimetry data, calculates height differences at the intersection points of ascending and descending elevation profiles. One of the major disadvantages of this approach is the fact that only a small fraction of the original data amount is used for the analysis (height information at crossovers only). In order to make use of the full potential of ICESat high-resolution elevation profiles we utilized the repeat-track analysis for our investigation. That approach calculates the height differences of corresponding along-track laser measurements (cf. Fig. 2(a)).

The ICESat spacecraft system was originally designed to maintain the repeat cycles within an across-track distance of ±35 m to the reference orbit (Zwally et al., 2002). Due to errors in pointing and smaller differences between the predicted and real satellite orbit, the across-track distances between the individual repeat-cycles can be larger than originally intended. Moreover, the distance varies from a few meters up to hundreds of meters (Pritchard et al., 2009). Under these circumstances it is impossible to infer elevation differences from corresponding along-track elevation measurements without taking the influence of local surface slope into account. Slobbe et al. (2008) avoided that problem by calculating the elevation change at overlapping footprints. To minimize the residual influence of the surface slope, Slobbe et al. (2008) used an external DEM to infer the surface slope effect on the