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25 years of elevation changes of the Greenland Ice Sheet from ERS, Envisat, and CryoSat-2 radar altimetry

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ABSTRACT

The shape of the large ice sheets responds rapidly to climate change, making the elevation changes of these ice-covered regions an essential climate variable. Consistent, long time series of these elevation changes are of great scientific value. Here, we present a newly-developed data product of 25 years of elevation changes of the Greenland Ice Sheet, derived from satellite radar altimetry. The data product is made publicly available within the Greenland Ice Sheets project as part of the ESA Climate Change Initiative programme.

Analyzing repeated elevation measurements from radar altimetry is widely used for monitoring changes of ice-covered regions. The Greenland Ice Sheet has been mapped by conventional radar altimetry since the launch of ERS-1 in 1991, which was followed by ERS-2, Envisat and currently CryoSat-2. The recently launched Sentinel-3A will provide a continuation of the radar altimetry time series. Since 2010, CryoSat-2 has for the first time measured the changes in the coastal regions of the ice sheet with radar altimetry, with its novel SAR Interferometric (SARIn) mode, which provides improved measurement over regions with steep slopes.

Here, we apply a mission-specific combination of cross-over, along-track and plane-fit elevation change algorithms to radar data from the ERS-1, ERS-2, Envisat and CryoSat-2 radar missions, resulting in 25 years of nearly continuous elevation change estimates (1992–2016) of the Greenland Ice Sheet. This analysis has been made possible through the recent reprocessing in the REAPER project, of data from the ERS-1 and ERS-2 radar missions, making them consistent with Envisat data. The 25 years of elevation changes are evaluated as 5-year running means, shifted almost continuously by one year. A clear acceleration in thinning is evident in the 5-year maps of elevation following 2003, while only small elevation changes observed in the maps from the 1990s.

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1. Introduction

The Global Climate Observing System (GCOS) has defined several essential climate variables (ECVs) (Bojinski et al., 2014) to support the work of e.g. the Intergovernmental Panel of Climate Change (IPCC). As the large ice sheets respond rapidly to climate change, these have been chosen by the European Space Agency (ESA) as key areas for deriving ECVs from satellite data. 25 years (1992–2016) of elevation changes over the Greenland Ice Sheet is derived by using the recently released re-processed ERS-1 and ERS-2 radar altimetry data together with Envisat and CryoSat-2 data to support this effort.

The elevation change method is a geodetic method for determining the mass balance of a glacier or an ice sheet. This method is widely used assess the state of the ice sheets (e.g. Pritchard et al., 2009; Helm et al., 2014; Zwally et al., 2005; Sørensen et al., 2011; Shepherd et al., 2012). In Sørensen et al. (2015), an along-track method was applied to Envisat radar altimetry data and the resulting elevation change maps showed significantly improved spatial resolution due to better coverage compared to previous studies based on cross-over point analysis (Johannessen et al., 2005).

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In a previous study Levinsen et al. (2015) it was concluded that the optimal method for deriving grids of elevation changes from satellite altimeters with short repeat periods, is to combine the results obtained by cross-over and along-track analysis, giving the advantage of the higher spatial resolution from the along-track method and the lower uncertainty associated with the cross-over method. We apply such a novel combination approach to derive 5-year running mean elevation change grids from conventional radar altimetry (ERS and Envisat), covering the Greenland Ice Sheet for the period 1992 to 2011. This time series of 5-year running mean elevation changes is supplemented by two 5-year mean elevation change grids (2011–2015 and 2012–2016) derived from CryoSat-2 data. The long repeat-period of CryoSat-2 means that a plane-fit approach (Simonsen and Sørensen, 2017) is preferred over the along-track approach for deriving elevation changes.

The construction of this long time series has been made possible partly through the recent reprocessing of the ERS data set in the REAPER (Reprocessing of Altimeter Products for ERS) project (Mullard Space Science Laboratory (MSSL), U.C.L., 2014), the purpose of which was to reprocess all ERS radar altimeter data to obtain an improved, homogeneous long-term data series of elevation and elevation changes. Furthermore, in the REAPER reprocessing, the ERS datasets have been processed with the geophysical and other corrections matching the Envisat dataset, making it possible to combine the data sets from these missions.

The study presented here was carried out in the ESA Greenland Ice Sheet project within the ESA Climate Change Initiative (CCI) programme (CCI, 2016), where the overall aim is to provide reliable, long-term, satellite-based data products of Greenland Ice Sheet ECVs, which can be of use for the general public and researchers e.g. climate modelers. Within the Greenland Ice Sheet CCI, one ECV parameter is the surface elevation change (SEC). Such SEC products have now been generated through a comprehensive analysis of various algorithms and corrections to ensure a validated data product, that fulfills the defined requirements for accuracy and resolution. The combined time series of all 5-year grids provide the longest possible time span of elevation changes of the Greenland Ice Sheet in the era of remote sensing radar altimetry. This data set is e.g. a crucial input to future and ongoing studies of how to correct for changing radar penetration into the snow, and hence form the basis for future estimates of mass changes of the ice sheet.

The current paper presents in detail the elevation change data product and the methods and data that was applied to create it. Any in-depth scientific analysis of its implications is out of the scope of this paper, but will be the obvious focus of future studies and publications.

2. Data

ESA has a long history of operating radar altimeters, and to span the period from 1992 to 2016 we use data from both the European Remote Sensing (ERS) satellites (Mullard Space Science Laboratory (MSSL), U.C.L., 2014), the Environmental Satellite (Envisat) (Batoula et al., 2011), and the CryoSat-2 mission (CryoSat product handbook, 2012). The radar altimeter on ERS-1 was in operation from 1991 to 1996, ERS-2 from 1995 to 2011, Envisat from 2002 to 2012, and CryoSat was launched in 2010 and is still in operation.

In this study, we utilize Level-2 (L2) ERS-1/2 and Envisat data consisting of quality-checked, geolocated height estimates, based on the “ice-1” waveform retracker (Wingham et al., 1986). Within the REAPER project, all radar altimeter, microwave radiometer and orbit products from the ERS satellites were consistently reprocessed and aligned with the Envisat data set and format (Brockley et al., 2017). This included applying the same retrackers for all the radar data sets (Mullard Space Science Laboratory (MSSL), U.C.L., 2014; Brockley et al., 2017). We used the ice-1 dataset since the consistency within this REAPER data set was more thoroughly validated than that from the ice-2 retracker, which is why the ice-1 retracker is used here. We used several geophysical corrections to correct the height data, while the backscatter coefficient waveform parameter, Bs, is used to correct height changes, and preprocessed the data sets as described in Sørensen et al. (2015). We obtained the Envisat data directly from ESA in the form of the Level-2 Radar Altimetry Geophysical Data Record (GDR) product, and the REAPER data were provided directly by the Mullard Space Science Laboratory (MSSL). We downloaded the CryoSat-2 data from ESA in form of the recent in-depth level-2 (L2i) baseline C product.

3. Elevation change algorithms

As previously stated, we apply and combine different SEC algorithms in order to obtain an optimal SEC grid solution. These along-track, cross-over, and plane-fit methods are described in the following. The repeat-track and plane-fit methods are fundamentally solving the same equations, but we describe them as individual methods here the sake reproducibility because they do require different implementations.

3.1. Repeat-track method

When using the repeat-track method, we use all data in segments along each repeated satellite tracks to solve for both SEC and the underlying topography. The algorithm used here for deriving along-track elevation change is very similar to those presented in Sørensen et al. (2015); Flament and Rémy (2012); Sørensen et al. (2011), but it has been modified to apply to the ice-1 retracked data, which provide the user with information on the backscatter coefficient Bs, but not on waveform parameters such as the leading edge width and trailing edge slope, which were used in the Sørensen et al. (2015); Flament and Rémy (2012) studies.

The least-squares regression applied in this study is performed on all data in along-track satellite track segments with a size of 2 km:

$$\begin{aligned} H(x,y,t) = {} & H_0(\overline{x},\overline{y}) + \mathrm{d}H/\mathrm{d}t(t-\overline{t}) \\ & + dB_s(Bs-\overline{Bs}) \\ & + sx(x-\overline{x}) + sy(y-\overline{y}) \\ & + \alpha\cos(\omega t) + \beta\sin(\omega t) \\ & + \epsilon(x,y,t), \end{aligned} \tag{1}$$

where dB_s is the model parameter for the backscatter, which is included since it has been shown by Legresy et al. (2005); Legrésy et al. (2006) that the retracked height changes with the backscatter. H_0 is the mean altitude, and sx and sy describe the surface topography by its slope. The overbar indicates the mean of the measurements in a segment, $\alpha\cos(\omega t) + \beta\sin(\omega t)$ describes the seasonal signal, and ϵ is the residual between the model and the data. The segments are partly overlapping (by 50%) to increase the along-track resolution. As in Sørensen et al. (2015); Flament and Rémy (2012), a 3σ outlier rejection criteria has been applied based on the $\epsilon(x,y,t)$ values to discard individual anomalous measurements. If data from multiple missions are included in the regression, we also solve for a (temporally varying) inter-mission bias.

Due to changes in orbits within and between missions, we adopt two different approaches for obtaining repeat-track elevation changes. These are described in the following.

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