Circum-Greenland, ice-thickness measurements collected during PROMICE airborne surveys in 2007, 2011 and 2015

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The Greenland ice sheet has experienced an average mass loss of 142 ± 49 Gt/yr from 1992 to 2011 (Shepherd *et al.* 2012), making it a significant contributor to sea-level rise. Part of the ice- sheet mass loss is the result of increased dynamic response of outlet glaciers (Rignot *et al.* 2011). The ice discharge from outlet glaciers can be quantified by coincident measurements of ice velocity and ice thickness (Thomas *et al.* 2000; van den Broeke *et al.* 2016).

As part of the Programme for monitoring of the Greenland Ice Sheet (PROMICE; Ahlstrøm *et al.* 2008), three airborne surveys were carried out in 2007, 2011 and 2015, with the aim of measuring the changes in Greenland ice-sheet thicknesses. The purpose of the airborne surveys was to collect data to assess the dynamic mass loss of the Greenland ice sheet (Andersen *et al.* 2015). Here, we present these datasets of observations from ice-penetrating radar and airborne laser scanning, which, in combination, make us able to determine the ice thickness precisely. Surface-elevation changes between surveys are also presented, although we do not provide an in-depth scientific interpretation of these.

Instrumentation

All three surveys were conducted using the same Air Greenland/Norlandair De Havilland DHC-6 Twin Otter aircraft, currently registered as TF-POF. This Twin Otter has been modified in such a way that part of the fuselage can be removed in the rear cargo hole providing an unobstructed view of the surface below the aircraft when airborne. The precise position of the aircraft (and instruments) is tracked by three geodetic dual-frequency GPS receivers each connected to one of two GPS antennas mounted on top of the aircraft. The orientation of the instruments is monitored by an inertial navigation system (INS). The primary INS is of the type Honeywell H-764G. During the last two flights, we also installed a back-up INS of the type OxTS Inertial+2.

For measuring snow- or ice-surface elevations, a near infrared, airborne laser scanner (ALS; Forsberg *et al.* 2001) was mounted in the rear cargo hole, alongside the INSs. The ALS flown on the Twin Otter in 2007 was of the type Riegl LMS-Q140i-60, which was upgraded to a Riegl LMS-Q240i in 2011 and 2015. In 2007 and 2011, a 60 MHz coherent ice-penetrating radar, developed at the Technical University of Denmark (DTU), was also mounted to measure bedrock topography (Christensen *et al.* 2000).

Survey design

The survey flight path was designed as a polygon to encircle the entire Greenland ice sheet where the surface of the ice

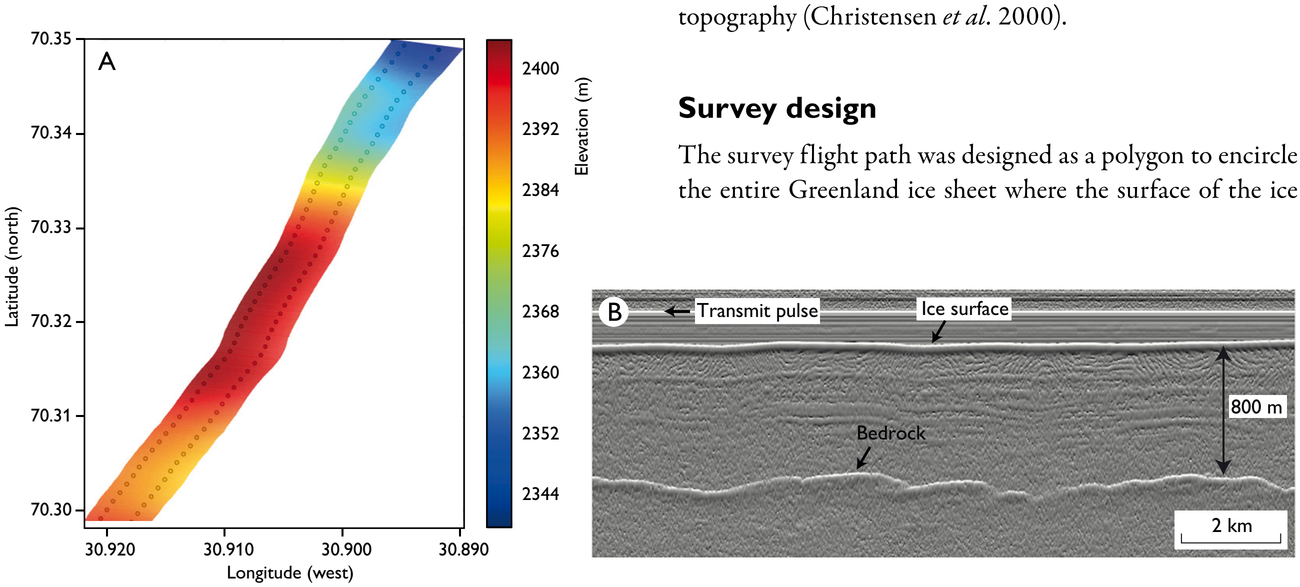

Fig. 1. **A**: Example of full-resolution versus reduced-resolution (circles) airborne laser scanner (ALS) data. **B**: Example of radargramme with a clear bedrock reflector.

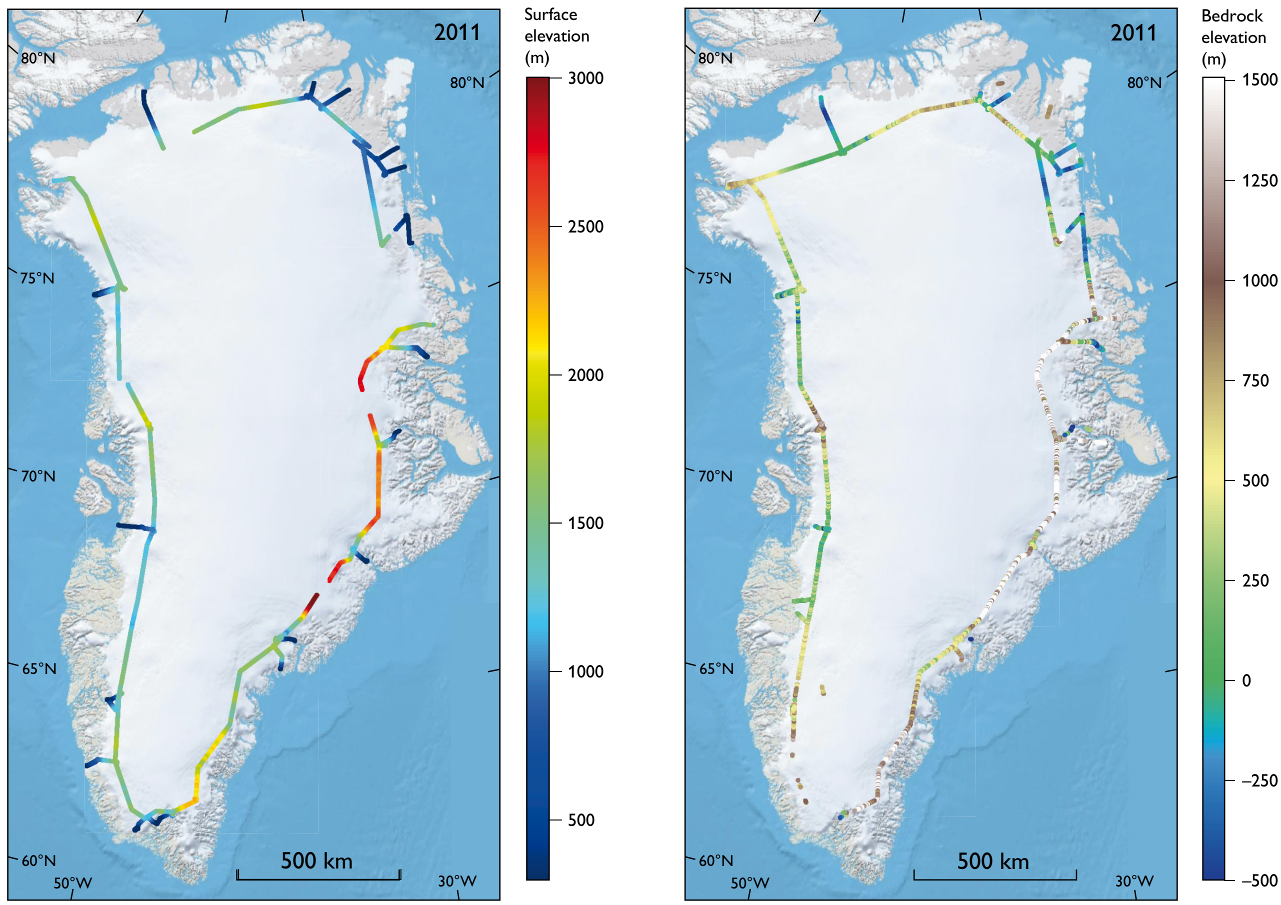

Fig. 2. **A**: Surface elevations along the PROMICE circum-Greenland flights in 2011. **B**: Bedrock elevations along the PROMICE circum-Greenland flights in 2011.

is at an elevation of *c.* 1700 m above sea level, as well as to include survey lines over the centerline of several main outlet glaciers. The surveys have been carried out at four-year intervals (2007, 2011 and 2015). The planned flight path in 2007 left a data gap on the east coast (from *c.* 72N to c. 74N) which was bridged during the 2011 and 2015 surveys.

All three surveys were planned to be carried out in August, as this timing represents the end of the melt season and ensures that the changes observed in surface elevations are not affected by individual accumulation events. Due to bad weather conditions in August 2015, half of the survey (the part from Constable Pynt in East Greenland clockwise to Kangerlussuaq in West Greenland) was carried out in October. The late acquisition of these data thus results in a potential bias of individual accumulation events due to snowfall in this dataset compared to the surveys in 2007 and 2011. As the flight path from 2011 was repeated in 2015, and since the bedrock elevation is not expected to change within this time frame, it was decided not to utilise the ice-penetrating radar on the last survey in 2015.

Surface-elevation data

The ALS operates in the near-infrared wavelength band, which is reflected from the snow or ice surface. This means that data can only be acquired during periods without clouds or fog below the aircraft. The sampling frequency of the ALS instrument is 10 kHz, resulting in 40 across-track scan lines per second. Each of these scan lines consists of 250 individual elevation measurements on-ground. The scan angle of 60° and the typical flight height of *c.* 300 m result in a swath width on ground of *c.* 300 m with *c.* 1 m resolution.

The processing of the ALS data combines the raw ALS data with the positioning data from the GPS and altitude data from the INS. Post-processing of the data includes visual inspection to filter out laser reflections from clouds. The positional uncertainty in both latitude and longitude is estimated to be ± 1 m, while the elevation uncertainty is estimated from track cross-over differences to be ± 0.05 to 0.1 m over flat surfaces.

To reduce the file size and to create a dataset which is more comparable to the resolution of the bedrock data, the full-resolution ALS data have been reduced to a spatial resolution of *c.* 100 m. This has been done through simple averag-

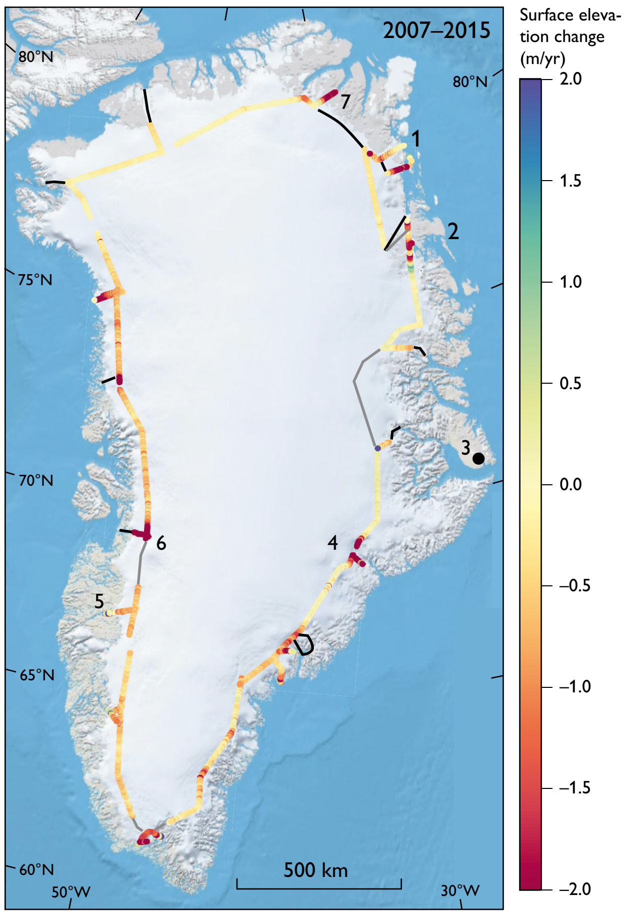

Fig. 3. Mean annual surface-elevation changes between 2007 and 2015 along the PROMICE circum-Greenland flight-paths. The part of the flight track for which only 2007 data are available is indicated in black, while 2015-only is indicated in grey. **1**: Nioghalvfjerdsfjorden. **2**: Storstrømmen. **3**: Constable Pynt. **4**: Kangerlussuaq Gletscher. **5**: Kangerlussuaq. **6**: Jakobshavn Isbræ. 7: Hagen Bræ.

ing of available height measurements along and across track. An example of full-resolution versus reduced-resolution data is shown in Fig. 1A. The data are compiled in one file per year (ALS_yyyy.ave) and can be downloaded from *http://promice.dk/DownloadAirborne.html*. As an example, the elevations from 2011 are shown in Fig. 2A.

Bedrock-elevation data

The ice-penetrating data acquisition consists of transmitting pulses at a pulse repetition frequency of 10 kHz (i.e. sampling in the flight direction) and sampling the returned echo at 75 MHz, which results in 4096 samples per transmitted pulse. While internal scattering masks the desired echo, reflection and absorption within the ice sheet reduce the strength of the returned echo. Substantial processing is therefore carried out to produce a radargramme that enhances the detection of the echo from the bottom of the ice-sheet.

A semi-automatic layer detection program is used to digitalise the surface and bedrock layers individually. In some areas, primarily near the ice margin in South Greenland, the radar was not able to detect the bedrock due to heavily crevassed ice or water present within the ice. Figure 1B shows a good example of a radargramme where a bottom echo was obtained. Based on radar system setup, vertical uncertainty in radar-derived ice-sheet bed elevation is estimated to be ± 35 m, which is confirmed by the cross-over differences between the two surveys.

The data are compiled in one file per year (ARS_yyyy.ave), which is also available for download from *http://promice.dk/DownloadAirborne.html*. As an example, the bedrock elevations from 2011 are shown in Fig. 2B.

Surface-elevation changes

Having three surveys of surface elevations spanning eight years enables us to derive and analyse surface elevation changes along the flight lines. In Fig. 3, we show the mean annual surface-elevation changes between August 2007 and August/October 2015. The map was generated by computing height differences between any points in the two (reduced resolution) datasets for the two years. Height differences are computed only if the points are located not more than 200 m apart. By knowing the exact date of the survey, the rate of surface-elevation change can be computed. In the map in Fig. 3, the part that was only flown in 2007 is plotted with black, while the parts only surveyed in 2015 are shown in grey. There are some clearly visible gaps: One leg of the flight line is missing in north-eastern Greenland from Nioghalvfjerdsfjorden to Hagen Bræ and similarly and a part of the line is also absent south of Jakobshavn Isbræ. The gap in the north is caused by gaps in the 2015 dataset due to time and weather constraints. The gap south of Jakobshavn Isbræ is due to cloud cover in 2007.

Figure 3 shows that the mean annual elevation changes in the period 2007–2015 is clearly dominated by thinning with some main outlet glaciers such as Jakobshavn Isbræ and Kangerlussuaq Gletscher thinning rapidly. Only a few places along the flight line are associated with thickening, e.g. at Storstrømmen. The sections of the flight path in the south-eastern parts that actually show modest thickening might be a result of accumulation since these parts of the 2015 survey were mapped in October after some snowfall in the area.

Elevation change data, such as presented here, are scientifically very valuable e.g. to validate satellite data and ice-sheet models. Furthermore, the data presented here represens an important supplement to the heights and height differences

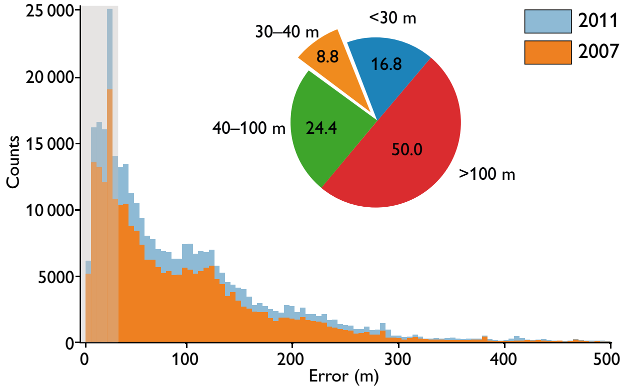

Fig. 4. Histograms showing the errors of the BedMachine bed topography grid in all the points where PROMICE bedrock elevation data are available. The grey area shows the <35 m interval (uncertainty in the bedrock data). The pie chart shows to what extent the BedMachine model error is 0–30 m, 30–40 m, 40–100 m and more than 100 m.

available from the NASA Operation IceBridge field surveys (Krabill *et al.* 2009; Krabill 2014) as the flight lines cover different areas, and also our measurements are made at the end of the melt season while Operation IceBridge data are collected mainly in the spring.

Comparison to BedMachine v3 bedrock elevations

The bedrock elevation dataset described above also represents a valuable legacy dataset that can be used by a wider scientific community. Knowledge of bedrock elevations in Greenland is essential in, e.g. ice-discharge studies and ice-sheet modelling. One widely used bedrock topography model is the one available in BedMachine v3 (Morlighem *et al.* 2017) which is based on the conservation of mass and constrained by available measurements. The BedMachine v3 model is provided together with an error map, which shows how the error increases with increasing distance to measurement points. To evaluate whether the PROMICE dataset can potentially contribute to an improvement of the BedMachine model in the future, we have extracted the BedMachine error values for all the 2007 and 2011 bedrock elevations in the PROMICE datasets. The two corresponding histograms in Fig. 4 show that in *c.* 50% of the data locations the error in the BedMachine v3 model is greater than 100 m, indicating that the PROMICE dataset with an uncertainty of ± 35 m could indeed contribute positively to a future, improved version of the model. It may also be noted that only 25% of the BedMachine data are related with similar or lower errors than the PROMICE dataset.

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