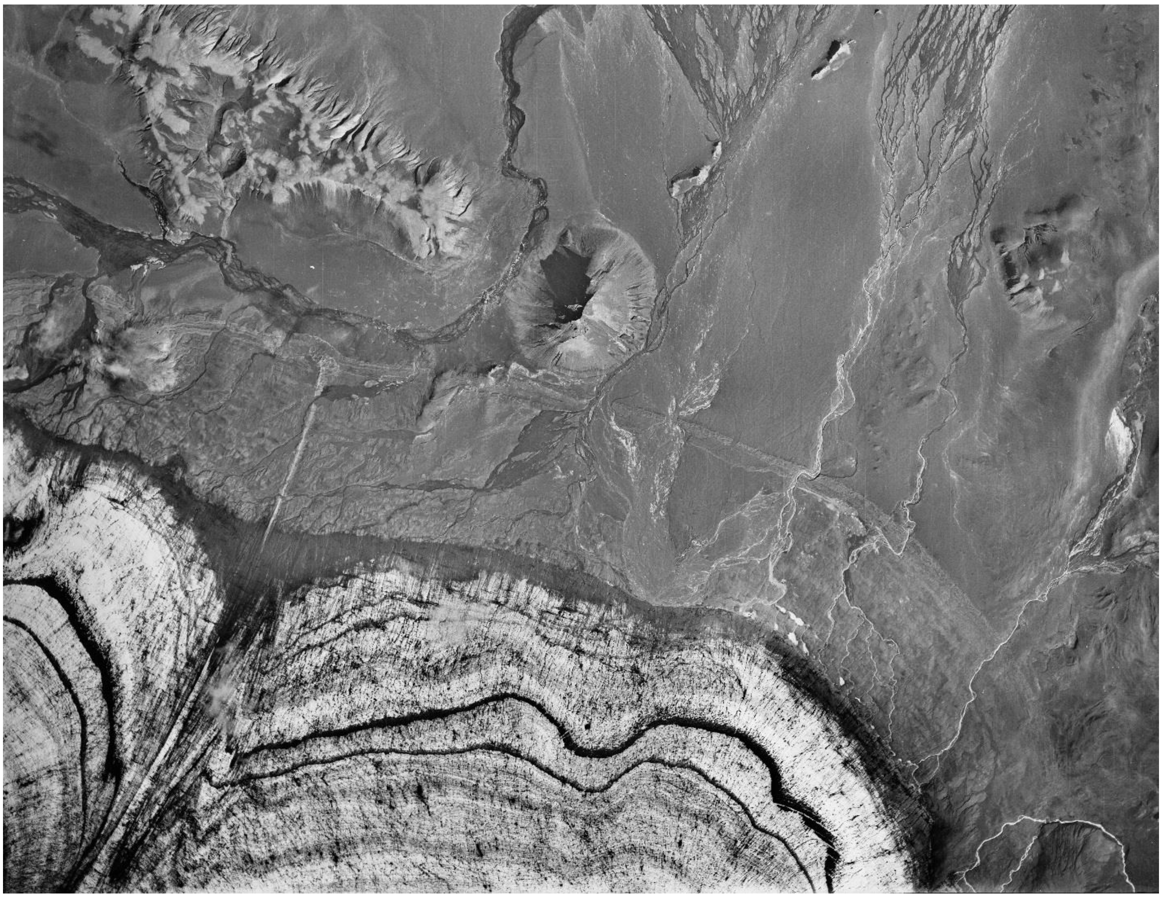
UNIVERSITY OF ICELAND
INSTITUTE OF EARTH SCIENCES



Surface elevation changes of Mýrdalsjökull ice-cap: 1960-2010

Ágúst Þór Gunnlaugsson*, Eyjólfur Magnússon, Finnur Pálsson, Joaquin M. C. Belart and Þóra Árnadóttir.

*Corresponding author (athg8@hi.is)

December 2016

RH-11-2016

ABSTRACT

Mýrdalsjökull ice-cap is located in south Iceland and covered 555 km^2 in 2010. This report presents surface elevation changes on Mýrdalsjökull ice-cap, for a 50 year period between 1960 to 2010. The elevation changes are deduced by comparing two Digital Elevation Models (DEMs). A DEM was created with photogrammetry from aerial images taken in 1960 and compared with a Lidar elevation model from 2010.

The results show annual geodetic mass balance rate of -0.54 5 ± 0.05 m water equivalent on average over the whole ice-cap. A total volume change is measured to be approximately -18.9 ± 1.6 km^3 during the period. On average, a surface lowering of 20 meters is measured on the high plateau of the ice cap and exceeding 150 meters on the outlet glaciers that flow to the east of the ice cap. Frontal retreat on some of the ice-cap outlets are up to 1.5 km. Area change over the period is measured to be -75 km^2.

INTRODUCTION

Icelandic glaciers have undergone substantial changes in recent decades (e.g., Björnsson *et al.*, 2013). Volume calculations from comparison of Digital Elevation models (DEMs) have been a key component in estimating the long term geodetic mass balance of Icelandic glaciers (Jóhannesson et al., 2013).

For some time, estimation of elevation and volume changes of glaciers with DEM differencing have been practiced by members of the glaciology group at the Institute of Earth Sciences. Examples of this is DEM differencing for glaciers in south Iceland (Guðmundsson *et al*., 2011), series of photogrammetrically derived DEMs work with images from Drangajökull ice-cap (Belart, 2013; Magnússon *et al.*, 2016) and DEM comparison and geodetic mass balance calculations for Langjökull ice cap (Pálsson *et al*., 2012).

Mýrdalsjökull ice-cap, situated at the south coast, is the fourth largest glacier in Iceland, covering an area of 555 km^2 in 2010, its volume was estimated to be ~140 km^3 in 1991 (Björnsson *et al.*,2000). Both Mýrdalsjökull and its neighbouring ice-cap, Eyjafjallajökull cover central volcanoes. The last eruption of Katla volcano, that penetrated the ice cover of Mýrdalsjökull, was 1918. In 2010, a prolonged eruption in the Eyjafjallajökull volcano spread volcanic tephra over the two ice-caps and their surroundings (Guðmundsson *et al*., 2012).

To date, little attention has been given to Mýrdalsjökull ice-cap surface elevation changes and mass balance. However, sparse surface mass balance measurements have been conducted in the accumulation area of Mýrdalsjökull ice-cap annually since 2007 by the Iceland Glaciological Society (Ágústsson *et al*., 2013). Since 2013, mass balance has also been measured at one site close to the margin of Sólheimajökull outlet. These measurements are, however, too sparse in time and limited in coverage of the ice-cap to make a comparison with the results in this report feasible.

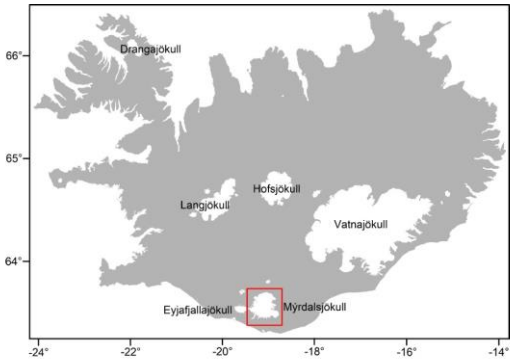


Figure 1. Location of the larger ice-caps in Iceland, Mýrdalsjökull in the south.

The aim of this study is to estimate elevation change, volume loss and average geodetic mass balance of Mýrdalsjökull ice-cap in south Iceland from 1960 to 2010 (Figure 1). A new DEM was created from aerial photographs acquired in August 1960 and compared to the 2010 Lidar DEM. The results will provide important data for the glacial history and volume changes that influence the observed crustal deformation around the Mýrdalsjökull glacier.

Creating a DEM of an ice-cap as large as Mýrdalsjökull from aerial images is a time consuming task. It involves hundreds of hours of manual editing of tie points and reviewing of point clouds. Mýrdalsjökull is roughly 3.7 times larger in area than Drangajökull, which was the subject of Joaquin Belart masters project (Belart, 2013) and the largest photogrammetry project conducted within the Glaciology group at IES until this study. Mýrdalsjökull is almost twenty times larger than Tungnafellsjökull, the study area in the Ágúst Þór Gunnlaugsson masters project (Gunnlaugsson, 2016).

This report gives an overview of the methods used in the study and the results of volume calculations.

METHODS

In order to create a digital elevation model of a given area, certain fundamental information is needed. The images from which the DEM is extracted, either aerial or satellite, need to be of an acceptable quality. Some ground truth as a set of features that can be recognized and pinpointed on the images with known 3D coordinates must be available, Ground Control Points, (GCPs).

The National Land Survey of Iceland (NLSI) archives the largest collection of aerial imagery of Iceland, the oldest aerial stereo images dating back to 1945. Good quality aerial images of Mýrdalsjökull from the year 1960 are part of their archive. They were assessed for quality and coverage (Figure 2). The images were preserved on films which were scanned with a photogrammetric scanner to minimize distortion in the scanned images, which is necessary for work like this.

Figure 2. Joaquin M.C Belart reviewing the 1960 aerial images from the NLSI archives in autumn 2015.

The images for the DEM creation were chosen from a selection of images surveyed on the 9th, 13th and 17th of August 1960. The number of images and survey flight lines are given in Table 1. DEM sections were created from consecutive overlapping image rows (images along a flight line). No seasonal correction was conducted between DEM sections as the photos were acquired in a span of 12 days.

Date	Number of images and image rows
9.8.1960	38 (3)
13.8.1960	34 (3)
17.8.1960	36 (3)

Table 1. Images and image rows (survey flight lines) from the aerial photo survey flights over Mýrdalsjökull in August 1960.

To extract a DEM from the aerial photographs we first need to establish GCPs with known 3D coordinates. These points can be chosen and then surveyed by e.g. land survey GPS or inferred from high resolution and high accuracy existing DEMs. For Mýrdalsjökull, DEMs from Lidar surveys in the years 2010 to 2012 were available for use as a reference surface for this work (Jóhannesson *et al*., 2013). In addition to the Lidar data the ArcticDEM (made accessible by the Icelandic Meteorological Office) derived from Worldview 2 satellite images was used as reference.

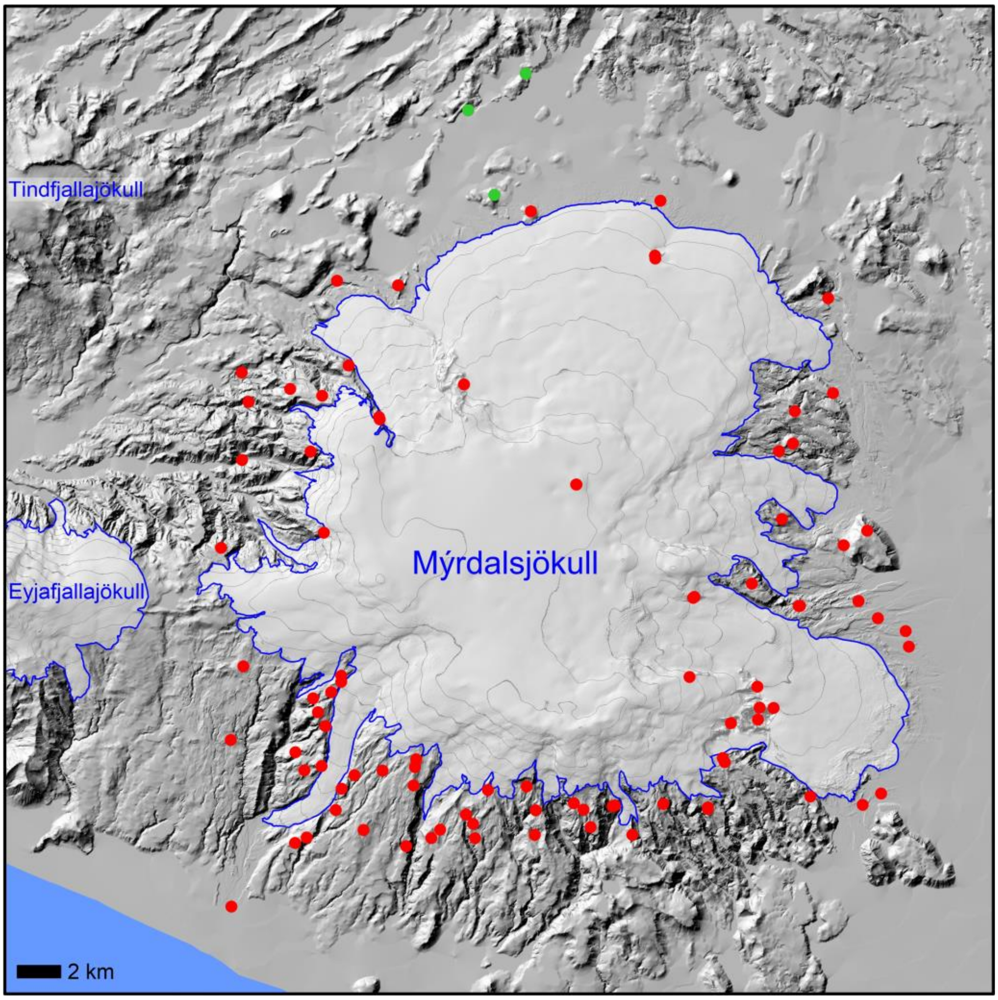


Figure 3. Distribution of ground control points over the area surrounding Mýrdalsjökull ice-cap. Red points were acquired from the Lidar DEM and the green points were acquired from the ArcticDEM. Shaded relief background from Lidar and IS50 DEM from NLSI.

The images were oriented and processed in the Leica Photogrammetry suit within the Erdas™ software bundle. Control points were chosen and extracted from the Lidar DEMs and the ArcticDEM and used as GCPs for reference in the DEM creation (Figure 3). Products of the photogrammetric processes are collection of elevation points, so called point clouds. Point clouds were manually edited in the Cloud Compare software and interpolation and DEM comparison conducted in Surfer 13 (© Golden Software, LLC). The surface that describes the surface change of a glacier over a period of time is usually with significantly less spatial variability (elevation change is highly correlated to elevation and the difference surface is mostly smooth, a low pass surface) and with much less elevation span than the glacier surface elevation. Therefore interpolation of the difference point cloud (rather than the glacier surface point cloud) is less likely to produce under- or overshoot errors. We interpolated the elevation difference point cloud calculated between the 1960 surface point clouds and the 2010 Lidar surface DEM rather than the elevation values of the 1960 point cloud.

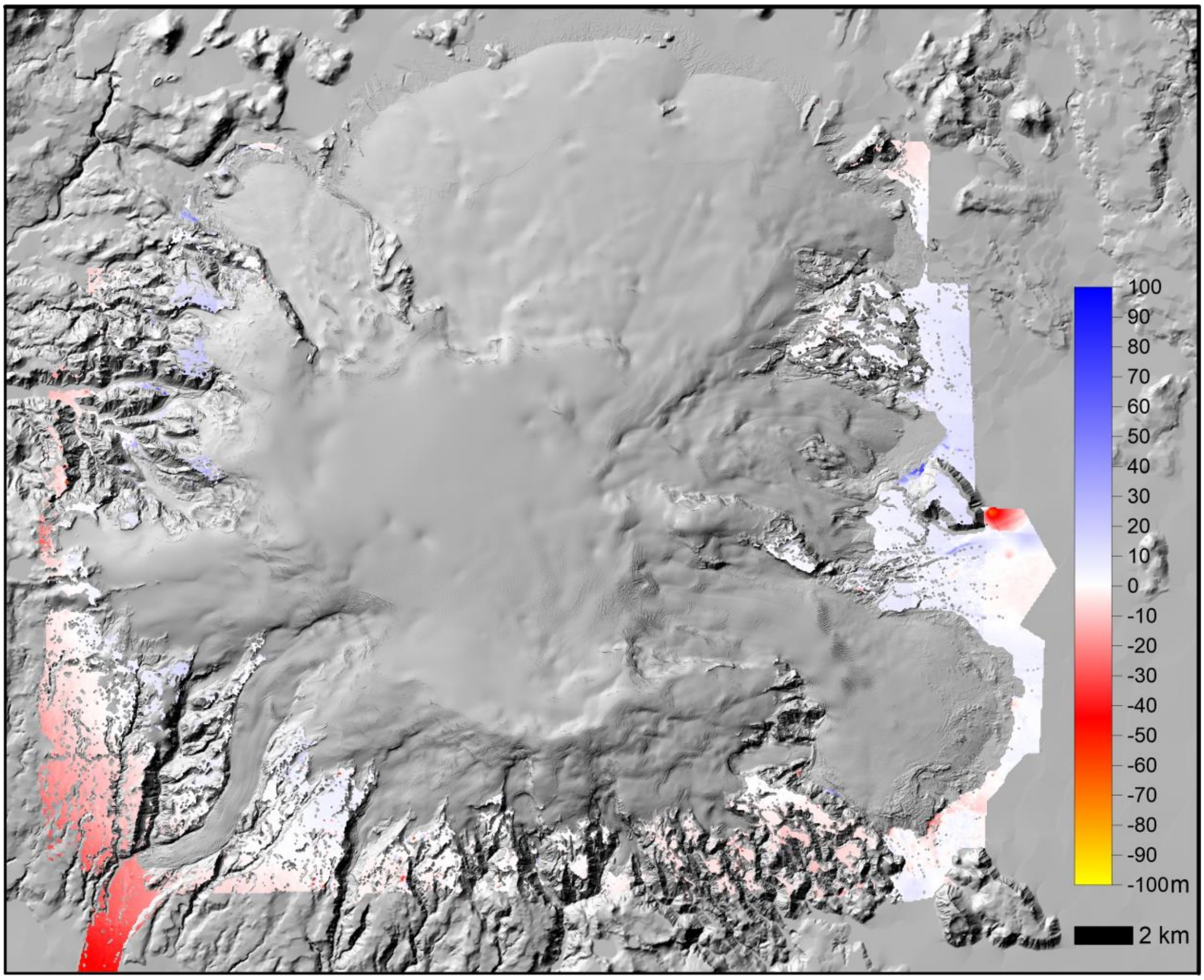


Figure 4. Elevation difference on ice free areas between the 1960 DEM and the 2010 Lidar DEM.

Thorough error estimation is yet to be conducted for the DEMs created from the 1960 images. This work will be done when more DEMs have been made from photogrammetry and comparison with other DEMs conducted. We however assume, based on experience from previous studies, that the error in elevation difference on the ice cap can be based on the elevation difference in the ice free areas (where the difference should be zero) (e.g. Magnússon et al., 2016; Gunnlaugsson, 2016). In this case, most of this DEM difference in ice free areas is expected to be due to errors in 1960 DEMs. The DEM of the ice-cap in 1960 obtained from the westernmost flightline showed significantly higher errors on the ice-free areas than the rest of the DEMs. Closer to the glacier margin the error is much lower. Because of that and the fact that less than 3% of the glacier fall within that flight line that significant error is not expected to have impact on the total volume calculations. Standard deviation of elevation difference on the ice free areas are around 10 meters, but are 5.1 meters when the westernmost flight line is excluded (Figure 4). Rigours error estimate of similar data from Drangajökull (Magnússon et al., 2016) indicated that the uncertainty in the average elevation change typically corresponding to 25-45% of the standard deviation. The average elevation change uncertainty is thus estimated

2.5 m (0.05 m per year over the period). More rigours study on the uncertainty is likely to reduce this uncertainty estimate. The corresponding uncertainty in the total volume change is 1.6 km^3.

To minimize errors in the volume calculations, the gridded DEMs were shifted vertically according to the elevation difference in the ice free areas. The difference between the DEMs created from photogrammetry and the reference surface, Lidar, was used for these vertical shifts. The volume changes between 1960 and 2010 were calculated by integrating the difference grid within the glacier margin (the outer margin of the two; the 1960 was almost always the outer margin, see Figure 3).

Further description on the methods and workflow in photogrammetry are provided by Gunnlaugsson (2016) and Belart (2013).

RESULTS

The surface elevation changes we estimate from August 1960 to August 2010 are presented in Figure 5. The red colour denotes surface lowering (melting) and blue colour surface heightening (accumulation). The same colour scale is used in Figures 5 to 9. Great surface lowering is noticeable on most of the Mýrdalsjökull outlets, especially in the north and east. Less elevation difference is measured on outlet glaciers to the south and west such as Sólheimajökull and Merkurjökull. The greatest surface lowering is visible where much retreat of the glacier margin has also occurred, such as on Sléttjökull, Sandfellsjökull and Öldufellsjökull.

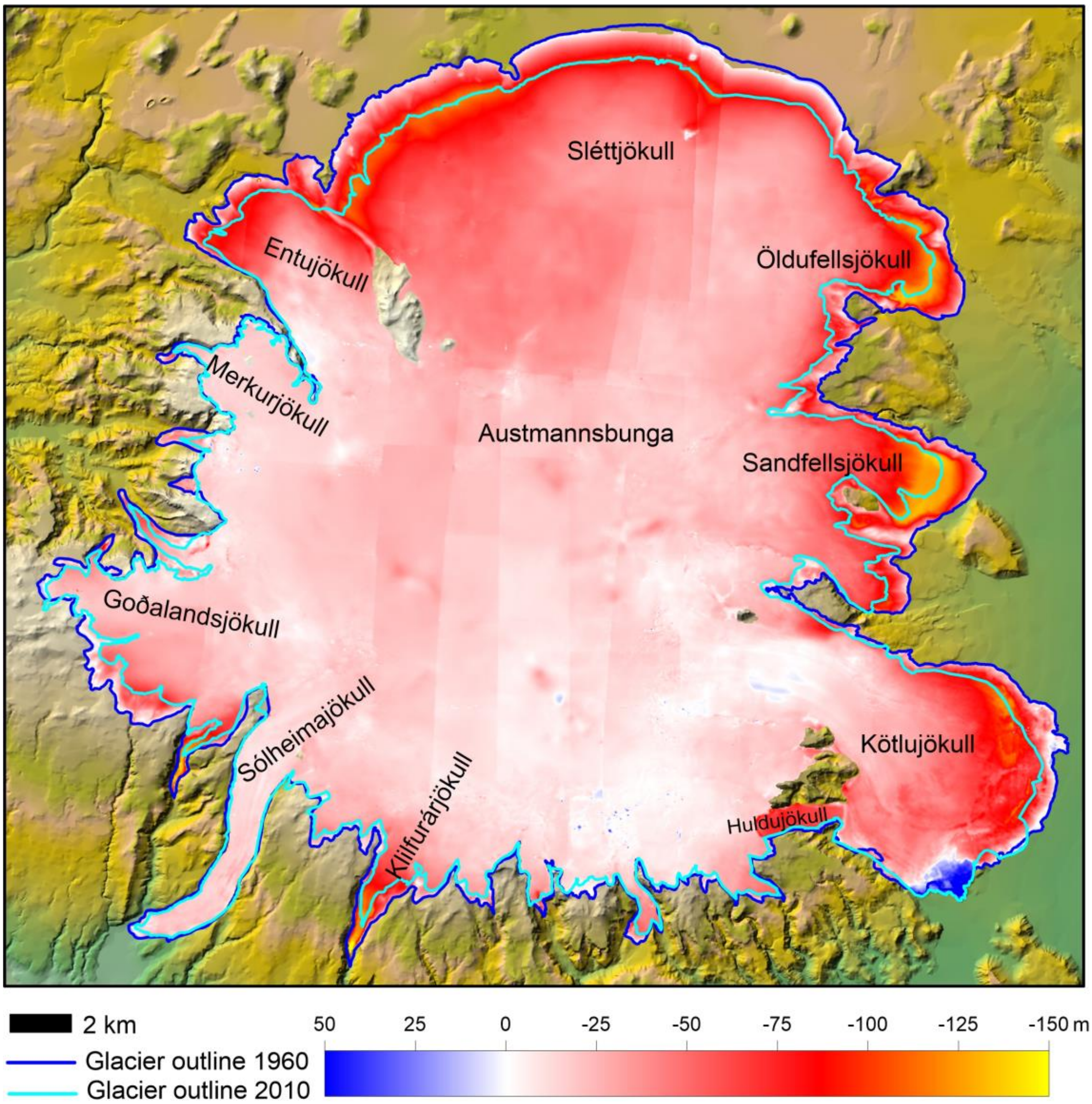


Figure 5. Surface elevation changes on Mýrdalsjökull ice-cap, 1960 – 2010.

We estimate a total volume decrease of Mýrdalsjökull for the period from 1960 to 2010 from the DEM comparison to be 18.9±1.6 km^3, or a -0.54eða5±0.05 m water equivalent average annual mass balance. A conversion factor of 0.85 (Huss, 2013) from glacier elevation change to equivalent water layer thickness was applied. Changes in the glacier area between the two DEMs are measured to be 75 km^2, or from 630 km^2 in 1960 to 555 km^2 in 2010.

The obvious few km wide north-south stripes in the coloured surface difference maps arise from a shift between the extracted surface elevation of individual survey flight lines. The elevation difference measured at two adjacent flight lines can be a few meters. This is explained by the fact that the further away from the control points you get the less constraint will be on the triangular solutions. Therefore, uncertainties in extracted elevation are higher in the centre of the ice-cap, where there is a lack of control points.

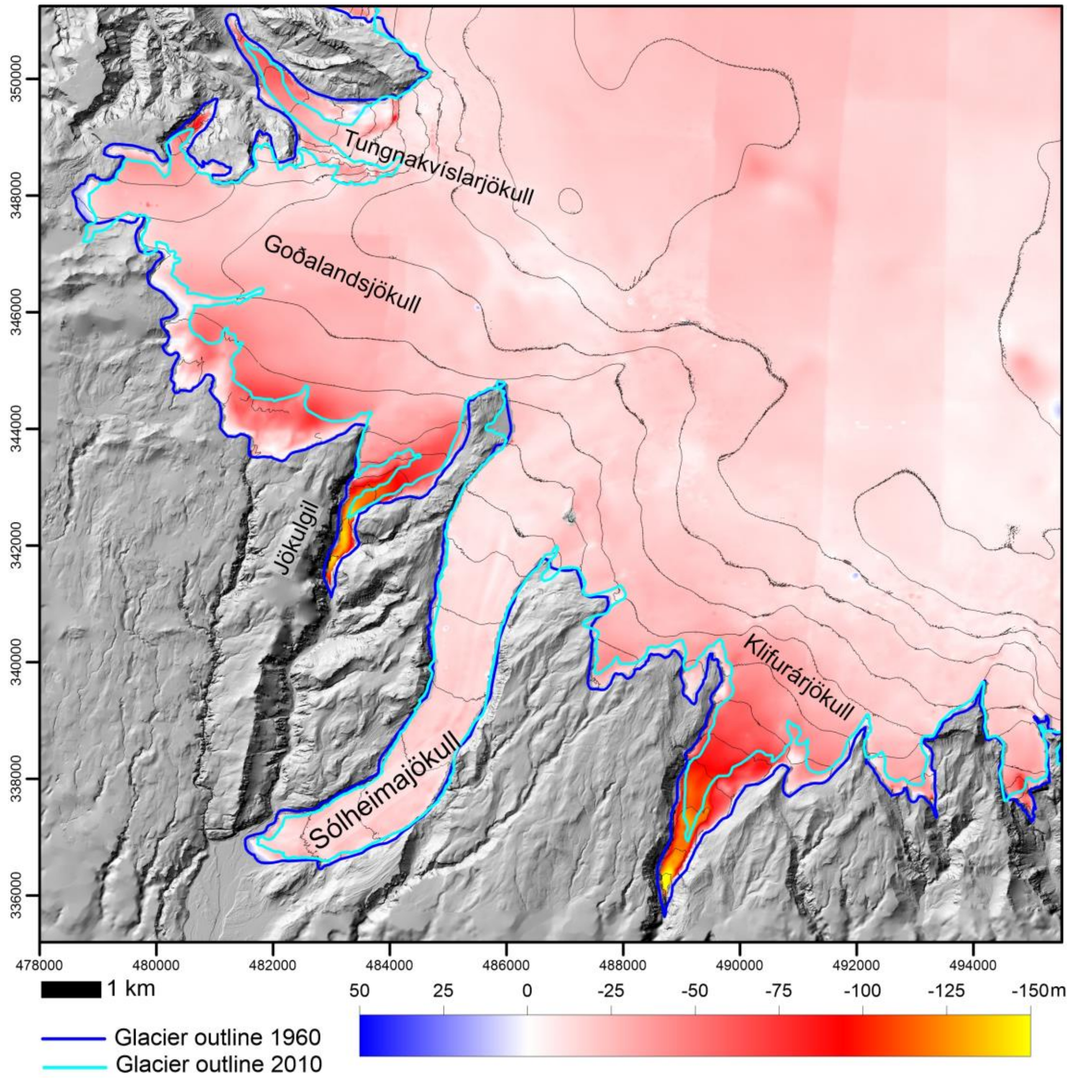


Figure 6. Surface elevation changes 1960-2010 on SW-Mýrdalsjökull ice-cap.

Surface elevation changes for SW- Mýrdalsjökull are shown in Figure 6. There is surface lowering between 15 and 20 meters on the Mýrdalsjökull ice-cap central plateau, but exceeding 120 meters at the margins of Klifurárjökull and Goðalandsjökull.

The map for 1960-2010 indicates a striking difference in the elevation change of Sólheimajökull and its neighbouring outlet glaciers. The elevation change of Sólheimajökull tongue during this period appears to be minor, and so is the retreat of the margin. Due to the long time span between DEMs in our study, however, the story of the advance of Sólheimajökull in the 1970s and 1980s and the continuous fast down wasting and retreat starting in the 1990s are not revealed in this 50 year average (see e.g. http://spordakost.jorfi.is/; Sigurðsson & Einarsson, 2014).

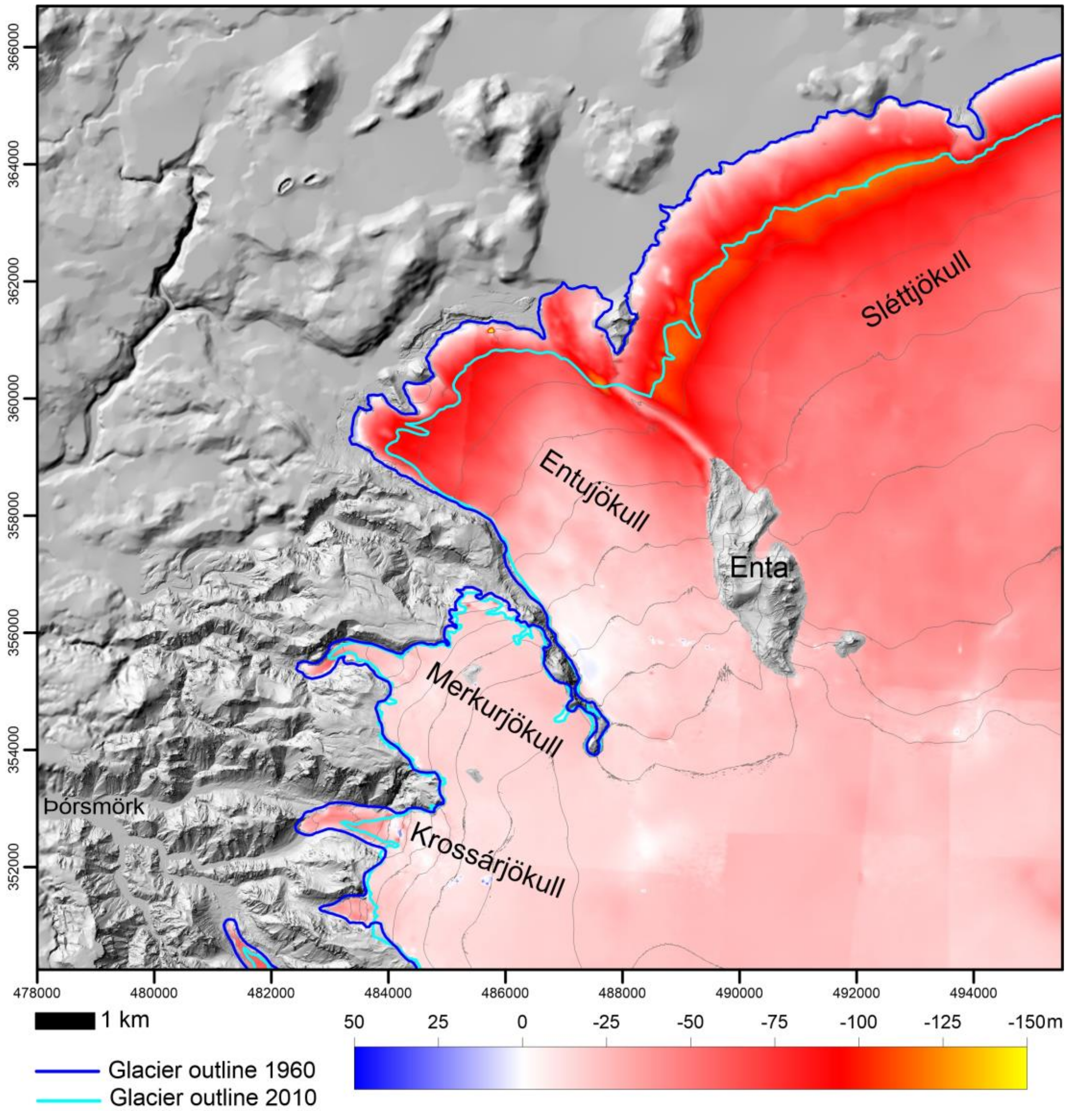


Figure 7. Surface elevation changes 1960-2010 on NW- Mýrdalsjökull ice-cap.

Figure 7 shows the surface elevation changes on NW- Mýrdalsjökull ice-cap. We estimate up to 100 meters surface lowering on the lower parts of Sléttjökull and Entujökull. The small outlet tongues that terminate in the valleys above Þórsmörk also show lowering and recession. The recession of the glacier tongue at Sléttjökull and Entujökull outlets are up to 1 to 1.5 km, respectively.

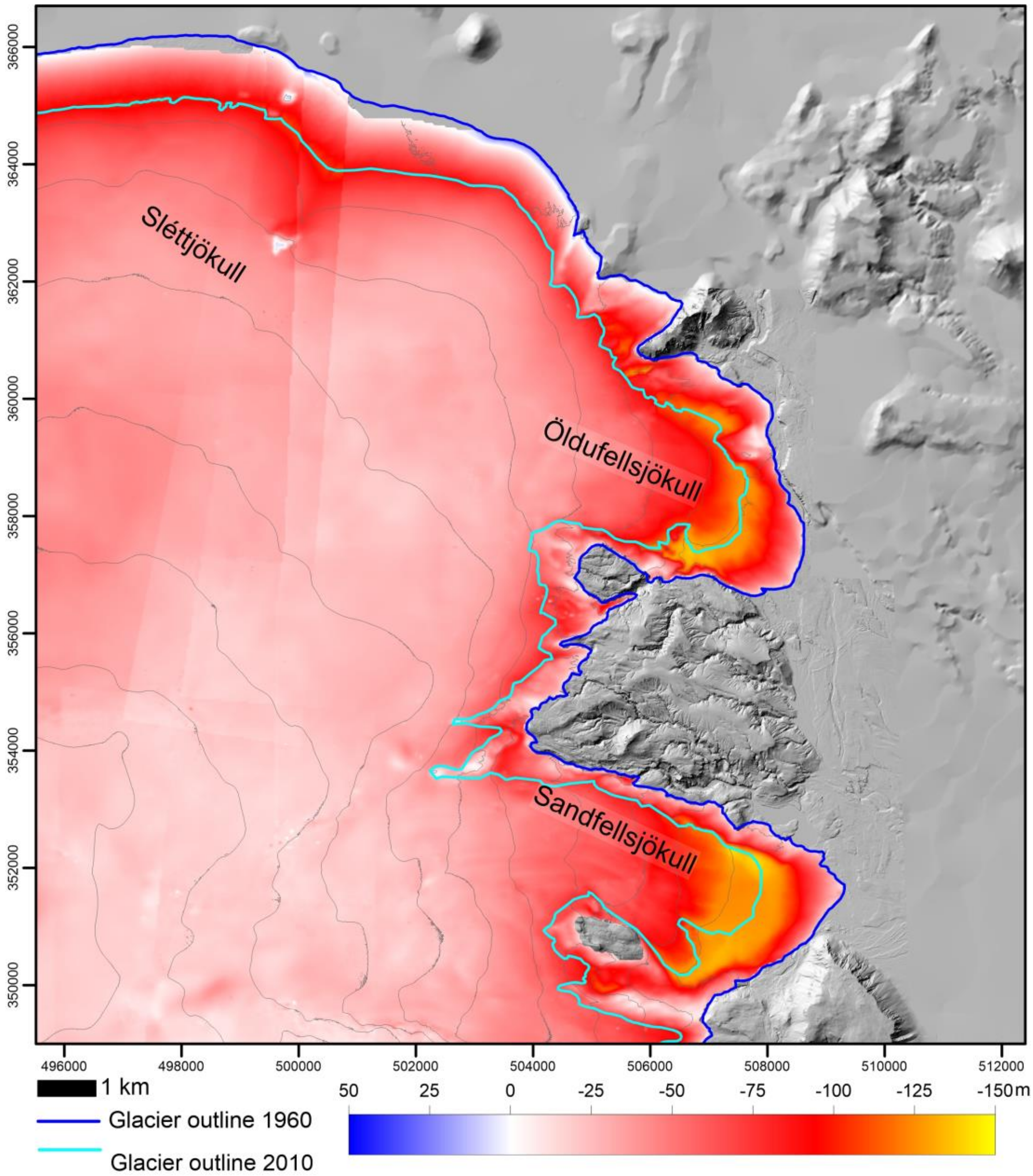


Figure 8. Surface elevation changes 1960-2010 on NE-Mýrdalsjökull ice-cap.

The NE part of Mýrdalsjökull ice-cap also shows great surface lowering over the 1960-2010 time period. The most notable changes in elevation are observed on Sandfellsjökull and Öldufellsjökull outlets, the snout lowering by more than 120 metres (Figure 8). A possible explanation for this great surface lowering is that these outlets terminate at a lower elevation than the N and NW outlets and are therefore exposed to higher temperatures and the warm winds blowing from the sea. The margin retreat of the eastern outlets of Mýrdalsjökull reaches up to 1.5 km at Öldufellsjökull outlet.

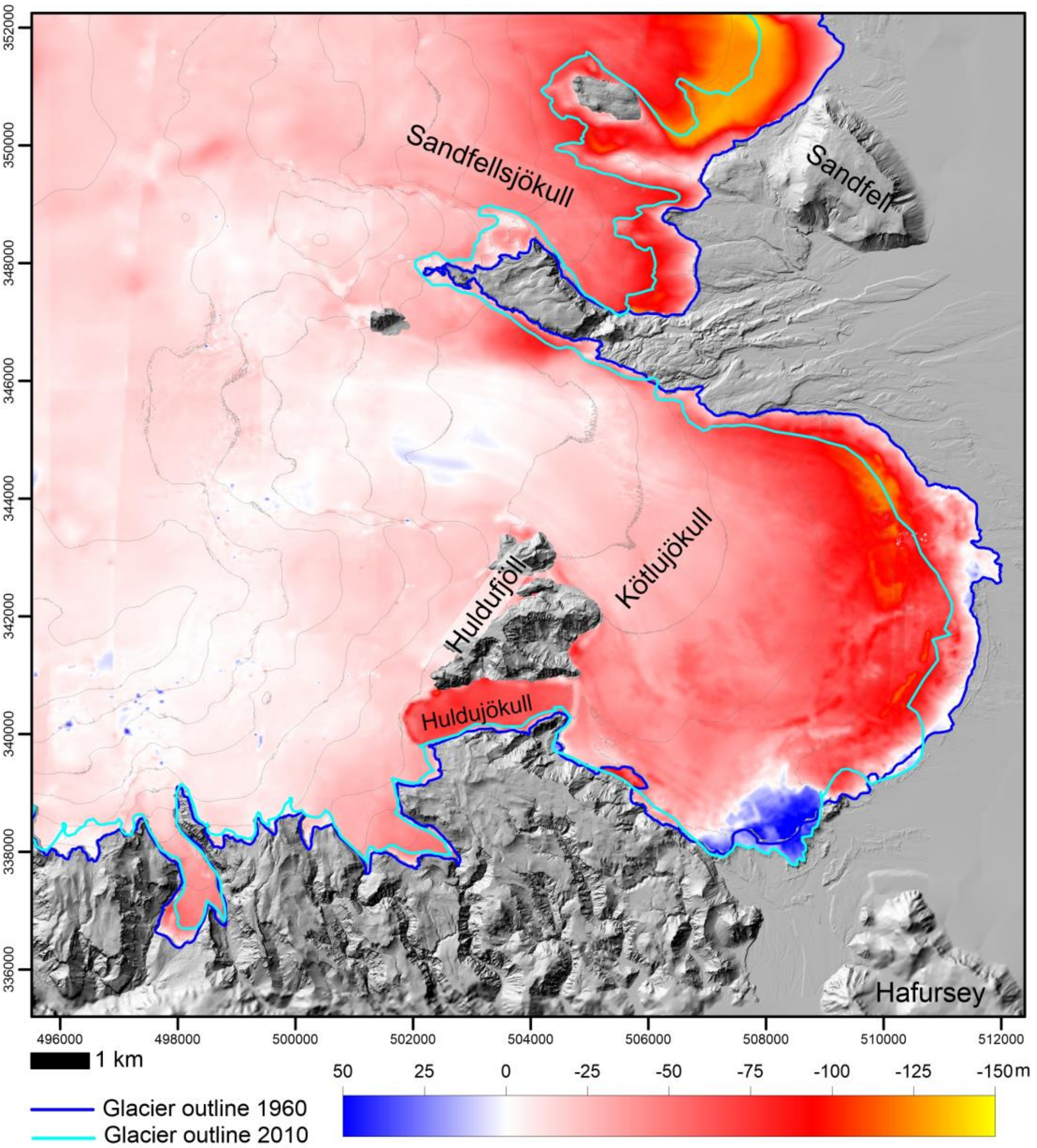


Figure 9. Surface elevation changes on SE-Mýrdalsjökull ice-cap.

On the SE-Mýrdalsjökull, surface lowering is also observed. On the low elevation Kötlujökull outlet widespread surface lowering exceeding 100 meters is observed. Over the decades a wide band of thick tephra from the 1918 eruption in Katla has covered large areas of this outlet. The tephra has insulated the ice below and hindered melt. This tephra band has now reached the glacier edge and has been washed off almost everywhere, but still insulates a small section NW of Hafursey. Dramatic (~75 m) surface lowering of Huldujökull is due to the fact that this is an ice fall that became disconnected from the higher glacier during the study period.

CONCLUSION

In this study, the elevation differences over Mýrdalsjökull are estimated for a 50 year time span. We constructed a new DEM from aerial photographs surveyed in August 1960 and compared this to an existing accurate DEM from Lidar measurements in 2010. From the difference in the two DEMs we estimate the elevation and volume changes and the average mass balance of the period. This of course does not describe the variability within the period.

An overall volume loss of 18.9 ±1.6 km^3 is measured which corresponds to -0.54±0.05 m water equivalent on average over the whole ice-cap annually. Frontal retreat of many of the ice-cap outlets is also noticed, up to 1.5 km at the greatest. The overall area decrease was 55 km^2, from 630 km^2 in 1960 to 555 km^2 in 2010.

ACKNOWLEDGEMENTS

This study was funded by grants from the University of Iceland Research Fund (Þóra Árnadóttir, PI). The work is intended to produce relevant data for studies of the changes in crustal deformation due to melting of Icelandic glaciers. We thank Carsten Kristinsson at NLSI for helping to access to the NLSI archives of aerial images and careful work in scanning the selected images. In the study the recent Lidar mapping of the glaciers in Iceland was used (The Lidar mapping was funded by the Icelandic Research Fund, the Landsvirkjun Research Fund, the Icelandic Road Administration, the Reykjavík Energy Environmental and Energy Research Fund, the Klima- og Luftgruppen (KoL) research fund of the Nordic Council of Ministers, the Vatnajökull National Park, the organization Friends of Vatnajökull, the National Land Survey of Iceland and the Icelandic Meteorological Office). Ragnar Heiðar Þrastarson and Tómas Jóhannesson at the Icelandic Meteorological Office provided access to the preliminary version of the ArcticDEM for Mýrdalsjökull. The ArcticDEM(s) were created from DigitalGlobe, Inc., imagery and funded under National Science Foundation awards 1043681, 1559691, and 1542736.

REFERENCES

Ágústsson, H., H. Hannesdóttir, Th. Thorsteinsson, F. Pálsson, and B. Oddsson. (2013). Mass balance of Mýrdalsjökull ice cap accumulation area and comparison of observed winter balance with simulated precipitation. *Jökull*, 63, 91-104

Belart, J. M.-C. (2013). *Mass balance analysis of Drangajökull ice cap (Iceland) from historical flights and LiDAR.* (M.Sc. thesis), University of Jaén, Jaén.

Björnsson H., F. Pálsson, M. T. Guðmundsson, 2000. Surface and bedrock topography of the Mýrdalsjökull ice cap, Iceland: The Katla caldera, eruption sites and routes of jökulhlaups. *Jökull 49*, 29-46

Björnsson, H. & Pálsson, F. (2008). Icelandic glaciers. *Jökull, 58*, 365-386.

Björnsson, H., F. Pálsson, S. Gudmundsson, E. Magnússon, G. Adalgeirsdóttir, T. Jóhannesson, and Th. Thorsteinsson. (2013). Contribution of Icelandic ice caps to sea level rise: trends and variability since the Little Ice Age. *Geophysical Research Letters, 40*(8), 1546-1550.

Gudmundsson, M. T., Th. Thordarson, Á. Höskuldsson, G. Larsen, H. Björnsson, F. J. Prata, B. Oddsson et al. (2012). Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. *Scientific reports* 2: 572.

Gudmundsson, S., H. Björnsson, E. Magnusson, E. Berthier, F. Palsson, M.T. Gudmundsson, J. Dall. (2011). Response of Eyjafjallajökull, Torfajökull and Tindfjallajökull ice caps in Iceland to regional warming, deduced by remote sensing. *Polar Research, 30*.

Gunnlaugsson, Á. Þ.. (2016). *The geodetic mass balance and thickness of Tungnafellsjökull ice cap.* (M.Sc. thesis), University of Iceland, Reykjavík. http://skemman.is/stream/get/1946/23639/54023/1/The_geodetic_mass_balance_and_ice_thickness_of_Tungnafellsj%C3%B6kull_ice_cap.pdf

Jóhannesson, T., H. Björnsson, E. Magnusson, S. Guðmundsson, F. Pálsson, O. Sigurðsson, and E. Berthier. (2013). Ice-volume changes, bias estimation of mass-balance measurements and changes in subglacial lakes derived by LiDAR mapping of the surface of Icelandic glaciers. *Annals of Glaciology, 54*(63), 63-74.

Magnússon, E., J. M. -C. Belart, F. Pálsson, H. Ágústsson and P. Crochet 2016. Geodetic mass balance record with rigorous uncertainty estimates deduced from aerial photographs and lidar data – Case study from Drangajökull ice cap, NW Iceland. The Cryosphere 10, 159-177, doi: 10.5194/tc-10-159-2016.

Pálsson, F., S. Gudmundsson, H. Björnsson, E. Berthier, and H. Haraldsson (2012). Mass and volume changes of Langjökull ice cap, Iceland, ~1890 to 2009, deduced from old maps, satellite images and in situ mass balance measurements. *Jökull, 62*, 81-96.