

ARCTIC MOUNTAIN GLACIERS LOVE AVALANCHES

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ABSTRACT: At ISSW and in general avalanches are usually discussed in the context of a natural hazard that harms people and infrastructure and needs to be managed to avoid disasters. On the contrary this presentation focuses on a positive effect of avalanches at least if we are worried that glaciers are melting fast due to climate warming. In recent years glacier mass balance is calculated according to high resolution geodetic mass balance measurements via LiDAR and/or SfM-photogrammetry that cover the whole glacier surface in sub-meter resolution. Those methods allow for determining precisely the influence that avalanches have on the annual glacier mass balance. This was not possible before with traditional stake measurements. That avalanche deposits have a significant positive effect on mass balance the glacier surface needs to be small, accordingly we present here data from small glaciers in Svalbard (Austre Lovénbreen; 4.48 km² in 2013) and Northeast Greenland (Freya Glacier; 5.5 km² in 2021). The geodetic mass balance of 8 years (2013/14 - 2020/21) of the Frey Glacier is even slightly positive. A main imprint of the near decadal mass balance stems from the exceptional (2.5 standard deviations above average) winter mass balance of 2017/18 with 1.85 ± 0.05 m w.e., when in addition to above average precipitation, snow avalanches affected more than one third of the glacier surface and contributed at least 0.31 m w.e. (17%) to the total winter mass balance of 2017/18. We estimate the contribution of avalanches to the accumulated mass balance 2013/14 - 2020/21 as 0.55 m w.e. Without those avalanche events the 8-year mass balance would have been slightly negative, -0.30 m w.e. instead of positive 0.25 m w.e.. Even though the annual mass balance of Austre Lovénbreen is negative since 2013/14, we show that avalanche deposits are the only remaining mass on the glacier surface that contributes positive in some years. However, avalanche deposits were not able to stop glaciers from melting due to climate warming as seen clearly in the data since 2020 also for the Freya Glacier.

KEYWORDS: Avalanche deposit, climate warming, arctic glacier, LiDAR, SfM-photogrammetry

1. INTRODUCTION

The direct or glaciological method (Østrem and Brugmann, 1991; Kaser et al., 2003) to measure the mass balance of a glacier is based on observations of ablation and accumulation at several points on the glacier. These point observations of mass change are then transferred to the whole glacier area, often using additional information like the position of the snowline. However, the specific implementation of this step may vary among glaciers and observers (Zemp et al., 2013) and depending on the number and distribution of the point measurements this introduces a considerable source of error (Hynek et al. 2022). Annual mass balance measurements are likely to accumulate systematic errors over the years (e.g. Huss et al., 2009), therefore it is recommended to compare and, if necessary, homogenise the annual mass balance time series using decadal volume change measurements (Zemp et al., 2013; Huss et al., 2009; Klug et al., 2018) Figure 1 shows the limitations of ablation stake measurements in comparison to spatial volume change measurements via terrestrial laser scanning.

Interestingly, there are only a few studies on the contribution of snow avalanches to the mass balance of glaciers (Turchaninova et al., 2020) although the importance of this accumulation process seems obvious. Glaciers with considerable accumulation from avalanches are usually associated with high and steep head-walls typical for High Mountain Asia (Laha et al., 2017). The influence of avalanches on the mass balance of some Himalayan glaciers has been quantified by Laha et al. (2017), but to our knowledge snow avalanches have not been shown to have a significant influence on the mass balance of glaciers outside the Himalaya. With increasing temperatures in the Arctic, pre-

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precipitation is expected to rise, which may lead to heavier single precipitation events as observed over NE Greenland in 2018 (e.g. Schmidt et al., 2019) which can lead to strong avalanche activity (Abermann et al., 2019a).

In the last decade, Image-Based 3D surface Modelling (IBM) via hybrid photogrammetric computer vision-based approaches has become commonplace in many academic fields. With photogrammetric methods at their core, these hybrid approaches mainly rely on the computer vision algorithms Structure from Motion (SfM) and Multi-View Stereo (MVS) to digitally extract three-dimensional (3D) surfaces from overlapping images. These 3D surfaces can then be used to produce accurate orthophotographs. Often, such SfM-MVS approaches rely upon terrestrial photographs acquired with consumer-grade cameras (Piermattei et al., 2015; Marcer et al., 2017; Bernard et al. 2017) or photos obtained via cameras mounted on uncrewed aerial vehicles (UAVs) (e. g. Gindraux et al., 2017; Rossini et al., 2018; Geissler et al., 2021).

Since now 20 years terrestrial laser scanning (TLS) is used to produce difference of digital surface models (DoD) maps (Prokop 2008 and 2009, Prokop and Panholzer 2009 and is applied to map glacier mass balance within the geodetic glacier mass balance measurement approach.

This study examines the effects of an extraordinary winter accumulation combined with widespread avalanche activity on the multi-year mass balance of an High Arctic mountain glacier. In particular, we quantify the contribution of avalanches to the mass balance 2013/14 – 2020/21 of Freya Glacier (FG) and of the Austre Lovenbreen (AL) glacier in Svalbard by taking advantage of the unique combination of high-resolution glacier elevation change measurements and distributed seasonal mass balance observations utilizing SfM-photogrammetry and terrestrial laser scanning.

2. MEASUREMENT SET-UP

Due to the ease of the process and the suitable topography, SfM-MVS-based image-based 3D surface modelling was the optimal choice for generating a DEM of Freya Glacier during the 2013 field campaign. No UAV was available, but the ridges around the glacier offered useful natural viewpoints for a ground-based survey. Between 11th and 18th August 2013 we took oblique 120 overlapping photographs of the glacier surface from about 450 locations on the slopes on both sides of the glacier using a Nikon

D7100 digital single lens reflex camera with a 20 mm fixed lens. Simultaneously with the image

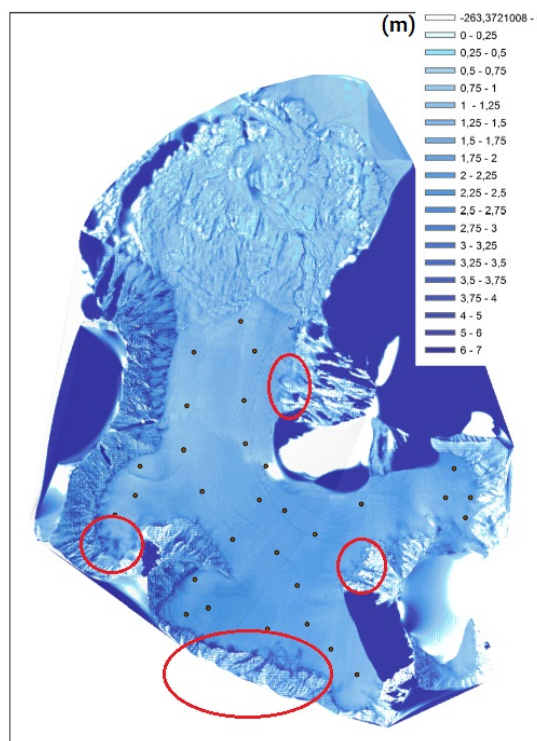


Figure 1: Avalanche deposits at Austre Lovenbreen glacier Svalbard (within red circles) measured by terrestrial laser scanning but not by traditional stake measurements. The position of the ablation stake is indicated by the red dots.

acquisition, we surveyed ~100 natural Ground Control Points (GCPs) using a differential GNSS (Global Navigation Satellite System) receiver. For postprocessing of the survey, a temporary GNSS reference station was established on stable rock next to the glacier. We surveyed the upper part of the glacier on the 11th and 12th of August 2013, when the glacier surface was almost snow free. A snowfall event on 14th August followed by a period of low visibility marked the end of the melt season. On 18th August 2013, we surveyed the lower part of the glacier. Surface ablation between the survey dates was below 0.15 m and was partly compensated by an average fresh snow height of 0.10 m.

Since 2012 we also measure the Austre Lovenbreen glacier basin via terrestrial laser scanning twice a year at peak accumulation of snow and after the melting period. We started using Riegl LPM-321 and from 2016 Riegl VZ-6000. The range of the laser scanner of 4000 m allows us to cover the whole glacier catchment from only 2 position without large shadow areas with no data. Avalanche deposits are easily recognized on the glacier surface as seen in figure 2 on reflectance images of LiDAR data.

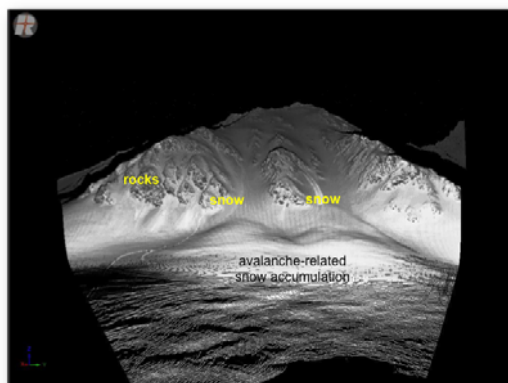


Figure 2: Avalanche deposits at Austre Lovenbreen glacier, Svalbard recognized on reflectance images of LiDAR data.

3. RESULTS

3.1 Elevation Changes and Geodetic Mass Balance

Elevation changes in 1 m resolution (Fig. 5b) were calculated for 95% of the glacier area, missing only some smaller parts in the upper accumulation zone of the glacier. Elevation changes for these areas were calculated by fitting a spline function to the elevation changes in the surroundings, to avoid a bias in the geodetic mass balance. Elevation changes show a high spatial variability. Surface lowering is observed on 20% of the glacier surface, dominating elevations below 600 m a.s.l., and reaching a minimum of -11 m in the lowest part of the glacier. Above 600 m a.s.l. elevation changes are mainly positive. At the centerline of the glacier, elevation gains are mainly smaller than 2 m. In several distinct areas predominantly along both sides of the glacier, elevation gains are up to several meters with a maximum of 17 m. These areas coincide with potential avalanche depositions from larger side valleys. The mean elevation change 08/2013 – 07/2021 for the total glacier area is 1.56 ± 0.10 m.

Main uncertainty is introduced by ablation during the survey, unmeasured areas, and the uncertainty in the delineation of the glacier surface area. Converting this volume change into a mass change – and hereby introducing another uncertainty using a density assumption – we obtain the specific geodetic mass balance 08/2013 – 07/2021 as $b_{\text{geod}} = 0.85 \pm 0.20$ m w.e. To get the geodetic mass balance for the full mass balance year of 2013/14-2020/21 we have to account for additional mass losses during August 2021. Based on the reading of 10 stakes we estimate this mass change to be $-0.60 \text{ m} \pm 0.05 \text{ m w.e.}$, which makes the total 8-

year geodetic mass balance 2013/14 – 2020/21 slightly positive: $b_{\text{geod.8y}} = 0.25 \pm 0.21 \text{ m w.e.}$

3.2 2018 avalanche deposition

While remnants of small snow avalanches are visible also in other years, they usually are not visible during spring field surveys. However, in spring 2018 signs of large avalanche deposits were visible all over the glacier. Especially in the middle part of the glacier several large avalanches originating from the tributary valleys on both sides of the glacier covered large parts of the glacier. In April 2018 avalanche deposits were found on 36% of the glacier area. Individual GPR-derived snow heights ranged from 2.2 m up to 12.1 m, with a median snow height of 4.0 m. The distribution of snow height and 220 the delineation of avalanche influenced areas is shown in Fig. 3a. Area averaged values of snow height on the entire glacier is 4.8 m, on avalanche deposits 6.2 m, and on areas with no avalanches 4.0 m. The snow height contribution from avalanches averaged over the whole glacier is 0.8 m. Mean snow density at the snow pit next to the AWS at stake 6 was 385 kg/m^3 . Assuming the same bulk snow density everywhere on the glacier, the specific mass balance contribution of avalanches is 0.31 m w.e. , which is 17% of the total winter mass balance of $1.85 \pm 0.05 \text{ m w.e.}$ This can be seen as a lower limit as the avalanche snow likely has a higher snow density than the undisturbed snowcover in the middle of the glacier, where the snow density measurement was carried out (Sovilla et al., 2001). If we assume an increase in bulk snow density of 10% due to compaction and overburden pressure within the avalanche deposits, the mass contribution of avalanches would be 0.39 m w.e. , being 20% of a winter mass balance of 1.93 m w.e. Remnants of the avalanches are still visible on the glacier surface 3 years after the anomalous year (Fig. 4 c,e) and have altered local surface mass balance significantly at stake 1 (-0.1 m), stake 4 (-2.4 m) and stake 11 ($+4.1 \text{ m}$) (Fig 3b).

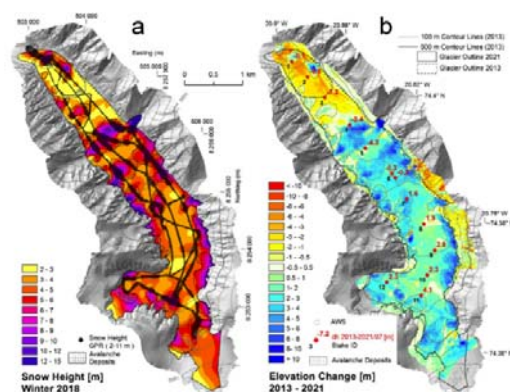


Figure 3: a) Measured (GPR) and extrapolated snow height in winter 2018 and delineation of avalanche affected areas. b) Elevation Change between 18.8.2013 and 27.7.2021 470 and stake/AWS locations.

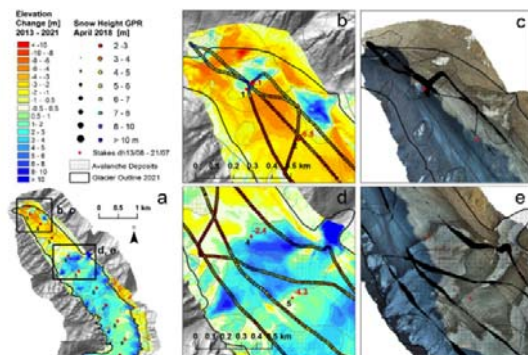


Figure 4: Picture a) Overview and (b, d) close-ups of Elevation Changes and (c, e) Orthophoto 2021 together with GPR snow height data of spring 2018 and measured ablation at the stakes.

3.3 *Influence of avalanches on the elevation changes*

The altitudinal distribution of the elevation changes are plotted for all grid cells and as a spatial average on 25 m altitudinal bins. Without the contribution from avalanches the mean elevation change would have been 0.71 m (instead of 1.56 m). The geodetic mass balance would have been 0.30 m w.e. (instead of 0.85 m w.e.). Hence, snow avalanches contributed 0.55 m w.e. to the multiyear mass balance. This value is significantly larger as the lower boundary of the contribution of avalanches to the winter mass balance of 2018 0.31 m w.e.

4. DISCUSSION AND CONCLUSION

Our study shows that the 8-year geodetic mass balance 2013/14 -2020/21 of FG has been slightly positive. A significant positive contribution to the mass balance originates from widespread avalanche depositions from the surrounding slopes in February 2018, which affected more than one third of the glacier area. We estimated the contribution of avalanches to the winter mass balance of 2018 as 0.31 m w.e. at least and the contribution to the cumulative 8-year geodetic mass balance as 0.55 m w.e. We showed that the 8-year geodetic mass balance of Freya Glacier would have been negative without the contribution from snow avalanches. A main uncertainty in this assessment is introduced by a lack of snow and firn density measurements especially within the avalanche deposits, but also in the upper firn areas. Measure-

ments of firn density should receive more priority in the future mass balance monitoring of FG. We found that avalanches contributed at least 0.31 m w.e. to the winter mass balance of 2018 and 0.55 m w.e. to the multiyear geodetic mass balance. We hypothesize, that the difference between these two values i.e. the larger contribution of avalanches on the multiyear geodetic mass balance could be attributed to 1) systematically higher snow densities within the avalanche deposits of 2018, 2) reduced melt rates at the avalanche deposits due to an increased albedo and 3) to enhanced internal accumulation and reduced runoff within the firn layer of the avalanche deposits as discussed before. The cumulative glaciological mass balance suffers from data gaps and only a few point observations in recent years and underestimates the mass balance significantly. As FG is surrounded by steep slopes, we assume that accumulation from avalanches might have contributed also in the past, but 2018 was the first and only time since the beginning of the monitoring in 2007, that avalanches have been observed widespread over the glacier area. Assuming a higher likelihood of strong winter precipitation events in a warmer climate, we expect that accumulation by avalanches might become more important on Arctic mountain glaciers that are situated in or surrounded by steep terrain.

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