Paraglacial adjustment of sediment-mantled slopes through landslide processes in the vicinity of the Austre Lovénbreen glacier (Ny-Ålesund, Svalbard)

Erik Kuschel[1,2], Christian Zangerl[1], Alexander Prokop[3,4], Eric Bernard[5], Florian Tolle[5] and Jean-Michel Friedt[6]

[1] University of Natural Resources and Life Sciences, Vienna, Institute of Applied Geology, Department of Civil Engineering and Natural Hazards, Vienna, Austria;
[2] The University Centre in Svalbard, Department of Arctic Geology, Longyearbyen, Norway;
[3] University of Vienna, Department of Geodynamics and Sedimentology, Vienna, Austria;
[4] Snow Scan GmbH, Vienna, Austria;
[5] Université de Franche-Comté, ThéMA CNRS, Besançon, France;
[6] Université de Franche-Comté, FEMTO-ST CNRS, Besançon, France

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The Austre Lovénbreen

The Austre Lovénbreen basin is located on the Brøggerhalvøya, roughly 5 km east of Ny-Ålesund, at the west coast of Spitsbergen at 79° North (see Figure 1). The basin is dominated by the relatively small valley based Austre Lovénbreen glacier, which covers roughly 4.5 km² of the 10 km² large catchment area. The glacier is to the east and west confined by two mountains: the Haavimbfjellet to the east and the Slåttofjellet to the west (see Figure 2).

The Austre Lovénbreen glacier was investigated by French and international scientists since the 1960s. This includes the terrestrial laser scans taken annually since 2012 in the framework of the Permafrost, Rock, Ice and Snow Monitoring in the Austre Lovén glacier basin (PRISM) project (PRISM, 2012; RIS-ID: 6815) and the sensor network established by the Hydro-Sensor-FlOWS project within the framework of the 2006-2010 International Polar Year.

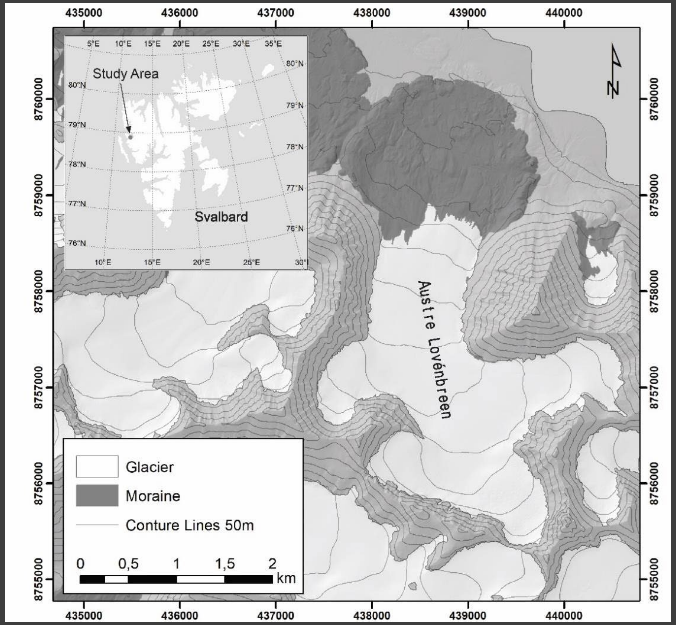

Figure 1: Overview map of Svalbard and the study area (NPI, 2014).

Figure 2: The Austre Lovénbreen basin seen from the Kongsfjorden in 2017. Shallow debris slides and the exposed subsurface ice layer can be seen on the slopes of Haavimbfjellet.

Geological Setting & Glacier Retreat

The Brøggerhalvøya is situated along the northernmost part of the Tertiary fold and thrust belt of western Spitsbergen, accompanied by a number of north-south striking faults. The stratigraphy of the Brøggerhalvøya is based on sedimentary rocks of Palaeozoic and Tertiary Age, which are underlain by metamorphic rocks of the Caledonian basement. The investigation area is located in the Kongsvegen group, which is the main basement unit of the Brøggerhalvøya and is divided into three formations: Nielsenfjellet, Steenfjellet and Bogegga Formation. These formations consist of low to medium metamorphic rocks (see Figure 3). The study areas are located on the low strength and penetrative foliated phyllites of the Nielsenfjellet Formation. The phyllitic rocks represent the main source for the periglacial talus accumulations studied in this thesis.

The Austre Lovénbreen shows a constant, but irregular retreat of the glaciers since the Little Ice Age (see Figure 4), which is similar to the other valley-based glaciers located on the Brøggerhalvøya (Hagen et al. 2003, Marlin et al. 2017). Smaller glaciers, such as the Austre Lovénbreen, tend to be more sensitive to climate change due to their shorter response times and therefore a more immediate response of the surrounding talus slopes can be expected (Paterson 1994; Benn and Evens, 2010).

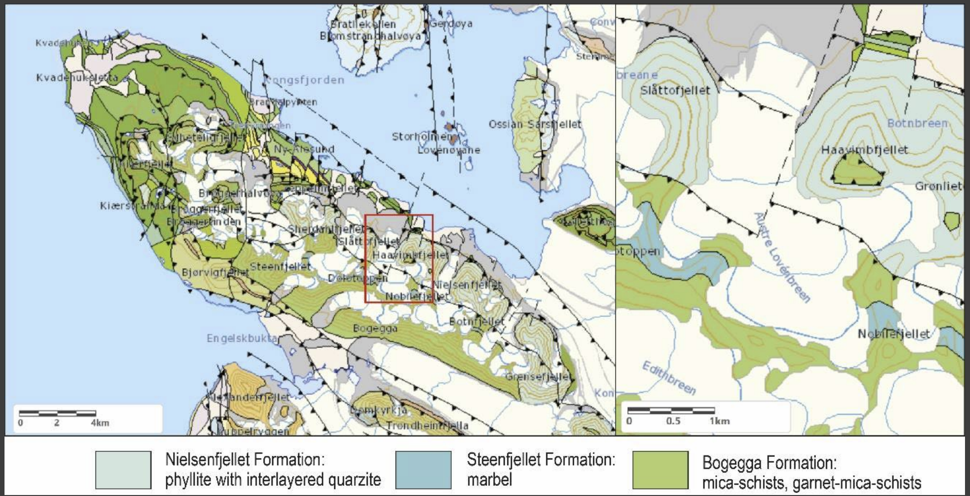

Figure 3: Geological Map of the Brøggerhalvøya (left) and the Austre Lovénbreen glacier basin (right). The investigation area is indicated by a red frame (Norwegian Polar Institute, 2019).

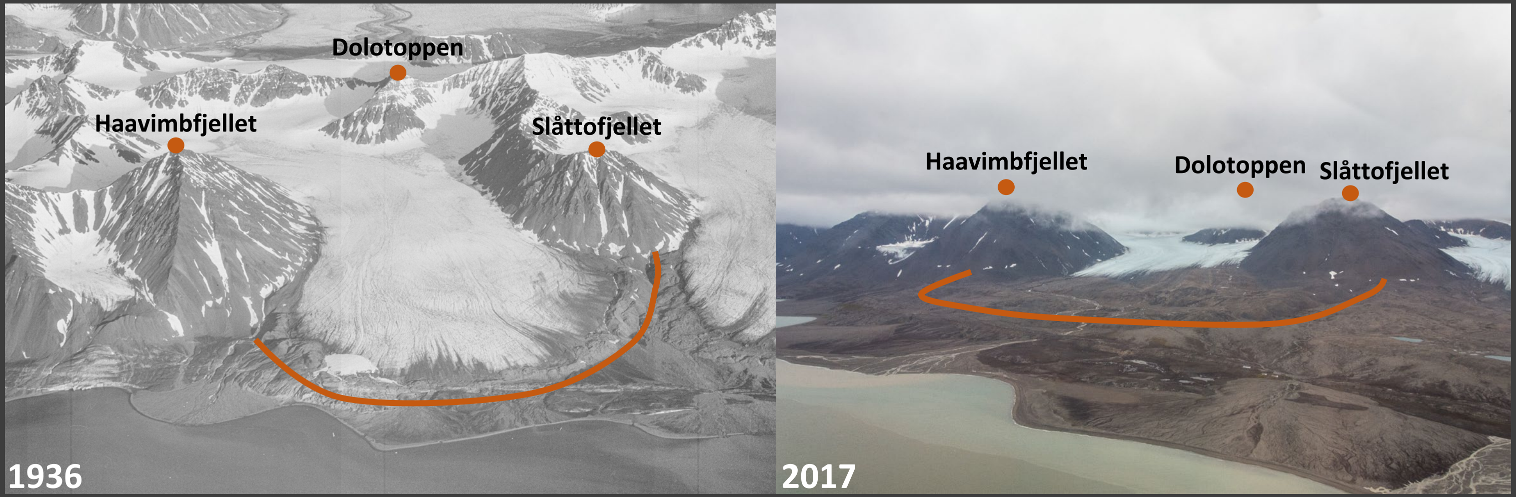

Figure 4: The Austre Lovénbreen glacier basin in 1936 (left; mod. Norwegian Polar Institute, 2018) and in 2017. The peaks of Haavimbfjellet, Dolotoppen and Slåttofjellet and the other edge of the moraine are indicated in both pictures.

Methods & Data

Figure 5: Overview of applied methods, including terrestrial laser scanning (top), electrical resistivity tomography (middle) and geological field surveys (bottom).

Landscape modifications within the Austre Lovénbreen basin have been investigated based on: I) high-resolution multi-temporal terrestrial laser scan data (TLS) measured annually from 2012 to 2018; II) images from stationary cameras taken between 2011 and 2018 monitoring the entire basin and; III) two geological field surveys in 2017 and 2018.

Terrestrial laser scanning was performed annually since 2012 in the framework of the Permafrost, Rock, Ice and Snow Monitoring in the Austre Lovén glacier basin Project (RIS-ID: 6518) measuring more than 300 single laser scans. The registration and the georeferencing, is done by matching the TLS point clouds onto an already georeferenced reference point cloud by use of an ICP algorithm (Huggel et al., 2012). For the georeferencing of the first TLS point cloud from 2012, an ALS point cloud (NPI, 2014) was used as reference point cloud. High resolution digital elevation models were derived from these, enabling the detection of topographical changes. Analyses of the terrain changes were conducted with the software package Geomorphic Change Detection (Wheaton., 2008; Wheaton et. al., 2009).

For a further investigation regarding the impact of meteorological factors on the spatial and temporal occurrence of landslides data with a higher temporal resolution was needed. Therefore, the daily images (>39.000 images) from several automated cameras monitoring the Austre Lovénbreen were used to improve the temporal analysis of rapid landslide events based only on annual TLS data. The monitoring system includes 6 stationary cameras covering 96% of the glacier surface (Bernard et. al., 2013).

Electrical Resistivity Tomography was applied on the slopes of the Austre Lovénbreen glacier basin in 2018. Due to technical difficulties encountered in the field the amount of data is limited.

Landslide quantification

Between 2012 - 2018 the sediment-mantled slopes were primarily affected by 84 shallow debris slides with have a total volume of approx. 69885 ± 5933 m³, 14 debris flows with a volume of 3773 ± 582 m³ and 3 rockfalls with 138 ± 22 m³. Therefore, in contrast to many other studies (Owen, 1991; Zimmermann and Haeberli, 1992; Rickenmann and Zimmermann, 1993; Ballantyne and Benn, 1994; Ballantyne 2002; Curry et al., 2006; Mercier et al., 2009) shallow debris slides and not debris flows were the dominant process modifying the sediment-mantled slopes of the Austre Lovénbreen basin during the observation period.

All observed landslides were shallow translational debris slides with depths ranging from 1-5 m (Figure 6 & 7). The basal shear zones of all slides were formed directly on the contact zone between the debris and a sub-surface ice layer. The exposed subsurface ice-layer is visible up to 150 m above the current glacier level.

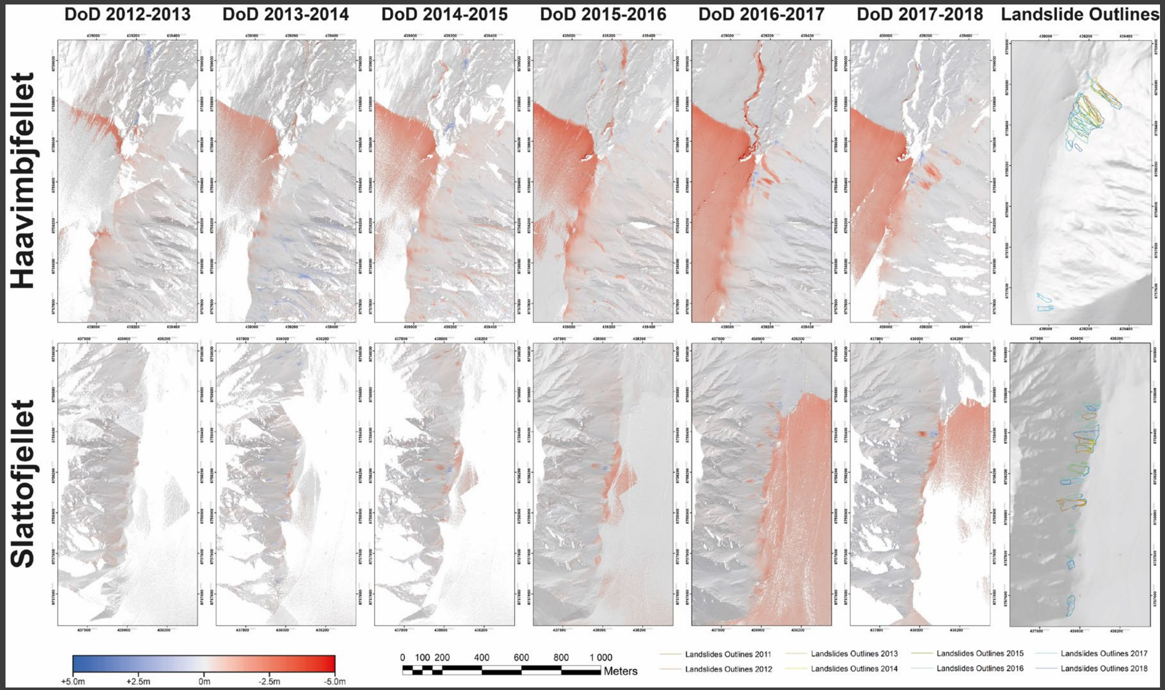

Figure 6: Annual high resolution DEMs of Difference for the North-West-facing slope of Haavimbfjellet and the East-facing slope of Slåttofjellet.

Figure 7: Several shallow debris slides observed on the northern flank of Haavimbfjellet in 2017, with the summit and the snout of the Austre Lovénbreen.

Debris slide structure

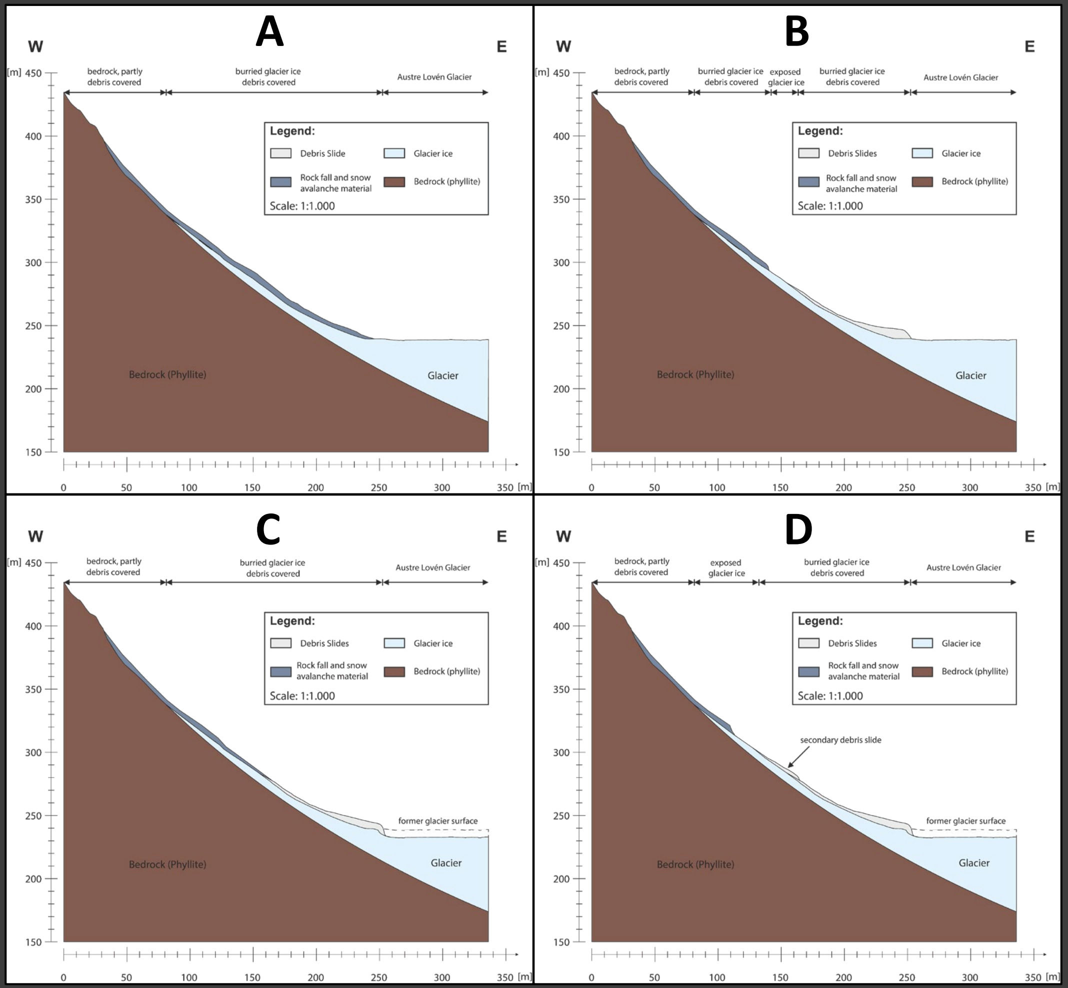

Figure 8: Schematic slope model of two debris slides in 2015 and 2016. Sediment from the slopes is subsequently reworked by landslides, burying and insulating parts of the glacier. As the surrounding glacier ice melts the landslide material spreads out forming ice-cored lobate landslide deposits on the glacier.

These shallow translational debris slides showed an uniform morphology and development. Figure 8 shows a schematic cross sections of two debris slides located at the slopes of Slåttofjellet in 2015 and 2016 (see Figure 9 & 10). For the illustration of the subsurface the Ground Penetrating Radar (GPR) studies of Bernard. et al. (2014) were incorporated. Furthermore, the scree material and debris slide thickness in Figure 8 was superelevated to improve their presentiveness.

Figure 8a depicts the initial state of the slope previous to a debris slide event. The inclination of talus deposits is in the range between 35 and 42°. All debris slides were formed on a distinctive failure plane at the contact zone of the subsurface ice-layer and talus deposits. The failure event lead to the exposure of this ice-layer (see Figure 8b), which was in many cases visible on the images form the stationary cameras (see Figure 10).

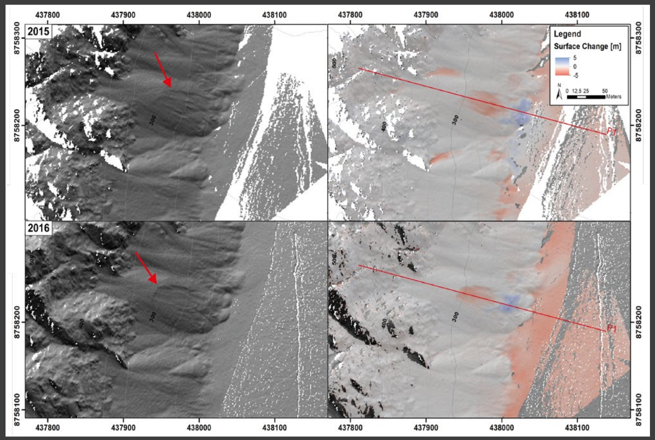

Figure 9: DODs of the landslides in 2015 and 2016 used for the schematic model on the slopes of Slåttofjellet (see Figure 8).

Figure 10: Monitoring of the debris slides in 2015 and 2016 observed via the stationary cameras(see Figure 9).

Debris slide structure

The toe of the debris slides reached in most cases the Austre Lovénbreen glacier burying in some cases >1500 m² of the glacier surface. The debris slide deposits insulated and preserved glacier ice beneath them. As the surrounding uncovered glacier ice melted, the flanks of the deposits collapse and further engulfed the buried glacier ice leading to ice-cored lobate deposits (see Figures 11-13).

All observed debris slides show a retrogressive behaviour at the main scarp and crown, which refilled the initial zone of depletion covering the exposed subsurface ice layer beneath it (see Figure 8c). This eventually causes increased movements of the talus deposits above leading to the formation of successive debris slide events in several cases (see Figure 8d, 9 & 10). During the observation period the Austre Lovénbreen lost continuously about 0.5 to 3 m in elevation per year near the foot of the talus slopes (Figure 6), which caused an oversteepening of the talus slopes.

Figure 11: Deposit of a debris slide at the slopes of Slåttofjellet in 2017. The debris slide occurred in 2011 and covered approx. 1500 m² of the glacier at that time.

Figure 12: Tongue shaped and ice-cored debris slide deposit of on the slopes of Slåttofjellet.

Figure 13: Ice-core of the debris slide seen in Figure 11 and 12. The picture was taken in 2018.

Temporal evolution of debris slides

The precipitation data and the mean daily temperature can be seen in Figure 14. The analysis of the imagery of the stationary cameras indicates that the were triggered at in autumn commonly accompanied by heavy rainfalls (see Figure 14). However, several debris slides, were activated without any observed additional trigger (e.g. heavy rainfall). This was especially the case at the glacier snout, which is not only affected by the loss of glacier ice, but also glaciofluvial erosion (see Figure 7). Furthermore, the data indicates that the impact of meteorological factors (e.g. rainfall duration and intensity during the summer, mean annual summer air temperatures and thawing degree days) on the formation of debris slides is dependent on the location and exposition of the slopes within the basin.

However, a significant increase in the annual debris slide activity (debris slide volume in m³/year) within the Austre Lovénbreen basin (ALB) could be observed during the between 2012 – 2018 (see Figure 15).

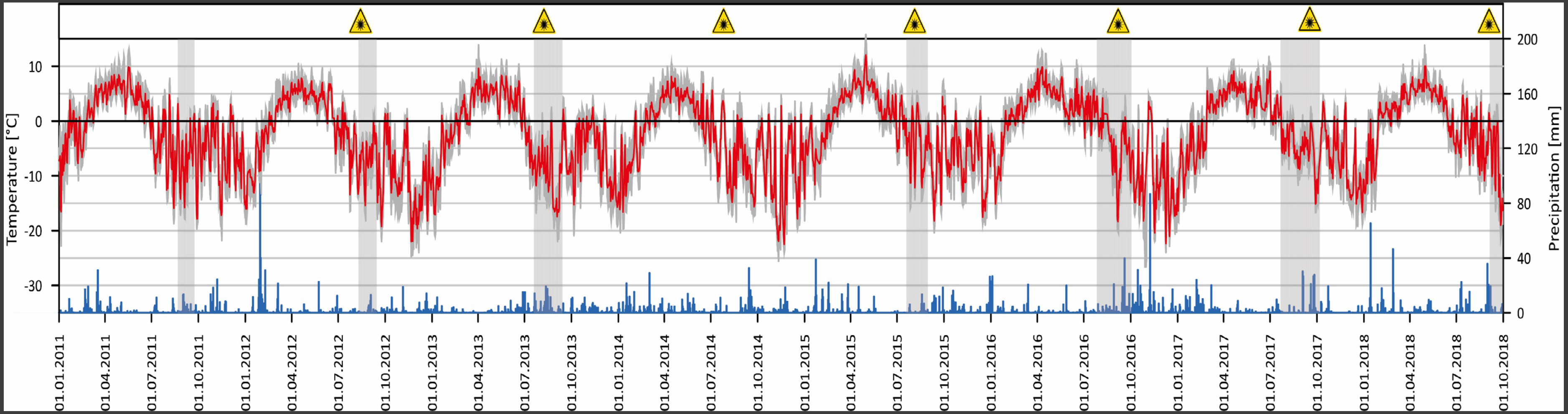

Figure 14: Mean daily temperature (red) and precipitation (blue) in Ny-Ålesund during the observation period (1st Jan. 2011 - 31rd Dec.2018). The grey vertical areas represent the observed periods of landslide activity, which were identified using daily images from stationary cameras. The yearly laser scan campaigns are indicated (yellow).

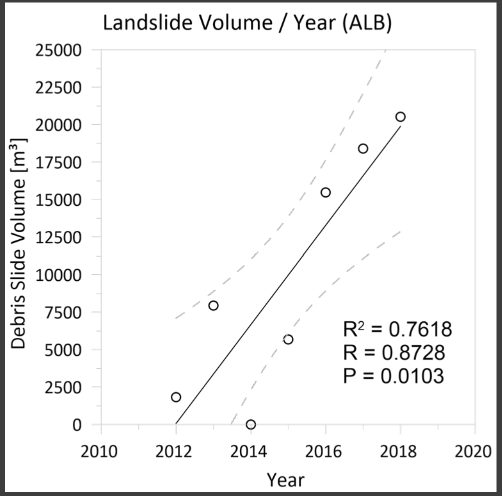

Figure 15: Landslide Volume per Year [m³/year] between 2012 and 2018.

Influence of Precipitation

In addition to study the impact of rainfall intensity on the debris slide activity the daily rainfall data was squared (X^2) summed up and normalized over a certain time period. Thus, assuring that higher rainfall intensities have a higher impact on the debris slide activity (Dietrich et al. 2018). This cumulative squared precipitation (Cum. PP^2) was calculated for the hydrological summer to exclude solid precipitation during the winter. As the all observed debris slides occurred at the end of summer (see Figure 14) it can be assumed that the winter precipitation has little to no impact on the formation of debris slides within the basin.

In Figure 16 the results of the Cum. PP^2 [mm^2] on the debris slide volume per year [m^2/year] for the Austre Lovénbreen basin (ALB), the slopes of Haavimbfjellet (HV) and Slåttofjellet (SL) can be seen. The correlation between the Cum. PP^2 and the landslide activity becomes highly significant for ALB and HV, when Zero-Values (the year 2014) are not considered in the analysis (see Figure 17). However, the results for SL remain non-significant. This might indicate that the precipitation has primarily an impact on the formation of debris slides on the slopes of Haavimbfjellet, which occur in the vicinity of the snout of the glacier. As, the surrounding slopes are dominated by the meltwater runoff and the associated erosion of the slope foot. Whereas the slopes of Slåttofjellet are not affected to this extent by meltwater runoff.

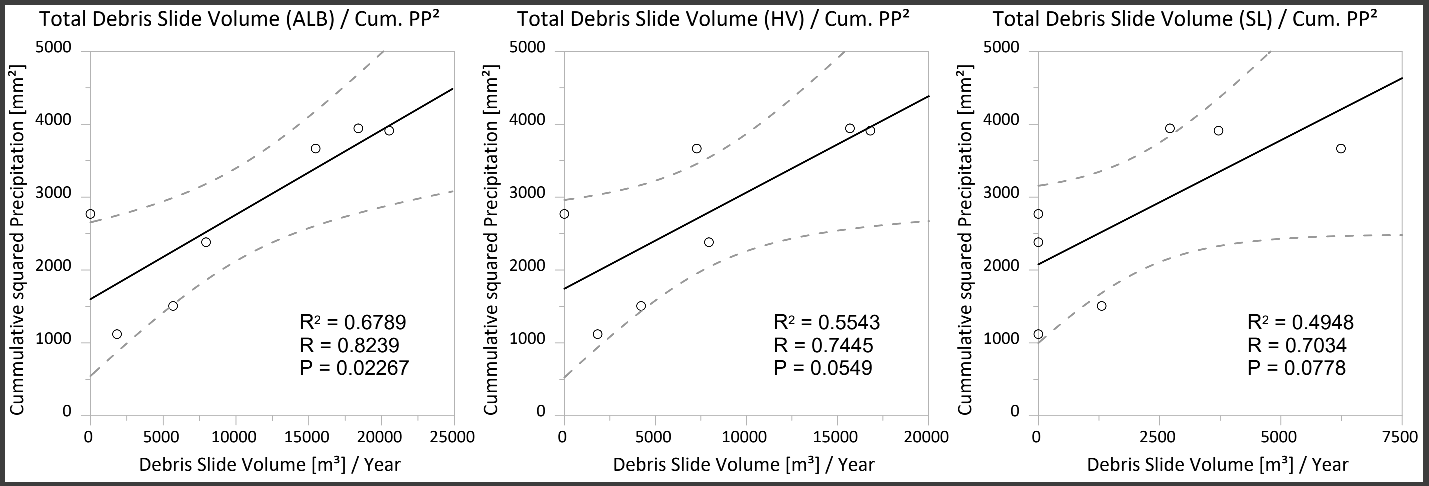

Figure 16: Cumulative precipitation squared for the hydrological summer and the debris slide volume per year [m^3/year for the entire Austre Lovénbreen basin (ALB), slopes of Haavimbfjellet (HV) and Slåttofjellet (SL).

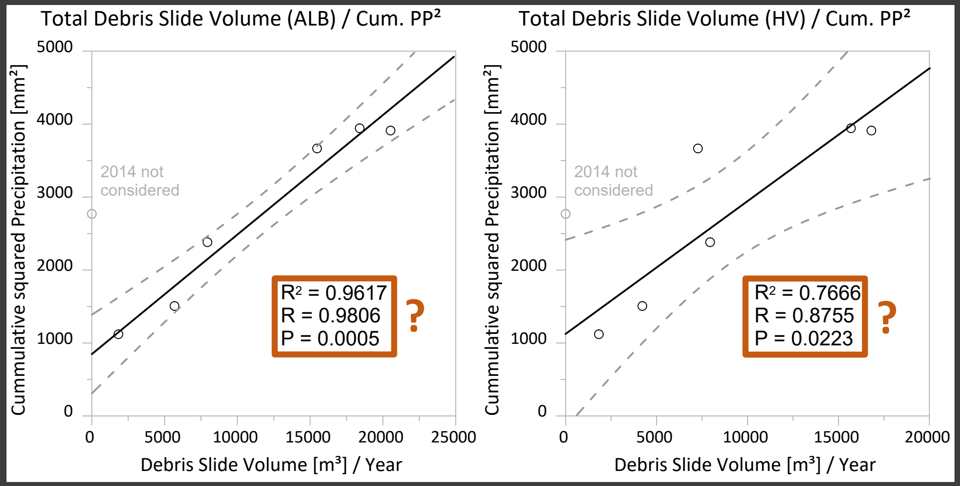

Figure 17: : Cumulative precipitation squared for the hydrological summer and the debris slide volume per year [m^3/year] without considering Zero-Values (year 2014).

Influence of Temperature

The analysis of the thawing degree days and other temperature related parameters (eg. MAAT, etc.) showed no significant correlation with the landslide activity for the entire the Austre Lovénbreen basin and the slopes of Haavimbfjellet, except for the slopes of Slåttofjellet (see Figure 18). This correlation becomes even highly significant when the year 2014, which was exceptionally cold within the observation period, is removed from the analysis (see Figure 19). This might indicate that for the formation of debris slides within the Austre Lovénbreen basin a certain temperature threshold needs to be met. However, the impact of the temperature regime and precipitation on the formation of debris slides within the Austre Lovénbreen basin is still poorly understood as no in-situ measurements were conducted and due to the limited extend of the presented time series.

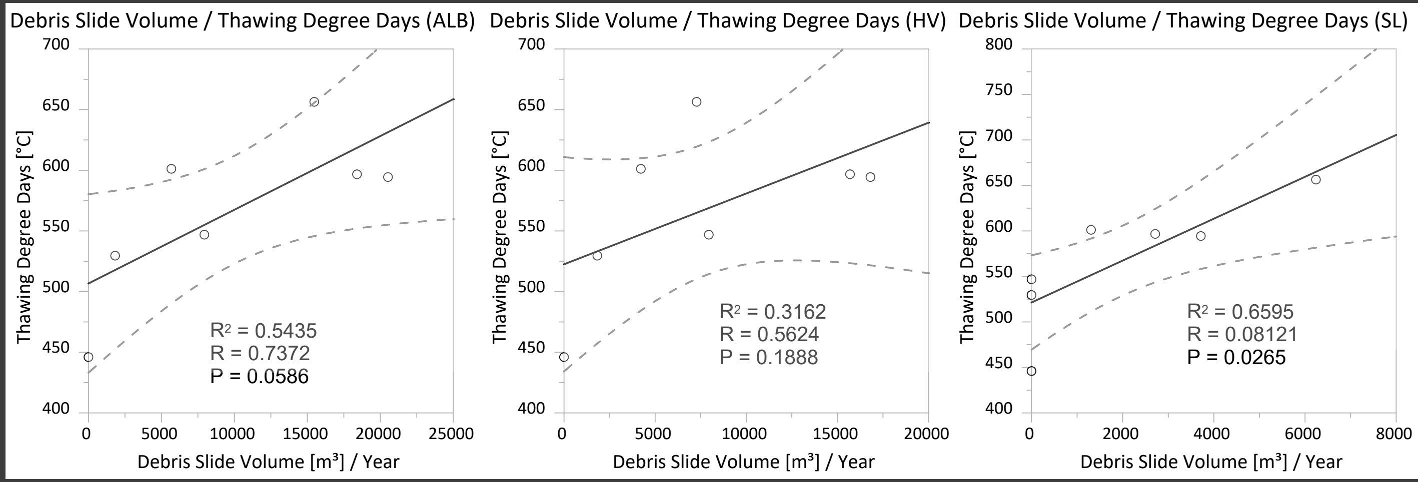

Figure 18: Thawing degree days and the debris slide volume per year [m³/year for the entire Austre Lovénbreen basin (ALB), slopes of Haavimbfjellet (HV) and Slåttofjellet (SL).

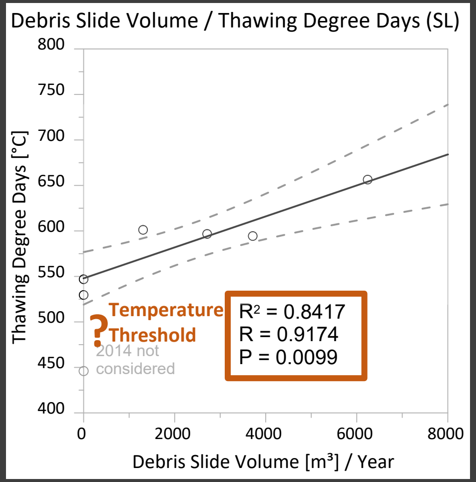

Figure 19: Thawing degree days and the debris slide volume per year [m³/year] for slopes Slåttofjellet (SL) without considering the year 2014.

Thank you
for the attention!

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