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„Automated processing of terrestrial photos for glacier monitoring at Hoher Sonnblick (Austria)"

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Autor’s declaration

Herewith I confirm that this thesis was written by me. I did not use any sources besides those cited as reference. Furthermore, this thesis was not submitted prior to this as an examination paper in any form. This thesis is identical with the version evaluated by the advisor.

Vienna, October 2019

Lucia Felbauer

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Abstract

Climate change is an omnipresent issue in the high mountains as they are highly sensitive to changes. The most obvious consequence is glacial retreat. Quantitative analysis leading to a better understanding of glacial processes has to build on detailed monitoring. The main issue dealt with in the present study is the snow cover on glaciers, targeting at the acquisition and analysis of information at high spatial and temporal resolution. The processing of terrestrial photos, taken by an automatic time-lapse camera, provides such information with a proper cost-benefit balance and an easy-to-handle workflow. Photos of two cameras are processed, operating at Hoher Sonnblick (Austrian Alps), where the two glaciers Kleinfleisskees (FLK) and Goldbergkees (GOK) are monitored. Photos of the ablation periods 2014 – 2018 are used in this survey, continuously monitoring the two glaciers. The aim of the present work is to develop a semi-automatic method to derive glacier surface classification maps operating on a daily or subdaily basis, and thereby to investigate on the spatio-temporal evolution of the snow cover patterns on two glaciers. The used image processing approach is done using two main steps: (i) Georeferencing all terrestrial photos is performed by the already existing tool PRACTISE. (ii) Surface classification is done by the newly developed model GLACIERIZER. The disappearance of the snow cover during the ablation period is quantitatively characterized. The calculated Accumulation Area Ratio (AAR) shows a decrease for the observed glaciers in the ablation periods. GLACIERIZER can be characterized as a semi-automated tool, because some manual digitizing is necessary. Challenges, limitations and further investigations for the future are discussed.

Zusammenfassung

Der Klimawandel ist das allgegenwärtige Thema im Hochgebirge und dieser Raum reagiert sehr empfindlich auf Veränderungen. Die offensichtlichste Konsequenz ist das Abschmelzen der Gletscher. Durch das Monitoring von Gletschern wird umfassendes Wissen gesammelt, auch als Basis für quantitative Analysen. In dieser Studie ist die Schneedecke das Hauptbeobachtungsobjekt, wobei auf eine hohe räumliche und zeitliche Auflösung abgezielt wird. Diese kann durch die Verarbeitung von terrestrischen Fotos, die mit einer automatischen Zeitraffer-Kamera aufgenommen wurden, ermöglicht werden, wobei es sich dabei um eine Methode mit hohem Kosten-Nutzen-Verhältnis und einem einfach zu handhabenden Ablauf handelt. Fotos von zwei Kameras werden bearbeitet, die auf dem Hohen Sonnblick (österreichische Alpen) die beiden Gletscher Kleinfleisskees (FLK) und Goldbergkees (GOK) beobachten. Für diese Studie werden Fotos für die Ablationsperioden 2014 - 2018 verwendet. Ziel der vorliegenden Arbeit ist es, eine halbautomatische Methode zur Ableitung von Gletscheroberflächen in Form von Klassifizierungskarten zu entwickeln und dabei die räumlich-zeitliche Entwicklung der Schneedecke auf zwei Gletschern zu untersuchen. Der verwendete Bildverarbeitungsansatz arbeitet in zwei Schritten: (i) Die Georeferenzierung aller terrestrischen Fotos wird mit dem bereits vorhandenen Tool PRACTICE durchgeführt. (ii) Die Klassifizierung der Oberfläche erfolgt mit dem neu entwickelten Modell GLACIERIZER. Für die beobachteten Gletscher zeigt sich eine Abnahme für die Rate der noch Schnee bedeckten Flächen am Ende der Ablationsperiode. GLACIERIZER arbeitet als halbautomatisches Werkzeug, da einige manuelle Digitalisierungen erforderlich sind. Herausforderungen, Einschränkungen und weitere Ziele für die Zukunft werden diskutiert.

Table of Contents

1 Introduction

Climate change is the issue of our time, especially high-mountain areas are vulnerable and sensitive to changes in the climate system (IPCC, 2007; European Environmental Agency (EEA), 2012). Climate forcing is determined by the variations and changes in temperature and precipitation, resulting in nonlinear responses, observed for example through time lags, feedback mechanisms, etc. (Knight and Harrison, 2016). The cryosphere and especially snow cover act as an important parameter for the global energy balance and the water cycle, for example by influencing radiation balance, groundwater, runoff, flora and fauna, glaciers and human activities (Tsai et al., 2019). The global and regional radiation balance is determined by snow cover through a direct feedback mechanism between surface albedo and surface temperature (IPCC, 2013). Because of the high albedo of snow (0.8 – 0.9) the incoming solar radiation is reflected, whereas other surfaces have mostly lower albedo (0.1 – 0.3) resulting in absorbing most of the radiation (Tsai et al., 2019). If the snow cover extent and the duration of its presence are decreasing, a reduction of the albedo is the result. This increases the warming process additionally, leading to an acceleration of snow cover melting (Winter et al., 2017). But the snow cover also plays an important role for the energy balance of glaciers, as due to its high albedo snow cover protects glacier from melting and the energy balance is controlled by the energy fluxes on the surface of the glacier (Rastner et al., 2015). Mass loss and gain on glaciers are mostly determined by melting and snowfall, both influenced by atmospheric processes and their current changes, for example changes in moisture, circulation and air temperature. Adjustments to such changes are seen in the surface mass balance (Bamber, 2015). A useful indicator for the annual mass balance can be observed by the altitude of the snow line at the end of the ablation period, because it roughly represents the altitude of the equilibrium line (Rastner et al., 2015). Especially in the high mountains the snowpack underlays strong variations for both spatial and temporal constituents (Piazzi et al., 2019), but this information is highly relevant and needed for further investigations (Pirazzini et al., 2018). Furthermore because of its multiple influences, snow cover is defined as a critical climate variable by IPCC (2013). Several methods for monitoring snow cover do exist, but when dealing on a high spatial and temporal resolution a lot of approaches (e.g. station data, satellites, manual measurements, etc.) are not sufficient enough (Bernard et al., 2013). Terrestrial photography, realized with automatic time-lapse cameras, achieve this high resolution aims, beside also acting as a cost-effective solution for remote places (Härer et al., 2013). Automatic approaches processing the photo data have already been established, but the surface classification procedure is still a gap (Salzano et al., 2019), especially when several classes should be distinguished and at the same time an adjustment to disturbing conditions like shadows should be gained (Bernard et al., 2013).

The aim of this master thesis is to develop and evaluate an easy to handle prototype of an automated image classification approach, which derives glaciers surface classification maps distinguishing into several classes on a daily or subdaily basis, and thereby (i) to identify the needs for further research and (ii) to investigate on the evolution of snow cover patterns on two glaciers in the Austrian Alps (Kleinfleisskees and Goldbergkees). This study will therefore address the following research questions:

i. Which level of automatization can be achieved in processing terrestrial photos for the detection of glacier changes, in particular snow-free areas on the glacier?

ii. What are the limitations and the key challenges in doing so?

iii. How did the patterns of snow cover evolution on the analyzed glaciers change in the period 2014 (2016) - 2018?

The main part of this master thesis consists in a manuscript prepared for submission to the journal “Remote Sensing of the Environment”. That manuscript is wrapped into a framework paper setting the scene and highlighting the main findings and conclusions.

The study area of Hoher Sonnblick is presented in Section 2. Section 3 provides an insight in the data and the methods used and developed. The submitted publication is presented in Section 4. Section 5 outlines the results. An insight in the discussion of limitations is given in Section 6, followed by an overall conclusion (Section 7).

2 Study Area

For testing the image classification approach two automated time-lapse cameras are selected, which monitor the two glaciers – Kleinfleiskees (FLK) and Goldbergkees (GOK). The study area is located in the central Austrian Alps, at the Alpine main divide. A strong climatic gradient resulting in different precipitation and snow distribution patterns is found between the south and the north, therefore also influencing the glacial evolution (Auer et al., 2002; Mott et al., 2008; Schöner et al., 2012a). Hoher Sonnblick forms the highest peak (3106 m) of the study area and is also well known for the observatory, having the longest continuous series for meteorological data on such an altitude (Schöner et al., 2012b). For both glaciers intense glacial monitoring is performed, demonstrating the evolution and retreat of the glaciers (Schöner et al., 2012a; Auer et al., 2002; Schöner et al., 2000). Because of the location in an area with high amount of precipitation, these glaciers are climatologically more sensitive than other glaciers in Austria (Schöner, 2009).

3 Data and Methods

The main data source for this survey are terrestrial photos, taken by automatic time-lapse cameras operated by ZAMG. The camera directed towards FLK operates since 2014, the one observing GOK since 2016. Automated georectification is needed to produce orthophotos out of a high number of taken photos. Therefore, a digital elevation model (DEM), information about interior and exterior orientation and the camera target point (center of the photo) are required (Härer et al., 2013; Arslan et al., 2017).

The methodical aim is to select representative photos for monitoring the snow cover over the ablation period, transforming them to orthophotos and afterwards distinguish several classes due to their surface appearance. Two main approaches are attached to each other: PRACTISE and GLACIERIZER. The georectification tasks is done by the open source code PRACTISE (Photo Rectification And ClassificaTIon SoftwarE) developed by Härer et al. (2013) which is based on the photogrammetric principle of monoplotting. Thereby a two-dimensional photo is transformed in such a way that three-dimensional points are representing the scene. In other words, the pixels of a photo are blended with the coordinates of a DEM, resulting as a virtual photograph of a DEM. PRACTISE is based on a procedure developed by (Corripio, 2004) and furthermore some optional features are included for improving the interior and exterior orientation parameters. Ground Control Points (GCPs) are used for a precise georectification, which are generated in two ways: differential GPS points are measured in the field (Messerli and Grinsted, 2015) and distinctive marks between an orthophoto and the corresponding photo are matched (Schwalbe and Maas, 2017). For this survey, several GCP sets do exist because of compensating camera movements. PRACTISE was modified in the way that various glaciers, survey periods, GCP files and camera parameters can be accessed in a new user-friendly setting. Because the classification approach within PRACTISE only works with fixed thresholds and the offered adaptations to these thresholds do not produce successful results, a new surface classification approach is developed, called GLACIERIZER. GLACIERIZER is a semi-automated surface classification tool, which handles multiple orthophotos and is programmed as a Python-ArcGIS Script. A most likelihood classification is performed by considering training areas based on a weekly or monthly basis. Several classes are distinguished and their RGB thresholds are adapted for every single orthophoto. This makes it possible that changing conditions (weather, illumination) are considered. The results are created within the automatic approach, linked to the software R, and presented through different kinds of maps.

4 Manuscript

This manuscript was prepared for submission to the Journal Remote Sensing of the Environment.

Automated processing of terrestrial photos for glacier monitoring at Hoher Sonnblick (Austria)

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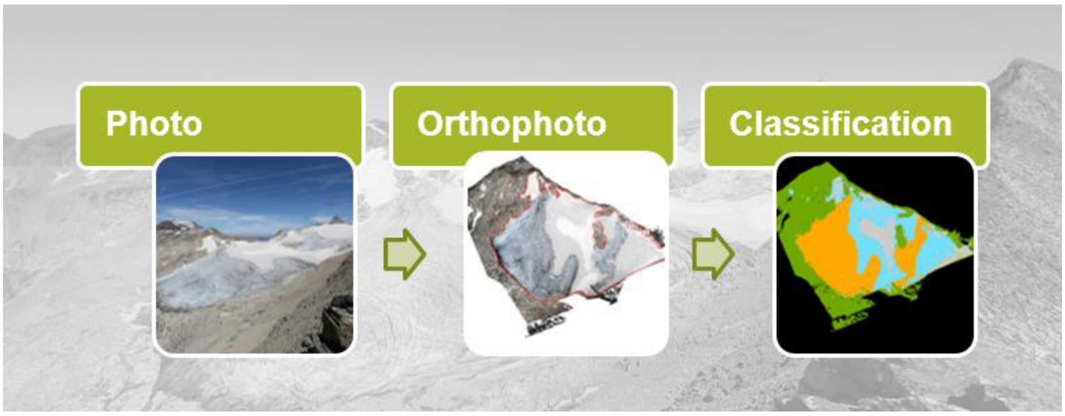
Graphical abstract



Keywords

Glacier monitoring, snow cover evolution, surface classification, automatic cameras, semiautomated model, Alps

Highlights

- Semi-automated surface classification approach operating for glacier monitoring.
- Time-lapse cameras perform as a distinguished method due to high spatial and temporal resolution.
- Newly developed and easy to handle surface classification tool GLACIERIZER, adaptable for diverse photo monitoring approaches.
- GLACIERIZER usable for showing snow cover evolution over several ablation periods

Abstract

High-alpine regions react highly sensitive to climate change, and the most obvious consequence of rising temperatures is glacier retreat. Continuous monitoring of glaciers at various spatial and temporal resolutions serves as a basis for quantitative analyses of changes. The aim of the present work is to develop a semi-automatic method to derive glacier surface classification maps operating on a daily or subdaily basis, and thereby to investigate on the spatio-temporal evolution of the snow cover patterns on two glaciers. We focus on the analysis of terrestrial photos, taken by automated time-lapse cameras installed at Hoher Sonnblick in the Austrian Alps.

Photos from two cameras are used to continuously monitor two glaciers (Kleinfleisskees and Goldbergkees) in the period 2014 – 2018.

The work flow of the image processing operates in two main steps: (i) The existing georectification tool PRACTISE is applied to automatically georectify all the selected terrestrial photos. (ii) The newly developed routine GLACIERIZER is employed for surface classification. A supervised classification method is applied, building on training areas. The entire framework is flexible enough to be applicable on other cameras. The classification results allow quantitative statements distinguishing in different classes and further analysis of the output data. However, GLACIERIZER is a semi-automatic surface classification model, since some steps have to be done by manual digitizing. Limitations and further investigations are discussed. The study demonstrates that GLACIERIZER is usable for monitoring snow cover evolution over several ablation periods, and that the proposed procedure represents an easy-to-handle and inexpensive way of snow cover monitoring on glaciers.

1 Introduction

Climate change is the challenge of our time and has already led to a wide range of impacts on environmental and societal systems (European Environmental Agency (EEA), 2012). The atmospheric warming in the Alps is two times larger than the global average for the last 50 years (Böhm et al., 2001). As a result, especially high mountain regions are sensitive and vulnerable to effects of changing climate through the coupling of rising temperatures and changes in precipitation regimes (European Environmental Agency (EEA), 2012; IPCC, 2007). The cryosphere as an important constituent of the earth's climate determines the energy balance and the hydrological cycle (IPCC, 2013). Snow cover seasonally extents over a large area, for example 40 % of the northern hemisphere are covered in snow during winter (IPCC, 2007). The seasonally wide-spread areal extent, the much higher albedo compared to other land surfaces, and the thermal properties make snow cover an important player in the earth's energy balance (Aalstad et al., 2018). High mountain area, the snowpack shows a strong variation in space and time, as a result of complex interactions between meteorological forcing and local topography, which are the main explanatories (Piazzi et al., 2019). Adequate information of the spatial and temporal distribution of snow cover is still highly relevant for various research purposes (Pirazzini et al., 2018). Due to its multiple influences snow cover is identified as a critical climate variable (GCOS, 2011; IPCC, 2013).

A globally seen phenomena are retreating mountain glaciers and negative mass balances of ice sheets, triggered by the effects of natural and anthropogenic climate change (Huss et al., 2017). Small glaciers (<1 km²), which are common in the Alps (80 %) experience the strongest areal reduction (Diolaiuti et al., 2011). Especially for this situation, snow cover represents an important parameter for a given glacier, because it controls the glacier mass and energy balance due to energy fluxes on the glacier's surface (Oerlemans and Fortuin, 1992). Fresh snow has a higher albedo than glacier ice and protects the glaciers from the incoming near infrared and shortwave radiation. The albedo of glacier ice is even lower as soon as it contains impurities (Dozier, 1989). At the end of the ablation period the altitude of the snow line roughly represents the equilibrium line on alpine glaciers, which serves as an indicator for the annual mass balance (Rastner et al., 2015). In summary, monitoring the snow cover distribution addresses the aim of snow cover regime changes at a regional scale (Dedieu et al., 2014).

Station data for snow monitoring are usually sparsely and unevenly distributed, even in the European Alps, and manual in situ measurements through field are hampered by the remoteness of glaciers, safety issues and harsh weather conditions (Klemes, 1990; Viviroli et al., 2011). Overall, both methods do not represent snow cover variations (Hinkler et al., 2002). Remote sensing methods, including global satellite systems, radar-based observations, laser-scanning techniques and photogrammetry are alternatives to ground based methods (Parajka et al., 2012). Satellites can capture large areas at regular intervals (Hinkler et al., 2002), but the lack of proper suitable, publicly available, high-resolution, optical and thermal data is still a limitation (Bhardwaj et al., 2016). Satellite-based methods are hardly applicable when both high spatial and temporal resolutions are required (Bernard et al., 2013). A further limitation is cloud cover for the Alps, the annual average of land surface areas hidden by clouds is 60 % (Dumont and Gascoin, 2016). In contrast terrestrial photography offers an easy-to-use land surface monitoring approach, which is cost-effective and yields information on a high spatial resolution, also for remote places (Härer et al., 2013). The usage of time-lapse cameras enables a high temporal resolution (Parajka et al., 2012) and if the data is referenced precisely, photos could be a valuable data source for qualitative analysis (Farinotti et al., 2010).

Automated time-lapse cameras are evolving into a popular research tool for a broad array of research topics, such as the breeding success of cliff-nesting seabirds (Merkel et al., 2016), estimation of plant biomass (Selsam et al., 2017), lake ice monitoring (Xiao et al., 2018), hydrological monitoring (Parajka et al., 2012), shoreline change monitoring (Ahn et al., 2017), or monitoring of river-channel changes (Chandler et al., 2002). Automated cameras are even used for obtaining a regular and direct insight into animal behavior by attaching them to individual animals (Kaczensky et al., 2019).

Time-lapse cameras have been used for snow cover monitoring e.g. by Arslan et al. (2017), Bernard et al. (2013), Härer et al. (2012), Huss et al. (2013), Jamkes et al. (2016), Messerli and Grinsted (2015), Rumpler et al. (2017) and Salvatori et al..

Although several approaches for processing photos of automated cameras do exist, Salzano et al. (2019) point out that, the surface classification of snow cover would still be susceptible to misclassifications. Especially the distinction into several classes remains a challenge (Bernard et al., 2013). Further, the method would strongly profit from fully automatization (Kaufmann and Ladstädter, 2008).

The aim of the present work is to develop and evaluate an easy to handle prototype of an automated image classification approach, which derives glaciers surface classification maps distinguishing into several classes on a daily or subdaily basis, and thereby (i) to identify the needs for further research and (ii) to investigate on the evolution of snow cover patterns on two glaciers in the Austrian Alps (Kleinfleisskees and Goldbergkees). Thereby, we elaborate on the following research questions: (i) Which level of automatization can be achieved in the processing terrestrial photos for the detection of glacier changes, in particular snow-free areas on the glacier? (ii)

What are the limitations and the key challenges in doing so? (iii) How did the patterns of snow cover evolution on the analyzed glaciers change in the period 2014 - 2018?

Dealing with these issues in this paper, the study area of Hoher Sonnblick is presented in Section 2. Section 3 gives an overview of the used data and Section 4 provides an insight into the methods used and developed. The classification results of GLACIERZER are shown in Section 5 and their limitations are discussed in Section 6, followed by an overall conclusion (Section 7).

2 Study Area

The image classification approach is tested at two glaciers in the Sonnblick area (see Figure 1), located in the Hohe Tauern region, part of the central Austrian Alps. Hoher Sonnblick (47°03'16''N, 12°57'25''E) forms the highest peak (3106 m) and hosts a meteorological observatory run by ZAMG (Central Institute of Meteorology and Geodynamics).

Figure 1. Study Area – Hoher Sonnblick: Located in the central Austrian Alps with the highest Peak of Hoher Sonnblick (3106 m), investigating two glaciers: Kleinfleisskees (FLK) and Goldbergkees (GOK).

The Sonnblick Observatory was built in 1886 (Graßl et al., 2012), having the stand out position as the high mountain observatory with the longest continuous meteorological data series on this altitude (Schöner et al., 2012b). South and east of Hoher Sonnblick, the two glaciers Kleinfleisskees (FLK) and Goldbergkees (GOK) (ca. 1 km²) are located, in steep alpine terrain. These glaciers are under intense investigation (Michlmayr et al., 2008; Schöner et al., 2012a; Schöner et al., 2009) and serve as the study sites also in the present work.

The Sonnblick area consists of gneiss of the "Tauernfenster" (Schober, 2002). Permafrost occurs probably above 2500 m a.s.l. on north-facing slopes, whereas for south-facing slopes only sporadic permafrost was detected above 2750 m a.s.l. (Schöner et al., 2012a).

Hoher Sonnblick is part of the Alpine main divide, resulting in a climatological separation into the wetter (high level of precipitation) part in the north (Salzach valley) and into the dryer part (inneralpine dry valleys) in the south (Möll valley). A strong gradient can already be recognized by changing precipitation pattern and snow distribution next to Hoher Sonnblick, also influencing a higher spatial variability of glacier development (Auer et al., 2002; Mott et al., 2008; Schöner et al., 2012a). The average annual precipitation is 2263 mm, the annual new snow is 2103 mm and the mean annual air temperature is at -5.1 °C (standard reference period 1981-2010) (Auer et al., 2012).

Due to early scientific measurements at Hoher Sonnblick, the strong glacier retreat is well documented since 1896 (Auer et al., 2002; Schöner et al., 2012a). Regular mass balance measurements started for Wurtenkees (1982) by Böhm and Hammer, GOK (1987) and FLK (1998), the results of which indicate a strong increase in temperature since 1980. The expansion of mass balance surveys was motivated in capturing the spatial glacier variability due to the climate divide by the central Alps. The long time series of intense glacier monitoring is outstanding for the Alps, summarizing that glacier retreat is determined by summer ablation, not by the reduction of winter accumulation for the glaciers in the Sonnblick area. The mass balance, both in summer and in winter, further strongly depends on the orography, representing the climatological variability of the region due to the location at the climate divide. Because the study site is located in an area with high amounts of precipitation, the glaciers show a higher climatic sensitivity than other Austrian glaciers (Schöner et al., 2009). The areal glacier extent of FLK is 0.85 km² (2016) and shows a maximum ice thickness of 162 ± 36 m (2004). GOK's extent is 1.11 km² (2016), with a maximum ice thickness of 153 ± 34 m (2004) (Binder et al., 2009; Schwaizer (nee Bippus) and Nemec, 2017).

3 Data

Photos of two camera spots are used to test the automated monitoring system. Two single lens reflex cameras: Canon EOS 1100D (FLK 2014-2017) and Canon EOS 1200D (GOK 2014ff, FLK 2018ff), with Canon EF-S 10-22 mm f/3.5 – 4.5 USM lens were installed and photos have been taken at an interval of ten minutes. The camera for monitoring FLK operates since 2014 (see Figure 2), is orientated to the northeast and is mounted on a ridge at 2970 m a.s.l.. The field of view covers the whole surface of the glacier. The second camera has been monitoring GOK since 2016 (see Figure 2), is orientated towards southeast and is fitted at a ridge at 2932 m a.s.l..

This camera only looks on the middle and lower part of GOK. All photos are transferred in real time, can be downloaded and ZAMG owns the copyright of the photos. In total 1433 photos were manually selected over the period of 2014 to 2018, due to the demand of high quality image exploitation (Bernard et al., 2013). Like recommended by Farinotti et al. (2010) the selected photos should afford a homogeneous chronology of the melt-out evolution. Only those photos taken between 9 am and 5 pm are considered for further selection. Additionally, considering only photos which are as little affected as possible by disturbing weather (fog, clouds, water droplets on camera window) and light conditions (nearly same time of day, constant illumination) are chosen (Farinotti et al., 2010; Messerli and Grinsted, 2015).

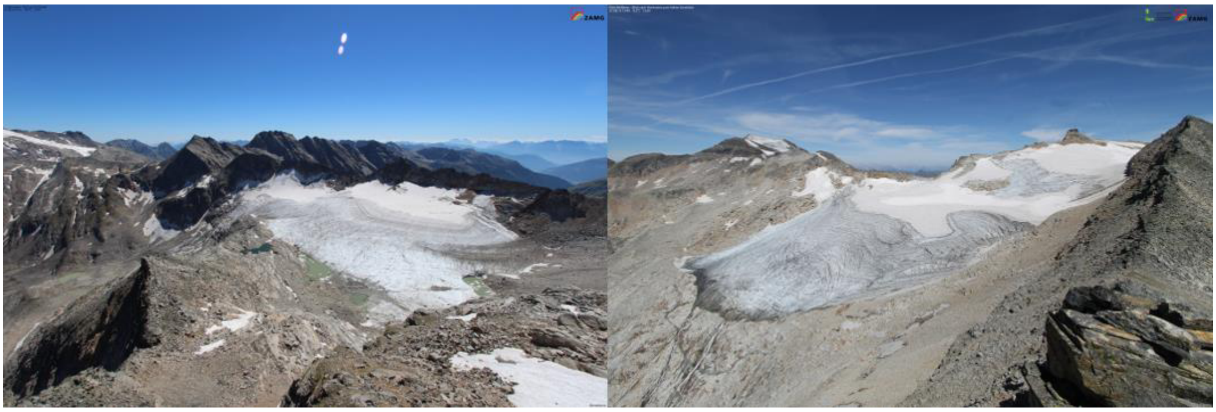


Figure 2. Automated time-lapse cameras: Monitoring two glaciers: Kleinfleisskees (FLK) (at the right) and Goldbergkees (GOK) (at the left), © ZAMG.

As input data for the used methods (see Section 4.1) photos, camera location with its orientation and a digital elevation model (DEM) are needed (Härer et al., 2013). We use a DEM with a spatial resolution of 1 m recorded through an airborne laser scanning campaign by the Province of Salzburg (© SAGIS) in 2009. We consider this the best choice as no newer DEM is available for the study area, which would be preferable (Corripio, 2004; Jamkes et al., 2016; Messerli and Grinsted, 2015). For the exterior orientation following parameters of the camera have to be integrated: latitude and longitude of the camera position, the camera target point (center of the photograph), and the roll angle of the camera. In addition, the parameters for the interior orientation have to be known, such as the sensor dimensions (height and width) and the focal length (Arslan et al., 2017; Härer et al., 2012). The precision of the input parameters defines the accuracy of the resulting orthophoto, especially if several photos are processed automatically (Hinkler et al., 2002). The camera dependent parameters were taken from the Canon manual. For the GOK camera we use a resolution of 5184 px vertically and 3456 px horizontally, which is also available for photos of FLK from 2018 onwards. For previous years on FLK a resolution of 4272 px vertically and 2848 px horizontally is available. The photos record 8 bits of information for each pixel. Latitude and longitude of the camera positions are measured by differential GPS. The target positions are visually estimated through an orthophoto of 2015 (resolution 0.2 m) recorded by the province of Salzburg (© SAGIS). Because the FLK camera has been operating since 2014, photos of the orthophoto survey day could be used for a more precise estimation of the target position. Within PRACTICE the implementation of dynamically dimensioned search (DDS) attempts to optimize the parameters of exterior and interior orientation. Therefore, ground control points (GCP) are measured and searched, which are required for an accurate registration to real-world coordinates (Jamkes et al., 2016). Several GCP sets regarding movements of the cameras are gathered via two approaches (i) differential GPS and (ii) determining distinctive marks in the area via desktop matching (Messerli and Grinsted, 2015), between the orthophoto of 2015, the DEM and the taken photos (Schwalbe and Maas, 2017).

Glacier outlines are manually digitized for each year based on the produced orthophotos. Additionally, training samples are digitized on a weekly and monthly basis, detecting the main input features for the classification task.

For validating GLACIERIZER a predicted data set based on the classification results as well as a reference data set based on the generated orthophotos were prepared. Both sets are compared via a confusion matrix and the trend of the main statics is shown.

4 Methods

Starting with several photos in a series the aim is to create orthophotos, which are subsequently classified due to their surface appearance. Therefore, the methods presented here are attached to each other, performing an automate image surface classification (see Figure 3). In a first step, the spatial information of each photo has to be reconstructed (Kappas, 2014), expressed through a ground coordinate system (Verykokou and Ioannidis, 2018). Thereby, we employ the photogrammetric principle of monoplotting, where photos are projected onto a digital elevation model (Kenner et al., 2018). Classification of the orthophotos generated is performed in a second step.

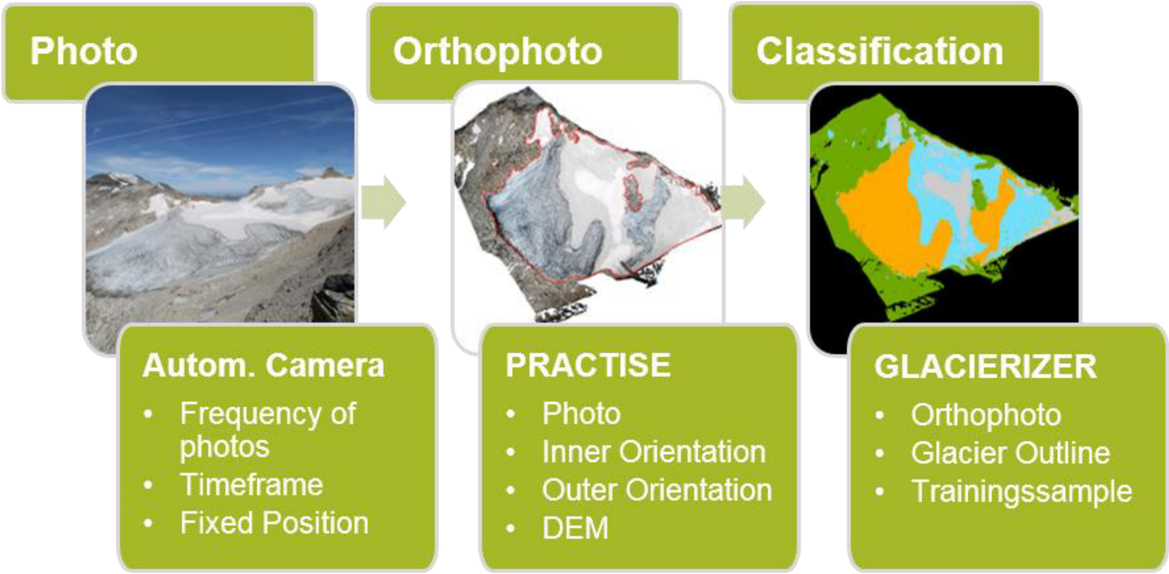


Figure 3. Overall work flow and visualization of image processing purpose: First row gained products, last row necessary input parameter; photo acquisition by automatic time-lapse-cameras, automatized georectification by PRACTISE and surface classification by GLACIERIZER (left to right); © ZAMG.

4.1 Georectification - PRACTISE

The algorithm PRACTISE (Photo Rectification And ClassificaTIon SoftwarE) is a freely available and modifiable source code written in Matlab by Härer et al. (2012). The georeferencing task in PRACTISE is based on the procedure of Corripio (2004): A function is defined in which a two-dimensional pixel of a photo is associated to a three-dimensional point in a DEM. After the coordinates of a DEM have been transformed on the camera coordinate system of a photo, a perspective projection is performed. In other words, the pixels of the photos are blended with the coordinates of the DEM. The result is a virtual photograph of a DEM, which contains the three-dimensional terrain information of the DEM, but is seen from the position of the camera and shows the current surface appearance, where also the RGB values are implemented. When scaling this representation based on the resolution of the photo the necessary linkage between pixels and the coordinate systems can be achieved

(Corripio, 2004). PRACTISE starts with the viewshed generation, where for every pixel on the DEM it is calculated, if the pixel is visible from the camera position or not. Camera position and target position display the viewing direction (Härer et al., 2012, 2013). The parameters describing the interior orientation are needed for calculating the horizontal and vertical view (Corripio, 2004). PRACTISE offers an optional feature for improving the exterior and interior orientation parameters, called "GCP accuracy assessment and DDS optimization". Through the usage of GCPs the spatial inaccuracy between the photo and the virtual camera image can be reduced. For this survey different sets of GCP sets (see Table 1 and Section 3) are developed, because two cameras are conducted and due to camera movements several sets are needed. Beside measurements of GCPs in the field via dGPS (see Table 1: FLK 2017 and 2018), also desktop matching (see Table 1: FLK and GOK 2015) is used for getting GCPs for older camera positions.

The dynamically dimensioned search (DDS) algorithm by Tolson and Shoemaker (2007) tries to reduce the offset between the real position of the GCPs and the georeferenced position. In an iterative process important variables are revised and optimized until the georeferencing task is performed with the best camera parameters (Härer et al., 2012, 2013).

Table 1. Overview of different GCPs data sets, using two matching methods in this survey: (1) Desktop matching via distinct features detected on orthophoto 2015 (SAGIS) and photos; (2) Matching between DGPS measurements and photos;

Camera	Year	Remote Sensing Product	Based on specific photo	Matching Method	Reference data set
FLK	2015	Orthophoto 2015	FLK-2015-08-28-1230	Desktop matching	Ref02
FLK	2017	DGPS 2017	FLK-2017-04-30 - 05-01	DGPS	Ref06
FLK	2018)	DGPS 2018	FLK-2018-04-21 - 04-22	DGPS	Ref08
GOK	2016	Orthophoto 2015	GOK-2016-08-24-1330	Desktop matching	Ref04
GOK	2018	DGPS 2018	GOK-2018-04-24	DGPS	Ref08

PRACTISE offers two approaches for surface classification. The first method is based on the manual detection of absolute RGB threshold values by analyzing the whole photo. The second approach gains to an automated image classification approach through the statistical analyses of a frequency histogram (Härer et al., 2013; Salvatori et al., 2011). For more detail information on PRACTISE see (Härer et al., 2016, 2013, 2012). Both approaches are tested, but could not achieve satisfying results, especially when automatization and distinction of several classes are intended. Like Salzano et al. (2019) also we experienced that limitations are found in the fields of illumination conditions, surface roughness and shadowing effects. Dealing with the demand of an automated routine, the new model GLACIERIZER was developed.

4.2 Modification on PRACTISE

We have modified the open source code of PRATICE for the purpose of automatization. Various glaciers, survey periods, GCP files and camera parameters can now be accessed via a logical data structure. The output is generated as an orthophoto in TIF format, serving as the main GIS input data for the surface classification (see Section 4.3). In addition, multiple photos can be georeferenced one after the other in an automated way.

4.3 Surface classification - GLACIERIZER

GLACIERIZER is a semi-automatized surface classification tool for multiple orthophotos, developed within the course of the present work. It consists of a Python script, which is connected to both ArcGIS (via Arcpy) and R. The study area outlines, glacier outlines, orthophotos and training areas are needed as input for the whole sample period. The main task is performing a maximum likelihood classification on a weekly or monthly basis, where the classification task is done on pixel level considering Regions Of Interests (ROIs) (Salzano et al., 2019). The same training data set is used for several orthophotos, thereby a new set of thresholds is calculated for each orthophoto, considering the current conditions. For improving the quality of the results and avoiding misclassifications, some rules and filtering processes are implemented. The main output consists in the classification results in terms of various maps: (i) only the orthophoto with glacier outline, (ii) in addition also the surface classification for the whole study area and (iii) classification results clipped to the glacier outline. The creation of training areas is based on the manual generation of samples. This allows for a flexible and adaptable automated choice of the classification thresholds (Ide and Oguma, 2013), due to the varying illumination and RGB signals caused by different weather and snow conditions (Schmidt et al., 2009). A representative set of training areas covering all surface classes has to be used for achieving adequate classification. The training areas have to cover the entire image in order to avoid misclassifications, if only parts of the orthophoto are affected by slight shadows. It should also be noted that the individual polygons have to be representative for the whole calendar week/ month.

4.4 Validation of GLACIERIZER

The results yielded by GLACIERIZER are evaluated through a confusion matrix. In the present work, 1433 photos are used for the classification task. 53 orthophotos with their matching classification raster are randomly selected from both cameras and all years. This selection performs as the validation data set of GLACIERIZER. 100 points are randomly spotted in each modelled class in each orthophoto, and their class values represent the predicted data set. The reference data set is built by the class values based on the orthophotos, which have to be visually determined. The predicted and reference data set are compared in the confusion matrix which gives an insight into the level of accuracy of the classification.

5 Results

5.1 Output of GLACIERIZER

The processing and implementation have been done for FLK and GOK, performed through all available photo series, representing the ablation periods. In total 1433 photos were selected, georeferenced through PRACTISE and classified in a semi-automated way by GLACIERIZER. An example of the results (see Figure 4) shows the situation at FLK from 27th August 2015 at 13:40 for different results produced by GLACIERIZER. The total scene covers 1.27 km² and the whole extent of FLK is under observation. Visual comparison between the orthophoto (see Figure 4 b) and the classification results (see Figure 4 c-d) show a high level of compliance, which could be achieved due to the good weather conditions and the clearly distinct surface classes. For the whole situation 115 655 m² of snow, 288 006 m² of firn, 377

466 m² of ice and 484 565 m² of bare ground were detected by GLACIERIZER. Snow, ice and bare ground can be distinguished quite well, whereas challenges occur for firn and debris cover on the glacier.

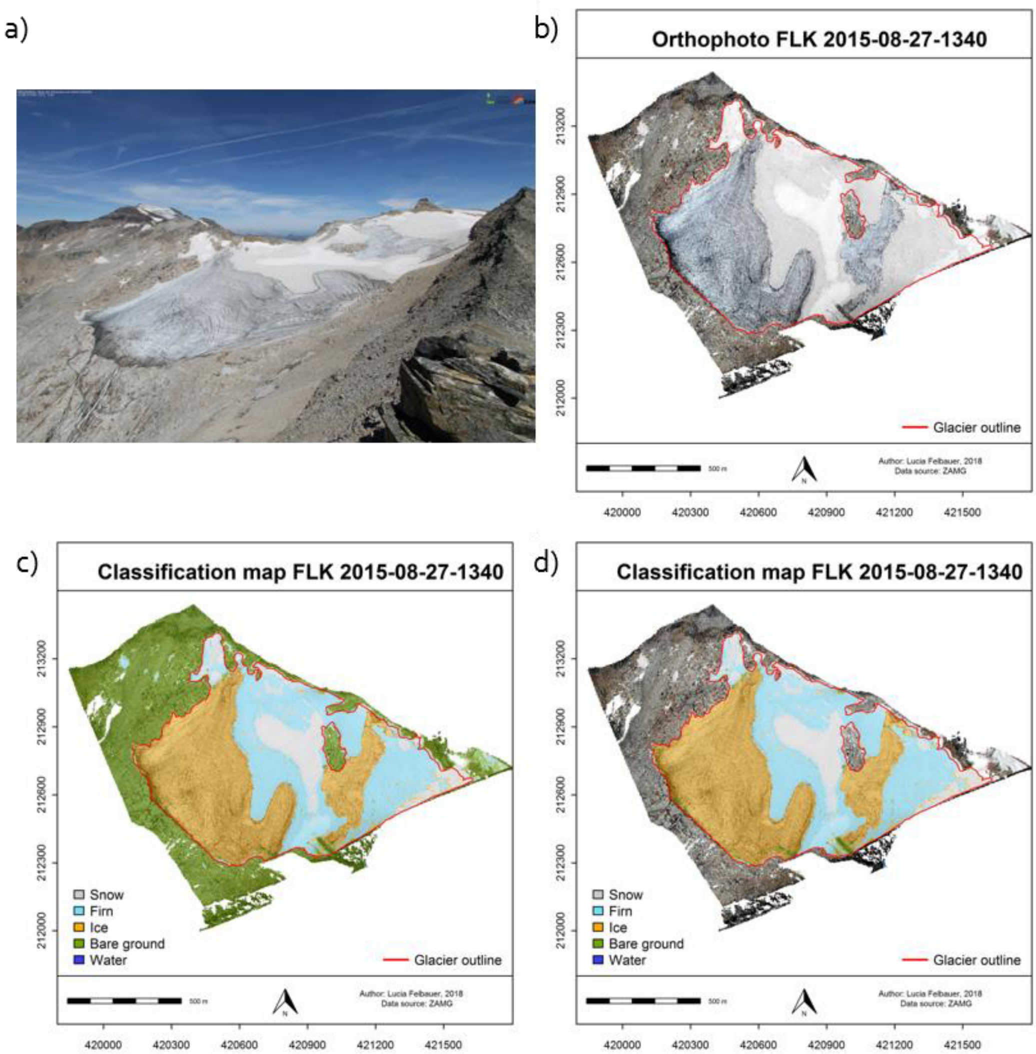


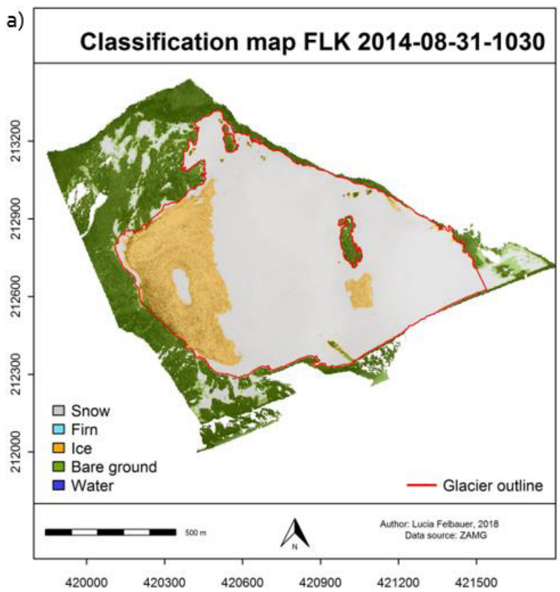
Figure 4. Exemplary, different products of the surface classification results of GLACIERIZER: FLK, 27th August 2015 at 13:40 in different working steps. (a) the original photo; (b-c) generated via GLACIERIZER: (b) orthophoto; (c) classification for the whole extent, (d) classification within the glacier extent, © ZAMG.

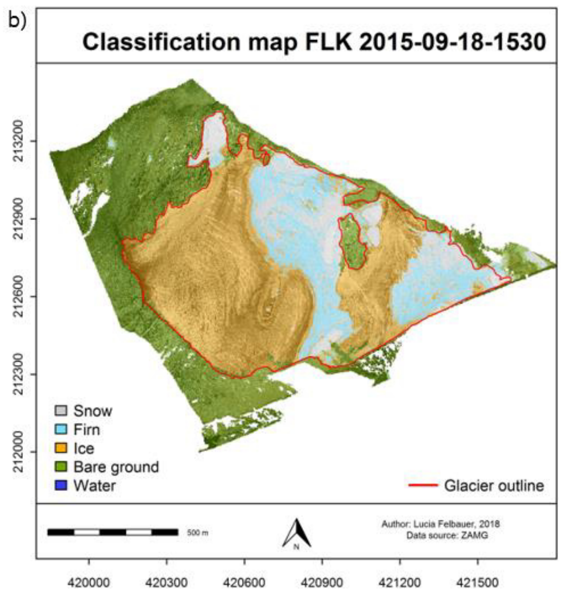
5.2 Observation of ablation periods

The classification results can be used for various glaciological applications. As an example, the maximum disappearance of the snow cover for each surveyed ablation period is represented by the Accumulation Area Ration (AAR). The AAR is the ratio between the still covered area of snow and firn, divided by the total glacier extent. Following AAR percentages represent the stage of minimum snow cover

5.2.1 FLK

A decrease of the AAR for FLK (2014-2018) can be detected (see Figure 5) even on a visual basis. This assumption can be verified through Table 2 and the diagram (see Figure 5 f). In the last five monitoring years the ratio has dropped, starting at a high AAR of 77 % in 2014, decreasing through the years: 41 % (2015), 38 % (2016), 22 % (2017) and 1 % (2018). For the last investigated survey year, 2018, only 13 % of the glacier has been covered by snow or firn at the stage of minimum snow cover extent. The large AAR of 2014 is explained by the dominance of southwesterly flow conditions during the winter months leading to above average winter snowfall. Prevailing cloudy conditions with reduced melting and frequent cold air outbreaks with snowfall events during the summer lead to positive mass balances for 2013/2014 on FLK (Hynek et al., 2019).





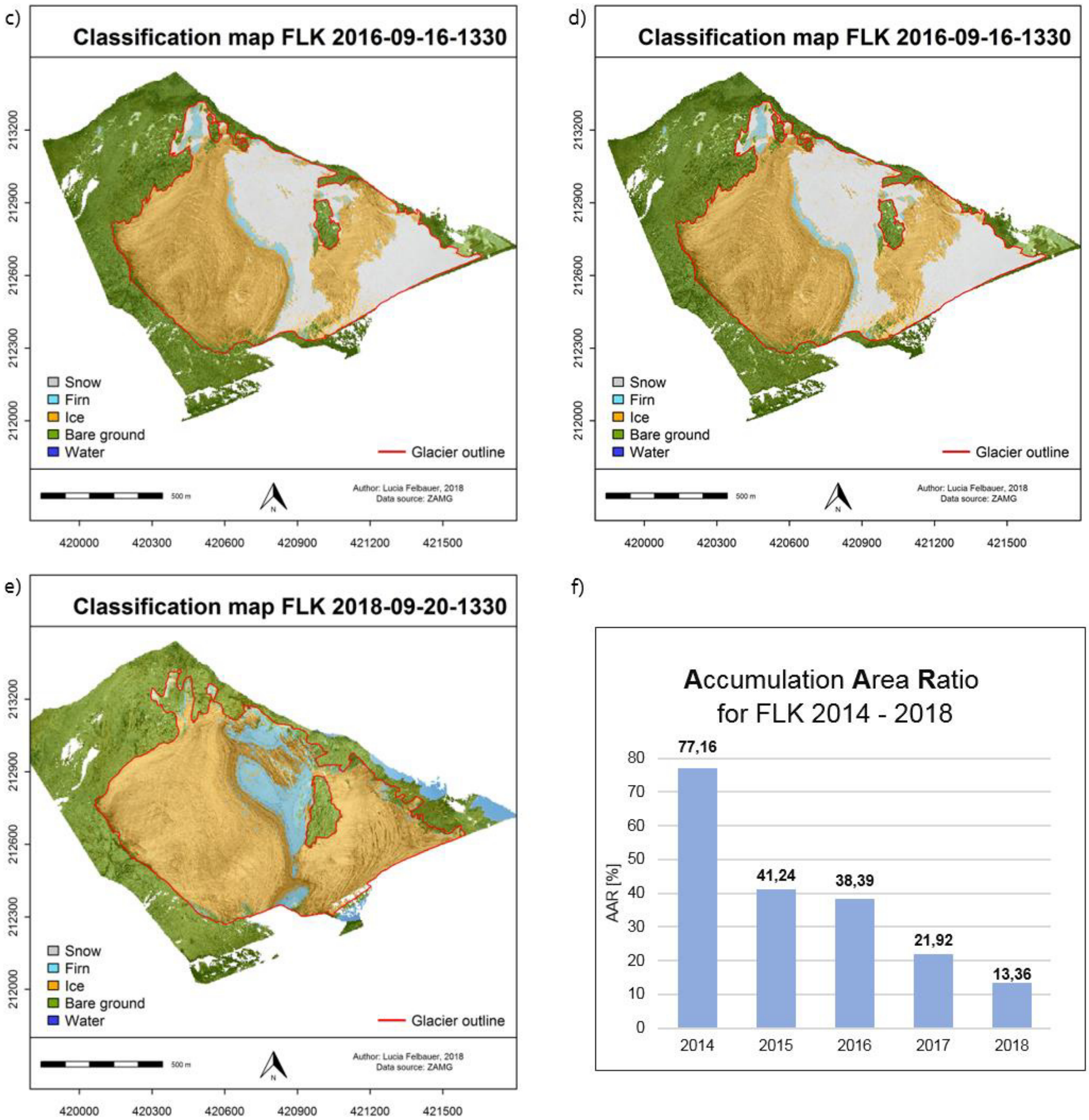


Figure 5. Minimum snow cover for FLK, ablation periods 2014-2018 classified by GLACIERIZER: (a-e) Classified maps showing the stage of minimum snow cover for each year; (f) Decreasing AAR; © ZAMG.

Table 2. Minimum snow cover for FLK (2014-2018) derived through surface classification via GLACIERIZER: The Accumulation Area Ratio (AAR) shows a decrease;

FLK	2014	2015	2016	2017	2018
Photo/date	2014-08-31-1030	2015-09-18-1530	2016-09-16-1330	2017-08-31-1500	2018-09-20-1330
Glacier area [m²]	818838	781490	798699	756847	792037
Class snow [m²]	623022	120937	278364	24257	2655
Class firn [m²]	0	182137	0	132246	95450
AAR [%]	76.09	38.78	34.85	20.68	12.39

5.2.2 GOK

GOK shows similar results as FLK. Table 3 and Figure 6 confirm the visual observations that the minimum AAR has dropped in the last three years: 12 % (2016), 2.5 % (2017) and 0.7 % (2018). For the year 2018 only 0.7 % of the glacier extent has been covered by snow or firn at the end of the ablation period. The results are constrained to a very short time span, so that they do not allow for conclusions on decadal evolution or future trends. Longer timespans and additional data would have to be acquired and analyzed for deriving such trends.

Table 3. Minimum snow cover for GOK (2016-2018) derived through surface classification via GLACIERIZER, The Accumulation Area Ratio (AAR) shows a decreasing trend;

GOK	2014	2015	2016	2017	2018
Photo/date	No data	No data	2016-09-16-1250	2017-08-31-1200	2018-09-23-1520
Glacier area [m²]	-	-	802122	719331	683707
Class snow [m²]	-	-	73528	14301	1783
Class firn [m²]	-	-	0	0	2341
AAR [%]	-	-	9.17	1.99	0.60

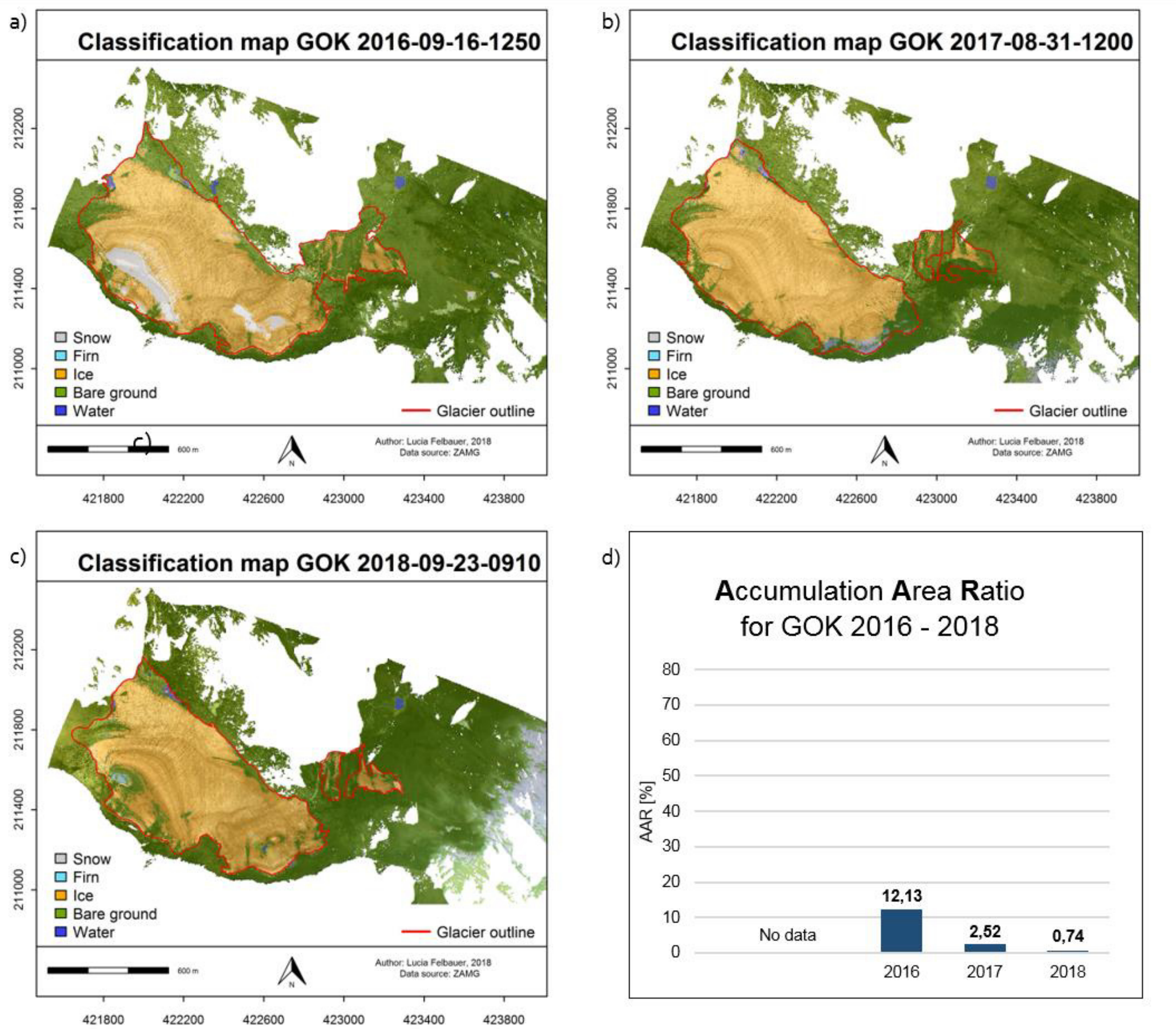


Figure 6. Minimum snow cover for GOK, ablation periods 2016-2018 classified by GLACIERIZER: (a-c) Classified maps showing the stage of minimum snow cover for each year; (d) Decreasing AAR; © ZAMG.

5.3 Validation of the classification results

53 classification results were randomly picked, from a total of 1433 classifications. For each validation map a confusion matrix was generated, where the predicted and the reference data set are compared. An exemplary confusion matrix is selected for demonstration in Table 4. The reference data set is represented through the columns and the predicted data set is shown through the rows. 100 points are evalu-

ated for each class. The rate of correct predictions is displayed in the field of corresponding classes, for example ice with 88 %. The producer's accuracy describes the probability that an observed point in the real environment is assigned to the same class through the classification model. The user's accuracy points out the probability that a classified point is found in the same observed class. The overall accuracy is calculated through the diagonal correct predictions, whereas all off-diagonal values are counted as failures. Kappa shows how well the classification results fit to the reference data set and are not randomly determined. High values of producer's and user's accuracy are found in Table 4. Bare ground even reaches a producer's accuracy of 100 %, being correctly predicted by GLACIERIZER. Firn has the lowest user's accuracy: 76 % of all classified firn points will be found in observed firn areas. The overall accuracy (0.88 %) shows a good result for this selected classification map.

Table 4. Comparison of predicted (classification by GLACIERIZER) and reference data set for the validation by a confusion matrix: Exemplary matrix for one (FLK 2017-08-15-1420) picked validation map.

Prediction/Reference	**Snow**	**Firn**	**Ice**	**Bare ground**	**User's Accuracy**	**Kappa**
Snow	95	3	2	0	0.95	
Firn	21	76	3	0	0.76	
Ice	6	6	88	0	0.88	
Bare ground	0	1	5	94	0.94	
Producer's Accuracy	0.778689	0.883721	0.897959	1	0.8825	
Kappa						0.83333

Sorted ratios for overall accuracy and kappa are presented for all 53 validated maps in Figure 7. Both statics are starting at a high level (about 90 %). 51 maps have a higher overall accuracy than 0.5, and 37 maps have a higher overall accuracy than 0.8. Kappa shows a more pronounced decreasing trend, because within Kappa the agreement that could be expected due to change alone is also considered. 46 maps have a higher kappa than 0.5, and 21 maps have a higher kappa than 0.8.

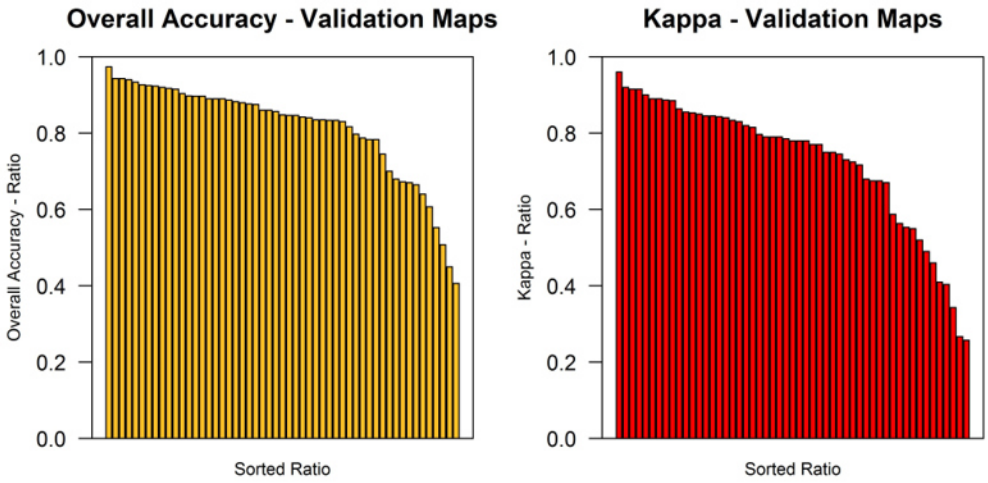


Figure 7. Validation results for 53 validations maps: Sorted statics for overall accuracy (left) and Kappa (right).

Producer's and user's accuracy for each individual class are also calculated and presented in a sorted way (see Figure 8). An overview of important thresholds is given in Table 5. The classes ice, water and firn are not represented in every orthophoto. Water is only present in the case of GOK (glacial lake). Nearly all classes achieve a better result than 50 %, several classes even exceed values of 0.8. The user's accuracy is quite constant for the classes snow (44 maps >0.8) and bare ground (44 maps >0.8), which means that the most points have been correctly classified. The producer's accuracy for water remains constantly high over all validation maps (13 out of 15 maps >0.9), whereas the user's accuracy for water is quite low.

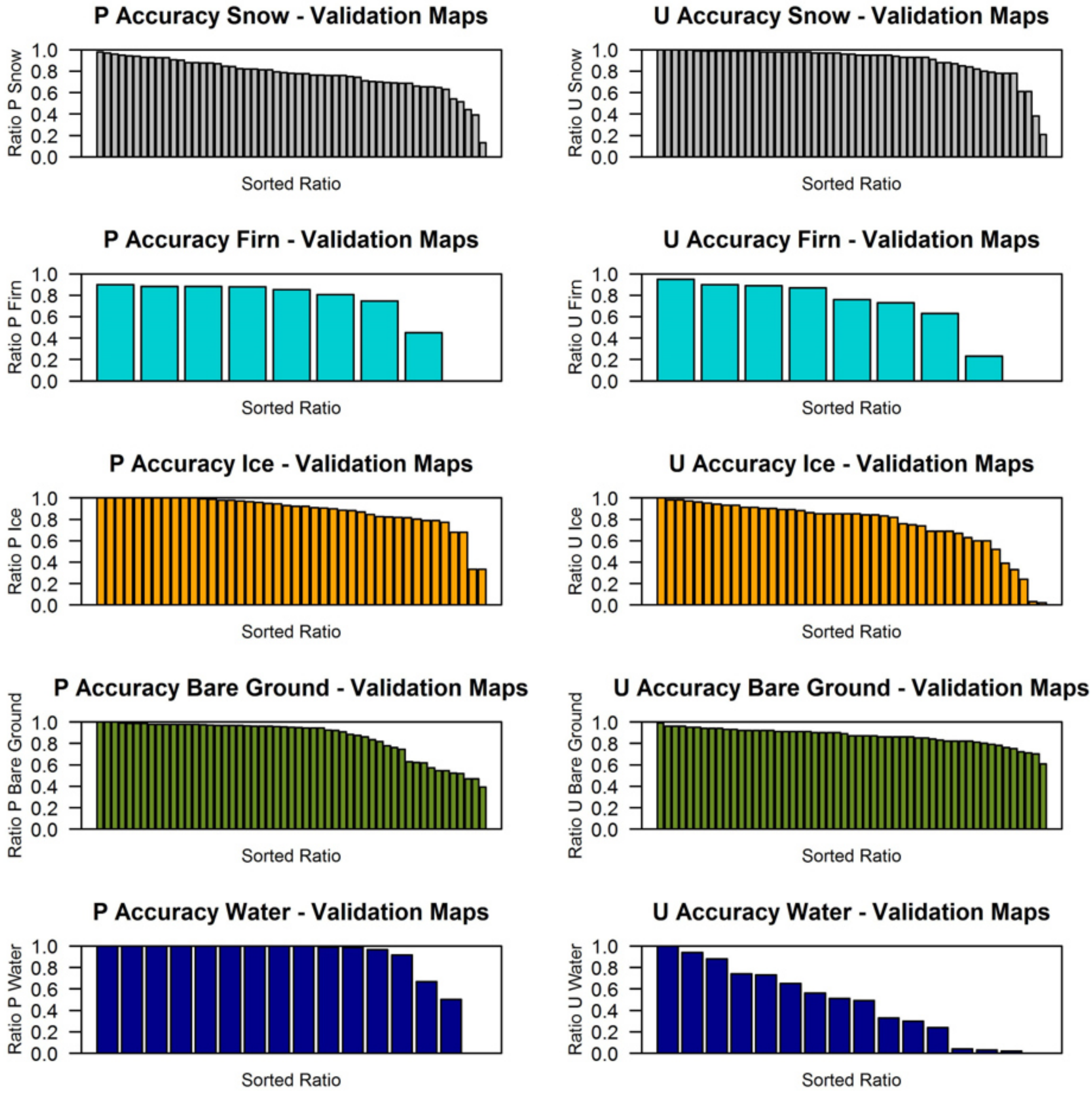


Figure 8. Validation results for 53 validated maps: sorted statics for Producer's accuracy (left) and User's accuracy (right).

Table 5. Results of the validation: Producer's (P) and user's (U) accuracy for all distinguished classes, showing the number of validated maps bigger than defined thresholds. Be aware of different sample size (see Figure 8).

	Snow [53]		**Firn [8]**		**Ice [42]**		**Bare ground [53]**		**Water [15]**	
	P	U	P	U	P	U	P	U	P	U
>0.5	50	51	7	7	40	37	50	53	14	8
>0.8	24	44	6	4	35	26	39	44	13	3
>0.9	12	38	0	1	25	11	34	21	13	2

6 Discussion

6.1 Glaciological results

The calculated AAR are based on the classification by GLACIERIZER, therefore the values are the result of a model and can vary in their accuracy. For the required scale and the purpose of the study, the values are sufficient precise. AAR is decreasing for both glaciers. Both glaciers barely show snow cover at the end of the ablation period in 2018, which is especially the case for GOK. The areal extent of the glaciers decreased and consequently both glaciers are affected by glacier retreat. Based on AAR and Equilibrium Line Altitude (ELA) the annual mass balance could be calculated by statistical relations, employing a well-established and readily applied method in different mountain ranges. Only those classifications where the ELA is representative, and not showing the short term dropping of the snowline due to sudden summer snow falls, can be involved into the glacier mass balance calculation (Huss et al., 2013). Perusing all the classified orthophotos, classification is performed easier in early and late season, where only snow and non-snow areas have to be distinguished. More classes are involved later in the season (July and August), challenging the classification task (Farinotti et al., 2010). The methodically most challenging situations occur when a fresh snow cover is melting again or when the snowline rises above the ELA, showing up as the new class firn (Huss et al., 2013).

6.2 Validation Results

Validating GLACIERIZER shows that several classification maps achieve high rates of overall accuracy and kappa. Differences can be observed between the individual classes. Snow and bare ground show high values, some even reaching 100 %. Especially the values for the user's accuracy remain constantly high whereas a higher proportion of lower values is observed for the producer's accuracy. This means that the results are better for mapped points to find them in reality than the other way around. Ice shows nearly the same results for producer's and user's accuracy, but producer's accuracy achieves constant higher values. The validation results for water are remarkable: whereas the producer's accuracy is quite high for nearly all validation maps, some maps show much lower values of user's accuracy. This phenomenon is related to the generation of the reference data set. Water is only classified for GOK and it occurs that especially snow patches on the sides of the photo are blurred. These features have a bluish blurred appearance and are therefore often classified as water. Further misclassifications for water can occur when lakes freeze and carry a snow layer above them. The training areas sometimes can't be adjusted that fast, so that misclassifications occur. Generally, the first validation of GLACIERIZER shows acceptable results. For avoiding misclassifications especially for water, it is recommended to clip the orthophotos as far as possible to avoid disturbing features at the side of the scene. The validation results will be useful for further revision of GLACIERIZER.

6.3 Camera, photos and georectification

Monitoring FLK and GOK via time-lapse cameras resulted in a huge amount of photos of both glaciers at a high spatial and temporal resolution (Corripio, 2004). Besides a visual evaluation of the snow cover evolution, quantitative information can be obtained through the attached processing steps. Some general limitations and challenges have been identified (see Table 6).

Table 6. Collection of limitations due to the surface classification approach, experienced in this survey: Keywords of challenges due to (i) Camera and photos (ii) Georectification (iii) Classification.

Camera/ photos	Georectification	Classification
- Camera movements	- Camera movement (lower accuracy)	- Limitation of methods due to varying RGB values
- Camera failure/ lack of data	- Old DEM	- Changing scene (summer snow cover)
- Covered camera window (snow, water droplets)	- Estimation target position	- Disturbing uneven clouds, shadows
- Exchange of camera or objective (long consistent time series)	- Inaccuracies of GCPS	- Restricted to calendar weeks
- Accessibility of the camera (maintenance, DGPS)		- Mismatching classes (debris on glacier)

Through the installed cameras and the amount of photo data it becomes possible to investigate and understand the phenomena in the captured scene in great detail. Because the scene is monitored at such a high temporal resolution, rare events such as snow cover creeping could be captured and studied in more detail (Bernard et al., 2013). The photos could also serve as a valuable data source and archive for other research disciplines. However, the huge amount of photo data has to be processed in an efficient way (Merkel et al., 2016). By looking through the original number of photos taken from FLK and GOK, it is recognized that a lot of photos cannot be used at all. Especially adverse weather conditions, but also other issues such as water droplets or hanging snow on the camera window or dazzling light conditions, required the elimination of numerous photos. Even though it is recommended to choose a short time interval for taking pictures (Farinotti et al., 2010), sometimes it is not even easy to get one usable photo per day (Härer et al., 2013). However, through advances in computer developments (data collection, processing) and photo technology, new opportunities are likely to be available in the future (Castillo et al., 2015). Furthermore, it is possible to supply and control devices located in remote places and even transfer the data in real time (Ahn et al., 2017), which is also the case for the here processed photos and satisfies an easy handling of the data.

Georeferencing convinces by its mathematical and photogrammetric principles, but the quality of the result may suffer due to the quality and scale of the available DEM (Corripio, 2004). For this case, our survey shows a distinct limitation, because the used DEM is from an aerial laser scanning campaign of 2009, nearly 10 years old. Especially glaciered environments are changing very rapidly and therefore a current DEM is needed urgently (Schwalbe and Maas, 2017). Another limiting factor for the accuracy of the georeferencing are the GCPs. While in this survey some GCP-sets are already measured with differential GPS (Corripio, 2004), resulting in precise coordinates, this task cannot be recaptured for older images if several GCP sets are necessary due to camera movements. To avoid workarounds, automatic image matching and shifting tasks could solve the problem, and additionally the here present problem of moving cameras would also be dealt with (Farinotti et al., 2010; Schwalbe and Maas, 2017). It is tried to respond to the big issue of camera movements for FLK and GOK, but unfortunately no proper implementation could be achieved, due to the high level of changes in the appearance of the photo scenes throughout the whole ablation period (Jamkes et al., 2016). Camera movement is still a challenging problem, as it is pointed out by several studies (Merkel et al., 2016; Messerli and Grinsted, 2015). Another limitation experienced within PRACTISE is the estimation of target points. Besides the high resolution of the photos and the high quality of the DEM, the target points should be measured precisely for producing high accurate orthophotos (Hinkler et al., 2002).

6.4 Surface Classification

GLACIERIZER does not use absolute RGB thresholds for each class, but instead uses training areas and the maximum-likelihood classification for creating the individual classes. The advantage of such an approach lies in the individual adjustment and the flexible thresholds that can be applied to each orthophoto (Ide and Oguma, 2013), based on weekly or monthly training data sets. We note that it is not weekly or monthly thresholds which are produced, but only the set polygons, which give the frame for the calculation of the thresholds. Because new thresholds are generated for every orthophoto, an individual adaptation to the changing conditions through the whole timespan, and varying illumination, disturbing weather and light conditions (e.g., light shadows from clouds) is achieved.

The surface classification is still influenced by changing weather conditions, which are in general a problem for optical remote sensing where good illumination conditions are needed (Fang et al., 2017). Also for GLACIERIZER, unsuitable weather conditions result in misclassifications in parts of the orthophoto. A problematic example is drifting clouds, which produce inconstant shadowing effects on the surface. The high contrast between shaded and non-shaded areas leads to misclassifications and is even a bigger problem for feature tracking purposes (Schwalbe and Maas, 2017). The set polygons cannot be adjusted to such changeable conditions. However, misclassifications also occur when the conditions change rapidly for the whole study area. Examples are sudden summer snowfall events, resulting in a consistent snow cover, or rapid snow melting phases. Due to the restriction of weekly/ monthly resolution, it has to be decided for which part of the week representative training areas should be created, because two diverse situations cannot be covered by one single training set. A solution would be to create training areas not on a regular time interval, instead by considering consistent weather conditions. Several timespans could be distinguished based on photos with lack of visibility. These gaps could be used for separating between timespans covered by different training data sets (Bernard et al., 2013). A further point to consider is that not very sunny and cloudless weather conditions lead to good classification results, but instead a constant cloud cover achieves better outcomes. This is a consequence of lack of topographic shadowing in cloudy weather.

Furthermore, creating training areas on a calendar-weekly basis requires a lot of time, and it may also be necessary to create multiple versions of the training data sets until the results of the classification are satisfactory. The polygons for the training data set have to be created in locations representative for the whole calendar week/ month. In addition, it is highly recommended to set the polygons to places, where the respective classes are represented the whole year long, avoiding too much effort in digitizing. It has been found that the uniform distribution of the polygons leads to the advantage that slight shadows, which only occur in parts of the orthophoto, can be compensated.

By looking at the classification of GOK it becomes visible that debris on the glacier is classified as ”bare ground”. In contrast to human users, the system can’t detect that the glacier is covered by debris and this part of the scene should still be classified as “ice”. This issue is considered as a bottleneck error in glacier mapping (Fang et al., 2017). Recent progress is based on the combination of thermal and DEM inputs for a distinction of debris covered glaciers and surrounding terrain (Bhardwaj et al., 2016).

Another idea of improving the classification could be in using images with broader colour ranges (e.g. RAW images) (Ide and Oguma, 2013) or with infrared bands. Because of the enlarged electromagnetic spectrum, further discriminations could be achieved. In satellite approaches the use of infrared (e.g. Normalized Difference Snow Index NDSI) is a common task for delineating snow cover (Burton-Johnson et al., 2016). But also in photogrammetry it is recommended to combine visible light and infrared for automatic snow cover detection (Farinotti et al., 2010). Authors claim that further research is needed in this field (Bühler et al., 2016). Additional approaches for surface classification could employ neural networks, fuzzy logic or support vector machines (Gauci et al., 2018). A recently promising method is shown by Gauci et al. (2018), where a photo series is categorized in several classes in a fully automated way without using infrared bands, done via a machine learning approach for vegetation surveys.

However, it should also be emphasized that GLACIERIZER has succeeded in automating the classification for several orthophotos in a row. GLACIRIZER is not a fully automated system, but a semi-automated model, since some steps have to be done by manual digitizing.

6.5 Overall approach: automatic time-lapse cameras

Generally, because terrestrial photos can even gather data under cloudy conditions, a complimenting usage for satellite data is possible (Portenier et al., 2019). Webcam photos can be used for validation and calibration purposes for satellite products (Salzano et al., 2019). The combination of photography and satellite products may improve the quality (Corripio, 2004), and even improve the cost benefit performance (Castillo et al., 2015). Field measurements (snow thickness, density, etc.) can also be complemented with the results of snow cover analysis through image processing (Bernard et al., 2013). Additionally the high resolution snow cover data can be delivered as important input data for hydrological models in near-real time (Foppa et al., 2007). Freely available images from webcams are not used in their potential and could serve as an important data source, especially for deep learning approaches (Xiao et al., 2018). Still the data quality of cheap webcams can be challenging (Tanis et al., 2018).

7 Conclusion

Automatic time-lapse cameras offer the possibility for a cost-effective monitoring of glacial systems. We have presented an integrated processing approach, combining three main steps: (i) Selection of representative snow cover photos for several ablation periods, taken by two automatic cameras, observing the glaciers FLK and GOK. (ii) Automatic georectification of all photos in order to obtain orthophotos, performed by PRACTISE. (iii) Semi-automated surface classification for distinguishing several classes by the newly developed tool GLACIERIZER.

The results show that a decrease of snow cover is found for the surveyed ablation periods and glaciers. A full automatization of the procedure could not be achieved yet, but still GLACIERIZER is an easily applicable semi-automated tool where good results can be achieved, depending on the quality of the input photos. Misclassifications are mostly triggered by scenes with discontinuous shadows, rapid changes of surface appearance, blurred effects at the edges and moving cameras. GLACIERIZER can easily be adapted for other monitoring purposes, also performing classification for different surfaces.

Further studies have to lay more emphasis on handling moving cameras. Generally, promising results are expected through the usage of cameras which are also sensitive to infrared radiation. Beside installing new cameras, publicly available time-lapse cameras offer the potential for diverse scientific surveys and should be addressed more likely. Looking forward, it will be interesting how deep learning approaches like neural networks or machine learning will be implemented in this study field. Concluding, automatic time-lapse cameras, as processed in this survey, can be successfully applied in long term glacier monitoring.

Description of author's responsibilities:

L. Felbauer did the main tasks of this project self-contained and this includes: literature research, data collection (DGPs, photos, DEM) and processing, parts of the modifications of the code PRACTISE and processing the orthophotos, idea and development of GLACIERIZER through the help of M. Mergili, validating the results, create figures and writing the manuscript of this paper.

M. Mergili accompanied the whole project with his broad knowledge and skills in geoinformatics. He especially supported the programming tasks for the model GLACIERIZER and the validation. M. Mergili gave substantive input for writing the manuscript and he offered constantly give and take about the project.

B. Hynek gave the main idea for this research project, due to his responsible function for the overall monitoring system of the glaciers at Hoher Sonnblick by ZAMG. During former projects the cameras were mounted and maintained. He organized the open source software PRACTISE and did parts of its modifications for our purpose. Additionally, B. Hynek supported the project through his experiences of monitoring with time-lapse cameras and gave input to the draft of the manuscript.

A. Neureiter did parts of the data collection, measured DGP points through fieldwork. He is part of the glacier monitoring working group, dealing with diverse tasks. Therefore A. Neureiter also wrote parts for the Chapter “Study Area”.

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Data References

Keuschnig, G. & Radlherr, F. (2019). foto-webcam.eu. https://www.foto-webcam.eu/ (accessed 05.10.2019).

Salzburger Geographische Informationssystem SAGIS. (2009). Digitales Oberflächenmodell. Amt der Salzburger Landesregierung Referat 10/04 Geodateninfrastruktur.

References

Aalstad, K., Westermann, S., Schuler, T.V., Boike, J., & Bertino, L. (2018). Ensemble-based assimilation of fractional snow-covered area satellite retrievals to estimate the snow distribution at Arctic sites. *The Cryosphere*, *12*, 247–270.

Ahn, Y., Shin, B., & Kim, K.-H. (2017). Shoreline Change Monitoring using High Resolution Digital Photogrammetric Technique. The 2nd International Water Safety Symposium. *Journal of Coastal Research, Special Issue*, *79*, 204–208.

Arslan, A.N., Tanis, C., Metsämäki, S., Aurela, M., Böttcher, K., Linkosalmi, M., & Peltoniemi, M. (2017). Automated Webcam Monitoring of Fractional Snow Cover in Northern Boreal Conditions. *Geosciences*, *7*, 55.

Auer, I., Böhm, R., Leymüller, M., Schöner, W., Kaiser, A., Scheifinger, H., Langer, M., & Häberli, C. (2002). *Das Klima des Sonnblicks. Klimaatlas und Klimatographie der GAW Station Sonnblick einschließlich der umgebenden Gebirgsregion.* Wien: Zentralanstalt für Meteorologie und Geodynamik.

Auer, I., Chimani, B., & Türk, K. (2012). Klimanormalperiode 1981–2010. ZAMG. In: Österreichischer Klimatag. Wien, Österreich, 14.-15.06.2012.

Bernard, É., Friedt, J.M., Tolle, F., Griselin, M., Martin, G., Laffly, D., & Marlin, C. (2013). Monitoring seasonal snow dynamics using ground based high resolution photography

(Austre Lovénbreen, Svalbard, 79°N). *ISPRS Journal of Photogrammetry and Remote Sensing*, *75*, 92–100.

Bhardwaj, A., Joshi, P.K., & Sam, L. (2016). Remote sensing of alpine glaciers in visible and infrared wavelengths: a survey of advances and prospects. *Geocarto International*, *31*, 557–574.

Binder, D., Brückl, E., Roch, K.H., Behm, M., Schöner, W., & Hynek, B. (2009). Determination of total ice volume and ice-thickness distribution of two glaciers in the Hohe Tauern region, Eastern Alps, from GPR data. *Annals of Glaciology*, *50*, 71–79.

Böhm, R., Auer, I., Brunetti, M., Maugeri, M., Nanni, T., & Schöner, W. (2001). Regional temperature variability in the European Alps: 1760-1998 from homogenized instrumental time series. *International Journal of Climatology*, *21*, 1779–1801.

Bühler, Y., Adams, M.S., Bösch, R., & Stoffel, A. (2016). Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): potential and limitations. *The Cryosphere*, *10*, 1075–1088.

Burton-Johnson, A., Black, M., Fretwell, P.T., & Kaluza-Gilbert, J. (2016). An automated methodology for differentiating rock from snow, clouds and sea in Antarctica from Landsat 8 imagery: a new rock outcrop map and area estimation for the entire Antarctic continent. *The Cryosphere*, *10*, 1665–1677.

Castillo, C., James, M.R., Redel-Macías, M.D., Pérez, R., & Gómez, J.A. (2015). SF3M software: 3-D photo-reconstruction for non-expert users and its application to a gully network. *SOIL*, *1*, 583–594.

Chandler, J., Ashmore, P., Paola, C., Gooch, M., & Varkaris, F. (2002). Monitoring River-Channel Change Using Terrestrial Oblique Digital Imagery and Automated Digital Photogrammetry. *Annals of the Association of American Geographers*, *92*, 631–644.

Corripio, J.G. (2004). Snow surface albedo estimation using terrestrial photography. *International Journal of Remote Sensing*, *25*, 5705–5729.

Dedieu, J.P., Lessard-Fontaine, A., Ravazzani, G., Cremonese, E., Shalpykova, G., & Beniston, M. (2014). Shifting mountain snow patterns in a changing climate from remote sensing retrieval. *The Science of the total environment*, *493*, 1267–1279.

Diolaiuti, G.A., Maragno, D., D'Agata, C., Smiraglia, C., & Bocchiola, D. (2011). Glacier retreat and climate change:. Documenting the last 50 years of Alpine glacier history from area and geometry changes of Dosdè Piazzi glaciers (Lombardy Alps, Italy). *Progress in Physical Geography*, *35*, 161–182.

Dozier, R. (1989). Spectral signature of alpine snow cover from the landsat thematic mapper. *Remote Sensing of Environment*, *28*, 9–22.

Dumont, M., & Gascoin, S. (2016). 4 - Optical Remote Sensing of Snow Cover. In N. Baghdadi, & M. Zribi (Eds.), *Land Surface Remote Sensing in Continental Hydrology* (pp. 115–137). San Diego: Elsevier Science.

European Environmental Agency (EEA) (2012). *Climate change, impacts and vulnerability in Europe*.

Fang, L., Wei, X., Yao, W., Xu, Y., & Stilla, U. (2017). Discriminative Features Based on Two Layers Sparse Learning for Glacier Area Classification Using SAR Intensity Imagery. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *10*, 3200–3212.

Farinotti, D., Magnusson, J., Huss, M., & Bauder, A. (2010). Snow accumulation distribution inferred from time-lapse photography and simple modelling. *Hydrological Processes*, *24*, 2087-2097.

Foppa, N., Hauser, A., Oesch, D., Wunderle, S., & Meister, R. (2007). Validation of operational AVHRR subpixel snow retrievals over the European Alps based on ASTER data. *International Journal of Remote Sensing*, *28*, 4841–4865.

Gauci, A., Abela, J., Austad, M., Cassar, L.F., & Zarb Adami, K. (2018). A Machine Learning approach for automatic land cover mapping from DSLR images over the Maltese Islands. *Environmental Modelling & Software*, *99*, 1–10.

GCOS, W.M.O. (2011). *Systematic Observation Requirements for Satellite-Based Data Products for Climate—2011 Update. Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)".* Geneva, Switzerland.

Graßl, H., Hantel, M., Rotach, M.W., & Rudel, E. (2012). Special issue: 125 years of high-mountain research at Sonnblick Observatory (Austrian Alps). *Theoretical and Applied Climatology*, *110*, 489–490.

Härer, S., Bernhardt, M., Corripio Javier G., & Schulz, K. (2012). *PRACTISE - Photo Rectification And ClassificaTIon SoftwarE. PRACTISE V.1.0 User's Manual.* München.

Härer, S., Bernhardt, M., Corripio Javier G., & Schulz, K. (2013). PRACTISE – Photo Rectification And ClassificaTIon SoftwarE (V.1.0). *Geoscientific Model Development*, *6*, 837–848.

Härer, S., Bernhardt, M., & Schulz, K. (2016). PRACTISE - Photo Rectification And ClassificaTIon SoftwarE (V.2.1). *Geoscientific Model Development*, *9*, 307–321.

Hinkler, J., Pedersen, S.B., Rasch, M., & Hansen, B.U. (2002). Automatic snow cover monitoring at high temporal and spatial resolution, using images taken by a standard digital camera. *International Journal of Remote Sensing*, *23*, 4669–4682.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R.S., Clague, J.J., Vuille, M., Buytaert, W., Cayan, D.R., Greenwood, G.B., Mark, B.G., Milner, A.M., Weingartner, R., & Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, *5*, 418–435.

Huss, M., Sold, L., Hoelzle, M., Stokvis, M., Salzmann, N., Farinotti, D., & Zemp, M. (2013). Towards remote monitoring of sub-seasonal glacier mass balance. *Annals of Glaciology*, *54*, 75–83.

Hynek, B., Neureiter, A., Binder, D., Greilinger, M., & Weyss, G. (2019). *Gletscher- und Schneedeckenmonitoring Sonnblick 2014-2018 (GCW-S_G), Endbericht.* Wien.

Ide, R., & Oguma, H. (2013). A cost-effective monitoring method using digital time-lapse cameras for detecting temporal and spatial variations of snowmelt and vegetation phenology in alpine ecosystems. *Ecological Informatics*, *16*, 25–34.

IPCC (2007). *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC.* London: Cambridge University Press.

IPCC (2013). *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, New York, USA: Cambridge University Press.

Jamkes, M.R., HOW, P., & Wynn Peter M. (2016). Pointcatcher software: analysis of glacial time-lapse photography and integration with multitemporal digital elevation models. *Journal of Glaciology*, *62*, 159–169.

Kaczensky, P., Khaliun, S., Payne, J., Boldgiv, B., Buuveibaatar, B., & Walzer, C. (2019). Through the eye of a Gobi khulan - Application of camera collars for ecological research of far-ranging species in remote and highly variable ecosystems. *PloS one*, *14*, e0217772.

Kappas, M. (2014). Aerial Photogrammetry for Glacial Monitoring. In V.P. Singh, P. Singh, & U.K. Haritashya (Eds.), *Encyclopedia of snow, ice and glaciers* (pp. 4–15). New York [New York], Boston, Massachusetts: Springer; Credo Reference.

Kaufmann, V., & Ladstädter, R. (2008). Application of terrestrial photogrammetry for glacier monitoring in alpine environments. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 813–818.

Kenner, R., Phillips, M., Limpach, P., Beutel, J., & Hiller, M. (2018). Monitoring mass movements using georeferenced time-lapse photography: Ritigraben rock glacier, western Swiss Alps. *Cold Regions Science and Technology*, *145*, 127–134.

Klemes, V. (1990). The modelling of mountain hydrology: the ultimate challenge. *IAHS-AISH P.*, *190*.

Merkel, F.R., Johansen, K.L., & Kristensen, A.J. (2016). Use of time-lapse photography and digital image analysis to estimate breeding success of a cliff-nesting seabird. *Journal of Field Ornithology*, *87*, 84–95.

Messerli, A., & Grinsted, A. (2015). Image georectification and feature tracking toolbox: ImGRAFT. *Geoscientific Instrumentation, Methods and Data Systems*, *4*, 23–34.

Michlmayr, G., Lehning, M., Koboltschnig, G.R., Holzmann, H., Zappa, M., Mott, R., & Schöner, W. (2008). Application of the Alpine 3D model for glacier mass balance and glacier runoff studies at Goldbergkees, Austria. *Hydrological Processes*, *22*, 3941–3949.

Mott, R., Faure, F., Lehning, M., Löwe, H., Hynek, B., Michlmayr, G., Prokop, A., & Schöner, W. (2008). Simulation of seasonal snow-cover distribution for glacierized sites on Sonnblick, Austria, with the Alpine3D model. *Annals of Glaciology*, *49*, 155–160.

Oerlemans, J., & Fortuin, J.P.F. (1992). Sensitivity of glaciers and small ice caps to greenhouse warming. *Science*, *258*, 115–117.

Parajka, J., Haas, P., Kirnbauer, R., Jansa, J., & Blöschl, G. (2012). Potential of time-lapse photography of snow for hydrological purposes at the small catchment scale. *Hydrological Processes*, *26*, 3327–3337.

Piazzi, G., Tanis, C., Kuter, S., Simsek, B., Puca, S., Toniazzo, A., Takala, M., Akyürek, Z., Gabellani, S., & Arslan, A.N. (2019). Cross-Country Assessment of H-SAF Snow Products by Sentinel-2 Imagery Validated against In-Situ Observations and Webcam Photography. *Geosciences*, *9*, 129.

Pirazzini, R., Leppänen, L., Picard, G., López-Moreno, J.I., Marty, C., Macelloni, G., Kontu, A., Lerber, A. von, Tanis, C.M., Schneebeli, M., Rosnay, P. de, & Arslan, A.N. (2018). European In-Situ Snow Measurements: Practices and Purposes. *Sensors (Basel, Switzerland)*, *18*.

Portenier, C., Hüsler, F., Härer, S., & Wunderle, S. (2019). Towards a webcam-based snow cover monitoring network: methodology and evaluation. *The Cryosphere Discussions*, 1–20.

Rastner, P., Nicholson, L., Sailer, R., Notarnicola, C., & Prinz, R. (2015). Mapping the snow line altitude for large glacier samples from multitemporal Landsat imagery. In *2015 8th International Workshop on the Analysis of Multitemporal Remote Sensing Images (Multi-Temp). July 22-24, 2015, Annecy, France* (pp. 1–4). Piscataway, NJ: IEEE.

Rumpler, M., Tscharf, A., Mostegel, C., Daftry, S., Hoppe, C., Prettenthaler, R., Fraundorfer, F., Mayer, G., & Bischof, H. (2017). Evaluations on multi-scale camera networks for precise and geo-accurate reconstructions from aerial and terrestrial images with user guidance. *Computer Vision and Image Understanding*, *157*, 255–273.

Salvatori, R., Plini, P., Giusto, M., Valt, M., Salzano, R., Montagnoli, M., Cagnati, A., Crepaz, G., & Sigismondi, D. (2011). Snow cover monitoring with images from digital camera systems. *Italian Journal of Remote Sensing*, *43*, 137–145.

Salzano, R., Salvatori, R., Valt, M., Giuliani, G., Chatenoux, B., & Ioppi, L. (2019). Automated Classification of Terrestrial Images: The Contribution to the Remote Sensing of Snow Cover. *Geosciences*, *9*, 97.

Schmidt, S., Weber, B., & Winiger, M. (2009). Analyses of seasonal snow disappearance in an alpine valley from micro- to meso-scale (Loetschental, Switzerland). *Hydrological Processes*, *23*, 1041–1051.

Schober, C. (2002). Zur Geologie des Sonnblicks unter Einbeziehung der Erosionsgefährdung und angepasster Sanierungsmaßnahmen. *Jahresberichte des Sonnblickvereins*, *98*, 3–24.

Schwaizer (nee Bippus), G., & Nemec, J. (2017). GLIMS Glacier Database. Boulder, CO. National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5V98602.

Schwalbe, E., & Maas, H.-G. (2017). The determination of high-resolution spatio-temporal glacier motion fields from time-lapse sequences. *Earth Surface Dynamics*, *5*, 861–879.

Schöner, W., Boeckl, L., Hausmann, H., Otto, J.-C., Reisenhofer, S., & Riedl, Claudia, Seren, Sirri (2012a). Spatial Patterns of Permafrost at Hoher Sonnblick (Austrian Alps) - Extensive Field-measurements and Modelling Approaches. *Austrian Journal of Earth Sciences*, *105*, 154–168.

Schöner, W., Böhm, R., & Auer, I. (2012b). 125 years of high-mountain research at Sonnblick Observatory (Austrian Alps)—from "the house above the clouds" to a unique research platform. *Theoretical and Applied Climatology*, *110*, 491–498.

Schöner, W., Hynek, B., Böhm, R., Binder, D., Koboltschnig, G., & Holzmann, H. (2009). Glazialhydrologisches Monitoring im Bereich des Rauriser Sonnblicks (Hohe Tauern, Österreich). *Österreichische Wasser- und Abfallwirtschaft*, *61*, 1–8.

Selsam, P., Schaeper, W., Brinkmann Katja, & Bühler, Y. (2017). Aquisition and automated rectification of high-resolution RGB and near-IR aerial photographs to estimate plant biomass and surface topography in arid agro-ecosystems. *Experimental Agriculture*, *53*, 144–157.

Tanis, C., Peltoniemi, M., Linkosalmi, M., Aurela, M., Böttcher, K., Manninen, T., & Arslan, A.N. (2018). A System for Acquisition, Processing and Visualization of Image Time Series from Multiple Camera Networks. *Data*, *3*, 23.

Tolson, B.A., & Shoemaker, C.A. (2007). Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resources Research*, *43*. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005WR004723.

Verykokou, S., & Ioannidis, C. (2018). Oblique aerial images: a review focusing on georeferencing procedures. *International Journal of Remote Sensing*, *39*, 3452–3496.

Viviroli, D., Archer, D.R., Buytaert, W., Fowler, H.J., Greenwood, G.B., Hamlet, A.F., Huang, Y., Koboltschnig, G., Litaor, M.I., López-Moreno, J.I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M., & Woods, R. (2011). Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences*, *15*, 471–504.

Xiao, M., Rothermel, M., Tom, M., Galliani, S., Baltsavias, E., & Schindler, K. (2018). Lake ice monitoring with webcams. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-2*, 311–317.

5 Results

The classification output can be used for diverse glaciological applications and is presented in form of maps. In this work the maximum disappearance of the snow cover is shown for every surveyed ablation period, represented through the Accumulation Area Ratio (AAR). Therefore the photos with the maximum snow cover disappearance are selected and processed for every ablation period. The date can vary for each year considerably. Both glaciers show a decrease in their AAR, but the percentage of the still available cover differs between the glaciers. For example, for the year 2016 FLK is covered by 38 % and GOK 9 %. In the year 2018 the values drop down to a minimum with 12 % (FLK) and 0.6 % (GOK). It has to be mentioned that the here dealt with time period is too short for estimating trends.

GLACIERIZER is validated by 53 randomly picked maps, where the predicted/ classified and the reference data set are compared in a confusion matrix. Various statistical parameters are presented in sorted bar plots for the 53 validation maps and for each class. 21 out of the 53 maps show a higher kappa value than 0.8 and 37 maps show a higher overall accuracy than 0.8. The classes Snow and Bare ground can be distinguished quite well, whereas for the other classes limitations due to influencing conditions arise.

6 Discussion

GLACIZER acts as a surface classification tool, tested for glacier monitoring based on terrestrial images with a high temporal and spatial resolution. The approach shows various advantages. However, also some general limitations and challenges have been faced, some could be dealt with and others stay open for further investigation. Due to the high spatial and temporal resolution, the scene can be monitored in great detail, and it is also possible to capture rare events (Bernard et al., 2013). The observations could also be used for other research disciplines, photos acting as a type of archive. But the huge number of photos has to be processed in an efficient way (Merkel et al., 2016), where a lot of photos with disturbing elements like bad weather conditions, droplets on the camera window or dazzling light conditions have to be eliminated. It is possible to monitor remote places with devices which are capable of supply themselves and transfer the data in real time (Ahn et al., 2017). A profound limitation concerning georectification is the used DEM. In the present study, even though an up-to-date DEM would be needed (Schwalbe and Maas, 2017), only a DEM of 2009 was available. Also the quality of the used GCPs limits the accuracy, because not all points could be acquired through a differential GPS (Corripio, 2004). Older records were matched with the help of distinct features found on the photos and on the orthophoto offered by the Province of Salzburg. Several sets of GCPs were needed because of movements of the cameras. Automatic image matching tasks would avoid this work around and would solve the problem of moving camera (Farinotti et al., 2010; Schwalbe and Maas, 2017). For this approach no proper implementation could be achieved, because the scene changes so much over the whole ablation period (Jamkes et al., 2016).

The main advantage of GLACIERIZER is the individual adjustment of the RGB thresholds for each class and especially for each orthophoto. The manually drawn training data sets only create the frame for the thresholds (Ide and Oguma, 2013). But the polygons have to be adapted on a weekly basis, because the scene is changing that fast. Additionally, disturbing conditions like slight shadows and varying illumination are considered within GLACIERIZER, because the training areas are uniformly distributed. Misclassifications still occur, for example when inconstant shadowing effects are seen on the surface and when the appearance of the whole scene changes quickly, e.g. due to snow fall events in summer. The weekly resolution of the training data sets is then a problem. A solution would be to set the training areas based on consistent weather conditions, instead of fixed time spans. The rather surprising insight is that not very sunny conditions lead to good classification outcomes, instead constant cloud cover avoiding any shadowing effects on the surface show the best results. Particular attention has to be laid on how to set the training areas. Although this task is quite time-consuming, it is critical for the quality of the classification results. A time-efficient way can be followed by a carefully considered strategy of how and where to set the polygons. Several thoughts of how to improve the classification can be found in the literature, like using images with broader colour ranges such as near infrared (Ide and Oguma, 2013). It is advised to combine visible and infrared light, also for snow cover detection (Farinotti et al., 2010). Other approaches would be to use neural networks, fuzzy logic or machine learning (Gauci et al., 2018). The complimenting usage of photos and satellite data can achieve higher quality, or act as validation data source (Salzano et al., 2019; Portenier et al., 2019). Freely available images from webcams have a high potential for monitoring purposes, also in combination with deep learning approaches (Xiao et al., 2018).

7 Conclusions

Various monitoring tasks can be supported by the use of automatic time-lapse cameras. Their main advantage is the high temporal and spatial resolution of the data they generate. This facilitates analyses towards a more detailed understanding of processes happening even in remote places. By combining the data with other methods and sources of information a broad picture can be gained. The here presented processing approach for snow cover monitoring on glaciers consists of three consecutive steps, where photos have to be selected, a georectification is done for generating orthophotos and afterwards a surface classification is performed for surface classification. While GLACIERIZER succeeded in doing the classification of several orthophotos in an automated way, it is not a fully automated system but can be defined as a semi-automated model. The surveyed glaciers and ablation periods showed a constant decrease of snow cover. However, due to the short time span addressed, conclusions on these trends have to be drawn with utmost care. Further studies should direct their focus on obtaining better classification results through additional methods such as the use of spectral cameras or the implementation of machine learning algorithms. In conclusion it can be stated that (i) time-lapse cameras fulfill the requirement of acting as a proper monitoring tool in the field of glaciology, but that (ii) there is still considerable potential for optimization of the image acquisition and analysis procedures.

References

Ahn, Y., Shin, B., & Kim, K.-H. (2017). Shoreline Change Monitoring using High Resolution Digital Photogrammetric Technique. The 2nd International Water Safety Symposium. *Journal of Coastal Research, Special Issue*, *79*, 204–208.

Arslan, A.N., Tanis, C., Metsämäki, S., Aurela, M., Böttcher, K., Linkosalmi, M., & Peltoniemi, M. (2017). Automated Webcam Monitoring of Fractional Snow Cover in Northern Boreal Conditions. *Geosciences*, *7*, 55.

Auer, I., Böhm, R., Leymüller, M., Schöner, W., Kaiser, A., Scheifinger, H., Langer, M., & Häberli, C. (2002). *Das Klima des Sonnblicks. Klimaatlas und Klimatographie der GAW Station Sonnblick einschließlich der umgebenden Gebirgsregion.* Wien: Zentralanstalt für Meteorologie und Geodynamik.

Bamber, J. (2015). Chapter 5 - Land Ice: Indicator and Integrator of Climate Change. In T.M. Letcher (Ed.), *Climate change. Observed impacts on planet earth* (pp. 63–77). Amsterdam, Bosten: Elsevier.

Bernard, É., Friedt, J.M., Tolle, F., Griselin, M., Martin, G., Laffly, D., & Marlin, C. (2013). Monitoring seasonal snow dynamics using ground based high resolution photography (Austre Lovénbreen, Svalbard, 79°N). *ISPRS Journal of Photogrammetry and Remote Sensing*, *75*, 92–100.

Corripio, J.G. (2004). Snow surface albedo estimation using terrestrial photography. *International Journal of Remote Sensing*, *25*, 5705–5729.

European Environmental Agency (EEA) (2012). *Climate change, impacts and vulnerability in Europe*.

Farinotti, D., Magnusson, J., Huss, M., & Bauder, A. (2010). Snow accumulation distribution inferred from time-lapse photography and simple modelling. *Hydrological Processes*, *24*, 2087-2097.

Gauci, A., Abela, J., Austad, M., Cassar, L.F., & Zarb Adami, K. (2018). A Machine Learning approach for automatic land cover mapping from DSLR images over the Maltese Islands. *Environmental Modelling & Software*, *99*, 1–10.

Härer, S., Bernhardt, M., Corripio Javier G., & Schulz, K. (2013). PRACTISE – Photo Rectification And ClassificaTIon SoftwarE (V.1.0). *Geoscientific Model Development*, *6*, 837–848.

Ide, R., & Oguma, H. (2013). A cost-effective monitoring method using digital time-lapse cameras for detecting temporal and spatial variations of snowmelt and vegetation phenology in alpine ecosystems. *Ecological Informatics*, *16*, 25–34.

IPCC (2007). *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC.* London: Cambridge University Press.

IPCC (2013). *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, New York, USA: Cambridge University Press.

Jamkes, M.R., HOW, P., & Wynn Peter M. (2016). Pointcatcher software: analysis of glacial time-lapse photography and integration with multitemporal digital elevation models. *Journal of Glaciology*, *62*, 159–169.

Knight, J., & Harrison, S. (2016). Mountain glacial and paraglacial environments under global climate change:. Lessons from the past, future directions and policy implications. *Geografiska Annaler: Series A, Physical Geography*, *96*, 245–264.

Merkel, F.R., Johansen, K.L., & Kristensen, A.J. (2016). Use of time-lapse photography and digital image analysis to estimate breeding success of a cliff-nesting seabird. *Journal of Field Ornithology*, *87*, 84–95.

Messerli, A., & Grinsted, A. (2015). Image georectification and feature tracking toolbox: ImGRAFT. *Geoscientific Instrumentation, Methods and Data Systems*, *4*, 23–34.

Mott, R., Faure, F., Lehning, M., Löwe, H., Hynek, B., Michlmayr, G., Prokop, A., & Schöner, W. (2008). Simulation of seasonal snow-cover distribution for glacierized sites on Sonnblick, Austria, with the Alpine3D model. *Annals of Glaciology*, *49*, 155–160.

Piazzi, G., Tanis, C., Kuter, S., Simsek, B., Puca, S., Toniazzo, A., Takala, M., Akyürek, Z., Gabellani, S., & Arslan, A.N. (2019). Cross-Country Assessment of H-SAF Snow Products by Sentinel-2 Imagery Validated against In-Situ Observations and Webcam Photography. *Geosciences*, *9*, 129.

Pirazzini, R., Leppänen, L., Picard, G., López-Moreno, J.I., Marty, C., Macelloni, G., Kontu, A., Lerber, A. von, Tanis, C.M., Schneebeli, M., Rosnay, P. de, & Arslan, A.N. (2018). European In-Situ Snow Measurements: Practices and Purposes. *Sensors (Basel, Switzerland)*, *18*.

Portenier, C., Hüsler, F., Härer, S., & Wunderle, S. (2019). Towards a webcam-based snow cover monitoring network: methodology and evaluation. *The Cryosphere Discussions*, 1–20.

Rastner, P., Nicholson, L., Sailer, R., Notarnicola, C., & Prinz, R. (2015). Mapping the snow line altitude for large glacier samples from multitemporal Landsat imagery. In *2015 8th International Workshop on the Analysis of Multitemporal Remote Sensing Images (Multi-Temp). July 22-24, 2015, Annecy, France* (pp. 1–4). Piscataway, NJ: IEEE.

Salzano, R., Salvatori, R., Valt, M., Giuliani, G., Chatenoux, B., & Ioppi, L. (2019). Automated Classification of Terrestrial Images: The Contribution to the Remote Sensing of Snow Cover. *Geosciences*, *9*, 97.

Schwalbe, E., & Maas, H.-G. (2017). The determination of high-resolution spatio-temporal glacier motion fields from time-lapse sequences. *Earth Surface Dynamics*, *5*, 861–879.

Schöner, W. (2009). Paläoklimainformationen aus Kenngrößen der Gletschermassenbilanz - Beispiele für die Alpen seit der ausgehenden Kleinen Eiszeit. In R. Schmidt, C. Matulla, & R. Psenner (Eds.), *Klimawandel in Österreich – Die letzten 20.000 Jahre … und ein Blick voraus* (pp. 127–144). Innsbruck: innsbruck university press.

Schöner, W., Auer, I., & Böhm, R. (2000). Climate variability and glacier reaction in the Austrian eastern Alps. *Annals of Glaciology*, *31*, 31–38.

Schöner, W., Boeckl, L., Hausmann, H., Otto, J.-C., Reisenhofer, S., & Riedl, Claudia, Seren, Sirri (2012a). Spatial Patterns of Permafrost at Hoher Sonnblick (Austrian Alps) - Extensive Field-measurements and Modelling Approaches. *Austrian Journal of Earth Sciences*, *105*, 154–168.

Schöner, W., Böhm, R., & Auer, I. (2012b). 125 years of high-mountain research at Sonnblick Observatory (Austrian Alps)—from “the house above the clouds” to a unique research platform. *Theoretical and Applied Climatology*, *110*, 491–498.

Tsai, Y.-L.S., Dietz, A., Oppelt, N., & Kuenzer, C. (2019). Remote Sensing of Snow Cover Using Spaceborne SAR: A Review. *Remote Sensing*, *11*, 1–44.

Winter, K.J.-P.M., Kotlarski, S., Scherrer, S.C., & Schär, C. (2017). The Alpine snow-albedo feedback in regional climate models. *Climate Dynamics*, *48*, 1109–1124.

Xiao, M., Rothermel, M., Tom, M., Galliani, S., Baltsavias, E., & Schindler, K. (2018). Lake ice monitoring with webcams. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *IV-2*, 311–317.