

Dear Editor,

We hereby submit the revised manuscript with a new title “Change detection of bare-ice albedo in the Swiss Alps?” by Kathrin Naegeli, Matthias Huss and Martin Hoelzle to be re-considered for publication as an article in The Cryosphere. We have taken into account all comments by the two anonymous reviewers and responded to all concerns raised.

The main revisions concern:

- the change of the title
- more details about the methodology of the analysis regarding the surrounding geology
- consistently distinguish between local and regional albedo change
- inclusion of more information about local, positive albedo changes
- expansion of discussion of possible causes for local, positive albedo changes
- reformulation of the conclusions

Below we respond to all comments by the two anonymous referees. The responses (bold font style) are following the referees’ comments (normal font style) directly. The corresponding revised sentences in the manuscript are given in quotation marks.

We would like to thank you in advance for your consideration of the article and we are looking forward to your reply.

Sincerely,

Kathrin Naegeli and co-authors

Comments by anonymous Referee #1

Reviewer comment: I acknowledge that the the Authors answered to my previous review of their paper. Most of my concerns were addressed. I still have some perplexities regarding the comparison with the lithology of rocks surrounding the glaciers. In section 3 (Methods) there is no explanation on how they performed the comparison between rocks and albedo trends. The CAI index (CERCHAR Abrasivity Index) is presented only in the results, there is no mention on how it was obtained and why. The relation between rock types and darkening trends is very interesting, and should be developed with more details in my opinion, since it could be an explanation of the variability in albedo trends.

Answer: We agree on the fact that this analysis was not well introduced. We thus added the following statements:

Related statement in the Study site and data section:

“To contextualise our results, the lithology surrounding the individual glaciers based on the lithological-petrographic map of Switzerland (GK500) provided by Swiss Geotechnical Commission (SGTK) was used; the map is at 1:500000 scale, and shows the subsurface strata subdivided into 25 groups according to their formation, their mineralogical composition, their particle size and their crystallinity. Based on *Käsling and Thuro*, [2010, see their Table 2] these groups were divided into less abrasive rocks (calcareous phyllites, limestones and marly shales, CERCHAR Abrasivity Index (CAI) 0–2) and very to extremely abrasive rocks (amphibolites, basic rocks, gneiss, granites, mica shists and syenites, CAI 2–6). Thereupon each individual glacier was assigned to one of the sub-groups (CAI 0-2 or CAI 2-6).”

Related statement in the Discussion section:

“Apart from the meteorological conditions that strongly influence bare-ice surfaces, the surrounding lithology of a glacier determines (at least partially) the availability of fine debris material that can be transported by wind and water, and be deposited on the glacier ice, reducing its albedo considerably (Di Mauro et al., 2015, 2017; Azzoni et al., 2016). Thus, easily erodible rock-types provide more loose material that might be transported by wind and water on to the glacier surface and, hence, impact the bare-ice albedo. This is supported by our analysis of the surrounding lithology and the albedo change of each individual glacier. However, no relation between the albedo of the surrounding geology and the magnitude of the ice albedo change was evident.”

Reviewer comment: In line 3 pg 18 I read: "No relation between the albedo of the surrounding geology and the magnitude of the ice albedo change was evident however"

So, I suppose that surrounding rocks were classified on the basis of their albedo (?) and then the albedo was compared (linear regression? PCA?) with the magnitude of ice albedo change (averaged for the whole glacier?). More details should be provided on this further comparison. I did not find anything in the methods.

Answer: To clarify these questions, we would like to note that we did not investigate the albedo of the surrounding rocks in detail. In fact, we classified the 25 rock types from the lithological-petrographic map based on the CERCHAR Abrasivity Index (CAI) into two groups (see also answer and clarification in the suggested text above) and assigned each glacier to one of the groups. We then analysed the albedo change per decade per glacier in regard to these two groups (less and very/extremely abrasive). As stated in the manuscript, no relation between the albedo of the surrounding geology (i.e. brighter and darker rocks) and the albedo change on the ice was found. Therefore, this analysis only supports the fact that easily erodible rock-types provide more loose material that might be transported by wind and water on to the glacier surface and hence impact the bare-ice albedo compared to very to extremely abrasive rock-types.

Comments by anonymous Referee #2

Reviewer comment: I thank the authors for considering my comments and submitting a revised version of their manuscript. Importantly, the authors considered my main concern about their conclusion by refining their glacier mask to exclude from the analysis some obvious areas of glaciers that did not qualify as bare-ice, namely medial moraines and areas where tributaries separated from the main glacier. I also appreciate that the authors tidied up the numerous oversights in dates of the images being used. It will certainly facilitate the consideration of this work in the future. Despite this modification, I however regret I do not find in this revision a large enough improvement to address fully my overarching concerns.

Answer: We regret that we did not fulfil the reviewer's expectations in our revision of the manuscript. Thanks to the comments below, we further improved the manuscript and addressed the concerns raised.

Reviewer comment: Despite this adjustment in the methodology and revised results, I still find that the areas of significant change in albedo remain largely indicative of step-change in surface conditions, change in flow and possibly compounded with imperfect co-registration that I find confusingly presented as a regional subtle decrease in bare-ice albedo.

Answer: We would like to point out that our results do not show any darkening of bare-ice at an ablation-area or regional scale and that this is clearly stated in the manuscript. While the uncertainty that might be introduced with imperfect co-registration is mentioned in the section "uncertainty assessment", the mentioned step-change in surface conditions or change in flow is not hindering the detection of an albedo change over time, but is rather a possible cause of the observed changes.

Related statement in the Method section:

"These data are geo-referenced with $\leq 12\text{m}$ radial root-mean-square error and intercalibrated across the different Landsat sensors (Young et al., 2017)."

Related statement in the Discussion section:

"In the frame of this study, we were unable to detect a spatially wide-spread, regional trend in bare-ice glacier albedo at a significant confidence level. However, for certain regions of the glaciers, such as the lowermost glacier tongues or along the lower margins, significant negative trends were found. Hence, a clear darkening was observed at the local scale for a limited number of grid cells rather than for entire ablation areas."

Reviewer comment: I don't think that the pattern of significant trends presented in Figure 5 and 6 when scrutinized with the corresponding images in the context of glacier flow and demise, fully and unambiguously support the conclusions being drawn or the way there are presented.

Answer: We fully understand the reviewer's concerns and have invested more effort to better isolate the significant conclusions given by our analysis. We also pay more attention to local effects, and have added a detailed discussion of these issues, and their impact on our results. Please see the revised conclusions at the very end.

Related statements in the Results section:

"The darkening can be attributed to different causes. At the glacier termini, an accumulation of fine debris due to the deposition of allochthonous material and/or melt-out of englacial debris is most likely. These materials, together with the presence of organic material, usually dark and humic substances, decrease local albedo values considerably and foster the growth of algae and bacteria (Hodson et al., 2010; Yallop et al., 2012; Takeuchi, 2013; Stibal et al., 2017)."

"Along the glacier margins an increase in debris cover due to small collapses or input of morainic material and, hence, a deposition of rather thick debris on the bare-ice is possible. Moreover, the appearance of debris-rich basal ice alongside the lower glacier margins due to the general glacier recession poses a further cause of local darkening (Hubbard and Sharp, 1995; Hubbard et al., 2009)."

"In contrast, we also find significant positive albedo trends for some locations on the glacier tongues (see Figure 7). These might be explained by the effect of glacier flow changing the position of the medial moraine, hence leading to a transition from debris-covered to

clean ice with a higher albedo for certain grid cells. Lateral shifts of the position of medial moraines are possible for retreating glaciers (Anderson, 2000).”

Related statements in the Discussion section:

“Thus, the occurrence of grid cells with positive albedo changes is not surprising, but hard to explicitly link to one specific cause such as the dynamics of medial moraines. The latter might favour local positive albedo changes over time. Localized microtopographic effects, i.e. changes in slope and aspect or modulations in the surface crust (e.g. growth of larger, brighter ice crystals) and the development of cryoconite holes (in contrast to a thin dispersed debris layer) can also strongly impact the evolution of bare-ice albedo.”

Reviewer comment: Figure 7 although restrictive in space remains revealing of the obvious departure between what appears discussed as a general trend and what pattern of change the analysis truly reveals.

Answer: To account for this comment, we distinguish between local, ablation-area and regional trends more clearly to align our discussion and conclusions more tightly with the obtained results, which indeed show no general trends (neither at ablation-area nor regional scale), but significant albedo changes at a local grid cell scale.

See related statements in the Discussion section above.

Related statements in the Conclusions section:

“While we did not find a darkening of bare-ice glacier areas at the regional scale or averaged for the ablation areas of individual glaciers, significant albedo trends (95% confidence level or higher) were revealed at the local scale. These individual grid cells or small areas were mainly located at the glacier termini or along the lower glacier margins in case of negative albedo trends, and along the central flowline further up-glacier in case of positive albedo trends.”

Reviewer comment: To some extent, I find the authors attach a lot of importance to the overall negative trend without fully discarding that the trend may be an effect of the relative share of bare-ice becoming largely debris-covered in a context of glacier recession, and despite some amendments to the glacier mask. Although this phenomenon is mentioned, I don't think its full effect on the general conclusion is fairly represented.

Answer: Again, we would like to point out that our results do not show any darkening of bare-ice at an ablation-area or regional scale. Due to accumulation of impurities mainly along the lower margins of the glaciers, a significant negative albedo change could be detected locally, however. This accumulation is linked to the increased availability of loose debris alongside the glaciers (lateral and end moraines) due to glacier recession or debris input from other source such as avalanches, wind transport or melt-out of englacial debris. We discuss the possible causes of this albedo change at a local scale at several places in the manuscript.

Related statements in the Results section:

“At the glacier termini, an accumulation of fine debris due to the deposition of allochthonous material and/or melt-out of englacial debris is most likely.”

“Along the glacier margins an increase in debris cover due to small collapses or input of morainic material and, hence, a deposition of rather thick debris on the bare-ice is possible.”

Related statements in the Discussion section:

“In the frame of this study, we were unable to detect a spatially wide-spread, regional trend in bare-ice glacier albedo. However, for certain regions of the glaciers, such as the lowermost glacier tongues or along the lower margins, significant negative trends were found. Hence, a clear darkening was observed at the local scale for a limited number of grid cells rather than for entire ablation areas.”

“(…), the surrounding lithology of a glacier determines (at least partially) the availability of fine debris material that can be transported by wind and water, and be deposited on the glacier ice, reducing its albedo considerably (Di Mauro et al., 2015, 2017; Azzoni et al., 2016). Thus, easily erodible rock-types provide more loose material that might be transported by wind and water on to the glacier surface and hence impact the bare-ice albedo.”

Reviewer comment: To some extent, the pattern of significant changes should equally invite to discuss areas of positive trend, which are however ignored.

Answer: We agree on the fact that the amount of grid cells exhibiting positive albedo trends was only mentioned in the results but not included in the discussion. We therefore added a respective statement to paragraph 5.3 “Possible causes and dependencies of bare-ice darkening” in addition to other places where the positive changes in albedo are mentioned.

Related statements in the Results section:

“For some grid cells, about 15% or 2 km², also positive albedo trends significant at the 95% confidence level were detected however.”

“In contrast, we also find significant positive albedo trends for some locations on the glacier tongues (see Figure 7). These might be explained by the effect of glacier flow changing the position of the medial moraine, hence leading to a transition from debris-covered to clean ice with a higher albedo for certain grid cells. Lateral shifts of the position of medial moraines are possible for retreating glaciers (Anderson, 2000).”

Related statements in the Discussion section:

“However, in the context of this study it is important to note that lateral shifts and growth and/or loss in volume of medial moraines might strongly impact the albedo evolution of some parts of the glaciers. Areas covered by thick debris were excluded from all analyses, but some mixed grid cells alongside medial moraines might still impact the results locally. Thus, the occurrence of grid cells with positive albedo changes is not surprising, but hard to explicitly link to one specific cause such as the dynamics of medial moraines. The latter might favour local positive albedo changes over time. Localized microtopographic effects, i.e. changes in slope and aspect or modulations in the surface crust (e.g. growth of larger, brighter ice crystals) and the development of cryoconite holes (in contrast to a thin dispersed debris layer) can also strongly impact the evolution of bare-ice albedo.”

Reviewer comment: Since no trend is detected overall, the question of where and how much the albedo has risen to compensate the decrease in ablation areas could also be expected.

Answer: As shown in figures 5 and 6 in the manuscript there is an overall trend for the investigated bare-ice areas of the 39 glaciers. However, this general trend is not significant (significant being defined with 95% confidence level or higher) and thus not discussed in detail. Albedo changes with a significant trend level only occur at local scale, both in negative and positive direction. We agree that the areas with significant positive albedo trends were not mentioned and discussed clearly so far and thus worked on this issue. Please see various answers to comments above and below.

Reviewer comment: This revision therefore does not fundamentally change my perception of a disconnect between the overall conclusions and what I believe can be interpreted from the results. The fact that the title remains a provocative question is also, to me, revealing of an analysis that is finally not truly conclusive as I suggested in my earlier comments.

Answer: The original title formulated as a question was intended to point out that there is no clear, simple, general conclusion about darkening of bare-ice in the Swiss Alps. However, as we do not want to mislead future readers by the title, we agree to adjust it and make the following suggestion:

“Change detection of bare-ice albedo in the Swiss Alps”

Reviewer comment: The fact that the study to assess change at the scale of each glacier considers variable bare-ice area that depend on the size of the remaining accumulation area for each year remains problematic. The albedo of ice is not equal everywhere and one could argue that albedo of bare ice would tend to decrease towards the terminus. In this study, the weight of such effect is unequal through each year and to me remain a methodological issue that the author did not address

in a way that I find suitable.

Answer: We agree with the reviewer that the methodology of this analysis is questionable. We thus investigated the effect of using variable, yearly outlines for one individual glacier (Findelen, greatest data availability) on the mean bare-ice albedo per year. The analysis showed, that the impact is negligible, i.e. less than 3% (or 0.0005) difference in mean bare-ice albedo, if yearly outlines are used compared to using the 2016 outline. For example, for the year 2005 we find a mean bare-ice albedo of 0.0196 when using the 2005 outline compared to 0.0191 when using the 2016 outline. The trend in ablation-area albedo remains insignificant. Thus, we will keep the results as they are stated in the manuscript. However, in response to the reviewer's comment we adjusted the wording to clarify the applied methodology and address the issue raised.

Related title and statements in the Results section:

"4.2 Regional and ablation-area trend in bare-ice albedo"

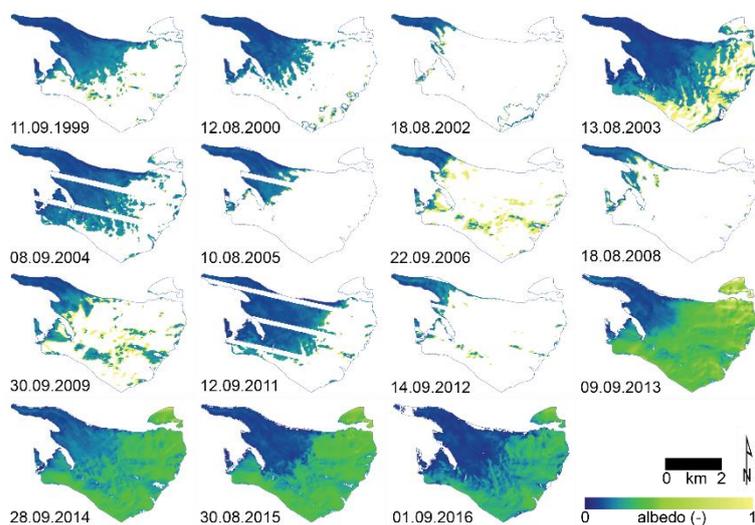
"We averaged mean albedo over the entire bare-ice area for each year and glacier to obtain 39 individual time-series for the study period 1999 to 2016. As the outlines from year 2016 are consistently used over time, constant, minimal extents per glacier are evaluated. In addition, overall, yearly averages were determined based on the individual time-series of the 39 glaciers (Figure 4a)."

Reviewer comment: Another example of obvious issues I can see is found in the map of albedo of Findelengletscher for 2016 in Figure 3. The potential effects of cloud misclassification remains visible close to the terminus. In this regard, I find that my earlier comment about the cloud masking approach is not convincingly addressed.

Answer: Unfortunately, Figure 3 was somewhat misleading as it included albedo values < 0.05 , which were completely excluded in our analysis, however (see statement in the Methods section). We updated the figure accordingly and the stated issue for year 2016 is fixed.

Related statement in the Methods section:

"Unrealistic albedo values, i.e. over 1 or below 0.05, are set to no data."



Revised Figure 3

Reviewer comment: I also stand by my earlier comment that the claim of albedo products being of "very high accuracy" and the reference of average deviation being less than 0.001 misrepresentative or ambiguous despite the author's response. I note that the authors stressed and introduced sources of uncertainties far more than in the earlier version. While addressing some of my specific comments, I don't find that this brought much of the expected modulation to their conclusion.

Answer: We agree on the fact that the statement of average deviation being less than 0.001 could be perceived as somewhat misleading: This number is attributed to the retrieval approach only (compared to a more sophisticated method to retrieve albedo) but does not include other uncertainties (e.g. input data, general data processing or environmental factors). We thus modified the statement accordingly.

Related statements in the Methods section:

“As shown by Naegeli et al. (2017) this albedo retrieval approach can be applied also to the most recent mission Landsat 8 and is suitable for mountain glaciers. It provides albedo products that have a high accuracy and only deviate marginally (< 0.01) from a more sophisticated albedo retrieval approach if using the same baseline dataset. Uncertainties in the albedo product not stemming from the retrieval approach but caused by the input data or the general data processing, such as saturation problems over snow covered areas or missing topographic correction on the radiometry, are elaborated in Section 3.5.”

Answer: With regard to the overall conclusions, we understand the reviewer’s comment and, thus, have revised the conclusions accordingly.

“Based on 159 Landsat scenes over a 17-year study period, we assessed the spatio-temporal evolution of bare-ice glacier surface albedo for 39 glaciers in the western and southern Swiss Alps. Our results indicate that the considered spatial scale (local versus regional) is crucial for the investigation of albedo trends and the detection of a potential darkening effect that is often referred to in recent literature (Takeuchi, 2001; Oerlemans et al., 2009; Dumont et al., 2014; Wang et al., 2014; Mernild et al., 2015; Tedesco et al., 2016). While we did not find a darkening of bare-ice glacier areas at the regional scale or averaged for the ablation areas of individual glaciers, significant albedo trends (95% confidence level or higher) were, however, revealed at the local scale. These individual grid cells or small areas were mainly located at the glacier termini or along the lower glacier margins in case of negative albedo trends (84% of all significant trends), and along the central flowline further up-glacier in case of positive albedo trends (16%).

The presented study is subject to various uncertainties stemming from the input data itself, its processing and availability, the albedo retrieval approach or environmental factors. However, unfortunately most of them are hard to numeralise. Nevertheless, our uncertainty assessment revealed highly similar trend patterns, thus indicating the robustness of the inferred albedo trends. We would like to emphasize the importance of the snap-shot uncertainty — limited availability of end-of-summer scenes demand recognition. Specifically, the meteorological conditions preceding the acquisition of the satellite data can influence bare-ice albedo, e.g. summer snow fall events, and ~~se~~ should be taken into account.

Although, only snap-shots of glacier surface albedo are available, the almost two-decade long time-series indicate significant trends for about 13.5 km² (corresponding to about 12% of the average end-of-summer bare-ice surface in the study area) at the local scale. Thereof almost 8 km² exhibit clear negative trends of ≤ -0.03 per decade. In contrast, only about 2 km² of all grid cells with significant albedo trends show positive ($\geq +0.03$ per decade) and about 4 km² show weak changes in bare-ice albedo (> -0.03 and $< +0.03$ per decade). For the areas with negative albedo trends over the last two decades, the ice-albedo feedback enhanced melt rates which are expected to be enforced in the near future. Even though the darkening of glacier ice has been found to occur over only a limited area of the investigated glaciers, the projected enlargement of bare-ice areas characterised by low albedo coupled with the predicted prolongation of the melt season will most likely strongly impact on the glacier surface energy balance and substantially enhance glacier mass loss.”

```
%\title{Darkening Swiss glacier ice?Change detection of bare-ice albedo in the Swiss Alps}
```

```
\title{Darkening Swiss glacier ice?Change detection of bare-ice albedo in the Swiss Alps}
```

```
% \Author[affil]{given_name}{surname}
```

```
\Author[1,2]{Kathrin}{Naegeli}
```

```
\Author[1,3,4]{Matthias}{Huss}
```

```
\Author[31]{Martin}{Hoelzle}
```

```
\affil[1]{Institut of Geography and Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland}
```

```
\affil[2]{Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Wales, UK}
```

```
\affil[3]{Department of Geosciences, University of Fribourg, Fribourg, Switzerland}
```

```
\affil[4]{Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich}
```

```
\affil[1]{Department of Geosciences, University of Fribourg, Fribourg, Switzerland}
```

```
\affil[2]{Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Wales, UK}
```

```
\affil[3]{Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich}
```

```
%% The [] brackets identify the author with the corresponding affiliation. 1, 2, 3, etc. should be inserted.
```

```
\runningtitle{Darkening Swiss glacier ice?Change detection of bare-ice albedo in the Swiss Alps}
```

```
\runningauthor{Naegeli et al.}
```

```
\correspondence{Kathrin Naegeli (kan1@aber.ac.ukkathrin.naegeli@giub.unibe.ch)}
```

`\received{}`

`\pubdiscuss{}` %% only important for two-stage journals

`\revised{}`

`\accepted{}`

`\published{}`

%% These dates will be inserted by Copernicus Publications during the typesetting process.

`\firstpage{1}`

`\maketitle`

`\begin{abstract}`

The albedo feedback is an important driver of glacier melt over bare-ice surfaces. Light-absorbing impurities strongly enhance glacier melt rates but their abundance, composition and variations in space and time are subject to considerable uncertainties and on-going scientific debates. In this study, we assess the temporal evolution of shortwave broadband albedo derived from 15 end-of-summer Landsat scenes for the bare-ice areas of 39 large glaciers in the western and southern Swiss Alps. Trends in bare-ice albedo crucially depend on the spatial scale considered. No significant negative temporal trend in bare-ice albedo was found on a regional to glacier-wide scale. However, at higher spatial scales, certain areas of bare-ice including the lowermost elevations and margins of the ablation zones revealed significant darkening over the study period 1999 to 2016. A total glacier area of 13.5 km^2 (equivalent to about 12% of the average end-of-summer bare-ice area in the study area) exhibited albedo trends significant at the 95% confidence level or higher. Most of this area was affected by a negative albedo trend of about $-\$0.05$ per decade. Generally, bare-ice albedo exhibits a strong interannual variability, caused by a complex interplay of meteorological conditions prior to the acquisition of the data, local glacier characteristics and the date of the investigated satellite imagery. Although, a darkening of glacier ice was found to be present over only a limited region, we emphasise that due to the recent and projected growth of bare-ice areas and prolongation of the ablation season in the region, the albedo feedback will considerably enhance the rate of glacier mass loss in the Swiss Alps in the near future.

`\end{abstract}`

%\copyrightstatement{TEXT}

\introduction %% \introduction[modified heading if necessary]

Glaciers are known to be excellent indicators of climate change \citep{IPCC2013}. Increasing air temperatures and changing precipitation patterns provoke snowlines to rise to higher altitudes and thus a spatially greater exposure of bare-ice surfaces. In connection with a general prolongation of the ablation season, the increased climatic forcing causes an amplification of glacier melt \citep{Kuhn1993,Oerlemans2001}. However, these changing glacier characteristics trigger feedback mechanisms, in particular the positive albedo feedback which enhances bare-ice melting \citep{Tedesco2011, Box2012}. Hence, the strongly negative mass balances of many glaciers are not solely a direct signal of atmospheric warming but result from a complex interplay of changes in climate forcing and related surface-atmosphere feedback mechanisms.

Currently, there is an on-going debate about the occurrence and rate of glacier and ice sheet darkening worldwide. While studies like those of \citep{Oerlemans2009}, \citep{Wang2014}, \citep{Takeuchi2001a} or \citep{Mernild2015} observed a darkening for one or several glaciers, respectively in the European Alps, the Chinese and Nepalese Himalaya or in Greenland's peripheral glacierised areas over varying time-scales, evidence of darkening from sectors of the Greenland Ice Sheet is less pronounced, leading to controversial discussions \citep[cf.][]{Box2012, Alexander2014, Dumont2014,Polashenski2015,Tedesco2016}. The recalibration of the MODIS sensors lead to a reduction in spatial extent and statistical strength of albedo trends over the Greenland Ice Sheet \citep{Casey2017}. Moreover, the emergence of legacy contaminants or radionuclides and heavy metals contained in cryoconite holes at lower elevations on Alpine glaciers \citep{Bogdal2009,Pavlova2014, Steinlin2014, Steinlin2016, Baccolo2017} or outcropping ice in the ablation zone of the Greenland Ice Sheet that contain high dust concentrations potentially associated with paleo-climatic conditions \citep{Wientjes2010,Wientjes2012,Goelles2017} and the recognition of the potential role of biological impurities \citep{Cook2017, Stibal2017, Tedstone2017} may emphasize and amplify the impact of light-absorbing impurities on ice melt.

To date, most long-term studies either used point data from automatic weather stations located in the ablation area of a glacier \citep[e.g.][]{Oerlemans2009}, coarsely-spaced satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) \citep[e.g.][]{Stroeve2013,Mernild2015}, downscaled MODIS data \citep{Dumont2012, Sirguey2016, Davaze2018} or other remote sensing datasets \citep[e.g.][]{Wang2014} to infer trends in ice albedo. Mostly, studies validated the satellite-derived albedo values with in-situ data measured at one to several locations on the ground, which is not always ideal \citep{Ryan2017a}. However, for the limited size of Alpine glaciers and the complex surrounding topography, the spatial resolution of MODIS data (500\,m) is not suitable, and no appropriate high-resolution albedo product is readily available. Thus, studies focusing on alpine glaciers often base their analysis on higher resolution datasets to obtain information about glacier surface albedo and related changes and processes \citep{Dumont2011, Fugazza2016, DiMauro2017} or point-measurements from an automatic weather stations, such as the long-term monitoring site on Vadret da Morteratsch, which revealed a point-based mean summer albedo decrease between 1996 and 2006 of 0.17 \citep{Oerlemans2009}. However, when debating the darkening of glaciers, a

clear distinction between glacier-wide versus point-based investigations is necessary to be able to clearly separate a darkening effect due to a changing ratio of snow-covered to snow-free areas of a glacier from other processes affecting the reflectivity of glacier surfaces. Moreover, a separation between albedo changes of bare ice or snow is required to correctly distinguish between differing processes and dependencies impacting snow and ice in particular ways.

In this study, we use Landsat data to obtain spatially distributed bare-ice albedo for 39 glaciers with a total area of 480 km² (corresponding to about a quarter of the present glaciation of the European Alps) located in the western and southern Switzerland over the 17-year period 1999 to 2016. We focus on the bare-ice areas, defined as glacier surfaces neither covered by snow nor by thick debris, only. Snow- or debris-covered glacier surfaces affect glacier mass balance by different processes and are thus not of interest to our analysis. We examine trends and their significance to better quantify and investigate a possible darkening of glacier ice in the western and southern Swiss Alps from the point to the regional scale. Causes and external factors that might impact bare-ice albedo and explain its spatial and temporal evolution are discussed.

\section{Study sites and data}

\label{sec:studysites_data}

Our study focuses on 39 glaciers located in the western and southern Swiss Alps (Figure \ref{fig:1}). All of them are characterised by a surface area of roughly 5 km² and larger, and thus offer a large-enough spatial extent to study the evolution of bare-ice surfaces and related albedo changes. The investigated glaciers vary considerably in size, ranging from about 5 km² (Giétro, Schwarzberg) to almost 80 km² (Aletsch), and span an elevation range from about 1850 m above sea level (m a.s.l.) to over 4500 m a.s.l. (Table 1). According to the most recent Swiss Glacier Inventory, the 39 glaciers covered a total area of 483 km² in 2010 \citep{Fischer2014}. We used a Sentinel-2 scene (20 m spatial resolution) acquired on the 23rd of August 2016 to manually adjust the glacier outlines and to obtain up-to-date glacier extents totalling 442 km² \citep{Paul2016}. For our analysis, we excluded heavily debris-covered parts, such as medial moraines or debris-covered glacier tongues, as we focus on the albedo of bare ice only. Hence, the area difference of 41 km² between 2010 and 2016 does not solely stem from glacier retreat, but is also due to our exclusion of all glacier areas with thick debris cover for this study, i.e. debris-covered glacier tongues (e.g. Zmutt, Unteraar, Zinal, Oberaletsch) or medial moraines (e.g. Aletsch). The obtained glacier outlines for the year 2016 are used in all consecutive analysis, thus the glacier outline is kept constant over the study period and does not evolve with time.

\begin{figure*}[h]

%\includegraphics[width=12cm]{figures/NEW/StudySites-01_small}

\includegraphics[width=12cm]{figures/NEW/Figure_1}

\caption{Overview of studied glaciers located in the western and southern Swiss Alps. The black frames mark the extent of detailed figures. The inset indicates the position of the study site in Switzerland.}

\label{fig:1}

\end{figure*}

We used the Landsat Surface Reflectance Level-2 science products of the USGS for Landsat 5 and 7 (TM/ETM+) and 8 (OLI) as a basis to obtain broadband shortwave albedo (see Section \ref{subsec:albedoretrieval}). For Landsat TM and ETM+, the product is generated from the specialized software Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS), whereas the Landsat OLI product is based on the Landsat 8 Surface Reflectance Code (LaSRC). These data products consist of six (TM/ETM+) or seven (OLI) individual spectral bands in the wavelength range of around 440 nm to 2300 nm, with slight deviations of the individual band widths for the specific sensors. Detailed information about these products can be found in \cite{Masek2006} for Landsat TM/ETM+, and in \cite{Vermote2016a} for Landsat 8, as well as in the product guides provided by the USGS. In the context of this study, it is important to mention that both products are neither corrected for topography nor shadow effects. \cite{Claverie2015} investigated the accuracy of retrieved surface reflectance values based on the LEDAPS algorithm by inter-comparing the product with data from the Aerosol Robotic Network (AERONET) and MODIS data obtained on the same day. This comparison showed good results overall with the poorest performance in the blue band, which is known to have the greatest atmospheric sensitivity \cite{Vermote2008}. Most importantly, they found no trend or significant year-to-year variability, suggesting this data product to be highly valuable for temporal analysis. Similarly, \cite{Vermote2016a} analysed the performance of the Landsat 8 surface reflectance product, concluding with high correlations between the MODIS and OLI surface reflectance values, with worst results found again for the blue band, and a general improvement of Landsat OLI surface reflectance product over the ad-hoc Landsat TM/ETM+ LEDAPS product.

All 39 glaciers are comprised in one scene (path 195, row 28) and we examined a total of 16 scenes between the years 1999 and 2016, whereupon in 2013 one scene was chosen per glacier individually (Table 2). To obtain maximum information about the bare-ice area of the glaciers, only scenes acquired at the end-of-summer (from months August or September) were chosen. Unfortunately, no good scenes are available for the years 2001, 2007 and 2010. The restriction to choose end-of-summer scenes only hampers the investigation of seasonal changes, but favours an intercomparison over multiple years. On average, a scene comprised 119 km^2 of bare ice (Table 2).

Our surface type retrieval approach based on the obtained broadband shortwave albedo (see Section \ref{subsec:albedoretrieval}) requires a digital elevation model. We used the DHM25 with an original spatial resolution of 25 m provided by Swisstopo \cite{swisstopo2005} and resampled it to 30 m spatial resolution to match the broadband shortwave albedo datasets derived from Landsat.

[To contextualise our results, the lithology surrounding the individual glaciers based on the lithological-petrographic map of Switzerland \(GK500\) provided by Swiss Geotechnical Commission \(SGTK\) was used; the map is at 1:500000 scale, and shows the subsurface strata subdivided into 25 groups according to their formation, their mineralogical composition, their particle size and their](#)

crystallinity. Based on \cite{Kasling2010} (see their Table 2) these groups were divided into less abrasive rocks (calcareous phyllites, limestones and marly shales, CERCHAR Abrasivity Index (CAI) 0–2) and very to extremely abrasive rocks (amphibolites, basic rocks, gneiss, granites, mica shists and syenites, CAI 2–6). Thereupon each individual glacier was assigned to one of the sub-groups (CAI 0-2 or CAI 2-6).

~~To contextualise our results, the lithology surrounding the individual glaciers based on the lithological-petrographic map of Switzerland (GK500) provided by Swiss Geotechnical Commission (SGTK) was used; the map is at 1:500000 scale, and shows the subsurface strata subdivided into 25 groups according to their formation, their mineralogical composition, their particle size and their crystallinity.~~

\begin{table}[ht!]

\caption{Overview of all 39 study glaciers, their area (2010 according to \cite{Fischer2014}, 2016 excluding thick debris coverage), elevation range and the lithology of rocks surrounding the glacier. Glaciers are ordered according to their surface area.}

\footnotesize

\centering

\renewcommand{\arraystretch}{0.92}

\begin{tabular}{lcccccc}\textwidth, column = lcccccc}

\topline

Glacier Name	& Area 2010	&	Area 2016	&	Elev. range	&	Lithology	\\
&	(km ²)	&	(km ²)	&	(m a.s.l.)	&	&	\\

\middleline

Grosser Aletsch	& 78.4	&	74.3	&	1872--4120	&	mica shists, gneiss	\\
Grenzg	& 40.2	&	37.3	&	2319--4536	&	mica shists, gneiss	\\
Fiescher (VS)	& 29.5	&	28.2	&	2102--4082	&	mica shists, gneiss	\\
Unteraar	& 22.5	&	15.9	&	2278--3925	&	granites, syenites	\\
Rhone	& 15.3	&	15.0	&	2300--3621	&	granites, syenites	\\
Trift	& 14.9	&	14.6	&	2191--3383	&	mica shists, gneiss	\\
Corbassière	& 15.2	&	14.2	&	2496--4306	&	calc. phyllites, marly shales	\\
Findelen	& 14.2	&	13.8	&	2661--3929	&	mica shists, gneiss	\\
Oberaletsch	& 17.5	&	12.7	&	2456--3831	&	granites, syenites	\\
Otemma	& 12.6	&	11.0	&	2607--3779	&	basic rocks	\\
Kanderfirn	& 12.2	&	11.4	&	2408--3203	&	granites, syenites	\\
Zinal	& 13.4	&	10.9	&	2466--4035	&	granites, syenites	\\

Gauli	& 11.4	& 11.1	& 2335--3597	&	gneiss	\\
Zmutt	&	13.7	& 10.1	& 2650--4030	&	amphibolites \\
Unterer Theodul	&	9.4	&	9.1	& 2611--4155	& basic rocks \\
Mont Miné	& 9.9	&	9.3	&	2403--3719	& granites, syenites \\
Allalin	&	9.2	&	8.9	& 2686--4167	& gneiss \\
Fiescher (BE)	& 9.4	&	8.4	&	1999--4086	& limestones \\
Ferpècle	&	9.0	&	8.6	& 2289--3659	& granites, syenites \\
Oberer Grindelwald	&		8.4	&	8.1	& 1931--3715 & granites, syenites \\
Plaine Morte	& 7.3	&	7.5	&	2514--2874	& calc. phyllites, marly shales \\
Lang	& 8.3	&	7.2	&	2461--3894	& mica shists, gneiss \\
Fee	&	7.3	&	7.1	& 2590--4014	& basic rocks \\
Ried	& 7.3	&	7.0	&	2400--4247	& mica shists, gneiss \\
Obers Ischmeer	&		7.3	&	6.8	& 2107--3880 & gneiss \\
Saleina	&	6.5	&	6.2	& 2320--3863	& granites, syenites \\
Brenay	&	7.1	&	6.0	& 2728--3824	& granites, syenites \\
Trient	&	5.8	&	5.8	& 2160--3477	& granites, syenites \\
Mittelaletsch	& 6.9	&	5.7	&	2599--4059	& granites, syenites \\
Stein	& 5.7	&	5.5	&	2190--3462	& amphibolites \\
Mont Durand	& 6.1	&	5.4	&	2769--4102	& mica shists, gneiss \\
Rosenloui	&	5.4	&	5.3	& 2102--3623	& granites, syenites \\
Giètro	&	5.2	&	5.1	& 2792--3815	& calc. phyllites, marly shales \\
Turtmann	&	5.2	&	5.1	& 2409--4141	& granites, syenites \\
Mont Collon	& 5.4	&	5.0	&	2532--3670	& granites, syenites \\
Brunegg	&		5.5	&	5.0	& 2715--3796 & granites, syenites \\
Schwarzberg	& 5.2	&	4.7	&	2728--3549	& mica shists, gneiss \\
Moming	&	5.3	&	4.6	& 2692--4036	& basic rocks \\
Tschingelfirn	& 5.2	&	4.4	&	2395--3318	& limestones \\

\bottomline

\end{tabular}

\label{tab:1}

\belowtable{} % Table Footnotes

Landsat 7 (ETM+) 2.5 \\	&	08.09.2004	&	132.0	&	29.9	&	0.0	&
Landsat 7 (ETM+) 1.0 \\	&	10.08.2005	&	72.6	&	16.4	&	5.9	&
Landsat 5 (TM) & \\	22.09.2006	&	95.8	&	21.7	&	0.0	&	6.0
Landsat 7 (ETM+) 0.8 \\	&	18.08.2008	&	24.6	&	5.6	&	0.1	&
Landsat 5 (TM) & \\	30.09.2009	&	185.2	&	41.9	&	0.0	&	7.2
Landsat 7 (ETM+) 2.8 \\	&	12.09.2011	&	146.8	&	33.2	&	0.4	&
Landsat 7 (ETM+) 3.7 \\	&	14.09.2012	&	22.1	&	5.0	&	0.8	&
Landsat 8 (OLI) & \\	09.09.2013*	&	\multirow{2}{*}{20.6}	&	\multirow{2}{*}{91.1}	&		&	
Landsat 8 (OLI) & & 0.5	25.09.2013*	&	14.0	&	4.5	&		&	
Landsat 8 (OLI) & \\	28.09.2014	&	153.5	&	34.7	&	1.0	&	8.3
Landsat 8 (OLI) & \\	30.08.2015	&	214.9	&	48.6	&	1.4	&	2.1
Landsat 8 (OLI) & \\	01.09.2016	&	189.4	&	42.8	&	2.3	&	3.1

\bottomline

\end{tabular}

\label{tab:2}

\belowtable{*For each individual glacier only one of these two scenes in 2013 is taken (based on minimal cloud and/or snow coverage).} % Table Footnotes

\end{table*}

\subsection{Albedo retrieval}

\label{subsec:albedoretrieval}

We applied the narrow-to-broadband conversion by \citet{Liang2001} to obtain shortwave broadband albedo α_{short} from the surface reflectance data. The conversion is based on five of the seven individual bands, and is formulated as follows:

```
\begin{equation}
```

$$\alpha_{\text{short}} = 0.356\alpha_{\{1\}} + 0.130\alpha_{\{3\}} + 0.373\alpha_{\{4\}} + 0.085\alpha_{\{5\}} + 0.072\alpha_{\{7\}} - 0.0018$$

```
\label{eq:1}
```

```
\end{equation}
```

where $\alpha_{\text{subscript}\{i\}}$ represents the narrowband ground reflectance of TM/ETM+ in band i . For Landsat OLI, the band numbers were adjusted accordingly. This conversion was developed based on a large empirical data set and the band configurations of Landsat TM/ETM+. As shown by \cite{Naegeli2017} this albedo retrieval approach can be applied also to the most recent mission Landsat 8 and is suitable for mountain glaciers. It provides albedo products that have a high accuracy and only deviate marginally (< 0.01) from a more sophisticated albedo retrieval approach if using the same baseline dataset. Uncertainties in the albedo product not stemming from the retrieval approach but caused by the input data or the general data processing, such as saturation problems over snow covered areas or missing topographic correction on the radiometry, are elaborated in Section 3.5. As shown by \cite{Naegeli2017} this albedo retrieval approach can be applied also to the most recent mission Landsat 8 and is suitable for mountain glaciers. It provides albedo products that are of very high accuracy and deviate by less than < 0.001 on average from a more sophisticated albedo retrieval approach. Unrealistic albedo values, i.e. over 1 or below 0.05, are set to no data.

```
\subsection{Surface type evaluation}
```

The delineation of bare-ice area versus snow-covered surfaces is based on a multi-step classification scheme of the surface albedo values (Figure \ref{fig:2}). The classification is thus based on a physical parameter specific for both snow and ice. In a first step, two threshold values for \textit{certainly snow} ($\alpha > 0.55$) and \textit{certainly ice} ($\alpha < 0.25$) are defined (\textit{primary surface type evaluation}), Figure \ref{fig:2}) based on recommendations in the literature \cite{Cuffey2010}. This results in a critical albedo range ($0.25 < \alpha < 0.55$), where an unambiguous assignment of the surface type, i.e. snow or ice, is not possible without considering other parameters. Within this range of albedo values, outliers are suppressed by adjusting all albedo values ($\alpha_{\text{subscript}\{\text{corr}\}}$) by multiplying with a constant value ($\text{SLA}_{\text{subscript}\{\text{const}\}}$). We, therefore, take advantage of a digital elevation model available for all glaciers to evaluate the average albedo in elevation bands of 20 m within this critical albedo range. The transition between ice and snow is typically characterized by a distinct change in albedo \cite[e.g.]{Hall1987, Zeng1983, Winther1993}. We thus derive an estimate of the mean snowline altitude (SLA) for each glacier and scene based on the greatest slope of the albedo-elevation profile. The albedo for this altitude is considered to be the site- and scene-specific albedo threshold discriminating snow and ice and is henceforth termed $\alpha_{\text{subscript}\{\text{crit}\}}$.

```
\begin{figure}[h!]
```

```
%\includegraphics[width=8.3cm]{figures/NEW/SurfaceTypeEvaluation_FlowChart_4-01}
```

```
\includegraphics[width=8.3cm]{figures/NEW/Figure_2}
```

\caption{Flow chart of the methodology applied to evaluate the surface type (snow/ice) of every glacier grid cell based on the derived shortwave broadband albedo. For further explanations please see text.}

\label{fig:2}

\end{figure}

In a second step, we use the SLA and α_{crit} as reference to evaluate the surface type within the range of critical albedo values, where there is ambiguity between snow and ice (\textit{secondary surface type evaluation}, Figure \ref{fig:2}). Finally, all grid cells are evaluated regarding their relative position compared to the SLA within a critical radius r_{crit} (\textit{probability test to eliminate extreme outliers}, Figure \ref{fig:2}). Grid cells located clearly above the SLA are more likely to be snow than ice, and vice versa. An increasing positive/negative vertical distance from the SLA thus results in penalties for the likelihood of the cell within the critical albedo range of being either snow or ice. As an example, a grid cell near the glacier terminus with an albedo of 0.42, i.e. a rather high albedo for Alpine glacier ice, will be classified as ice. An albedo of e.g. 0.35 observed for the highest regions of the glacier, in contrast, will be classified as snow, as the low albedo is more likely to be explained by an erroneous albedo determination (e.g. shadows) than by actually snow-free conditions. In summary, our procedure to distinguish between snow and bare-ice surfaces relies on remotely-determined surface albedo and merges this information with surface elevation with a probability-based approach to detect outliers and to automatically adapt the classification to the site- and scene-specific conditions.

\subsection{Trend analysis}

Over the study period 1999 to 2016, one end-of-summer Landsat snapshot was available for 15 years (cf. Table \ref{tab:2}). Unfortunately, in three years no end-of-summer scene is available due to obscureness of clouds,. Thus, at most the albedo trend of an individual grid cell is characterized by 15 end-of-summer albedo values. However, due to cloud coverage, differing amounts of snow-covered areas in the scenes and/or sensor artefacts, less scenes were usually available to evaluate a temporal bare-ice albedo trend for single grid cells. We arbitrarily set the necessary number of scenes to 50%, thus at least eight albedo values are required for calculating the albedo trend of one individual grid cell. We used the non-parametric Mann-Kendall (MK) test \citep{Mann1945, Kendall1975} to evaluate the confidence level of the trends (significant at the 95% / 90% / 80% level, or not significant). For grid cells with significant trends, the magnitude of the trend was determined based on linear regression through all available data points. Trends are given as albedo change per decade.

\subsection{Uncertainty assessment}

Our results are subject to uncertainties arising from errors in the input data, the general data processing, the albedo retrieval approach and the availability of data as well as environmental factors. In general, the used input data, the Landsat Surface Reflectance Level-2 science products for Landsat 5 and 7 (TM/ETM+) and 8 (OLI) (see Section \ref{sec:studysites_data}), are Tier 1 products offered by and suggested to be used for time series analysis at pixel level by the USGS. These data are geo-referenced with $\leq 12\text{m}$ radial root-mean-square error and intercalibrated across the

different Landsat sensors \citep{Young2017}. Major drawbacks of these data are the missing topographic correction on the radiometry \citep{Young2017}, the saturation problem over snow-covered areas in the TM and ETM+ data and the SLC failure in the ETM+ data post May 2003 resulting in missing data. While the latter is negligible due to the rather small areas studied (see also Section \ref{subsec:spatiallydistributed}), the former are of minor impact as only bare-ice areas situated in rather flat terrain on glacier tongues are considered for the analysis of temporal albedo evolution in this study. The retrieval of albedo values from the reflectance products is limited by the availability of spectral information of the input data. The application of a narrow-to-broadband equation (Equation \ref{eq:1}) is known to perform reliably, in general and over glacierised areas in particular as outlined by different studies \citep{Knap1999, Liang2001, Greuell2002, Naegeli2017}. Moreover, the impact of a missing Bidirectional Reflectance Distribution Function (BRDF) correction scheme is negligible, but generally results in a slight underestimation of albedo values \citep{Naegeli2017}. Overall, the uncertainties stemming from the input data, the general data processing and the albedo retrieval approach are hard to quantify and, hence, no exact number is given here. However, as this study focuses on relative changes of albedo rather than absolute values, the conducted analyses based on the given input data can be considered as reliable and robust.

The general data availability is limited, and only end-of-summer albedo evolution could be analysed. For investigating sub-seasonal variations, the frequency of cloud and/or snow-free and high-quality Landsat scenes was too sparse. This lack of data throughout the entire ablation season of the glaciers is mainly caused by the occurrence of clouds, but also other environmental factors, such as fresh snow falls, hinder the investigation of bare-ice albedo. Subsequently, no data was available for three years of the study period (see Section \ref{sec:studysites_data}). The occurrence of fresh snow on the glacier surfaces is manifested in elevated albedo values and/or strongly reduced bare-ice surfaces. We checked the scenes used in this study to minimise the impact of environmental factors on our retrieved albedo values. For example, for the year 2013, two different scenes are considered and for each individual glacier the more valuable (less snow and/or cloud/shadow coverage) was selected.

The evaluation of bare-ice versus snow-covered grid cells might result in some misclassified cells. Clouds and shadows that were not detected by the removal algorithms may influence/falsify calculated bare-ice albedos of individual grid cells. However, manual checks revealed a low frequency of such cases. Uncertainty due to mixed pixels, specifically pixels along the margins of a glacier, can influence the temporal albedo trend observed in these areas. We minimized this effect by using glacier outlines updated to 2016 in order to exclude grid cells from the analysis that become ice-free towards the end of the study period.

To account for the uncertainty introduced by the use of one end-of-summer scene only and thus the exclusion of sub-seasonal variability in albedo, the snapshot uncertainty, we performed a comprehensive uncertainty analysis based on ten end-of-summer Landsat 8 scenes acquired between 2013 and 2016 (Table \ref{tab:4}). The analysis was performed for one glacier, Findelen, as more scenes were available for this glacier due to the overlapping coverage by two different Landsat scenes (path/row 194/28 and 195/28) of this glacier. For the same grid cell and multiple satellite scenes acquired during the same year (1--5 weeks apart at maximum) we found an average variability in inferred albedo of 0.026 over all four investigated years (2013--2016) (Table \ref{tab:4}). Assuming that bare-ice albedo remains constant over this short time period in reality, this value

provides a direct uncertainty estimate for local satellite-retrieved albedo that is assumed to be representative for all investigated glaciers in this study.

`\begin{table*}[h]`

`\caption{Overview of scenes used in the snap-shot uncertainty analysis. Px refers to the number of pixels that were used to derive uncertainty. Mean (α_{mean}), minimum (α_{min}) and maximum (α_{max}) albedo, as well as the mean (σ_{mean}) standard deviation of point-based bare-ice albedo for each individual scene pair or triple per year are given.}`

`\centering`

`\begin{tabular}{|cccccc|}%{\textwidth, column = c}`

`\topline`

`Year & Day & Px & α_{mean} & α_{min} & α_{max} & σ_{mean} \\`

`\middleline`

`\multirow{2}{*}{2013} & 09 Sept. & \multirow{2}{*}{1190} & 0.204 & 0.052 & 0.370 & \\`
`\multirow{2}{*}{0.040} \\`

`& 25 Sept. & \\`
`& 0.233 & \\`

`0.051 & 0.361 & \\`
`\\`

`\middleline`

`\multirow{3}{*}{2014} & 27 Aug. & \multirow{3}{*}{3869} & 0.213 & 0.051 & 0.382 & \\`
`\multirow{3}{*}{0.024} \\`

`& 12 Sept. & \\`
`& 0.224 & \\`

`0.052 & 0.383 & \\`
`\\`

`& 28 Sept. & \\`
`& 0.255 & \\`

`0.054 & 0.396 & \\`
`\\`

`\middleline`

`\multirow{3}{*}{2015} & 07 Aug. & \multirow{3}{*}{3446} & 0.174 & 0.052 & 0.403 & \\`
`\multirow{3}{*}{0.031} \\`

`& 30 Aug. & \\`
`& 0.178 & \\`

`0.051 & 0.356 & \\`
`\\`

Figure \ref{fig:3} shows the spatio-temporal evolution of glacier-wide shortwave broadband albedo for Findelengletscher. The retrieval of meaningful albedo values is restricted by the quality of the surface reflectance data and, thus, the availability of realistic values in the individual bands needed for the narrow-to-broadband conversion. For Landsat TM/ETM+, a saturation problem over snow-covered areas exists, resulting in missing values for these regions (years 1999--2012 in Figure \ref{fig:3}). This problem is not present in the Landsat 8 data (years 2013--2016 in Figure \ref{fig:3}). Missing data in some of the Landsat ETM+ data, generated due to the scan line corrector (SLC) failure post May 2003, also occurs in our albedo retrievals (e.g. 08.09.2004 in Figure \ref{fig:3}). We tested the impact of the SLC failure by simulating missing data for three scenes with an intact SLC for Findelengletscher. SLC failure resulted in slightly higher mean bare-ice albedo values (1.2 to 2.2\%, e.g. 12.08.2000 SLC-on mean bare-ice albedo 0.204 versus SLC-off mean bare-ice albedo 0.209 indicating a difference of 2.2\%), which is a negligible impact. Although, we applied a cloud removal algorithm, our results are still impacted by cloud shadows that are harder to detect without manual effort (e.g. 18.08.2002 in Figure \ref{fig:3}). However, the bare-ice area is almost always well represented and inferred albedo is realistic, hence allowing for a monitoring through time.

Generally, the average albedo values for the bare-ice surfaces are rather low, ranging from 0.18 to 0.31 for individual glaciers as a mean over the entire study period. For all 39 glaciers and over the entire study period we obtained a mean bare-ice surface albedo of 0.22. Extreme years with generally very high snowline altitude (2003, 2011, 2015) or very low snowline altitude (2013, 2014) are linked to summers with exceptionally long and warm or rather cold and humid weather situations, and thus strong or weak ablation, respectively \citep{GlaciologicalReports}.

```

\begin{figure*}[h]
%\includegraphics[width=12cm]{figures/NEW/AlbedoGrids_FIN_2-01_small}
\includegraphics[width=12cm]{figures/NEW/Figure_3}
\caption{Spatio-temporal evolution of shortwave broadband albedo between 1999 and 2016 for Findelengletscher.}
\label{fig:3}
\end{figure*}

```

\subsection{Regional and ablation-area trend in bare-ice albedo~~Regional and glacier-wide trend in bare-ice albedo~~}

We averaged mean albedo over the entire bare-ice area for each year and glacier to obtain 39 individual time-series for the study period 1999 to 2016. As the outlines from year 2016 are consistently used over time, constant, minimal extents per glacier are evaluated. In addition, overall, yearly averages were determined based on the individual time-series of the 39 glaciers (Figure \ref{fig:4}a).

~~We averaged mean albedo over the entire bare-ice area for each year and glacier to obtain a 39 individual time series for the study period 1999 to 2016. In addition, the overall average series was evaluated as the mean bare-ice albedo of all glaciers and each year (Figure \ref{fig:4}a).~~

Individual glaciers show considerable variations (up to 0.45 difference between minimum/maximum values) of mean bare-ice albedo between years. However, some glaciers show only minor interannual variability of about 0.06 such as for Grosser Aletsch and Unteraar. On average, the glaciers exhibit a range of 0.22 in minimum and maximum values in-between individual years. Due to these large interannual variations, no significant trends in average glacier-wide bare-ice albedo between 1999 and 2016 for 37 out of the 39 glaciers were found. Only two (Brenay, Ferpècle) show slightly positive trends that are significant at the 95\% confidence level according to the MK test.

The yearly values of the 39-glacier average albedo time series range from 0.18 to 0.29, with a mean of 0.22. As for the individual glaciers, no significant trend was found for the averaged time series over the period 1999 to 2016.

```
\begin{figure*}[h!]
```

```
%\includegraphics[width=12cm]{figures/NEW/bareice_albedo_MB_combined_new_large}
```

```
\includegraphics[width=12cm]{figures/NEW/Figure_4}
```

```
\caption{(a) Time series of mean bare-ice albedo of all 39 glaciers (grey dots) and their overall average (black dots with dashed line). }
```

```
\label{fig:4}
```

```
\end{figure*}
```

```
\subsection{Local trend in bare-ice albedo}
```

As trends in bare-ice albedo for the entire ablation area of glaciers might be diluted by averaging over larger areas, or be affected by data uncertainty, we also evaluated the trend in albedo for all grid cells individually. For 114.5 km² (26\%) of the entire surface area of all glaciers, trends were significant at the 80\% level according to the MK test (Table \ref{tab:3}). Thereof, 13.5 km² (12\%) showed trends significant at the 95\% confidence level or higher. Trends were classified according to their magnitude for interpretation. Our classification is shown in Table 3. Classes with clear negative trends (class 1--3) are more abundant compared to classes with no clear or positive trends (class 4--7) at very high confidence level (95\% or higher) (Table 3). Thus, significant albedo trends at a confidence level of 95\% or higher in the bare-ice areas of the studied glaciers were only detected for grid cells with a rather strong reduction of albedo over the 17 years. Surprisingly, more than 80\% of all grid cells with significant albedo changes at the 95\% or higher confidence level showed negative trends: 25\% exhibited changes of around $-\$0.02$ per decade, but almost 60\% of cells showed trends more negative than $-\$0.03$ per decade. For some grid cells, about 15\% or 2 km², also positive albedo trends significant at the 95\% confidence level were detected however.

```
\begin{table*}[h!]
```

```
\caption{Overview of classes of bare-ice albedo trends for individual grid cells between 1999 and 2016 corresponding to the confidence levels of 80\% and 95\% according to the MK test. Numbers refer to the sum of all bare-ice grid cells of all 39 study glaciers.}
```

```
\centering
```

```
\begin{tabular}{|ccccc|}{\textwidth, column = c}
```

```
\topline
```

```
Class & Albedo trend & \multicolumn{2}{c}{Confidence level 80\%} &
```

```
\multicolumn{2}{c}{Confidence level 95\%} \\\
```

```
(\#) & (albedo change decade\textsuperscript{-1}) & (\%) & (km\textsuperscript{2}) & (\%)  
& (km\textsuperscript{2}) \\\
```

```
\middleline
```

```
1 & <  $-\$0.05$  & 8.8 & 10.1 & 28.9 & 3.9 \\\
```

```
2 &  $-\$0.05$  to  $-\$0.03$  & 11.2 & 12.9 & 28.2 & 3.8 \\\
```

```
3 &  $-\$0.03$  to  $-\$0.01$  & 21.5 & 24.6 & 25.6 & 3.5 \\\
```

```
4 &  $-\$0.01$  to 0.01 & 26.0 & 29.8 & 1.8 & 0.2 \\\
```

```
5 & 0.01 to 0.03 & 17.9 & 20.5 & 2.7 & 0.4 \\\
```

```
6 & 0.03 to 0.05 & 8.4 & 9.7 & 5.8 & 0.8 \\\
```

```
7 & > 0.05 & 6.1 & 7.0 & 6.9 & 0.9 \\\
```

```
\middleline
```

```
Total & & 100 & 114.5 & 100 & 13.5 \\\
```

```
\bottomhline
```

```
\end{tabular}
```

```
\label{tab:3}
```

```
\belowtable{} % Table Footnotes
```

```
\end{table*}
```

```
\begin{figure*}[h]
```

```
%\includegraphics[width=12cm]{figures/NEW/Trend_Signi_50_plot_new_samescales_NEW}
```

```
\includegraphics[width=12cm]{figures/NEW/Figure_5}
```

\caption{Confidence levels of bare-ice albedo trends over the study period 1999 to 2016 according to the MK test. See Figure \ref{fig:1} for the location of the different panels in the Swiss Alps.}

\label{fig:5}

\end{figure*}

\begin{figure*}[h]

%\includegraphics[width=12cm]{figures/NEW/Trend_50_plot_new_7classes_numbers}

\includegraphics[width=12cm]{figures/NEW/Figure_6}

\caption{Classified albedo trends per decade for all grid cells with trends significant at the 80% confidence level or higher according to the MK test. Averages for areas with bare-ice albedo trends significant at the 95% confidence level are given for selected large glaciers. See Figure \ref{fig:1} for the location of the different panels in the Swiss Alps.}

\label{fig:6}

\end{figure*}

For most of the bare-ice area, the derived trends in albedo were only significant at low levels. Compared to the glaciers' overall ablation area only relatively few grid cells with trends significant at the 95% confidence level or higher (dark blue areas in Figure \ref{fig:5}) are present. The cells with significant trends at high confidence levels are usually situated at the termini or along the lower margins of the glaciers and trends are mostly negative (cf. Table \ref{tab:3}, Figures \ref{fig:5}--\ref{fig:7}). The darkening can be attributed to different causes. At the glacier termini, an accumulation of fine debris due to the deposition of allochthonous material and/or melt-out of englacial debris is most likely. These materials, together with the presence of organic material, usually dark and humic substances, decrease local albedo values considerably and foster the growth of algae and bacteria \citep{Hodson2010, Yallop2012, Takeuchi2013, Stibal2017}. However, many of these effects and interactions are still unclear. Along the glacier margins an increase in debris cover due to small collapses or input of morainic material and, hence, a deposition of rather thick debris on the bare-ice is possible. Moreover, the appearance of debris-rich basal ice alongside the lower glacier margins due to the general glacier recession poses a further cause of local darkening \citep{Hubbard1995, Hubbard2009}. Along the central area of the glacier tongue, particularly in the vicinity of medial moraines (e.g. in the case of Gornergletscher, Figure \ref{fig:7}), a strongly negative albedo trend indicates an expanding medial moraine, changing the local area from clean to (partly) debris-covered ice. In contrast, we also find significant positive albedo trends for some locations on the glacier tongues (see Figure \ref{fig:7}). These might be explained by the effect of glacier flow changing the position of the medial moraine, hence leading to a transition from debris-covered to clean ice with a higher albedo for certain grid cells. Lateral shifts of the position of medial moraines are possible for retreating glaciers \citep{Anderson2000}.

The investigation of the lithology surrounding the 39 individual glaciers and their overall albedo trend observed for the study period (Table \ref{tab:1}) revealed that glaciers predominantly surrounded by

less abrasive rocks (calcareous phyllites, limestones and marly shales, CERCHAR Abrasivity Index (CAI) 0--2 after \cite{Kasling2010}) exhibited a stronger negative albedo change of $-\$0.05$ per decade compared to glaciers that are located in an area of very to extremely abrasive rocks ($-\$0.03$ albedo change per decade; amphibolites, basic rocks, gneiss, granites, mica shists and syenites, CAI 2--6 after \cite{Kasling2010}).

```
\begin{figure}[h]
```

```
%\includegraphics[width=8.3cm]{figures/NEW/Trend_Signi_50_ge95_plot_new_samescales_ALETSC  
H_NEW2-01}
```

```
\includegraphics[width=8.3cm]{figures/NEW/Figure_7}
```

```
\caption{(a) Close-up of bare-ice albedo trends per decade significant at the 95\% confidence level or  
higher for the tongue of Aletsch, and (b) time-series of bare-ice albedo between 1999 and 2016 for  
ten randomly selected points on the terminus (crosses in (a)) including a linear fit (dashed purple,  $r =$   
 $-\$0.5$ .)}
```

```
\label{fig:7}
```

```
\end{figure}
```

```
\section{Discussion}
```

```
\subsection{Temporal evolution of shortwave broadband albedo}
```

Throughout the study period of 17 years, the spatial pattern of bare-ice albedo remained relatively stable for the 39 glaciers. However, the extent of the bare-ice area exhibits a strong interannual variability (Table \ref{tab:2}). This is mainly determined by local, temporary meteorological conditions varying strongly from year to year. The meteorological conditions prior to the acquisition dates are crucial as they considerably alter the surface characteristics and thus the observed broadband shortwave albedo. Moreover, a prolonged ablation period has a strong impact on surface properties such as surface roughness and, hence, also impacts on glacier surface albedo \cite{Cathles2011, Rippin2015, Rossini2018}. On smaller spatial and temporal scales, variations in glacier surface albedo are further evoked by meltwater redistribution of impurities \cite{Hodson2007, Irvine-Fynn2012}.

However, these complex surface-atmosphere interactions are still rather poorly constrained, in particular the temporal dimension, and further research in this area is needed. Nevertheless, as this study focused on end-of-summer (August and September) scenes only, the relative variations between the individual years is comparable and robust.

In general, relatively low bare-ice albedo values were detected for all glaciers and over the entire study period. It is therefore conceivable that a darkening process occurred before the beginning of our observation period in 1999. However, unfortunately there is no data to investigate this hypothesis. The general conclusions of this study are thus valid for the investigated period, but do not exclude a possible darkening over a longer time span.

\subsection{Spatial scales of trends}

A clear distinction between regional/glacier-wide bare-ice and local albedo changes is necessary if temporal trends are investigated. A negative trend in glacier-wide albedo (i.e. including both the ablation and the accumulation area) does not necessarily indicate a darkening of the glacier surface but rather a shift in snowline, or in other words, an enlargement of the bare-ice area relative to the total glacier surface. This effect is particularly pronounced in times of rising air temperatures and prolonged ablation periods. In contrast, a negative trend in bare-ice albedo can be an indicator of a darkening phenomenon due to an increased abundance of light-absorbing impurities (mineral dust, organic matter, algae, soot, etc.). Similarly, a lack of trends in bare-ice albedo change at the regional scale does not necessarily exclude the presence of significant trends at the local scale for individual grid cells.

In the frame of this study, we were unable to detect a spatially wide-spread, regional trend in bare-ice glacier albedo **at a significant confidence level**. However, for certain regions of the glaciers, such as the lowermost glacier tongues or along the lower margins, significant negative trends were found. Hence, a clear darkening was observed at the local scale for a limited number of grid cells rather than for entire ablation areas. These findings are in agreement with published literature, but also show that findings of previous studies conducted at the local scale cannot be generalized for an entire glacier or the regional scale. For example, \citet{Oerlemans2009} observed a strongly negative albedo trend at a fixed location close to the terminus of Vadret da Morteratsch, Switzerland, based on weather station data. They found an albedo reduction of 0.17, from 0.32 to 0.15, between 1996 and 2006. This trend is substantially higher than those detected in the present study over the period 1999 to 2016 (see also Table \ref{tab:3}). Other studies investigated glacier-wide albedo trends and found negative albedo trends of around 0.1 over the period 2000 to 2013 for Mittivakkat Gletscher, Greenland \citet{Mernild2015} or up to 0.06 during the period 2000 to 2011 for nine glaciers in western China \citet{Wang2014}. However, the differing study periods, the varying observation scales and the impact of local characteristics on albedo changes make a direct comparison of albedo trends susceptible to misinterpretations.

\subsection{Possible causes and dependencies of bare-ice darkening }

In contrast to the quasi-continuous measurement setup of an automatic weather station, which is however only representative for a limited spatial extent \citet{Ryan2017a}, airborne and spaceborne remote sensing datasets only represent a snap-shot in time. Hence, the temporal variability is only included to a certain degree and thus provokes a snap-shot uncertainty in surface albedo for evolution analyses. The meteorological conditions prior to the acquisition of the remote sensing

imagery are highly important for the snap-shot uncertainty \citep{Fugazza2016}. \cite{Naegeli2017} highlighted this fact by cross-comparing albedo products from three different sensors with acquisition times within one week. If glacier-wide albedo is compared, a dataset acquired later in the ablation season is expected to show a larger bare-ice area characterised by low albedo values compared to a dataset acquired at the beginning of the melting period. However, this is only true, if meteorological characteristics between the individual acquisition dates are relatively constant. Snowfall or heavy rainfall events might significantly alter the ice surface conditions and the associated albedo values. While fresh snow increases the albedo strongly \citep[e.g.][]{Brock2004} and decreases the extent of the bare-ice area \citep{Naegeli2017}, rain can have a two-sided effect. A heavy precipitation event can lead to a short-term (between 1 to 4 days \citep{Azzoni2016}) increase in albedo due to decreasing surface roughness and/or wash-out of fine debris present on the ice surface (between 5 to 20\% according to \cite{Brock2004} and \cite{Azzoni2016}), whereas light rainfall can cause the presence of a thin waterfilm on the glacier ice surface that absorbs radiation much stronger than the underlying ice and thus result in a decreased albedo. Similarly, a long-lasting phase with high air temperatures or intense shortwave radiation input during mid-day can lead to a permanent or temporary waterfilm on the ice surface that reduces reflectivity and thus shortwave broadband albedo considerably \citep{Cutler1996, Jonsell2003, Paul2005}. Moreover, a remaining thin snow cover might cause slightly increased albedo values in the ablation area (still being in the typical range of glacier ice) that is difficult to be recognized with remote sensing data sets only \citep{Naegeli2017}. Besides these more direct linkages between meteorological conditions and the presence of impurities on the glacier surface, there are many indirect and still rather poorly studied relations. The evolution of the uppermost ice layer, often referred to as weathering crust, is strongly modulated by the local meteorological conditions throughout the ablation period. Surface properties such as microtopography or grain/crystal size are thus changing strongly over time and with them the basic conditions of the bare-ice surface to hold light absorbing impurities and/or facilitate an environment for organisms living in and on the ice surface in cryoconite holes \citep{Irvine-Fynn2011, Cook2016, Vincent2018}. Again, the available data sets are thus only representing a snap-shot of the ice surfaces and all its components \citep{Hodson2007}.

Apart from the meteorological conditions that strongly influence bare-ice surfaces, the surrounding lithology of a glacier determines (at least partially) the availability of fine debris material that can be transported by wind and water, and be deposited on the glacier ice, reducing its albedo considerably \citep{DiMauro2015, DiMauro2017, Azzoni2016}. Thus, easily erodible rock-types provide more loose material that might be transported by wind and water on to the glacier surface and, hence, impact the bare-ice albedo. This is supported by our analysis of the surrounding lithology and the albedo change of each individual glacier. However, no relation between the albedo of the surrounding geology and the magnitude of the ice albedo change was evident.

~~Apart from the meteorological conditions that strongly influence bare-ice surfaces, the surrounding lithology of a glacier determines (at least partially) the availability of fine debris material that can be transported by wind and water, and be deposited on the glacier ice, reducing its albedo considerably \citep{DiMauro2015, DiMauro2017, Azzoni2016}. Thus, easily erodible rock-types provide more loose material that might be transported by wind and water on to the glacier surface and hence impact the bare-ice albedo. No relation between the albedo of the surrounding geology and the magnitude of the ice albedo change was evident however.~~ These findings indicate the importance of the surrounding rocks as possible debris input source on a glacier, in particular as lateral moraines tend to become steeper and more instable due to general glacier recession in times of global atmospheric warming \citep{Fischer2013}, as well as their influence on the energy balance of the

nearby glacier ice and snow surfaces. While some glaciers are surrounded by large lateral moraines that provide a great source of debris that can be transported on to the glacier, others are partly covered by wide medial moraines. The dynamics of these medial moraines due to the general glacier dynamics are poorly studied. However, in the context of this study it is important to note that lateral shifts and growth and/or loss in volume of medial moraines might strongly impact the albedo evolution of some parts of the glaciers. Areas covered by thick debris were excluded from all analyses, but some mixed grid cells alongside medial moraines might still impact the results locally.

Thus, the occurrence of grid cells with positive albedo changes is not surprising, but hard to explicitly link to one specific cause such as the dynamics of medial moraines. The latter might favour local positive albedo changes over time. Localized microtopographic effects, i.e. changes in slope and aspect or modulations in the surface crust (e.g. growth of larger, brighter ice crystals) and the development of cryoconite holes (in contrast to a thin dispersed debris layer) can also strongly impact the evolution of bare-ice albedo.

The discussion of these uncertainties and dependencies, highlights only parts of the complex spatio-temporal evolution of glacier surface albedo. While some influential factors mediating bare-ice albedo are obvious but challenging to quantify (e.g. meteorological conditions prior to the acquisition of data, micro-topography of the surface, etc.) others despite being quantifiable, are more ambiguous (glacier geometry, surface slope and aspect, surrounding lithology, etc.). Based on the presented results we therefore emphasize the need for further investigations of temporal and spatial dependencies of bare-ice albedo changes regarding various meteorological or geomorphological conditions and their interactions.

%\subsubsection{HEADING}

%TEXT

\conclusions %% \conclusions[modified heading if necessary]

Based on 15 Landsat scenes over a 17-year study period, we assessed the spatio-temporal evolution of bare-ice glacier surface albedo for 39 glaciers in the western and southern Swiss Alps. Our results indicate that the considered spatial scale (local versus regional) is crucial for the investigation of albedo trends and the detection of a potential darkening effect that is often referred to in recent literature \citep{Takeuchi2001a, Oerlemans2009, Dumont2014, Wang2014, Mernild2015, Tedesco2016}. While we did not find a darkening of bare-ice glacier areas at the regional scale or averaged for the ablation areas of individual glaciers, significant albedo trends (95\% confidence level or higher) were, however, revealed at the local scale. These individual grid cells or small areas were mainly located at the glacier termini or along the lower glacier margins in case of negative albedo trends (84\% of all significant trends), and along the central flowline further up-glacier in case of positive albedo trends (16\%).

The presented study is subject to various uncertainties stemming from the input data itself, its processing and availability, the albedo retrieval approach or environmental factors. However, unfortunately most of them are hard to numeralise. Nevertheless, our uncertainty assessment revealed highly similar trend patterns, thus indicating the robustness of the inferred albedo trends. We would like to emphasize the importance of the snap-shot uncertainty --- limited availability of end-of-summer scenes demand recognition. Specifically, the meteorological conditions preceding the acquisition of the satellite data can influence bare-ice albedo, e.g. summer snow fall events, and so should be taken into account.

Although, only snap-shots of glacier surface albedo are available, the almost two-decade long time-series indicate significant trends for about 13.5 km² (corresponding to about 12% of the average end-of-summer bare-ice surface in the study area) at the local scale. Thereof almost 8 km² exhibit clear negative trends of ≤ -0.03 per decade. In contrast, only about 2 km² of all grid cells with significant albedo trends show positive ($\geq +0.03$ per decade) and about 4 km² show weak changes in bare-ice albedo (> -0.03 and $< +0.03$ per decade). For the areas with negative albedo trends over the last two decades, the ice-albedo feedback enhanced melt rates which are expected to be enforced in the near future. Even though the darkening of glacier ice has been found to occur over only a limited area of the investigated glaciers, the projected enlargement of bare-ice areas characterised by low albedo coupled with the predicted prolongation of the melt season will most likely strongly impact on the glacier surface energy balance and substantially enhance glacier mass loss.

Based on 19 Landsat scenes over a 17 year study period, we assessed the spatio-temporal evolution of bare-ice glacier surface albedo for 39 glaciers in the western and southern Swiss Alps. Our results indicate that the spatial scale is crucial for the investigation of albedo trends and the detection of a potential darkening effect that is often referred to in recent literature \citep{Takeuchi2001a, Oerlemans2009, Dumont2014, Wang2014, Mernild2015, Tedesco2016}. While we did not find a darkening of bare-ice glacier areas at the regional scale or averaged for the ablation areas of individual glaciers, significant negative albedo trends were revealed at the local scale. These individual grid cells or small areas were mainly located at the glacier termini or along the lower glacier margins.

The presented study is subject to various uncertainties stemming from the input data itself, its processing and availability or the albedo retrieval approach. However, unfortunately most of them are hard to numeralise. Nevertheless, our uncertainty assessment revealed highly similar trend patterns and thus indicated the robustness of the obtained albedo trends. We like to emphasize the importance of the snap-shot uncertainty --- limited numbers of end-of-summer scenes demand recognition. Specifically, the meteorological conditions preceding the acquisition of the satellite data can influence albedo, e.g. summer snow fall events, and so should be taken into account.

Although, only snap-shots of glacier surface albedo are available, the almost two-decade long time-series indicate a highly significant darkening trend for about 10% of the ablation areas which typically ranges from about -0.05 to -0.03 per decade. For these areas, the positive ice-albedo feedback enhanced melt rates and is expected to be enforced in the near future. Even though the darkening of glacier ice has been found to occur over only a limited area of the investigated glaciers, the projected enlargement of bare-ice areas characterised by low albedo coupled with the predicted

~~prolongation of the melt season will most likely strongly impact on the glacier surface energy balance and substantially enhance ice mass loss.~~

%% The following commands are for the statements about the availability of data sets and/or software code corresponding to the manuscript.

%% It is strongly recommended to make use of these sections in case data sets and/or software code have been part of your research the article is based on.

%\codeavailability{TEXT} %% use this section when having only software code available

%

%

%\dataavailability{TEXT} %% use this section when having only data sets available

%

%

%\codedataavailability{TEXT} %% use this section when having data sets and software code available

%\appendix

%\section{} %% Appendix A

%

%\subsection{} %% Appendix A1, A2, etc.

%

%

%\noappendix %% use this to mark the end of the appendix section

%% Regarding figures and tables in appendices, the following two options are possible depending on your general handling of figures and tables in the manuscript environment:

%% Option 1: If you sorted all figures and tables into the sections of the text, please also sort the appendix figures and appendix tables into the respective appendix sections.

%% They will be correctly named automatically.

%% Option 2: If you put all figures after the reference list, please insert appendix tables and figures after the normal tables and figures.

%% To rename them correctly to A1, A2, etc., please add the following commands in front of them:

%\appendixfigures %% needs to be added in front of appendix figures

%

%\appendixtables %% needs to be added in front of appendix tables

%% Please add \clearpage between each table and/or figure. Further guidelines on figures and tables can be found below.

%

%\authorcontribution{TEXT} %% optional section

%

%\competinginterests{TEXT} %% this section is mandatory even if you declare that no competing interests are present

%

%\disclaimer{TEXT} %% optional section

\begin{acknowledgements}

This study is funded by a grant of the Swiss University Conference and ETH board in frame of the KIP-5 project Swiss Earth Observatory Network (SEON). KN was further supported by an Early Postdoc.Mobility fellowship of the Swiss National Science Foundation (SNSF, grant P2FRP2_174888). Landsat Surface Reflectance products were provided by the courtesy of the U.S. Geological Survey Earth Resources Observation and Science Center. The digital elevation model was obtained from the Federal Office of Topography swisstopo. We thank T. Irvine-Fynn for his constructive comments on the manuscript. Two anonymous reviewers are acknowledged for their constructive comments.

\end{acknowledgements}