The role of debris cover in the evolution of Zmuttgletscher, Switzerland, since the end of the Little Ice Age

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Reply to reviewer's comments

General reply

First of all, we thank both reviewers for thoroughly reading through the manuscript and for all the helpful critique, ideas, and suggestions. We greatly appreciate the valuable comments and the promptness of the feedback.

We acknowledge the view of the referees highlighting the long-term evolution aspect, the general relevance, as well as the extensive and unique set of data and analysis.

They also came up with critical comments and major drawbacks, which mainly referred to the issue of losing the focus on the main message in the number of different analysis and the overall length of the manuscript. We are thankful for these valuable comments and think they will considerably improve the manuscript.

Here we reply to the major concerns raised by the reviewers and present our ideas for revisions and amendments. The mainly encompass the removal of parts of the analysis, a shortening and streamlining of the discussion, the removal of figures, parts of figures, or figures being shifted to the supplements, and the combination of data presented in figures.

The majority of the specific/minor comments refer to language or detailed content or are specific examples of the major concerns. All these corrections will be addressed in the revised manuscript.

We would greatly appreciate the view of the editor on the suggested revisions before our submission of the revised manuscript.

Reply to major concerns

R2: 'The title is a tad misleading'.

We agree with the concern of R2 that the title is not perfectly appropriate for the focus of the study. To better reflect the main content of the manuscript we chose to focus the title on the glacier evolution rather than on debris cover and adjusted the title to:

'Unravelling the evolution of Zmuttgletscher and its debris cover since the end of the Little Ice Age'

R1 & R2: 'Text as well as figures are too long and partly repetitive. It is sometimes confusing to follow the story due to the large number of analysis and results'.

We acknowledge the fact that the manuscript is rather long in places and that the presentation of 17 figures significantly contributes to this length. We agree that the main messages of the manuscript

got somewhat `blurred´ by the shear amount of data and analysis presented. We also agree that there would be enough information for two stories but the main point of the study is the longer-term glacier evolution and the interaction and feedback between the different variables. We therefore strongly think we should not slice this paper as separating the results would not allow to bring these results together and investigate their inter-relationships (dynamic feedbacks).

Overall, we therefore plan to make the text more concise, move/remove seven figures/parts of figures, present some of the content in different format and even remove some smaller analysis. Specific details of the suggested changes are listed below:

- Remove the generation of a moraine-based DTM for the end of the LIA (part of chapter 3.5) as it is not used for further analysis.
- Remove the elevation change of different debris thickness classes (chapters 3.6.2 and 4.4.3). The message of this analysis is the insulation effect of the debris cover, which is already contained in the analysis of ablation stakes.
- Shift Figure 3b (the table) to the supplements. It is not essential in the main text (but still useful to refer to in the discussion).
- Remove Figure 6. The debris surface is described in the text and partly presented in Figure 16. The photos will be placed in the supplement.
- Substantially shorten the chapter on tongue-wide elevation changes (chapter 4.4.1) and make it easier to follow.
- Modify the concept and figure (Fig. 10) of the mass balance gradient (chapter 4.4.3). As suggested by R2, we will do the analysis for elevation bins (of 50 m) instead of the glacier sections (see Figure 1) as in this way it will be easier to understand the concept and to present the results. Additionally, we will need neither the section map (Fig. 10b) nor the table (Fig. 10c). We will reduce the number of periods to show from 10 to 7. Also the terminology will be changed from mass balance gradient to elevation change gradient, which is the correct term in this case.

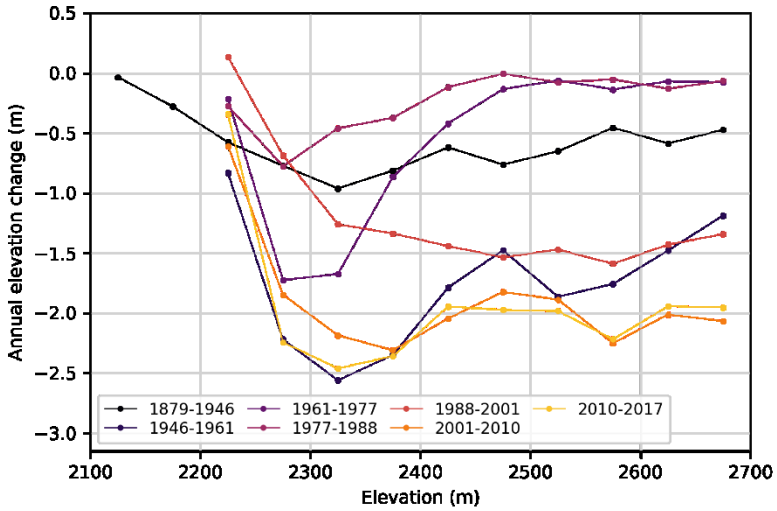

Figure 1: Elevation change of Zmuttgletscher tongue for 50m elevation bins for different periods.

- The temperature time series (Figure 14) will be integrated into Figure 11 as a small, additional subplot sharing the same x-axis. In this way the evolution of the geodetic mass balance can be directly compared to the temperature evolution.
- Figure 13 (flow velocities from feature tracking and radar interferometer) will be moved to the supplements. This figure displays partly redundant information (already contained in Fig.

12) and partly information that is not necessary for the main message (reduction over time, stagnant frontal part).
- Remove Figure 14 (temperature time series, see comment above on integrating it in Fig. 11).
- Strongly reduce the discussion on the comparison to other glaciers outside of the Alps (a reduction of ~1/3 of the text is possible without losing the message, on the contrary). We still think that a basic comparison gives a useful context, e.g. very few studies have compared debris extent changes over time.

Overall, this would result in removal (or shift to supplement) of four figures (Fig.4, Fig.6, Fig.13, Fig.14) and three figure parts (3b, 10b, 10c) as well as the shortening of a significant amount of text.

R1 & R2: 'Text on analysis and results and even the discussion do not always focus on the main messages, making these messages a bit blurry.'

First of all, we will make the main messages stick out clearer in the discussion and conclusion. To make it clear also here, these main messages are:

- Climate is responsible for the net mass balance
- The observed debris increase over time is very strong and unprecedented
- Debris cover provokes spatial and temporal change patterns (reduced length and area change)
- Ice cliffs are persistent as features but do not compensate the debris insulation, thus the larger glacier area is responsible for the comparable mass balance
- Ice dynamics directly influences ice cliff as well as debris cover evolution

We will amend the text to always serve arguments to arrive at these messages in the end. Together with the language comments by the reviewers as well as an additional correction by a native-speaking glaciologist we are confident that the story will be much clearer, thus increasing the impact of the study.

R2: 'Methods are not always reproducible.'

We will further clarify the methods and add additional details. For the technical aspects and detailed analysis of the DTMs (specific comment) we refer to Mölg & Bolch (2017) as they described the method in detail. Also note that this study focuses on the glacier evolution and the links between variables and is not designed as a technical assessment or development of methods.

Specific steps to undertake regarding this concern are:

- Slight changes in text by adding further details of explanation and amendments of the text for clearer language (e.g. for the geodetic mass balance, debris cover mapping, ice cliff influence)
- Refer to further existing studies where references were not sufficient (e.g. in surface feature mapping)
- Remove analysis that are not necessary and thereby reduce the complexity of the text and analysis descriptions (e.g. the moraine-based surface topography)
- Change analysis to a clearer concept (ice cliff influence)
- Clarify our terminology to better distinguish between exposed-ice areas and ice cliffs.

R2: 'Ice emergence and horizontal displacements should be considered when calculating the influence of ice cliffs on total elevation change.'

The objective of this analysis is to understand the potential influence of ice cliffs on elevation change. To do so, we compared area-averaged elevation change with or without ice-cliff and their surrounding areas but could not see substantial differences. Importantly, we do not explicitly compare different time periods. Also, both horizontal displacements and cliff backwasting are inherently accounted for by applying the buffer. Thus, our main conclusions only refer to elevation change per date (not ablation) and are in our view robust and do not require emergence velocities and horizontal displacements. We will adjust the description to make the objective of the analysis and the conclusion drawn from it clear.

R2: '…The elaborate comparisons of Zmutt with other glaciers could be removed/reduced. … Some of it would be suited for a review on the state of Swiss glaciers.'

We do not quite agree with the referee. A major aspect of this paper is the difference/non-difference in evolution/dynamic behaviour between debris-covered and clean-ice glaciers. Thus, we consider it crucial to set the evolution of Zmuttgletscher in context with other clean-ice and debris-covered glaciers in the region (on the basis of simple measures such as length, area, and elevation change patterns).

R2 raised a specific concern regarding the analysis represented by figure 17. This analysis clearly yields that debris-free and debris-covered glaciers can be separated based on elevation change patterns, and that Zmuttgletscher can clearly be grouped to the latter. The y-axis of the figure shows only elevation bins and no absolute numbers because the absolute elevation was normalised for comparison. This is necessary to account for the different elevation ranges of the glaciers. To make this clear we will change the axis caption from 'Elevation class' to 'Normalised elevation class'.

R1: 'The influence of ice cliffs is shown in both a table and a figure.'

We suggest to keep Table 2 in the main text. It shows information that is complementary to the figure, such as ice cliff area and area share per date. However, we will use it more intensely in the discussion and focus on the cliff area reduction as a consequence of increased dynamics. This is an important result to show as it is related to dynamic interactions (see main messages).

R1: 'I suggest placing [section 4.4.3] after you have discussed the changes in surface velocities.' …

We agree and suggest to slightly change the structure of the manuscript: The surface flow velocities will be moved up and newly represent chapter 3.4 instead of 3.8 in the methods, and chapter 4.3 instead of 4.7 in the results. We follow this suggestion by R1 because the flow dynamics is somehow inherent in the surface features and the mass balance and even referred to in the text.

Likewise, the chapter on the elevation change gradient will be moved down to after the mass balance to newly represent chapter 4.6.1 instead of 4.5.3.

R2: ‘To have an accurate curve the melt rates have to be normalized by the clean ice melt rate at the same elevation. Does normalized in this figure mean that you had a stake at the same elevation on a clean part of ice, representatively close to the debris stake, that was used to normalize each point?’

We will change the depicted values from ‘normalised melt’ to ‘melt per day’, since the clean-ice stake used for normalisation is not placed in a comparable climate as the other stakes (which would not be possible). We present the results of the 7-weeks period to proof and roughly quantify the insulation effect of the debris and not to establish an individual ‘Östrem-curve’ for Zmuttgletscher, which we also do not need for our further analysis. We think that our conclusion of melt reduction can be drawn because (i) debris of the observed thickness does substantially reduce ablation, (ii) the ablation rather depends on debris thickness than on elevation (there is zero correlation between elevation and melt, but an R^2 of 0.95 when we apply a logarithmic function to the measurements above 0 cm thickness), (iii) the measurements for two stakes with 5 and 25 cm, respectively, yield almost the same melt rate even though the stakes are located in quite different elevations.

R1: ‘Elevation change vs. debris thickness information is repetitive.’

We do not exactly know what the referee is referring to but we will streamline the figures and remove repetitive content in the results as well as the discussion. Additionally, the analysis of elevation change on different debris thickness classes will be removed as the temporal coverage on debris thickness information is limited.