Review of "The role of debris cover in the evolution of Zmuttgletscher, Switzerland, since the end of the Little Ice Age" by Mölg et al.

The study describes the evolution of Zmuttgletscher from the Little Ice Age (~1850) to present combining DEMs, aerial/satellite imagery, and field work. The study finds that the glacier's evolution is mainly driven by climatic forcing, and that the debris cover impacts how the glacier evolves in response to these forcings. Specifically, the debris cover reduces the rate of length and area changes compared to clean ice glaciers as it causes the glacier to development a low-sloped, stagnant tongue as opposed to simply retreating upglacier. The authors make the distinction clear however that this gently-sloped tongue is caused by a change in the ice flux upglacier as opposed to any differential melting caused by changes in the spatial variability of debris thickness over a long period of time.

I found one of the most impressive elements of this paper to also be the cause of my biggest critique, i.e., the study incorporates a broad range of data/methods (generation of historical DEMs, geodetic mass balance estimates, surface velocity measurements, debris thickness field surveys, ablation stakes, etc.), which provide a great deal of information to evaluate the evolution of this glacier, but also make this paper very long and at times sound repetitive. This is clear in that there are 17 figures in this paper, many of which report the same data in a different format. For example, Figure 17 shows the normalized elevation change, which is similar to Figure 10a (elevation change vs glacier section), which is similar to Figure 9 (spatial map of elevation change). The changes in area, debris-covered area, and length are shown in Figures 3, 4, and 5, yet they are all linked together (and Figure 3 has a table of the values). The influence of ice cliffs is shown in both a table (Table 3) and a figure (Figure 8). Similarly, portions of the text are repetitive, e.g., elevation change vs. debris thickness is shown as the elevation change, the thinning rate, and then as the ratio between the two, so the same values are reported 3 separate times in a row. I encourage the authors to get creative in how they present this data, and think about what data is critical to show in a figure or table, and what can be moved to the supplementary material. If these changes are made, then I think the text will also become more concise, and the conclusions of the study will become more prominent.

Overall though, I think this is an important contribution to the literature and advances our understanding of the evolution of debris-covered glaciers. References to previous studies were very thorough and results were placed in broad context (perhaps too broad in some cases). There were many grammatical errors throughout; however, these grammatical errors are minor revisions. That said, while I believe the methods are rigorous, the amount of data is impressive, and the conclusions are well supported, all of which would justify the manuscript to be accepted, I think it requires fairly significant revisions to reduce the repetitiveness of the figures/tables and text. Therefore, I recommend the manuscript be reconsidered after major revisions.

<u>General Comments</u>

Section 4.4.3 – Given that this is describing the mass balance, i.e., the combination of the surface mass balance and the flux divergence, I would suggest placing it after you have discussed the changes in surface velocities. For example, "the wave of additional mass flux" has no meaning here given that surface velocities have yet to be mentioned.

There are multiple figures and tables that appear to show the same thing. This is repetitive (e.g., Table 3 and Figure 11). I commend the authors for explicitly stating the data such that it can be used by other studies in the future; however, if it is simply taking up space in the manuscript and repeating information that is shown visually, then it should be provided in the supplementary material. Additionally, there are many figures that have tables included within them, which seems unusual (e.g., Figures 3 and 10). The manuscript is already quite long with 17 figures and 3 tables, so this could help to make the study more concise.

Specific Comments
P refers to page
L refers to line number
Italics indicate suggested grammatical changes

P1 L2 – changes *in* debris cover over time

P1 L2 – "changes in debris cover over time, or surface flow velocities" is a bit unclear. Do you mean they are investigating changes in debris cover or surface flow velocities over time? Or is this surface flow velocities meant to be on its own so there are 4 separate items here? Please clarify.

P2 L7-12 – This paragraph is a single sentence. Consider breaking this paragraph down into multiple sentences to make it easier to read. Also, are referring to all the studies that have been conducted on debris-covered glaciers? Or are you referring to the numerical modeling studies?

P2 L18 – increase *in* debris cover. General note as this is the second time, increase "of" typically followed by a number, while increase "in" typically refers to the object/thing. Consider revising this change from "of" to "in" throughout the text.

P2 L22-23 – if you are going to say they are in the center of attention due to their importance, then you should state the reason why they are important. I'm not sure this is necessary though, since the main point is simply that the data is not available to investigate.

P2 L28 – "at the example of" doesn't make sense. Consider "… debris-covered glaciers through the study of Zmuttgletscher in the Swiss Alps."

P4 L4-7 – Remove from the caption of Figure 1.

P4 L10 – Table 1 shows the topographic maps, satellite, and aerial images, so move "(Table 1)" to after the satellite images. You could consider breaking this into two separate blocks of data like "topographical maps, …, and satellite images (Table 1) in addition to various field observations and long-term temperature measurements." To make the distinction that Table 1 is related to these 3 products even more apparent.

P5 L6 – First time DTM abbreviation is used it should be spelled out fully.

P6 L15 – "This resulted in a glacier area information for each data" doesn't make sense. Please clarify. Also, is this different than the first line of this section stating that glacier area was measured since 1859? It appears to be repetitive.

P6 L24 – until 1997, *and* an additional data point…

P6 L32-33 – A bit unclear: were the two historic maps with debris cover symbols manually digitized as well? If so consider, "Debris cover extent for the orthophotos and historic maps that contained a debris cover symbol were manually digitized (Figure 2a and b)."

P6 L33 – … Siegfriend map (1879) *was* verified using two photographs…

P6 L34 – This information *was* valuable …, which *was* the region of the strongest changes. Switching from past tense in first sentence to present tense in this last sentence. Suggest keeping the tenses the same for the paragraph to make it easier to read.

P7 L5 – A bit confusing. First, you should reference Figure 1, since they show where these were provided. Second, what do you mean by "for setting the elevation change observations into context"? Do you mean you were doing this to compare to the elevation change estimates from aerial/satellite imagery? Or were you measuring the surface mass balance to be able to break the elevation change in the aerial/satellite imagery into the surface mass balance and the flux divergence? I assume this will become clearer in the results, but it should be clarified here as well.

P7 L12-14 – A bit unclear as well. Do you mean "Debris thickness was measured via manual excavation along several transects perpendicular to the glacier tongue."? This seems to be the case from the figure and results.

P7 L15-16 – "used to put observations into context" does not provide any information to the reader. What observations were you trying to put into context? What context? Additionally, stations had to be close to what? To each other? To the ablation stakes? Please clarify.

P8 L28 – *which* reaches up to …

P8 L40-41 – consider consolidating the two sentences "Independent of the method, 100 m elevations bins (starting from 2100 m) were used to get a representative value for elevation change calculations in order to reduce the susceptibility of elevation change calculations to outliers due to the incomplete coverage of some areas of the glacier."

P9 L22 – Do you mean, "change in debris thickness may impact the changes in surface elevation"?

P9 L25 – 20,000 m^2? Or 20.0 m^2?

P9 L37 – delete "additionally"

P10 L2 – The interferograms *were*…

P10 L4 – negative velocities *were* considered *to be* noise…

P10 L18 – this *study*.

P10 L11 – The wording is a little awkward. Consider "From close to the end of the LIA (~1850s) to 2017, Zmuttgletscher has retreated by 1907 +/-12 m (12.1 +/- 0.09 m/yr). The maximum rate of retreat peaked between 1961 and 1977 at 21.7 +/- 0.04 m/yr."

Figure 3 – is there a reason Figure 3b, which is a table, is listed as a figure? What is the cause of the difference between Zmuttgletscher (this study) and GLAMOS 2018? They appear to be substantially different, albeit showing similar trends.

P10 L25 – "was with" does not make sense. "Until 2013" also sounds awkward. Consider something along the lines of "At the end of the LIA 2.8 +/- 0.2km^2 of Zmuttgletscher was debris-covered, which has increased to > 5 km^2 in 2013. During this time, the total glacier area has …"

P11 L4 – "all parts of the glacier" is fairly vague, perhaps in "all tributaries"?

P11 L5 – the *extent of* debris has expanded …

P11 L5 – you refer to the debris-covered extent getting closer to Dent d'Herens, but isn't SBG (which is included in since you state "both" at the beginning of the sentence) getting equally as close to the headwalls of Dent Blanche?

P11 L4-10 – I think it's important to be specific when referring to properties of the debris cover. In this paragraph you are discussing the extent of debris cover, so this should be made clear. The "debris cover grew strongly" could refer to the thickness of debris cover or the extent of debris cover. Since both are discussed in this paper, it's important to always distinguish between the two.

P11 L8-10 – This sentence is very confusing. What does "after the exposure of the rock wall" mean? Please clarify.

P11 L18-20: difficult to read. Consider "In such cases, the typical base layer consists of fine-grained material (sand and even silt) lying directly on the ice, which is overlain by a few centimeters of pebbles. Above this typical base layer, there is no specific sorting."

P11 L12 – You state these are over several periods, but the caption states these measurements are from 05/07 – 22/08 2017, which is a single period in time. Please clarify.

P12 L20 – what does "number" refer to? The number of ice cliffs?

P12 L21 – "lower parts of the glacier tongue until the terminus" is redundant.

P13 L2 – delete “only very”

P13 L10 – delete “only”

Figure 8 – there appears to be a line along the top of the figure?

P13 L19-20 – A bit redundant saying in some periods, then stating the period, and then doing the same later. Additionally, I’m not sure “strong” is the best choice of words to describe elevation change. It’d be better to be specific: “most negative” or the “surface lowering was greatest”, something along those lines. For example, “The elevation change was most negative near the terminus between 1946-1977. Since 2001 though, the elevation change over the tongue has become more heterogeneous.”

P13 L22 – “Between 2879 and 1946, the *average* surface elevation change was -0.63 m/yr and most pronounced at the terminus. *Surface lowering increased* to …”. Note: This is a bit repetitive of L19-20.

P13 L26 – the tongue’s *average* surface elevation *change* was almost balanced at -0.11 m/yr.

P14 L1 – use either “surface lowering” or “surface elevation change”. Previously, you’ve used “surface elevation change”, so be consistent. This is especially true because you’re using positive and negative values for elevation change, so surface lowering with a positive value makes this difficult to read.

P14 L3 – *slight*

P16 L4 – do you mean the ratio of thinning for thick debris compared to bare ice?

P16 L14 – please clarify what “no clear hint of an increasing balancing effect” means? There is no clear trend in the mass balance gradient flattening towards the terminus?

P16 L24 – again, this appears to be a ratio. Ratios are not very intuitive. For example, if both regions were positive, they could still have the same ratio. Why are you reporting and discussing the ratio and changes in ratios? Is it providing information about how “connected” the upper and lower portions of the glaciers are? Is it used to understanding the dynamical state that the glacier is in? Please add a sentence or two to clarify what the ratio is actually telling us about the glacier.

P16 L26 – *still show*

Section 4.5 – Is this referring to the “glacier-wide” mass balance? If so change the heading.

P17 L1 – showed an *increase in elevation* …

P17 L2 – After 1988, the mass balance *became* more negative again, even *while* the lowest areas on the tongue *had a* stable or positive mass balance.

P17 L4 – When did this negative trend intensify? Rearrange this sentence if it was in 2001.

P18 L4 – add the year that this was done again for reference, so that it is clear in the text. It is obvious this this is an independent measurement, so you can delete "as an independent measurement"

P19 L13 – and *thus have* little impact …

P19 L14 – delete "also"

P19 L31-L36 – this reads as a methods section, i.e., the reason you chose the methods you did as opposed to a discussion section. Consider moving this to the methods, although I leave this choice up to you. The other ones "suitability" of methods seem to discuss other studies, shortcomings, etc., which is why I don't think the other parts of this subsection are out of place.

P19 L39 – "Nevertheless we think…" are you referring to the long-term trend or are you saying that despite potentially underestimating the area, you still think the trend is significant?

P20 L13-5 – "similar behavior", perhaps similar trend? "pointing out" also sounds awkward here. Perhaps "Zmuttgletscher has shown a similar trend indicating that its glacier-wide mass balance has foremost been governed by climatic changes rather than a response to changes in debris cover."

P20 L31 – Be careful with "higher" elevation change rate as this could imply a positive elevation change, but here it seems to be referring to being more negative? Please clarify.

P21 L3-5 – A bit confused here as to how the debris-covered area was stable if the upper margin of the zone was moved down-glaciers? Are you suggesting that the glacier advanced and that's what kept the debris-covered area constant? Otherwise, if the upper margin, which I assume is referring to the debris/ice extent interface moved downglacier, how could the debris extent remain constant?

P21 L8-10 – "again" typically does not follow the verb, e.g., became more negative again, or the debris-covered area strongly increased again.

P21 L23 – and *also likely* thicker debris

P25 L18 – delete a period

P25 L18-21 – In Section 5.2.1 you state that the magnitude of mass change is governed by changes in climate as opposed to changes in debris cover. However, here you are stating that the different magnitudes in mass balance between Zmuttgletscher compared to glaciers in the Himalaya is likely attributed to the differences in debris cover. While this could play a role in

the differences between the two, how do you know that this difference is not caused by differences in climate forcing?

P26 L6-14 – Can this be consolidated? While it is nice to place the changes in debris-covered area into a regional context, the point gets a bit lost in this long list of every study, region, and change.

P27 L5 – "re-thickening"? It thickened, so why include the "re-"?

P27 L7 – These observations *prove* a …