Response to RC1

Dear Martin Truffer,

Thank you for your comments, which indicated some important points which we address below. First we respond to the two major issues raised, afterwards the detailed comments are addressed individually. We hope that you agree with the changes we propose based on the suggestions.

1) In the paper erosion from several sources (headwall, lateral, basal) is treated similarly and independently. But this is not really the case. All sediment in lateral moraine has originated from headwall erosion, transported by the glacier and is now remobilized. It's not primary erosion. So it doesn't really make sense to compare rates, these are two different things. It would improve the paper greatly if this distinction was clearly made in the Introduction as well as the Discussion. This would also outline some of the issues that need to be addressed in coupled debris/ice flow models, namely sediment deposition and re-activation.

We agree that this is an important distinction, which should be made clear. Therefore this direct comparison is removed from the discussion and we have specifically referred to it as a 'remobilization' therein (P2 (L16)), pointed out the lack of this process in relevant models (P12 (L8-11)) and have also reformulated in the Introduction (P2 (L29)). We have kept the comparison to rates found in (Watanabe et al., 1998) in the introduction, as their rates also include remobilized lateral moraine erosion and that is probably the reason they found much higher elevation change rates as generally observed on rock walls. For the rates found in other studies, the lateral moraine has the same characteristics as those observed in this paper, though not anymore bordered by a glacier. Therefore we think that these rates are comparable.

2) The derived rates are based on the assumption that none of the elevation changes on the moraine are due to melting ice. This seems like a big assumption and it is only mentioned in one sentence and no potential errors due to this assumption are discussed.

As noted by several reviewers, we have failed to address the presence of an ice-core within the moraine in our original manuscript. While there is no actual evidence of an ice-core, the formation process of lateral moraines suggests they are likely present and field evidence from other debris-covered glaciers in HMA exists (e.g. (Hambrey et al., 2009)). However at least for the case of Lirung and other debris-covered tongues in the Langtang catchment, field observations suggests that these ice cores are covered in a very thick mantle of debris, very likely larger than 2 m, contrary to more thinly covered moraines elsewhere (e.g. (Lukas et al., 2005)). During many walks in multiple field seasons on the glacier tongue, including the flanks, nowhere along or within 50 m of the foot of the moraine have we observed any ice, neither as ice cliffs nor as ice covered under thin moraine material. Furthermore, none of the debris thickness measurements ever taken in the field close to the moraine on the glacier surface where thinner than 50 cm (see e.g. (Ragettli et al., 2015)), and since the debris progressively thickens (see e.g. (Nicholson et al., 2018) towards the moraine it is likely much thicker there (Nicholson et al., 2018). We estimate the maximum downwasting rate under the moraine by quantifying the elevation change in a relative flat zone of 20 meter wide close to the moraine. We removed sections which showed clear depositional features, to limit the noise caused by debris deposition. The maximum downwasting rate is approximately 0.6 m yr^{-1}. The top melt of buried ice declines exponentially with increasing debris-cover thickness (Östrem, 1959; Schomacker, 2008), but as debris thickness on the glacier is generally > 50 cm (McCarthy et al., 2017; Ragettli et al., 2015), the decline of melt rates underneath the moraine due to the additional debris thickness is relatively small.

Assuming a maximum downwasting rate of 0.6 m yr^{-1} due to the ice core, the remaining elevation change due to mass transport in this part is +0.19 m yr^{-1}. This results in a significantly reduced rate of material reaching the glacier surface and hence our interpretations of the results. As a consequence, we removed the explanation on page 10 (line 20-27) as suggested.

While we acknowledge that further detailed analysis could be carried out to ascertain presence of a potential ice core (i.e. GPR) or to understand the processes in recent decades and centuries, our aim here was to determine the volume of debris that moved onto the glacier surface in recent years using an UAV. We believe that the use of high-resolution DEMs in combination with geomorphological analysis has great potential to understand the dynamics of debris-covered glacier tongues.

Detailed comments:
p.1, l.5: I don't know if this is standard terminology, but I find the use of 'headwall' confusing, especially in the abstract, which should be readable without looking at figures. From what I can tell, 'headwall erosion' is basically all primary erosion that is not subglacial. In particular it includes erosion from valley sides, if it does not originate from moraines. To me, headwalls are the mountain sides at cirques at the very top of an accumulation area.

Indeed the term headwall gives a wrong impression, as it is mostly used for steep scarps (or cirques) at the onset of erosion or accumulation area. The term is therefore changed to rockwall throughout the manuscript, which is the general terminology for steep bedrock faces bordering glaciers.

p.1, l.14/15: rewrite sentence or split into two
Changed

p.2, l.1: I'm not a fan of the proliferation of acronyms. You only use debris-covered glaciers two or three times, just write it out.
Changed throughout the manuscript

p.2, l.1: The numbers are not clear: Is 11% the area that is debris covered, or are 11% of the glaciers debris-covered glaciers? Also, you must mean 'ice area' not 'ice mass'
We meant that that 11% of all glacier areas are debris-covered. Secondly, we do indeed refer to ice mass (Kraaijenbrink et al., 2017; p.2, l.2/3). This has been modified.

p.2, l.15-: See my overall comment 1.
We have added the distinction between direct and indirect (remobilized) sources of debris.

p.2, l.26: are -> is; vary -> varies
Changed

p.3, l.4/5: Why are you mentioning this here? What is the relevance of englacial vs supraglacial transport?
This was mentioned to indicate that debris is transported over the surface and adds to the debris cover. Sentence changed.

p.3, l.8: larger -> longer
Changed

p.3, l.1-16: see my comment 1.
Rates can indeed not always be compared directly. Important differences in source areas or study sites are now mentioned more clearly.

p.4, l.15/16: It is not clear to me what you're doing here. Is it legitimate to remove outliers, because they might represent 'extreme events'? A large event should not be ignored if it is not just a data artifact? I suppose you have a way of checking this; the imagery should show large events.
It is definitely not legitimate to remove extreme events from the data, and such is also not the goal of the 10-90 percentile range. Our text was misleading in this regard. It may be true that some signal is also removed using this method, but the imagery still shows larger events as rockfall and intense gully erosion, which we managed to retain. We have adapted the text accordingly in P4 (L19-21).

sec. 3.3: When using correlation techniques on debris cover it seems you have to be careful with processes that can generate apparent motion, such as back-wasting of cliffs? The flow field in Fig. 6 looks very odd with vectors pointing across the glacier.
Indeed, processes that cause apparent motion do affect the surface velocities computed by (Kraaijenbrink et al., 2016). However we can account for this problem by choosing the window size of the cross-correlation appropriately and validating the results with orthophotos. As can be seen from Fig. 6, ice cliffs are not present where the vectors point inwards, and no process that generates apparent (but not actual) motion seems to play a role here. The pattern of flow velocity is furthermore recurring in multiple years (Kraaijenbrink, in prep.) and can be explained with flow (Kraaijenbrink et al., 2016). Therefore it is likely that this velocity actually indicates the surface velocity. We updated the caption to further elaborate on the origin of surface velocities.

p.4, l.23/24: Can you be more specific how you capture large events that happen 'within a few minutes' and how this information is used?
Unfortunately our wording here was confusing. Large events, where debris flows or rockfalls travel over multiple window sizes between the two time steps (the maximum window size used is 26.5 m), are not captured as velocity but rather as noise in the algorithm and hence do not influence the velocity fields. While we still capture such events visually and in the DEM differencing, they do not bias our average velocities on the moraines. We have changed the text respectively on P5 (L1-2).

sec 3.6: Isn't debris that falls onto the glacier in the accumulation area and then transported englacially protected from rounding and will thus preserve its angularity?
We distinguish between passive and active glacial transport. Passive transport consists of most englacial transport and material at the glaciers surface, on which no large forces are exerted. Active glacial transport takes place at the glacier bed or within deforming subglacial sediment (while forming the lateral moraine in times of glacial advancement in this case), and does cause the angularity to decrease debris under high pressures (Benn & Ballantyne, 1994). In the case of passive transport, the original angularity of the clasts is approximately maintained (Benn & Ballantyne, 1994). Therefore we assume that material on the glacier, which originated from the rockwalls in the accumulation area (and might afterwards be englacially transported), is more angular than the clasts currently on the moraines. We adapted sec 3.6 to make this distinction more clear.

p.6, l.20: You say most change occurs on the loose part (0.35 m/yr), but this is almost the same rate as the average (0.31 m/yr) mentioned two lines earlier.
The 0.35 m yr^{-1} for the loose part of the moraine was a typo throughout the manuscript. The correct value (0.41 m yr^{-1}) could already be found in Table 3. The remaining difference is caused by differences in area, as the loose area covers 74% of the total moraine area, and the firm part only covers 26%.

p.6, l.21/22: Again, these rates are not comparable. One is a long term denudation rate, lateral moraine erosion cannot proceed at such high values for centuries; the sediment will be exhausted relatively quickly.
That is correct and the comparison is removed from the manuscript.

sec. 4.3: I suggest rewriting the first few sentences, because the same things are presented twice, first as averages and then as ranges. This is confusing.
We combined the presentation of both elevation change values and ranges at the start of section 4.3.

p.8, l.20: What is 'advection of a prominent zone'?
We have adapted the terminology to 'dispersal of the deposited slump sediments', which we hope will make this clear.

p.8, l.24/25: I don't understand this sentence
Changed paragraph in line with next comment.

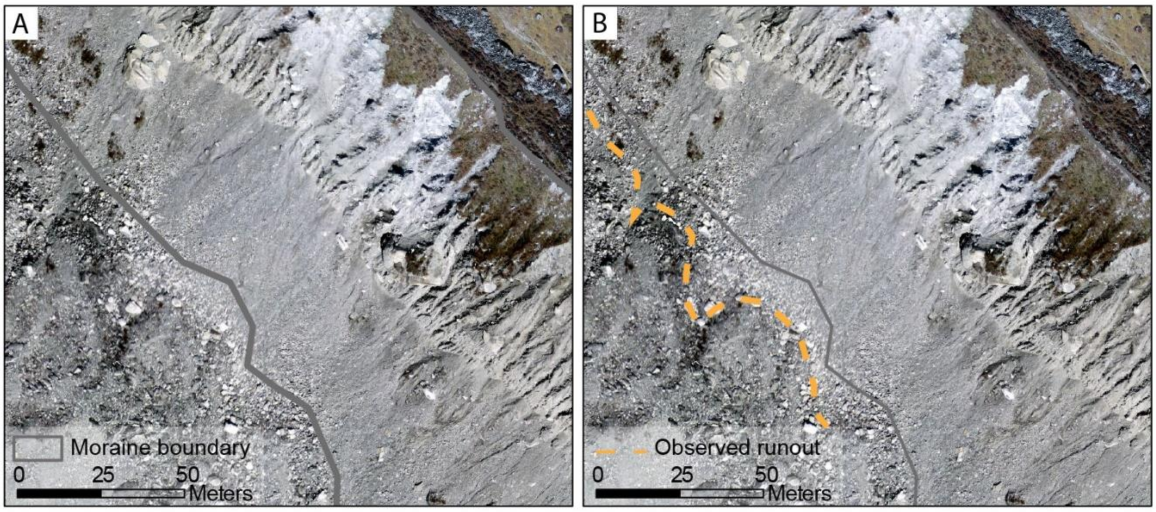
p.8, l.27: '... of this process.' What process? The whole paragraph should be edited for clarity.
Changed

p.8, l.30: Is it legitimate to assume something to be small, just because it's infrequent? For example, individual large landslides might only occur on decadal timescales or longer, but can dominate the sediment budget of a glacier.
We agree that infrequent events can be the main source of sediment on a supraglacial surface, and it is not unlikely that this is also the case for Lirung Glacier, where large mass movement events are observed near the rockwalls. We however argue that the moraine-derived sediment budget is not dependent on infrequent events for three reasons:

- Really large events are not a possibility, as the source area is small. The steep part of the moraine is generally only 30-40 meters wide, with a maximum of 60. With a high gully density, the source area per gully is really small and prevents the occurrence of large flows. Furthermore such events were also not observed while we revisited the site biannually between 2013 and 2018.
- Individual tumbling rocks are observed almost each time step. However, with only 1-2 rocks per half year, the removed volume is in the order of 100 m^3 yr^{-1}. This can be neglected in respect to the total volume of 126000 m^3 yr^{-1}.
- The same goes for 'larger' landslides, which are only observed once in the studied period. Its volume of 2000 m^3 is still small in regard to the total volume. We added our reasoning to the manuscript in P9 (L19-22).

p.9, sec. 4.5: Significant figures! Don't state numbers to sub-meter, which is meaningless in this context.
Changed

p.9, l.6: what is the 'observed runout length'? Is that extracted from imagery?
The maximum observed runout length is indeed manually extracted from imagery, where the active depositional area can often be distinguished from the inactive subglacial debris by differences in roughness and color. For example in the figure below, debris flow runout lobes are recognized and outlined.



p.9, l.26: check sentence for missing word
Word added.

p.9, l.29: why 'through the ice'? Isn't it just being dragged along the sides?
This was indeed misleading and should be 'dragged along the glacier bed'. We have changed this in the text at P10 (L29-30).

p.10, l.7: delete 'being'
Deleted.

p.11, l.1: I would hope that observations are plausible! The question is whether the interpretation of the observations are plausible.
We removed this part of the sentence, and focused on the interpretation.

p.11, l.1: an -> a
Changed

Figure 1: It took a bit of reading and re-reading to understand the difference between process b and c2; this comes back to the issue of what a headwall is
The terminology of both b and c2 has been adapted. Rockwall is now used to indicate steep bedrock faces bordering the glacier, and rockfall is used to refer to both tumbling rocks and rockfall of the steep bedrock faces, as the mass movement process is the same.

Figure 2 would be nice if it could be made bigger
Figure is enlarged a bit. To further explain the study area characteristics, an additional figure with cross-glacier transects is created, and old figure 3 (now 4) is enlarged too.

Figure 6: give a scale for the velocity arrows.
The velocity arrows were non-linearly scaled to best suit visual interpretation. If linearly scaled, most arrows would become small and illegible, most definitely the ones on the moraines. Therefor the legend label is now changed to Surface flow direction, to imply that magnitudes are just indicative.

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