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Interactive comment on “Estimating lateral moraine sediment supply to a debris-covered glacier in the Himalaya” *by* Teun van Woerkom et al.

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Referee Comments Earth Surface Dynamics Discussions Manuscript #: ESURF-2018-63

Title: Estimating lateral moraine sediment supply to a debris-covered glacier in the Himalaya

Authors: Teun van Woerkom, Jakob F. Steiner, Philip D.A. Kraaijenbrink, Evan S. Miles, and Walter W. Immerzeel

General Comments: The authors seek to quantify the amount of erosion occurring

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Discussion paper

on exposed lateral moraines from a Himalayan glacier and the characterize the redistribution of said material onto the modern glacier surface. This particular feature is an important aspect of glacier mass balance, especially in the Himalaya where debris covered glaciers are common. The authors utilize high resolution digital elevation model (DEMs) collected from unmanned aerial vehicles (UAVs) between May 2013 and March 2018 to quantify changes in moraine elevation which are inferred as equal to the amount of sediment transport from the moraines to the adjacent glacier surface. They conclude that lateral moraines are an important source of debris to the tongues of retreating debris covered glaciers. I applaud the authors on a simple, yet elegant, use of high resolution DEMs and clast observations to characterize the evolution of lateral moraines at an individual glacier and in an attempt to determine the contribution of the moraines to glacier debris cover. Overall the text of the manuscript is written clearly and organized in a logical manner, the methods utilized are, in general, well described. However, I do have some outstanding concerns regarding assumptions made by the Authors, DEM differencing, and the significance of the presented data, detailed below.

Specific Comments: âĂć The Authors allude (in the abstract in on pg. 3, ln 2) to the fact that debris input from lateral moraines is more important for retreating glaciers or for glaciers with stagnant tongues. What is not explicitly stated is that contribution from lateral moraines only occurs when the surface of the glacier is below the crest of the lateral moraines; though this is partly common sense, I think that explicitly stating this in the introduction is worthwhile. It may also be pertinent to expand upon the temporal variability with regards to debris input; an advancing glaciers will have a higher proportion of debris sourced from the headwall, while a retreating glacier can accept debris input from lateral moraines. The authors speak to a this later in the discussion, but setting the stage in the introduction may better lead into the later discussion.

âĂć Section 2 states that the moraines are ‘disconnected’ from upper slopes. I take this to mean that the outboard face of the lateral moraines have an opposite aspect as the valley wall (i.e., debris falling from the valley walls will likely not travel over the moraine onto the glacier). Perhaps obvious to persons on the ground observing the glacier system, but explicitly stating this is important for justifying no debris input from valley walls. Also, comparing Fig. 1 to current google earth imagery, it is not clear if the upper part of the mapped moraines are actually disconnected from the valley wall.

âĂć After referring to the potential for ice cored moraines potentially contributing mass as they degrade over time in the introduction, the Authors assume that no melting ice core exists in the moraine (such that all elevation changes are due to sediment transport off the moraines; pg. 3, ln 10). In a seemingly contradictory statement, the authors discuss a '...hillshade with a hummocky appearance is an indicator for sub-debris ice' (pg. 5, ln 4) when discussing the lateral moraines. Ice cored moraines are generally quite commonly associated with debris covered glaciers (Clark et al., 1994), and this catchment is no exception. The authors provide no observations or other evidence to support their assumption that the moraines are not ice cored. Ice cores within moraines are known to persist for thousands of years and can help maintain steeper moraine slopes (Crump et al., 2017), which are present in the Lirung glacier. Visual observations from current Google Earth imagery shows that appears to be a consistent debris cover across most of the glacier and pro-glacial area, which suggests that the glacier very likely could have formed ice cored moraines in the past. Without concrete evidence that the existing lateral moraines are not significantly ice cored, I am hesitate to agree with the assumption that all elevation changes on the moraines are solely due to sediment transport.

âĂć In section 4.1 a vertical error of 0.02 ± 0.33 m y-1 is quoted, citing (Immerzeel et al., 2014). Upon further reading of (Immerzeel et al., 2014), it is difficult to tell, but it appears that the off-glacier area used to compute this error is actually the lateral moraines themselves, which are likely to change in elevation between May and Oct 2013); perhaps I am interpreting this incorrectly, but moraines don't seem like an ideal location to compare the accuracy of DEMs due to their changing elevation. Maybe the vegetated areas are more stable, so are appropriate to use to constrain DEM accuracy at different timesteps? Also the quoted accuracy of the DEMs is only calculated for DEMs produced in May and Oct of 2013; what about the accuracy of DEMs produced up through 2018? Further reading of the more recent Kraaijenbrink et al. (2016) indicates that “The bulk of the vertical errors at the tie points are within 50cm, and 75% are even within ∼25cm.” I am by no means an expert in DEM creation, let alone from high resolution UAV imagery, but if this is the actual uncertainty in elevations between DEMs, then the reported elevations changes in this manuscript (e.g., Table 3) are well within this uncertainty. Therefore, how can you be certain that your extracted measurements are above the vertical uncertainty and noise between your DEMs from different times? Perhaps I am not reading Kraaijenbrink et al. (2016) correctly, but at minimum, it would be appropriate to add more detail regarding the vertical errors associated with your DEMs into this study (in addition to citing Immerzeel et al. (2014) and Kraaijenbrink et al. (2016)), since changes in elevation are the key component of this study. The Authors mask out vegetation areas from the DEMs to ensure that the moraine elevations changes represent real change. I am confused by this. Mass wasting events and sediment transport within vegetated areas aren’t real change? Perhaps I am not interpreting this correctly. The Authors also state that they correct the DEMs for off-glacier and off-moraines elevation changes with the assumption that those landscapes should be stable. Again it is not entirely clear why the DEMs must be corrected for these large changes; aren’t large sediment transport events possible on ‘stable’ landscapes (though less common)?

âĂć Table 3 presents the elevation changes derived from differencing various DEMs over the study period. I am assuming that the mean the 1sigma uncertainty is presented, but this is not explicitly stated in the table (see technical corrections). When plotted, the mean and uncertainties all overlap well within each other’s (see attached Fig. 1). Are these measurements statistically different from each other? Enough to back up the arguments regarding the spatial and temporal patterns presented in the manuscript? It would be nice to see the raw data plotted in a histogram to see the distribution of elevation changes within each different moraine region/time period (e.g., Immerzeel et al. (2014) Fig. 6). This would allow the reader to get a better sense for how the calculated elevation differences vary within a region and a nice accompaniment to Fig. 6.

Technical Corrections: âĂć Please see attached PDF for technical corrections.

Overall Comments: I applaud the authors for tackling a complex problem that is nonetheless very pertinent for understanding the dynamics of debris covered glaciers. Using higher resolution DEMs to investigate many aspects of moraine evolution through space and time is an important task. However, I have a few concerns that I believe should be addressed before this manuscript moves forward towards publication. First, the assumption of no ice-cored moraines is substantial, and one that should be backed-up with field observations or other evidence. Debris covered glaciers are notorious for producing ice cored moraines, and elevation changes triggered by melt-out could be an important component. Also, the large variability of reported elevation change measurements and the overlap between measurements makes delineating significant differences between measurements difficult (see Fig. 1 above). A more detailed treatment of variability in reported elevation changes would greatly benefit the manuscript.

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Please also note the supplement to this comment:
https://www.earth-surf-dynam-discuss.net/esurf-2018-63/esurf-2018-63-SC1-supplement.pdf

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Figure 1: Data from Manuscript Table 3 plotted (dots = μ and error bars = σ).

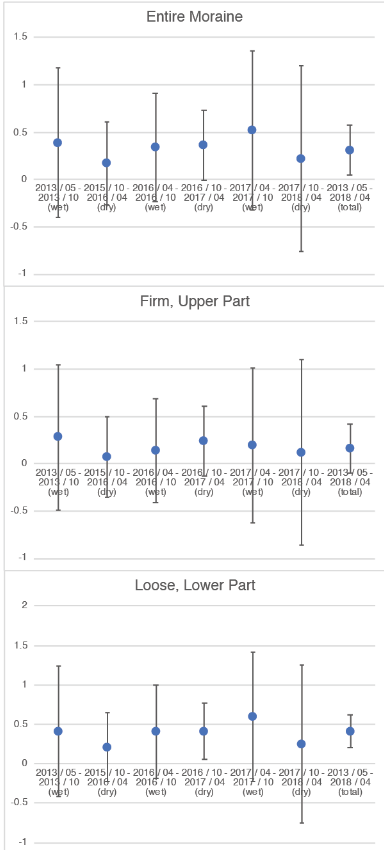

Fig. 1. Plotted Data from Manuscript Table 3

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