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Comment on esurf-2021-18

Samuel McColl (Referee)

Referee comment on "Intensified paraglacial slope failures due to accelerating downwasting of a temperate glacier in Mt. Gongga, southeastern Tibetan Plateau" by Yan Zhong et al., Earth Surf. Dynam. Discuss., <https://doi.org/10.5194/esurf-2021-18-RC1>, 2021

GENERAL COMMENTS

This paper documents changes to the unstable hillslopes adjacent to a retreating glacier using observations from satellite and UAV imagery and field visits. Three main types of hillslope response are documented – rockfall, debris sliding, and gullying – and the authors attempt to explain the occurrence of these with reference to observed changes in the climate and glacier. The paper presents data that is of interest for several reasons; 1) the research context - a relatively understudied type of glacier environment [monsoon temperate, within Southeast Tibet]; 2) several types of hillslope failure mechanisms are documented, adding to the growing knowledge of the complex response of hillslopes to glacier retreat; 3) the authors use these data to make observations on the interactions between hillslope and glacier processes, topical for research on alpine hazards, climate science, and paraglacial geomorphology. While the observations are of interest, the overall purpose and aim of the manuscript is a little unclear from the introduction, without the identification of key research questions tied to the objectives or without a set of hypotheses being developed and then tested. It rather feels like the data was collected for the sake of collecting it in the hope that it might yield some interesting observations (which it does, but the lack of a clear study setup/purpose detracts from the paper's impact). The manuscript falls short of delivering any major discoveries that change the current understanding of landscape response to deglaciation, instead providing a more incremental increase in data documenting the range of responses (which in itself can be useful, but is currently not sufficiently capitalised upon). Other than further confirming the significant role of glacier down-wasting (which is already a very well-established process of hillslope destabilisation), the manuscript is unable to provide much more than speculation on other factors responsible for the hillslope response patterns observed (e.g. long-term strength reduction or frost weathering responsible for the rockfalls observed). On the interactions between the hillslopes and the glacier, these are also rather descriptive without detailed analysis. In my 'specific comments' below I offer some suggestions for how you might address some of these shortcomings and better utilise your (nice) data to give your manuscript more impact. I hope that the specific comments and technical corrections below will be useful in reshaping this manuscript and enhancing its clarity, focus, and overall contribution.

SPECIFIC COMMENTS

- The introduction needs to do a better job of setting up the objectives of this work. For example, what key research gaps or questions (e.g. in paraglacial hillslope response) is the manuscript addressing? How will your 3 objectives stated on L82-87 help to address these? Why is the HLG study site important/useful for addressing these questions? (I note that on L113-117 there is clearly a hazard motivation for the selection of the HLG site, so perhaps this could be presented better in the introduction as one of the justifications for addressing the key research questions and for the selection of the HLG site).
- The classification of the types of hillslope response could be better justified and used consistently throughout the manuscript: e.g., the description of the three types (A, B, C) are described differently in the abstract than in the conclusion (in which they are also labelled differently, as i, ii, iii). On lines 35-40 five main classes/modes of hillslope response are described from the literature, but it is not clear how the three types (Type A, B, C) described in the manuscript relate to these 5 modes. Also note that Mode (5) *paraglacial debris cones and valley fills* seems to describe a product of hillslope erosion, not a type/process/mechanism of hillslope response. Debris cones and valley fills presumably can be produced by a variety of mass movement processes. So there is some inconsistency in the 5 modes presented.
- The term Paraglacial Slope Failures (PSFs) is used as a catch-all for the three main hillslope responses that are documented. However, given that the Type C response seems to be focused on headward gully erosion and said to involve fluvial processes (L411), it casts doubt on the suitability of the term 'Paraglacial Slope Failure' to represent this, as fluvial processes are not traditionally considered to be a slope failure process. Perhaps a better term is needed?
- Related to the previous comment, I feel that the processes involved in the Type C response are somewhat unclear. Does this response type involve mostly debris flow processes (in which case the term PSF may be OK), or is it mostly fluvial erosion (rilling and gullyng)? While I suspect there are not sufficient (temporal) data to confidently identify the processes causing expansion of these gully areas, perhaps there are clues from the deposits they produce (i.e. are the fans below these gullies more typical of fluvial or debris flow process?).
- For each section of the Data and Methods (i.e. sections 3.1, 3.2, 3.3, 3.4) I suggest starting with a brief explanation of the purpose of the method, trying to link back to the objectives where relevant. This will help readers to understand why you are doing each part.
- I would like to see some more explanation of how the three response types were identified, i.e. what key criteria were considered (i.e. elaborating on the comment on L228-230). As I understand it, the key criterion for assessing the presence of a hillslope response was the appearance of bare ground (especially sediment?). I have two potential issues/queries with this:
 - a) not all bare ground exposed by the glacier will be unstable, so how do you differentiate unstable ground from stable ground (e.g. using signs of disturbance, or a slope angle threshold?), and can you quantify the abundance of stable vs unstable ground?
 - b) You state that due to the climate conditions vegetation colonisation is extremely fast in this environment. This presumably means that much of the bare ground exposed in the early part of your study becomes colonised by vegetation by the end of your study,

especially for Type B responses which do not necessarily prevent vegetation from establishing on the main body (i.e. vegetation rafting). Does this pose a challenge for the identification of bare ground through time, and if so how do you get around this or how much does it affect your results?

- L148-149: Please elaborate upon how you calculated the 'mean quality of 0.15 m in XY'. Did you calculate this by withholding a sub-set of your ground control points not used in the georegistration, in order to provide an independent check of georegistration error? It would be preferable to also provide the maximum error or at least a measure of dispersion (e.g. standard deviation), not just the mean. Please explain what you mean by 'successfully occupied positions' or revise this wording to make it clearer what you are referring to.
- The five profile lines A-E and their data (ice surface elevation, thinning rates, flow velocity) provide some interesting data on changes to the glacier, but it is hard to see how these data are actually used to help understand the hillslope response processes. It is unfortunate that these data are not more thoroughly used to explore the relationships in space and time between glacier changes and hillslope changes. Although on L452-454 you state 'our analyses show a temporal and spatial component to PSF development' there is no real attempt to combine the data of Figure 3 with the data of Figures 4-7 in any quantitative way. It might have been worth setting up a hypothesis, for example that the rate of Type B movement will correlate with the rate of ice thinning, or that the magnitude of ice thinning would correlate with the growth in size of Type B and Type C responses, and then quantitatively/systematically test these. Such relationships are only somewhat qualitatively/subjectively commented on in the manuscript. Likewise, why were four (and not some other number of) transverse profiles chosen and what was the rationale for their placement – was the hypothesis that thinning and hillslope response will differ depending on distance up-valley of the terminus, or were there differences in terrain type, geology, or some other environmental variable that were being captured in these profiles?
- The glacier velocity data are interesting in themselves but do not seem to be well utilised or particularly relevant to the objectives. What was the hypothesis that was being explored with this, or why would changes in glacier velocity be expected to cause (or respond to?) hillslope processes? On L430-438 we get a sense that the velocity data is being used to infer that the high flow rates have been responsible for a high erosion rate and steepening of the valley flanks. But this is not supported with any data or further context – there are no data to show that the valley walls are steeper than other glacial valleys with lower flow velocities, and there is no comparison made between the rates of hillslope response in the HLG to other locations to explore whether the rates are unusually high and therefore are correlated with a high flow rate. I suggest that unless there is a good case for retaining the glacier velocity data, then it is removed from the manuscript because currently it adds little insight into the hillslope processes observed.
- There could be more information provided on the rockfalls. At present it seems that only the largest is described in any detail, with the other failures described only in general terms (e.g. L253 'We also observe other major rockfalls...suggesting that numerous smaller scale rock falls have occurred in this locality' or L258 'small magnitude rockfalls occur more frequently' Can you present the data for these events – e.g. a freq/mag histogram or table showing their source elevations, when they occurred, and their magnitude, and a map showing location? Presenting these data may help to tease out relationships between the failure patterns and the factors governing them.
- The role of mass movements for producing supraglacial debris (e.g. L45-43) seems to be a theme introduced and returned to several times in the manuscript, but at present the manuscript makes little contribution to this topic. While rockfalls were observed to deposit sediment onto the glacier (e.g. L260, L448), this manuscript is hardly the first to identify the role of rockfall in producing supraglacial material so this is not a particularly helpful finding. Moreover the actual effect that these few documented

failures have had to glacier ablation is not in anyway quantified in the manuscript, so as it stands the qualitative observation of supraglacial debris accumulation is not particularly insightful. Therefore, I would suggest that either this aspect of the manuscript is removed, to improve the focus of the manuscript, or this aspect is enhanced. Enhancements could be to:

- a) provide more quantitative data on the total areal contributions to supraglacial cover of the rockfalls documented in the manuscript and make comparisons with other studies (i.e. substantiate the statement on L448-450 with data and context).
- b) include a more detailed description of the contributions (or not) of the other two types of hillslope response (B and C). To what extent have these processes also delivered supraglacial material to the glacier during the observation period, and if they have been delivering sediment then to what extent has supraglacial sediment delivery by these types of hillslope process previously been documented in the literature, and are your findings consistent with that?
- c) there is a nice opportunity to discuss sediment delivery to glacier systems more widely than just supraglacial sediment delivery. You pick up on the fact that some of the Type B failures are deforming the glacier (sensu McColl and Davies 2013), which is a nice observation – to what extent are these failures also delivering sediment sub-glacially, similar to what was identified by Cody et al., 2020 in the Fox Valley, or are the slopes at your site not engaging this recently-documented sediment pathway? Further, it appears that some of the Type C processes are providing sub-glacial water supply, and therefore presumably these are also delivering sediment to the sub-glacial environment? If so, exploring to what extent these paraglacial transport pathways (i.e. from recently exposed moraines) have been previously documented in the literature would be a good point of discussion.
- Related to the previous point, on L45 you refer to the role of 'high-frequency, low-magnitude PSFs' in delivering a 'considerable volume' of debris onto glacier surfaces. But what about the low-frequency, high-magnitude events (e.g. large rock avalanches) that are well documented in the literature for their role in dramatically changing glacier ablation? Why do you focus on the small high-frequency events here?
- L265, L270, & L287. Please describe the process(es) by which the Type B features become larger; e.g. is this through glacier downwasting exposing more of the slope, lateral expansion of the failure mass, or headward expansion from retrogressive failure or degradation of the scarp (e.g. from surface erosion processes)?
- The observation of nested processes (e.g. gullies developing within Type B failures) is nice but it would have been great to see an analysis of the temporal evolution of these. For example, in Cody et al., 2020 they describe a temporal evolution in hillslope response, whereby moraines initially begin collapsing through sliding and internal deformation, and then later surficial debris flow processes (i.e. gully forming processes) takeover, and eventually both processes relax as the slope adjusts to its angle of repose. Are you able to see a similar or a different evolution in the slopes you observe? This would make another very nice comparison.
- L272-275: Comparison is drawn between the Type B failure process and the conceptual model of moraine evolution by Eichel et al (2018). However, this comparison is hard to follow. Eichel et al describe a transition from an unstable state dominated by debris flows and gully erosion through to a period of solifluction modification, through to stabilisation. It appears to me that the typical Type B hillslope responses you describe in this manuscript seems to be more dominated by debris sliding than debris flow or gully, and therefore is not a great comparison to stage A of the Eichel model (for the sites they studied) – perhaps your Type C is a better comparison? It would be good therefore, if you could further explain why you make this comparison, and it would be really interesting if you additionally compare the evolution of the moraines at your site to the other two stages of the Eichel model – do they also transition to solifluction and then stabilisation, i.e. the older lateral moraines nearer to the LIA terminus? Perhaps you can identify solifluction features in the imagery data or from your field visits, or perhaps the climate is not suitable for this? If you do find differences then you could

instead suggest that at your site you observe a different evolution pathway to what is found for the European Alps? This would be a nice contrast and provide a rich vein of discussion (in the discussion section) if in fact there are differences that can be observed.

- L300-306: Please elaborate further on what is meant by a 'transition form', and 'landsliding behaviour' and what is different between the two zones referred to.
- The observation that south-facing slopes were generally more unstable than north-facing slopes is a potentially interesting observation, but one that is not robustly analysed. For example, the authors might consider a wider range of (intrinsic and extrinsic) factors explaining this difference, e.g: a) differences in the availability of material (i.e. asymmetrical deposition of glacial drift and moraine construction on either side of the valley), with more sediment on the south-facing slopes; b) asymmetry in morphology (i.e. differences in slope angle). The latter could be easily tested using DEM analysis; the former could possibly be explored through aerial image interpretation?
- Section 5.1. Unfortunately, this section is heavily reliant on speculation, and analysis of only the 2018 rockfall. Analysing the location and timing of a single (and a not particularly spectacular) rockfall in the valley is not sufficient for making meaningful generalisations of the causes of rockfall in the valley. Perhaps this section could be strengthened if more attention was paid to the smaller rockfalls - e. examining patterns in the timing and location of several failures and not just a single failure.
- L389-390: 'instability typically have a slope angle of 25'. Upon what basis is this statement made? Do you systematically measure the slope angles from the DEMs? Are you able to more robustly compare slope angles between the unstable debris-covered slopes and the stable debris-covered slopes to test whether the unstable sites tend to be oversteepened? Perhaps an examination of the slope angle of stabilised moraines closer to the LIA terminus will give some rough indication of the 'long-term' angle of repose of the till making up the moraines in the valley. This could provide a useful test of your hypothesis presented on L457 'we hypothesise that this (moraine collapse) will continue until critical angles of repose are reached which will be followed by vegetation colonization and advanced soil development'.
- L395-402: The role of vegetation colonisation is (reasonably) discounted for stabilising the Type B failures that involve deeper-seated sliding, but what about the role of vegetation colonisation for stabilising other types of erosion process in the valley? Do you see a reduction in say Type C hillslope responses over time? Again, this might make for another comparison/contrast with the Eichel et al (2018) model.
- L400-403: It is a shame that there was not more effort made to understand why all Type B sites appeared to increase in movement rate between 2017-2018. What further analysis could be done to explore this? Did Type C response (i.e. gullyng) also increase? Can the data from Figure 3 be used to analyse this further? Did any slopes downstream of the glacier terminus show any increases in movement or erosion during this time (i.e. helping to rule out glacier thinning as a cause)? Did the upper parts of the slope failures speed up to the same extent as the lower parts (perhaps more suggestive of rainfall as a driver) or did the lower part speed up the most (perhaps suggesting removal of toe support from ice thinning)?
- In terms of key literature, please consider some of the following for examples of seminal or highly relevant work on moraine modification that could be referred to:
 - Curry, A. M., & Ballantyne, C. K. (1999). Paraglacial modification of glacial sediment. *Geografiska Annaler: Series A, Physical Geography*, 81(3), 409-419.
 - Curry, A. M. (2000). Observations on the distribution of paraglacial reworking of glacial drift in western Norway. *Norsk Geografisk Tidsskrift*, 54(4), 139-147.
 - Curry, A. M. (1999). Paraglacial modification of slope form. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 24(13),

1213-1228.

- Ballantyne, C. K., & Benn, D. I. (1994). Paraglacial Slope Adjustment and Resedlmenfation following Recent Glacier Retreat, Fåbergstølsdalen, Norway. *Arctic and Alpine Research*, 26(3), 255-269.
- Curry, A. M., Cleasby, V., & Zukowskyj, P. (2006). Paraglacial response of steep, sedimentâ□□mantled slopes to postâ□□'Little Ice Age'glacier recession in the central Swiss Alps. *Journal of Quaternary Science: Published for the Quaternary Research Association*, 21(3), 211-225.

TECHNICAL CORRECTIONS

L19: the term 'slope slide and collapse' is inconsistent with standard mass movement terminology. Consider revising (e.g. see Hungr et al., 2014 classification)

L37: remove 'and' after '(4)' since this is not the end of the list.

L96: the statement 'stretching to the Little Ice Age (LIA) end-moraine' seems to contradict the later statement on L100 that the 'HLG has retreated more than 2 km since the LIA'. Please reconcile.

L104: do you mean 'proglacial' instead of 'preglacial'?

L113-117: perhaps this hazards rationale could be moved to or restated in the introduction.

L129-130: consider improving clarity of statement 'NDVI can eliminate a part of the effect of hill-shade...' (i.e. explain more clearly).

L132: consider different choice of words: 'less suffered from'

L134: what is meant here by 'partly'?

L137: add 'and' before '19 August...'

L196-198: consider revising sentence 'Field observations indicate...' This is unclear and needs further elaboration.

L240: you describe the slope failure as coming from a 'south-west facing slope' but on L244 refer to a 'steep north-facing slope'. Are these the same failure, and if so, is there a mistake with the latter?

L247-249: it is hardly a surprise that rockfalls are able to reach the glacier and become supraglacial debris. Perhaps this sentence adds little and can be removed?

L259: this sentence 'each with a mean area of 750 m²' reads that all 15 rockfalls had the same area. But I presume 750 m² was the mean area, and that they each had different sizes? Perhaps provide the size range.

L283: what type of 'analysis'?

L329: what is 'an increase in sediment-covered area' referring to? Is this the supraglacial sediment cover?

L409-410: what is meant by 'sediments were transported along the transport'? What is 'with a fast erosion' referring to? 'largest change in area of C1 travels about 150 m...' is unclear. Confusing use the term 'travels'.

L415: consider revising text 'seasonal plus of enhanced or uprush erosion rates'. This is unclear.

L448: 'a large number of debris fell into the glacier surface' From which process? Rockfall, debris sliding, etc?

L486: this is the first mention of 'debris avalanching' so it should not appear in the conclusion for the first time.

Kind regards,

S McColl