Reply to the Comments of Referee #1

We wish to thank referee #1 for the helpful and constructive comments on our manuscript (Manuscript No.: nhess-2021-57). We have revised the manuscript carefully to address the issues. Our item-by-item responses to the comments are provided below.

This is over large parts a sound and thorough study about the interesting unusual slow surge-type motion of a small glacier on the Tibet Plateau. The manuscript is well written. I recommend publication in NHESS after consideration of the following remarks, some of them substantial.

Reply: Thank you very much for you positive comments.

SUBSTANTIAL COMMENTS

A. The glacier velocities need further work and explanation:

i. I recommend very much to extend the velocity measurements to 2021. There seems to be much continued activity during this period (see also below).

Reply: Good suggestion! We have added two cloud-free Planet images acquired on 2020/08/29 and 2021/03/23 to extend the velocity measurements. The figures showing the glacier snout advance velocity and tongue flow velocity have also been updated. Note that the image 2021/03/23 was not used for flow velocity measuring because the glacier tongue was partly covered by snow at the time.

ii. The fact that advance velocities seem larger than surface velocities is puzzling. Your measurement grid is so dense that I don't believe your explanation 2 (L 350 and following) can be right (local underestimation of displacement). I do not understand fully your explanation 1. It could be that the very terminus lowers and slides out. You would have to assess closer if this is able to explain the magnitude of advance observed.

Reply: Sorry for the puzzling explanations on the flow velocities. We have checked the image correlation processing and found that we initially gave wrong flow velocity estimates. We have redone the cross-correlation using MicMac with multiple parameter combinations. We found that we can obtain reasonable flow velocity measurements by specifying a privileged direction for regularization (i.e., the main flow direction) when doing the correlation. We have also verified the velocity estimates by implementing the image cross-correlation using the ImGRAFT software (Messerli & Grinsted, 2015). The renewed correlation results show that the glacier tongue moves at a maximum velocity of about 30 $m \cdot a^{-1}$ in recent years, comparable to the snout advance velocity inferred from visual interpretation. We have updated the results and descriptions for the flow velocity field of KLP-37 in the revised paper.

iii. I checked the Planet images you used for the velocities, and I am little convinced by your results. Over 2009-2012, there are large distortions between the images. How did you correct for them? For the other periods it is very difficult to follow features over 2-4 years as they are changing too much. Visually, I manage to follow features in a good way only over 1-year periods. If I compare (visually) 1-year periods, I can well see that only the lowermost part of the tongue well below the lake is accelerating. You will have to thoroughly redo the velocity measurements, I guess.

Reply: Thanks a lot for the insightful comments and good suggestion. As stated above, we have redone the image correlation processing with Planet images. The cross-correlations have been conducted on image pairs with one-year separation in the revised paper. We have also added the velocity estimate between 2019/08/06-2020/08/29.

B. The authors shortly touch upon permafrost, but not on creeping permafrost landforms. Obu et al. (2019) model mean annual ground temperatures for the glacier tongue area of -4 - -6 deg

Reply: Yes, we inferred that the glacier tongue is located in a permafrost environment. We have checked the permafrost map based on TTOP modeling by Obu et al. (2019), and have found that the permafrost probability value over the KLP-37 glacier region is 1. We have clarified this in the revised manuscript. We indeed did not touch more about creeping permafrost landform in the initial version of the paper. We have added some discussions on whether the landform should be interpreted as an active rock glacier or ice-code moraine, according to your suggestion below (comments #C)

C. The glacier front has a sharp steep front, reminding of rock glaciers. So, the acceleration of the tongue should also be seen in terms of the dynamics ice-cored moraines and rock glaciers. Both are known to be able to show collapse-like behavior. In particular rock glaciers have recently been shown to accelerate and collapse. This aspect needs to be discussed in the paper.

Reply: Thanks for the insightful comments. In the discussion part (Section 5.1), we have explained why the landform in the front of KLP-37 is part of the glacier itself and not a rock glacier or ice-cored moraine.

The KLP-37 glacier tongue differs from a rock glacier both in morphology and kinematic pattern. (1) Rock glaciers are landforms consisting of mixtures of unconsolidated rock debris and ice in an alpine environment. The debris cover on a rock glacier is usually thick (>3 m), and the ice content is lower than 45% (Janke et al., 2015). Compared to the debris-covered glacier, rock glaciers' debris cover is less homogenous and coarser. The field photo in 2016 (Fig. 2c) shown that the debris cover on the KLP-37 glacier tongue was thin and uniform. The exposed clean ice in the photo also indicated rich ice content of the landform. (2) On the surface of the KLP-37 glacier front, we did not observe distinctive ridges and furrows, which are distinctive characteristics of rock glaciers. (3) Rock glaciers typically move downslope at velocities smaller than 10 m·a^{-1} (Delaloye et al., 2010; Kääb et al., 2021), while the flow velocity from our cross-correlation measurement reaches a maximum velocity of ~30 m·a^{-1}.

Ice-cored moraines are ice-marginal landforms that comprise a discrete body of glacier ice buried underneath sediment (Singh et al., 2011). Ice-cored moraines are generally formed by the isolation of a body of glacier ice through the establishment of a sediment/debris cover near the margin, which, if sufficiently thick, shields the ice from melting. The different melting between the protected sediment-covered ice and clean ice up glacier then often results in the sediment-covered ice body cut off from the supply of active pure ice. Therefore, a typical ice-cored moraine should be disconnected from the active glacier ice margin. However, some authors prefer to use the term much more loosely to include moraine-like ridges in supraglacial sediment underlain by ice, irrespective of the fact that the ice s still flowing (active) and continuous underneath the sediment cover (i.e., Lønne & Lyså , 2005; Evans, 2009).

Here we follow the strict definition that ice-cored moraine is a landform that (1) is disconnected from the active glacier ice margin and (2) contains a discrete body of ice that is surrounded by sediment (Singh et al., 2011). Regarding the front of the KLP-37, the long-term advance of the glacier front without cut-off indicates the inner body is connected with the glacier margin. Therefore, we suggest that the landform we investigated is part of the KLP-37 glacier tongue covered by a thin debris layer.

References

Evans, D.J.A.: Controlled moraines: origins, characteristics and palaeoglaciological implications, Quaternary Science Reviews, 28, 183–208, 2009.

Janke, J.R., Bellisario, A.C., and Ferrando, F. A.: Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile, Geomorphology, 241, 98–121, 2015.

Lønne, I., and Lyså, A.: Deglaciation dynamics following the Little Ice Age on Svalbard: implications for shaping of landscapes at high latitudes, Geomorphology, 72, 300–319, 2005.

Singh, V. P., Singh, P., and Haritashya, U. K.: Encyclopedia of snow, ice and glaciers, 2011.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmuller, B., Kholodov, A., Khomutov, A., Kaab, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T. H., Yamkhin, J., and Zou, D. F.: Northern Hemisphere permafrost map based on TTOP modelling for 2000-2016 at 1 km^2 scale, Earth-Sci Rev, 193, 299-316, https://doi.org/10.1016/j.earscirev.2019.04.023, 2019.

Some random relevant papers on rock glacier acceleration and collapse:

Delaloye, R., Lambiel, C., and Gärtner-Roer, I.: Overview of rock glacier kinematics research in the Swiss Alps: Seasonal rhythm, interannual variations and trends over several decades, Geographica Helvetica, 65, 135-145, https://doi.org/10.5194/gh-65-135-2010, 2010.

Kääb, A., Strozzi, T., Bolch, T., Caduff, R., Trefall, H., Stoffel, M., and Kokarev, A.: Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungöy Ala-Too, northern Tien Shan, since the 1950s, Cryosphere, 15, 927-949, https://doi.org/10.5194/tc-15-927-2021, 2021.

Bodin, X., Krysiecki, J.-M., and Iribarren-Anacona, P.: Recent collapse of rock glaciers: two study cases in the Alps and in the Andes, 12th INTERPRAEVENT, Grenoble, 2012, Kofler, C, Mair, V, Gruber, S, et al. When do rock glacier fronts fail? Insights from two case studies in South Tyrol (Italian Alps). Earth Surf. Process. Landforms. 2021; 1– 17. https://doi.org/10.1002/esp.5099

Kääb, A., Frauenfelder, R., and Roer, I.: On the response of rock glacier creep to surface temperature increase, Global Planet Change, 56, 172-187, https://doi.org/10.1016/j.gloplacha.2006.07.005, 2007.

… and many others that are cited in the above.

SPECIFIC COMMENTS

L 105: To suggest that the lower terminus is a sign of an earlier collapse is quite speculative and should not appear in the study site description. In addition, I doubt you can draw this conclusion. The debris-covered lower part of the glacier might be an ice-cored moraine as there are many found in the region. I cannot see how this feature is so different from the other ice-cored moraines in the region that you can suggest it might be from a collapse.

Reply: We have removed the statement in the study site description. We have added some discussions to explain why we interpreted the KLP-37 front as part of the glacier tongue.

L 129: scanned at 7 mm is certainly wrong. 7 micrometers? Please check the USGS pages

Reply: Yes, the KH-9 images were scanned at a resolution of 7 micrometers. We have corrected it in the paper.

Fig. 3 could perhaps go into the Supplement. NHESS readers are less interested in such technical details as they may distract from the hazards aspects. If you agree, move lines 186-193 to the Suppl.

Reply: Good suggestion. We have moved Fig. 3 and the relevant descriptions (i.e., Lines 186-193) to the Supplementary file.

L 196: something wrong with the date 2104/10/18. 2014?

Reply: Thanks for pointing out this type error, and we have corrected it to 2010/12/05.

L 202: could be interesting to add the C-band – X- band differences in the Supplement. Did you apply the 2.82 m correction also on the debris-covered lowest part of the glacier? I doubt the penetration will be 2.8 m through a debris layer.

Reply: We have added a figure showing the elevation difference between the C- and X-band DEMs over the KLP-37 glacier in the Supplementary file. The penetration depth indeed varies with the changes of elevation (see Fig. R1 below). Note the DEM difference values >±10 m were defined as outliers and were removed. Statistics show that the mean elevation differences were about 0.43 m and 2.36 m for regions below and above 5000 m, respectively. We have followed the suggestion of reviewer #2 by choosing a curve fitting to the elevation differences and then applied the correction with the fitted function.

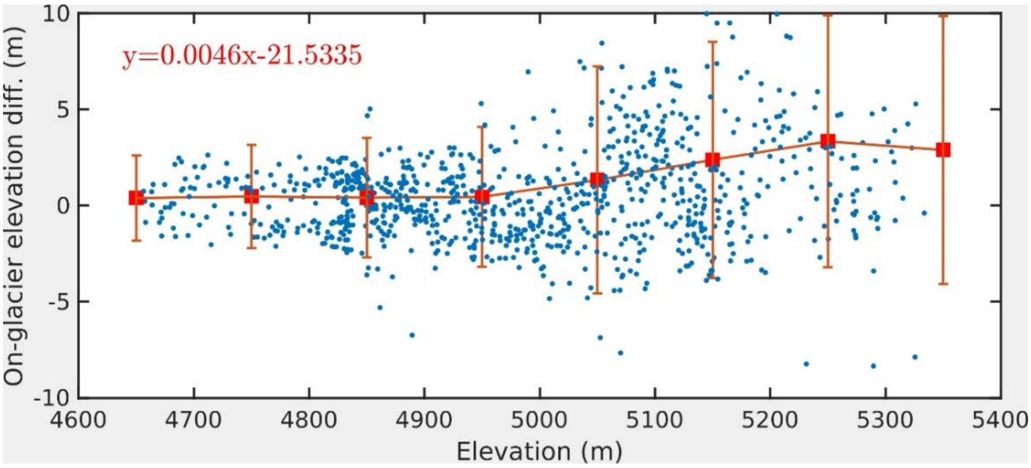

Fig. R1. Plot of surface elevation difference between SRTM C-band and X-band DEMs against elevation. The red squares indicate mean values of elevation differences for elevation bins with a 100 m separation.

L233: Why do you stop matching surface displacement in 2019. From a quick check of the Planet archive I see that displacements 2019-2020 and 2020-2021 would be very interesting to describe the instability. I strongly recommend to update the velocities after 2019. I almost consider that mandatory for the purpose of your work.

Reply: We have added two cloud-free Planet images acquired on 2020/08/29 and 2021/03/23 to extend the velocity measurements. The figures showing the glacier snout advance velocity and tongue flow velocity have also been updated. Note that the image 2021/03/23 was not used for flow velocity measuring because the glacier tongue was partly covered by snow at the time.

L 254: the question is if a 40-year continuous development should be called "unstable".

Reply: We have modified the sentence to "The highly developed crevasses in the glacier accumulation region since the 1970s and the widening of the crevasses in recent years indicate that the glacier may develop toward destabilization."

L 261: the lake *was* not visible …

Reply: We have replaced the word "were" to "was".

L 306: Calling a 40-year mass displacement "surge-like" might be open to discussion. How about calling it "… and imply a slow surge-like mass transfer process in the tongue area …"? See above, where I suggest though from checking repeat Planet images that only the lower most part of the tongue is actually accelerating. I would not call that surge-like at all. It seems more a slow landslide of the frontal ice-cored moraine, or similar.

Reply: Good suggestion. We have modified the sentence to "Elevation changes confirm the stepwise glacial termini advance (see Section 4.1) and imply a slow surge-like mass transfer process in the tongue area". Here we use the word "surge-like" according to the flow velocity patterns of KLP-37. The advance velocity of the glacier snout shown an abrupt increase during 2015 and 2016, while the rates before 2015 and after 2016 were relatively stable. This kind of flow behavior resembles glacier surging (Kääb et al., 2018) and has also been reported on several detached glaciers preceding ice avalanches, such as the Aru and Amney Machen glaciers in Tibetan Plateau (Paul, 2019; Kääb et al., 2021).

L 341: trebled –> tripled ?

Reply: Corrected.

L 342: "unstable"? see above, not sure this is destabilization?

Reply: The sentence has been modified to "The almost tripled mean velocity below 4800 m in the recent decade suggests that the glacier tongue has been getting more active towards destabilization."

L 350 and following: the two reasons why the advance should be faster than the surface velocities are not convincing to me. This effect is quite unusual and seemingly violates physical laws of flow/creep.

Reply: We have re-done the image correlation processing and updated the velocity field from 2009 to 2020.

L 411. Section 5.2 is to a large extent methods and results. I recommend to describe the model in the method section, and the model outcome in the results. Only the discussion of the model results (different parameter settings; not whole glacier collapse modelled, etc.) would then come in the discussions.

Reply: Good suggestion. We have split Section 5.2 following the suggestion. We have moved the modeling descriptions into the Method part and modeling results into the Results section. In Section 5.2, we discussed possible factors that may influence the modeling results.

L 413: changing ice flow direction: do you mean a change over time (I don't find that in the results) or a change in direction along the glacier (spatial change)?

Reply: Here we mean the change of flow direction in the spatial domain. We have clarified that: "the ice flow directions along the two glaciers have both changed due to the local topography."

L 463: … an avalanche from …

Reply: Corrected.

END OF REVIEW