Responses to the Reviewer's comments:

<u>TO REVIEWER#1, Wilfried Haeberli :</u>

General

The authors present and discuss the results of a rock glacier inventory in southeastern Tibet. Their work follows a number of other recent studies in the larger region, is at present-day level of knowledge and understanding, and represents an important contribution to the internationally coordinated efforts to map and monitor mountain permafrost as part of global climate observation (IPA-RGIK, GTN-P). The text is mostly clear, well-structured and accompanied by a good number of adequate references. Further improvements are mainly possible with respect to (1) the physical background and technical terminology of the treated phenomena, (2) more precise information about climatic conditions as key factors of permafrost existence and evolution, and (3) adequate treatment of related environmental aspects.

We sincerely thank the reviewer’s comments, which are valuable for us to improve the quality of our manuscript. As you are concerned, several problems need to be addressed. The comments are listed in italics, and the answers are given in the blue text.

■ Physical background and technical terminology

Mapping the landform "rock glaciers" for inventory work is perfectly adequate. It would, however be important to more precisely and explicitly mention the physical conditions and processes behind such landforms. The striking flow features used to define the landform "rock glacier" are expressions of coherent (or cohesive) viscous flow (or creep) taking place in perennially frozen materials (talus, debris) rich in ice. The term "perennially frozen" implies two fundamentally important physical aspects: the subsurface material remains below 0°C throughout the year and contains ice (in whatever form). The volumetric ice content of about 40-60% as applied in the paper is based on core drillings and numerous geophysical soundings worldwide and hence realistic. Such high ice contents exceed the pore volume of the involved talus or morainic material in unfrozen conditions by roughly a factor of two or even more. It is this "ice-supersaturation" or "excess ice" which not only induces cohesion by relating individual rock particles with each other but at the same time also reduces internal friction by separating them from each other. The resulting viscous flow through steady-state (or secondary) creep enables the formation of the recognizable landform "rock glacier" a result of cumulative deformation over time scales of millennia (typically Holocene). The "thickness" value very roughly estimated by the authors using the "Brenning approach" most likely represents a characteristic thickness of the moving body as defined in many cases by internal stress-related shear horizons or by bedrock occurrence at depth. Perennially frozen materials can, however, exist far beyond this depth as well as in the surroundings of striking creep features. As a consequence, the water volume calculated from moving frozen materials only represents a lower limit of the totally existing subsurface ice in the permafrost of a region. Cicoira et al (2020) and Krainer et al (2014) with their literature references can be consulted concerning such aspects.

Thank you very much for your helpful comment. We have now revised the manuscript to better illustrate the physical conditions and processes behind rock glaciers. We acknowledge that our study conservatively estimates the thickness of the rock glacier in the study area, resulting in a conservative estimate of the actual water equivalent. The empirical rule we used to estimate the thickness is proposed by Brenning (2005b) based on field measurements of rock glacier geometry. This approach has been widely used in previous studies to estimate the water equivalent of rock glaciers worldwide, so we used it to compare the results with others more conveniently. To determine whether the estimated results obtained by this method are reliable, we also calculated the water equivalent according to the method provided by Cicoira *et al.* (2020) (Eq. (1) and (2)), and compare the estimated results from different methods (see Table.1). The detailed data will be attached to the revised manuscript.

$$H = \frac{\tau}{\rho\ g\ sin\alpha} \pm 3.4m \tag{1}$$

where τ is the sheer stress (τ= 92 kPa), g is the gravitational acceleration, H is the thickness of the moving rock glacier, α the surface slope angle and ρ is the density of the creeping material, which is given by the contribution of volumetric debris w_{d} and ice content w_{i} and the relative densities (ρ_{i} = 910 kg m^{-3} and ρ_{d} = 2700 km m^{-3}):

$$\rho = \rho_{\mathrm{d}}\, w_{\mathrm{d}} + \rho_i\, w_i \tag{2}$$

Table 1: Ice volume (km3) and corresponding WVEQ (km^3) regionally and GKLRJ-wide (All).

Brenning, 2005					
Region	Glacier - WVEQ (km^3)	RG - WVEQ (km^3)			RG: Glacier WVEQ ratio
		40%	50%	60%	
All	9.29	4.55	5.69	6.82	1:1.81
1	0.19	0.34	0.43	0.51	2.26:1
2	6.60	3.73	4.66	5.59	1:1.42
3	2.51	0.48	0.60	0.72	1:4.18
Cicoira et al., 2020					
Region	Glacier - WVEQ (km^3)	RG - WVEQ (km^3)			RG: Glacier WVEQ ratio
		40%	50%	60%	
All	9.29	2.76 – 3.68	3.85 - 5.00	5.20 – 6.58	1:2.30
1	0.19	0.15 - 0.22	0.21 - 0.29	0.28 - 0.38	1.74:1
2	6.60	2.30 - 3.15	3.21 - 4.14	4.33 - 5.46	1:1.68
3	2.51	0.31 - 0.41	0.44 - 0.56	0.59 - 0.74	1:3.98

WVEQ = water volume equivalent.

The range of results in RG - WVEQ (km^3) (Cicoira *et al.*, 2020) corresponds to the H±3.4m.

The WVEQ calculated by the '*Brenning approach*' is approximately 4%-24% higher than the maximum results calculated by the '*Cicoira approach*'. However, the typical driving stress of alpine rock glaciers is 92 ± 13 kPa (Cicoira *et al.,* 2020). If we assume that τ= 105 kPa and H= τ /ρgsinα + 3.4m, the result could be 1-17% higher than that calculated by the '*Brenning approach*'.

In summary, although the actual thickness of the rock glacier and water equivalent may exceed what our method predicts, the results based on the two methods is close, which may be related to the fact that less underground water content in the study area leads to less perennially frozen materials, but it needs to be further study based on more detailed data to determine.

■ Climatic conditions

Permafrost is a specific geothermal condition (negative subsurface temperature throughout the year) directly related to climatic conditions at regional scale (especially air temperature) and to microclimatic conditions (mainly snow cover, radiation, surface characteristics) at local scales. Instead of giving a "mean temperature" for an entire region, mean annual air temperatures (MAAT) should be defined as a function of altitude and time. This then enables to define MAAT at sites where creeping permafrost occurs.

Thank you for the comment. To better define MAAT at sites where creeping permafrost occurs, we drew the map of MAAT in the study area (Fig.1) based on the data provided by Du and Yi (2019). And we extracted the MAAT for each rock glacier in ArcGIS 10.7. The detailed data will be attached to the revised manuscript.

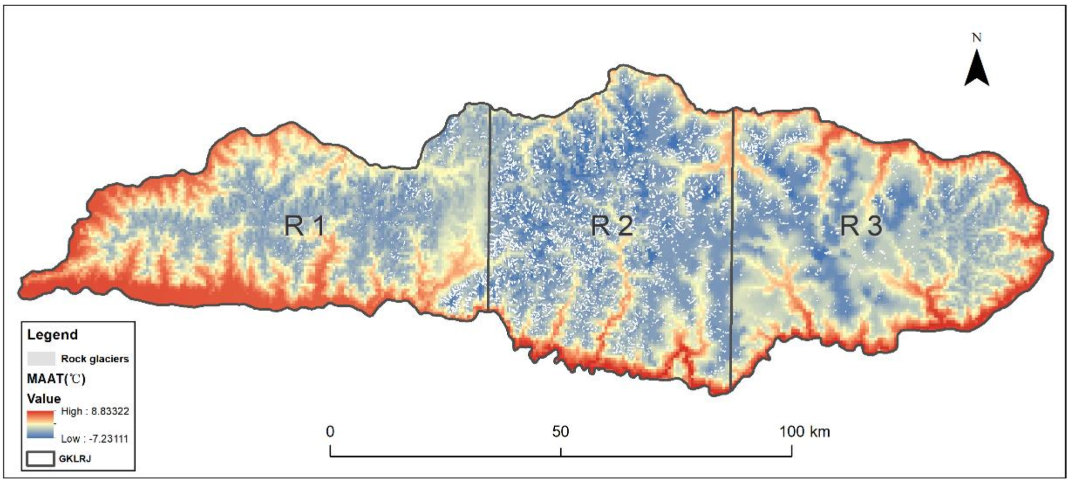

Figure 1: Mean annual ground temperatures (Du and Yi, 2019) and rock glacier inventory in GKLRJ.

An advanced calculation of mean annual ground temperatures (MAGT) after Ran et al is used in the present study, enabling definition of corresponding values for the documented permafrost landforms. From the mean altitudes and the mean MAGT provided in the paper for the region(s), most likely values for active rock glaciers there are likely to be between about 0 and -5°C. Such quantitative information should be provided in the paper and discussed with respect of ongoing warming trends (which must also be more precisely defined).

Thank you for the above suggestions. We extracted the MAGT for each rock glacier and found the average MAGT of active rock glaciers is approximately -0.6℃, and about 81% of rock glaciers are distributed in the region where MAGT is below 0℃. The remaining 19% is probably due to these reasons. The possible reasons for this result are: (i) MAGT may be overestimated in some areas due to limitations in the amount of borehole data and simulation methods, (ii) differences may be between the acquisition time of the remote sensing image used to map the rock glaciers and the covered time of MAGT data, (iii) the data resolution of MAGT may lead to some deviation in the extraction results. The 19% temperature is a little different from 0℃, and the detailed data will be attached to the revised manuscript.

A brief explanation of the applied MAGT model should be given and a more detailed discussion with respect to the involved variables of the quantitative approach used concerning probabilities of permafrost occurrence is also needed.

Thank you for your suggestions, we have made modifications according to them.

- The MAGT data provided by Ran *et al.*(2019) derived from the predicted mean annual ground temperature (MAGT) at a depth of zero annual amplitude (10–25 m) by integrating remotely sensed freezing degree-days and thawing degree-days, snow cover days, leaf area index, soil bulk density, high-accuracy soil moisture data, and in situ MAGT measurements from 237 boreholes on the TP by using an ensemble learning method that employs a support vector regression model based on distance-blocked resampled training data with 200 repetitions.

- We calculated the regression model in SPSS 27, and 7 climate-topographic factors were included by the Forward Selection (Likelihood Ratio), *i*.e. longitude, latitude, mean altitude (ASTER GDEM V3), mean annual precipitation in 2015 (Du and Yi, 2019), mean annual ground temperature in 2015 (Du and Yi, 2019), mean slope and area (calculated in ArcGIS 10.7 based on ASTER GDEM V3). The regression model's overall fit as well as all coefficient estimates were highly significant ($p < 0.05$, Table.2), and the Hosmer–Lemeshow test also means the model is a good fit (p=0.709, p > 0.05). The area under the ROC curve (AUC) was calculated to be 0.85.

Table 2: Logistic regression output.

	B	SE	*p*	Exp(B)	BCa 95% CI(B)	
					Lower	Upper
Mean altitude	0.007	0.000	0.000	1.008	1.007	1.008
Mean annual precipitation	-0.021	0.002	0.000	0.979	0.976	0.982
Mean slope	-0.041	0.009	0.000	0.960	0.943	0.977
Mean annual ground temperature	-0.145	0.073	0.047	0.865	0.750	0.998
Area	0.000	0.000	0.016	1.000	1.000	1.000
Longitude	4.327	0.215	0.000	75.742	49.659	115.524
Latitude	-2.320	0.275	0.000	0.098	0.057	0.168
Constant	-359.428	22.036	0.000	0.000		

■ Related environmental aspects

General environmental aspects potentially related to the completed work are only briefly mentioned. Such aspects as water quality, slope instability, or global climate-related permafrost monitoring are serious matters, needing at least a minimum of specific formulations (e.g. heavy metals in water from thawing rock glacier permafrost, large rock and rock/ice avalanches from steep icy peaks, RGIK-GTN-P, GCOS) and up-to-date literature referencing. Examples could be: Deline et al (2021: slope stability), Etzelmüller et al (2020: evolution of borehole temperatures in European mountain permafrost), RGIK/IPA.

Thanks for your suggestions. We agree with you that the related environmental aspects you mentioned are really important, and we will further understand these aspects and mention more relevant matters existing in our manuscript.

Minor remarks

The English needs smoothing in places. Write "rock glacier inventory" (instead of rock glaciers inventory; check throughout the paper). Use present tense when describing results concerning present-day conditions.

Detailed technical remarks are contained in the annotated PDF.

We sincerely thank you for your careful reading. We have made the corrections to make the word harmonized within the whole manuscript. And we plan to invite a native English speaker to help polish our article. We hope the revised manuscript could be acceptable for you.

Reference

Cicoira, A., Marcer, M., Gärtner-Roer, I., Bodin, X., Arenson, L. U., and Vieli, A.: A general theory of rock glacier creep based on in-situ and remote sensing observations, Permafrost and Periglacial Processes, 32, 139-153, https://doi.org/10.1002/ppp.2090, 2021.

Du, Y., Yi, J.: Data of climatic factors of annual average temperature in the Xizang (1990-2015). National Tibetan Plateau/Third Pole Environment Data Center, 2019.

Du, Y., Yi, J.: Data set of annual rainfall and climate factors in Tibet (1990-2015). National Tibetan Plateau/Third Pole Environment Data Center, 2019.

Liu, S., Guo, W., Xu, J.: The second glacier inventory dataset of China (version 1.0) (2006-2011). National Tibetan Plateau/Third Pole Environment Data Center, DOI:10.3972/glacier.001.2013.db. CSTR:18406.11.glacier.001.2013.db, 2012.

Ran, Y., Li, X.: The mean annual ground temperature (MAGT) and permafrost thermal stability dataset over Tibetan Plateau for 2005-2015. National Tibetan Plateau/Third Pole Environment Data Center, DOI:10.11888/Geogra.tpdc.270672. CSTR:18406.11.Geogra.tpdc.270672., 2019.