Author's response:

Dear Dr. Tobias Bolch:

Thanks very much for your kind work and for giving us an opportunity to make revisions. On behalf of my co-authors, we would to express our great appreciation to you and the reviewers.

We have made extensive modifications to the revised manuscript according to the comment, and the point-by-point responses to the two nice reviewers are listed below this letter. We sincerely hope that the revised manuscript will meet the requirements of the journal.

If there are any other modifications we could make, we would like very much to modify them.

Thank you again for your positive comments and valuable suggestions to improve the quality of our manuscript.

Looking forward to hearing from you.

Best regards.

Yours sincerely,

Mengzhen Li

Corresponding author:

Yanmin Yang
Zhaoyu Peng
Gengnian Liu

30 Mar. 2023

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 has been attached to the revised manuscript.

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

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}):

$$\rho = \rho_d\, w_d + \rho_i\, w_i \qquad (2)$$

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	1.93 – 2.85	2.71 – 3.86	3.69 – 5.07	1:3.20
1	0.19	0.16 - 0.23	0.22 - 0.31	0.30 - 0.41	1.42:1
2	6.60	1.54 – 2.29	2.16 – 3.09	2.94 – 4.06	1:2.51
3	2.51	0.24 - 0.34	0.34 - 0.46	0.45 - 0.61	1:6.28

WVEQ = water volume equivalent.

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

The mean thickness of rock glaciers calculated using a perfectly plastic model (Cicoira et al., 2020) is 19.15±3.4 m, 9.33 m thinner than that estimated using the empirical area-thickness formula. The mean value of the WVEQ estimated using this method is ~ 56-67% of the mean value obtained using the 'Brenning' method. As the estimated WVEQ of rock glaciers decreases, the ratio of rock glaciers' to clean ice glaciers' WVEQ is also lower than that obtained using the 'Brenning' method (Brenning, 2005a).

In comparison, we found that the thicknesses of rock glaciers calculated using the flow plasticity model (Cicoira *et al.*, 2020) are significantly lower than the corresponding results calculated using the empirical area-thickness formula (Brenning, 2005a), potentially due to the following three main reasons. Firstly, the angle of slope used to calculate the thickness may have been overestimated. Due to the lack of actual measurement data, we calculated the length of each rock glacier in ArcGIS based on the digitized results, extracted its altitudinal difference using DEM data, and finally applied trigonometric functions to calculate each angle of slope. Secondly, the angles of slope of some rock glaciers are outside the applicable slope range of this model (10°-30°). Since tongue-shaped rock glaciers on steep hillslopes tend to have steeper slopes and greater driving stresses, our estimates of thickness using the mean parameters in the model may be lower. Thirdly, the applicability of different estimation methods may be different across the study area. The mean thickness of rock glaciers in the study made by Brenning (2005a) is ~ 10 m higher than the sample of rock glaciers selected in the study conducted by Cicoira et al. (2020). The thicknesses of rock glaciers estimated using Brenning's method may therefore be overestimates.

■ 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(c)) 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 have been attached to the revised manuscript.

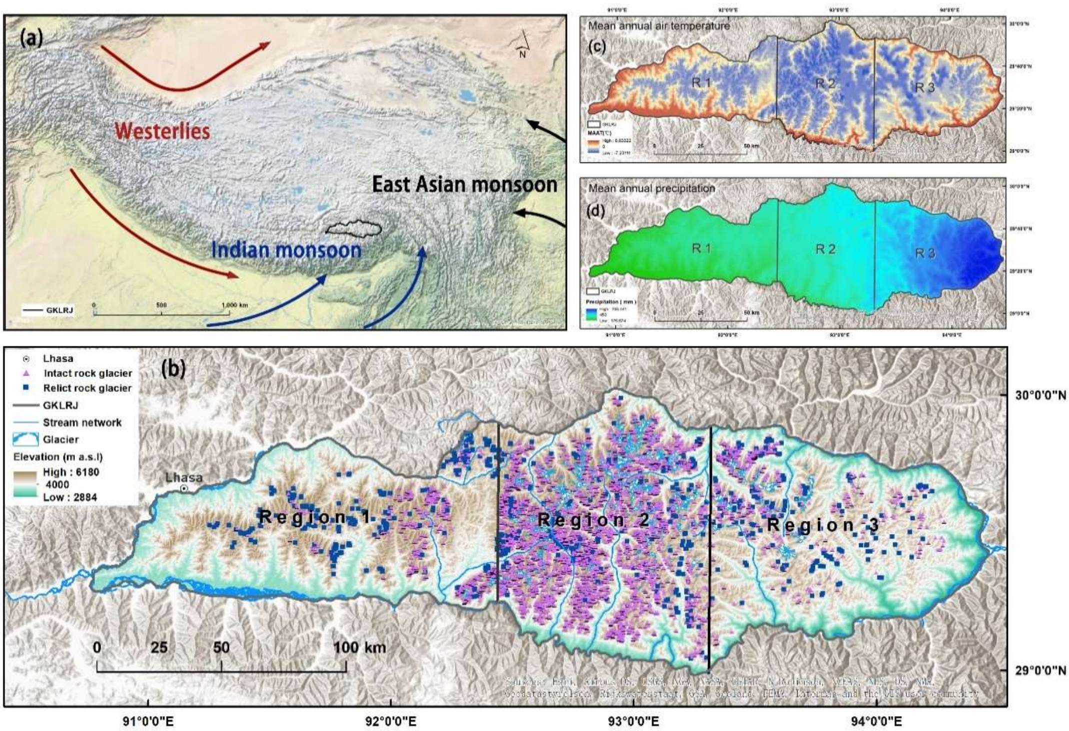

Figure 1: (a) The location of the GKLRJ on the TP; (b) The three sub-regions and the spatial distribution of streams. Rock glaciers are categorized as purple (intact rock glaciers), blue (relict rock glaciers), and glaciers are shown in blue and white; (c) Mean annual air temperature map for the GKLRJ (Du and Yi, 2019); (d) Mean annual precipitation map for the GKLRJ (Du and Yi, 2019). Maps were created using ArcGIS® software by Esri.

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 have been 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 have further understood 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 have invited 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.

Responses to the Reviewer's comments:

TO REVIEWER#2

General comments

This paper presents a new rock glacier inventory in the Guokalariju region of the Tibetan Plateau, then estimate the hydrological water stores and the permafrost index based on the distribution of rock glaciers. This is a good contribution as new inventories are needed globally, hence the work is relevant to the community. However, I find that the paper needs significant improvement both in terms of methodology writing and in the way that results are presented. There are some concerns about the terminology used, which have already been addressed by a previous review, so I will not comment of these here but I agree with them. My additional concerns relate to:

We feel great thanks for your professional review work on our manuscript. We have provided point-by-point answers to your comments below, and we have revised the manuscript according to your valuable suggestions. The comments are listed in italics font, and our answers are given in blue text. As the whole manuscript has undergone major changes, some problematic areas have been reexpressed or deleted, so we only list the partial line numbers that remain after modification.

- ***Methods:***

RG delineation: these are not detailed or specific enough, particularly with respect to the mapping. This is covered only in one or two sentences, and there is no information about how exactly RGs were delineated with respect to RGIK updated guidelines. Without this, it is hard to assess if this is a significant contribution as we now need to ensure that inventories are constructed using standardized methodology following existing guidelines.

Thank you for your suggestion. Our work started before the RGI_PCv2.0 updated (RGIK, 2022), we mainly applied the methods used in previous studies (Scotti *et al*., 2013; Jones *et al*., 2021). Details are as follows: the outline of the entire rock glacier surface was delineated, extending from the rooting zone (i.e. uppermost extent) to the foot of the front slope (i.e. lowermost extent). When the frontal lobes of two (or more) rock glaciers originating from distinct source basins join downslope, they are considered the two components as separate bodies. Where the limits between lobes are unclear and the lobes share other morphological characteristics, the whole system is classified as a unique rock glacier (Scotti *et al*, 2013). In occurrences where rock glaciers grade into upslope landforms, a clear distinction between the two landforms cannot be set and they are delineated as the whole body (Scotti *et al.*, 2013; Jones *et al.*, 2021).

In addition, following the update of the guidelines, the rock glacier outline in the study area was re-examined and adjusted to better comply with the guidelines in accordance with the latest standards. And we have added more details in the revised manuscript.

(Line 105-111.)

Section is lacking Data sources which makes is hard to follow which data were used and their characteristics and accuracy. Please consider adding one.

Thank you for pointing out this problem. In the reply to the next question, we list the relevant information of topo-climatic data. And we have given a more comprehensive explanation of each data in the revised manuscript.

(Line 201-208.)

Topo-climatic factors: there is limited information given about this, and it is mostly vague. Authors need to be more specific and carefully describe each factor.

Thank you for your suggestion. We have listed the information of relevant variables (see Table 1), which is obtained by extracting and calculating the mean value of the topo-climatic data of the range of rock glaciers in ArcGIS 10.7. We have rewritten this part in the revised manuscript.

(Line 201-208.)

Table 1: Topo-climatic data information.

Factor	Year	Data source	Resolution	Software
Latitude/Longitude	/	Google Earth Pro	/	ArcGIS 10.7
Altitude	2000-2013	ASTER GDEM V3	30 m	ArcGIS 10.7
Slope/Aspect	2000-2013	ASTER GDEM V3	30 m	ArcGIS 10.7
MAAT	2015	Du and Yi, 2019	1 km	ArcGIS 10.7
MAGT	2005-2015	Ran *et al.*, 2019	1 km	ArcGIS 10.7
MAP	2015	Du and Yi, 2019	1 km	ArcGIS 10.7
PISR	2015	ASTER GDEM V3	30 m	SAGA GIS 8

MAAT: mean annual air temperature

MAGT: mean annual ground temperature

MAP: mean annual precipitation

PISR: potential incoming solar radiation

The link with climatic conditions: similar to what was suggested before, this needs to be much more thought of; for example, the question of special resolution is not even mentioned, while most climatic data come at coarse spatial resolution.

Thanks. You have raised an important point. However, due to the limitation of the difficult field environment and observation conditions, less meteorological data can be obtained in the study area, and it is still difficult to obtain high-resolution climate data in our study area. In the next study, we will further explore available data and try to improve the resolution of the data through relevant methods.

Uncertainty section is spread throughout the paper, it would be much more convenient to have an uncertainty assessment as a separate section.

Thank you for your suggestion. We have added a separate chapter in the revised manuscript to account for the uncertainty associated with the rock glacier inventory, water volume content estimation, and permafrost probability distribution estimation.

(Line 140-146, and Table 2 in the manuscript.)

The logistic regression is presented too briefly, it needs to be clearer how variables were selected; besides, many of them were correlated- how was this dealt with?

Thank you for your suggestion, we have added this part of the explanation in the revised manuscript. In order to reduce the influence of multicollinearity, we adopt a stepwise regression method (Forward Selection (Likelihood Ratio)) to solve this problem. The method is a process of starting from the model with no independent variables, and then gradually increasing and screening the independent variables. Through this method, we can gradually build a robust and reliable regression model under the condition of multicollinearity of variables in the equation.

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 total fitting and all coefficient estimates are 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		

(Line 209-213 and line 292-296, Table 7 in the manuscript.)

■ ***Results/discussion:***

The main issue here is that the language is vague in many places, and not quantitative. I have marked these in the specific comments. The way the results are presented, it is hard to pick out what is important from these results. For example, R2 stands out as an anomaly compared to R1 and R3 in terms of estimated water storage- this could be interesting to make a more detailed analysis/comparison among the regions, doing some statistical tests to see if the *difference is significant. This is at present not presented.*

Thank you for providing the suggestions. We restate the vague places in the manuscripts, and the response is made in the specific comments below. Our results emphasize the control of temperature, precipitation, and other environmental factors to the distribution of the rock glacier and give the key factors for the distribution of the rock glacier in the region of GKLRJ. We give the evaluation of the water resources in the region and the hot spots of the permafrost distribution.

To the water storage of R1, R2 and R3, we conducted an analysis of variance (ANOVA) on the WVEQ of the three groups of rock glaciers in R1, R2, and R3, and the results showed that all of the different groups showed significance ($p < 0.05$) for the WVEQ (see Table 3), implying that the WVEQ of rock glaciers in R1, R2 and R3 were all different. We will also continue to explore potential possibilities in the results based on this and add them to the revised manuscript.

Table 3: The statistic result for ANOVA.

	Sum of Squares	df	Mean Square	*F*	*Sig.*
Between Groups	34.435	2	17.217	58.263	0.000
Within Groups	1.773	6	0.296		
Total	36.208	8			

(Line 380-390.)

Also, the authors average the WEQ over the 3 regions then compare to Jones et al, which is not ideal. A weighted analysis would be needed

We agree with that. We calculated a ratio of intact rock glaciers to clean ice glaciers' water volume equivalence (WVEQ) by using the weighted average method from the following equation. We also add it to our revised manuscript.

$$\text{WVEQ ratio}_{\text{Rg: Glacier}} = \frac{\text{WVEQ R1}_{\text{Rg}} \times \frac{\text{R1}_{\text{Rg}}}{\text{All}_{\text{Rg}}} + \text{WVEQ R2}_{\text{Rg}} \times \frac{\text{R2}_{\text{Rg}}}{\text{All}_{\text{Rg}}} + \text{WVEQ R3}_{\text{Rg}} \times \frac{\text{R3}_{\text{Rg}}}{\text{All}_{\text{Rg}}}}{\text{WVEQ R1}_{\text{Glacier}} \times \frac{\text{R1}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}} + \text{WVEQ R2}_{\text{Glacier}} \times \frac{\text{R2}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}} + \text{WVEQ R3}_{\text{Glacier}} \times \frac{\text{R3}_{\text{Glacier}}}{\text{All}_{\text{Glacier}}}}$$

where $\text{WVEQ ratio}_{\text{Rg: Glacier}}$ is the ratio of intact rock glaciers to clean ice glaciers' WEVQ; $\text{WVEQ Rn}_{\text{Rg}}$ (n=1,2,3) respectively are the WVEQ for rock glaciers in R1, R2 and R3; Rn_{Rg} (n=1,2,3) respectively are the number of rock glaciers in R1, R2 and R3; All_{Rg} is the number of rock glaciers in the whole GKLRJ; $\text{WVEQ Rn}_{\text{Glacier}}$ (n=1,2,3) respectively are the WVEQ for clean ice glaciers in R1, R2 and R3; $Rn_{Glacier}$ (n=1,2,3) respectively are the number of clean ice glaciers in R1, R2 and R3; $All_{Glacier}$ is the number of clean ice glaciers in the whole GKLRJ. After recalculation, the ratio changed from 1:1.63 to 1:1.81 (see Table 4), which is still relatively high compared with most of the study areas in the world.

Table 4: Ice volume (km3) and corresponding WVEQ (km^3) regionally and GKLRJ-wide (All).

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	6.6	3.73	4.66	5.59	1:1.42
3	2.51	0.48	0.60	0.72	1:4.18

(Line 180-189, Table 5 and Table 6 in the manuscript.)

Conclusions are brief and some are I find they tend to be speculative, and contradictory to some of the results (for ex the role of precipitation in the formation of RG). The authors present the possible links between climate and RG development but these are not on the same time scale! This needs to be addressed, or the analysis should be revised to present this as a climate" index" rather than temperature and precipitation values.

We think this is a helpful suggestion. We have focused on using more quantitative language instead of speculative words to illustrate the relationship between the regional occurrence characteristics of rock glaciers and the climate.

(Line 417-439.)

Figures are small and hard to see. Also, these need more extensive presentation

Thank you for pointing out this problem. We have redrawn the figures with this problem in the revised manuscript.

(Figure 1,3,4)

Reference list is adequate

Thanks. We have checked and updated.

The language needs much improvement both in terms of the English language and in terms of scientific language, I am providing below very thorough edits to *help with this, but it should again be checked by a language editor.*

Thank you for your careful reading and helpful suggestions concerning our manuscript. We have invited professionals to help us further improve our language.

Specific comments

- ***Abstract***

L8 remove “more” because there is nothing given as comparison

Corrected.

L 9 specify on what basis (manual delineation etc).

We delineated rock glacier boundaries by the manual method.

L 11 what does the altitude refer to? mean altitude of RG? Please specify

Yes. The altitude is the mean altitude of RG.

L 12 “distributed. . ” - > a word seems to be missing here, distributed in what way?

Thank you for pointing this out. What we want to express originally is that most of the rock glaciers are located in the semi-arid region of the study area.

L 13 remove “which are more” for conciseness

Corrected.

L 14- 15 “A huge potential . . .was found. . ” ï rephrase as it reads awkward The potential is estimated not found, and “huge” is qualitative

Corrected. We have changed ‘huge’ to ‘considerable’.

- ***Introduction***

L32 “then causing” -- > I suggest “with possible consequences on” since this is not a certainty

Corrected as suggested.

l 42 Add “The” before Tibetan Plateau

Corrected.

l 44 “mapped” -- > “constructed” or “created” (an inventory is not mapped)

Corrected.

l 45 add “the” after “Nepalese”

Corrected.

l 48 I suggest not using the acronym of the region in the intro, but rather introduce *it in the study area. Also what is meant by "is a typical region"?*

Corrected. The sentence has been removed in the manuscript.

l 51 "study… has mapped" is not correct, need a subject (author or personl). Also specify what method was used previously

Corrected. (Line 52-55)

l 54 "Thus" is not appropriate, replace ("To fill this gap" or "To address this. . ")

Corrected. We have modified it to "To address this…".

l58 remove "the"

Corrected.

- ***Study area***

L 60 see my previous comment, I suggest introducing the acronym here and first spell out the region name. Also refer to the figure here

Corrected. Thanks for your suggestion.

L 64 "In the division of the tectonic unit" is ambiguous, rewrite

Corrected. We have rewritten this part according to the Reviewer's suggestion.

(Line 92-103 and Table 1)

L 70 spell out ISM

Indian summer Monsoon (ISM).

L 70 is this R2 and R1? Then why not introduce them here directly?

Thank you for your suggestion, we have not used R1 and R2 directly here because the boundaries of the climatic zones do not exactly correspond to those of R1 and R2, with parts of the northeastern part of R2 belonging to the temperate humid region.

L 72 073 reference?

The mean annual temperature and mean annual precipitation datasets were provided by Du and Yi (2019).

L 73 is this across the region? please specify

Yes. The mean annual precipitation of the entire study area is about 400 mm. We have referred to your suggestions and provided the table below for more detailed information.

L 78 “can be further divided” ï we divided”; also rephrase to clarify, “3 regions referred to as R1 (east) and so on”

Corrected. Thanks for your suggestion. (We divided the GKLRJ into three sub-regions: R1(east); R2 (central); and R3(west).)

L 80 split the phrase “The mean altitude” and specify this is about R1

Corrected.

L 80 -88 needs re-writing to be more compact. I suggest making a small table with the 3 regions, the MAGT, altitude, etc. . in each, as the text is heavy. Some things are vague, for ex l83 “significantly greater” ï there is no statistical text so this cannot be used

Thanks for your suggestion.

(see Table 1.)

- ***Materials and methods***

This section needs work as the mapping methods are not clear, they are only described in a short paragraph from l 95 - 100. Based on what criteria, exactly? How many analysists? What auxiliary data were used? Along the same lines, there is no data sources section so it is hard to know what was used. Please revise this section accordingly

Thanks for your kind suggestion. We have tried our best to revise the manuscript according to your kind construction comments and suggestions.

L 90 remove “s” from glaciers

Corrected.

L 95 “Firstly. . ” l100 “secondly” and l109 “Thirdly” are not needed for each step, suggest removing

We agree and have moved them.

L 95 add “from” after images and remove parenthesis

Corrected.

L 102 add Jones et al papers

Corrected.

L 104 reference (RGIK group?)

The conceptual categorization of rock glacier activity refers to the previous works (Scotti *et al.*, 2013; Baral *et al.*, 2019) and RGIK (2022).

L 107 – 109 I suggest removing the acronyms; it makes the paper harder to read and it is not particularly needed

Corrected. Thanks for your suggestion.

L 109 "them" ï "the shapefiles"

Corrected.

L 110 not sure how these can be calculated in Excel since these are spatial data!

We are sorry that we didn't express this clearly. We extracted the corresponding information of each rock glacier in ArcGIS 10.7, and then carried out further statistical calculations in Excel.

L 112 present tense used here while past was used in previous phrase. Please check all manuscript for consistency

Thanks for your careful checks. We are sorry for them. Based on your comments, we have made corrections to harmonize the consistency in the whole manuscript.

L 115 – 120 the uncertainty section is too brief and it is not clear, please address. Same with the Table on l125. A separate section on uncertainty would be needed

Thank you for your suggestion. We have added a separate paragraph in the revised manuscript to account for the uncertainty associated with the rock glacier inventory.

(Line 140-146, and Table 2 in the manuscript)

L 118 "In addition, we used…" ï rewrite, for ex "All shapefiles were in XX projection" or move to the end, This is not an "addition".

We have made the change as "All shapefiles were in 1984 UTM Zone 46N projection system". (Line 130.)

L 119 – 124 this section as well is short and vague. How were the attributes derived, I assume mean of each glacier? What about lat long? Center of the glacier

The attributes derived from each rock glacier. The 'lat' and 'long' from the location of the point we mapped by manual method, nearly the center of each rock glacier.

Please put this in a new paragraph and add the necessary detail

Thank you for your suggestion.

(Line 136-139.)

L 120 ASTGMT2 DEM- there is no mention of the spatial resolution, no reference and no justification on why this was chosen. Please address.

Thank you for pointing this out. In the revised manuscript we have updated the latest version of DEM data (ASTER GDEM v3) for the study area to better capture topographic information. The Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 3 (V3) provides a global digital elevation model (DEM) of land areas on Earth at a spatial resolution of 1 arc second (approximately 30-meter horizontal posting at the equator). It was generated using 1,880,306 Level-1A scenes acquired between March 1, 2000, and November 30, 2013. And it was created by stacking all individual cloud-masked scene DEMs and non-cloud-masked scene DEMs, then applying various algorithms to remove abnormal data (Abrams *et al.*, 2015). We chose this data because of its high spatial resolution and ease of access, which serves as an effective way to meet the basic requirements of our study.

Section 3 .2 does not follow the order in the objectives on l55

Thank you for pointing this out. We have revised the objectives order in the Introduction.

(Line 61-64.)

L 128 – 133 this is background, please re-write

Thanks for your suggestion. We have moved this part to the "Introduction" part.

L 133 remove "that has been" for more conciseness

Corrected.

l 135 remove "a calculation by" so it reads "requires multiplying". Also, the equation is needed here upfront (eq 2 but for RGs). The detail each part of that equation into Eg1.

Thanks for your suggestion. We have reorganized this part in the revised manuscript.

(Line 151-158.)

Also, remove "estimated" as the method in the ideal case requires the known thickness and ice content. Then in the following phase state that these were estimated as follows etc ...

Thanks for your suggestion. We have corrected it here in the revised manuscript.

L 142 "lower, etc" is unclear- you mean the volume ranges?

Yes. For example, "lower" means that the ice volume accounts for 40% of the volume of the rock glacier.

L 147 this is confusing as it is not mentioned in the beginning of the section anything about clean ice volume, should be clarified on l 127. Also, same comment as before, there is no section on data sources and so there is not enough detail on The Second Inventory Glacier dataset (what year, what source?) and GlabTop2. I strongly suggest adding a data sources section to detail all these data.

Thanks for your suggestion, we did neglect to introduce the detail of the calculating method of clean ice volume in this section. We mainly refer to the approach used by Jones *et al.* (2018b) in the Himalaya-Karakoram region, and the ice volumes of clean ice glaciers also were calculated from Eq (2) in the manuscript. The area of each clean ice glacier is derived from the second glacier inventory dataset of China (version 1.0) (2006-2011) (Liu *et al.*, 2012), and the thickness is calculated by the GlabTop2 in Python 3.10 (Linsbauer *et al*., 2009).

L 151 "ice glacier" – revise, "clean ice glaciers"

Corrected.

L 153 "has been found" -- > "has been used"

Corrected.

L 154 "has been applied" -idem

Corrected.

L 156 use past tense for consistency

Corrected.

L 160 - 161 rephrase for English language; and move "using SPSS software at the end" explain what is the progressive forward method

Corrected. We have modified the "progressive forward method" to Forward Selection (Likelihood Ratio). This method with entry testing is based on the significance of the score statistic, and removal testing is based on the probability of a likelihood-ratio statistic based on the maximum partial likelihood estimates.

(Line 209-210.)

"Was used to conduct correlation analysis"ï check English; vague, please be specific, correlation of what to what? Which variables exactly?

Thank you for pointing this out. The variables we used for factor analysis include mean altitude, mean slope, mean aspect, area, mean annual precipitation, mean annual ground temperature and potential incoming solar radiation.

L 168 same comment as before, these data would be listed in a data sources section. What was the resolution of the climate data? Resampling it does not add any detail and this should be discussed (differences on resolution)

Thanks for your suggestion. The main reason for resampling is to keep the resolution of the climatic data consistent with the resolution of the DEM data. And we have listed the data sources and resolution information for the relevant climate variables in the previous section.

(Table 3 in the manuscript)

L 170 "by" -- > "using". What method? Nearest neighbor? Bilinear? Also note that this is not a suitable method, as proper downscaling would be needed

Corrected. We used the Nearest Neighbor method to resample data and will also try to find better ways to downscale.

- ***Results***

L 176 not clear: "categorized as visual uncertainty". Again, I suggest adding these separately in an uncertainty section which should be expanded

Thanks for your suggestion, we have added a new section on uncertainty to illustrate relevant content.

(4.1.2 Validation of the rock glacier inventory, line 259-266)

L 177 Certainty should not be in caps

Corrected.

L 179 see comment before, acronym can be removed

Corrected.

L 179 do you mean their mean altitude? Please be specific

Yes. It refers to the mean altitude of rock glaciers, which has been be corrected

L 181 vague, please quantify and remove acronyms

Corrected.

L 188 how is this different than previous paragraph? Seems to be the same topic (altitude) so please merge and re-write

Thanks for your suggestion. We have rewritten this paragraph.

(Line 226-231.)

L 189 "gradually" is vague, Is there a significant trend?

Thanks for your comment. We have removed "gradually" from the sentence. The mean altitude of rock glaciers from R1 to R2 decreased from 5116 m a.s.l. to 5060 m a.s.l, and finally decreased to 4845 m a.s.l. in R3.

To further validate the relationship between the mean altitude of rock glaciers and changes in longitude, we conducted a linear regression analysis of the variables in SPSS software, and the results showed that the linear regression model was statistically significant (F=1779.51, p<0.001), indicating a linear relationship between the mean altitude of rock glaciers and longitude (see fig.1). This also illustrates a gradual decrease in the altitude of rock glaciers from R1 to R3.

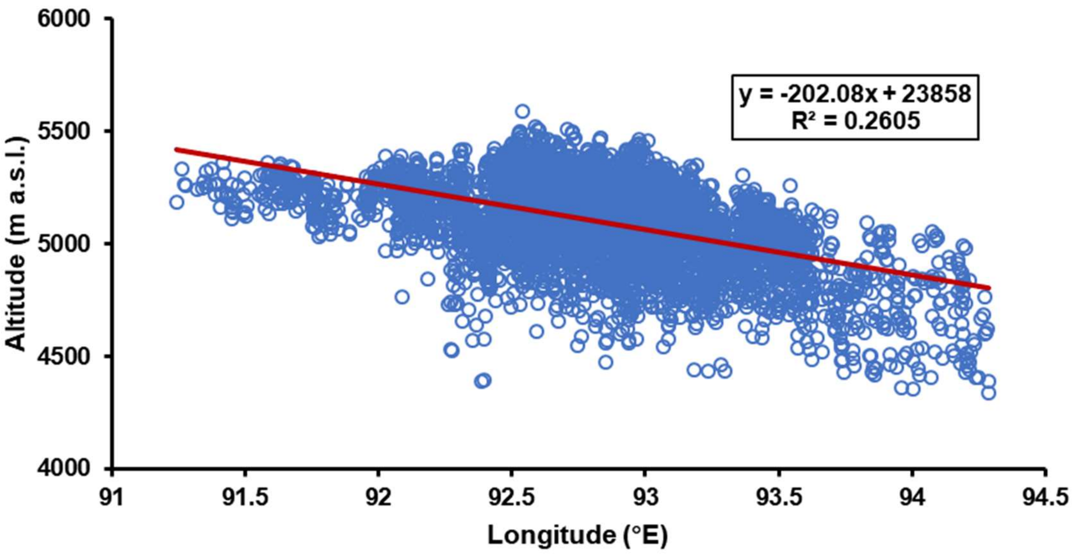

Figure 1: The scatter plot and fit line for altitude and longitude.

L 188 – 207 this entire section is vague and a lot needs quantification (eg "longer length, "higher altitude") and cluttered with acronyms so it is hard to pull out the important bits, please revise.

L 215- 222 same comment here.

We apologize for the confusion caused by the acronyms used in the manuscript. To illustrate the result in this part more clearly, we have reorganized the content of this paragraph in the revised version and no longer use acronyms.

(Line 234-257.)

L 221 "geometry classification" – check English. Not so sure of the utility of the geometry classification with the two sets of aspect figure, I suggest reflecting and picking the most interesting to show

We sincerely appreciate the valuable comments. In our results, rock glaciers with two different planar geometric features did not show much difference in aspect distribution. We have rewritten this part according to your suggestion.

L 225 there is no mention of PCA in the methods, please revisit and the methods accordingly

Thanks for your kind suggestion. We have reconsidered the value of this part of the research and removed it in the manuscript.

L 226 here and elsewhere, avoid starting the phrases with "As shown in Fig xx.

Rather, add it in parenthesis at the end eg (see Fig xx)

Corrected.

Not clear which environmental factors you refer too precisely

I'm sorry we didn't make that clear. By this we mean all the variables including mean altitude, mean slope, mean aspect, area, mean manual precipitation (MAP), mean manual ground temperature (MAGT), and potential incoming solar radiation (PISR) of each rock glacier.

L 227 please use standard term correlation "coefficient" ï "Pearsons' r" and mention the confidence interval

Thanks for your suggestion, we have removed this part in the manuscript.

L 227 which altitude? Mean? Also. Should be plural

Corrected. It is the mean altitude of each rock glacier.

L 228 this does not mean much, as PPT and T are often correlated. Table 3 needs to be presented in more detail, this section is too succinct

Thanks for your suggestion.

- We agree that precipitation and temperature are often correlated, and we have considered the impact of the correlation between temperature and precipitation in the stepwise regression method (Forward Selection (Likelihood Ratio)). And we didn't discuss this relationship in the following part but focused more on the relationship between precipitation and altitude. Because the KMO value is 0.443 which indicates that the original variables are not suitable for PCA (KMO < 0.5, see Table.6), and most correlations here are weak, so we have decided to delete this part in the revised manuscript.
- The more detailed information for Table 3 in the manuscript is below:

Table 6: KMO and Bartlett's test.

Kaiser–Meyer–Olkin measure of sampling adequacy		0.443
Bartlett's test of sphericity	Approx. χ^2	3913.967
	Degree of freedom	21
	Significant level	0.000

Table 7: Correlation matrix of rock glacier variables.

		Area	Mean altitude	Mean slope	Mean aspect	MAP	MAGT	PISR
Correlation	Area	1.000	-0.057	-0.269	-0.062	0.057	-0.096	0.052
	Mean altitude	-0.057	1.000	-0.036	-0.026	-0.462	-0.065	0.213

	Mean slope	-0.269	-0.036	1.000	0.076	-0.042	0.096	-0.217
	Mean aspect	-0.062	-0.026	0.076	1.000	0.024	-0.090	0.030
	MAP	0.057	-0.462	-0.042	0.024	1.000	-0.413	-0.067
	MAGT	-0.096	-0.065	0.096	-0.090	-0.413	1.000	-0.184
	PISR	0.052	0.213	-0.217	0.030	-0.067	-0.184	1.000
Significant level	Area		0.000	0.000	0.000	0.000	0.000	0.000
	Mean altitude	0.000		0.006	0.034	0.000	0.000	0.000
	Mean slope	0.000	0.006		0.000	0.001	0.000	0.000
	Mean aspect	0.000	0.034	0.000		0.044	0.000	0.016
	MAP	0.000	0.000	0.001	0.044		0.000	0.000
	MAGT	0.000	0.000	0.000	0.000	0.000		0.000
	PISR	0.000	0.000	0.000	0.016	0.000	0.000	

L 232 same comment as above "As illustrated in table. . " in the beginning of the phrase

Corrected.

L 234 give these in percent

Corrected.

L 236 what is meant by regional area? Please check formulation

Regional area means the area of rock glaciers in R1, R2, and R3.

L237 "According to" is not correct, can only be used for a person, revise

Corrected. (Base on…)

L 238 confusion here, as it is not GlabTop2 model that estimates the WVEQ ratio, please revise and use active voice

Corrected.

(Line 269-270.)

L 243 name the topo-climatic factors and please be more detailed, re-state the dependent variable. How was the accuracy calculated, on the basis of which data? I do not think this is in the methods

We have listed some topo-climatic factors and variables information in the 'General Comments-Method' part. And the accuracy is the percentage accuracy in classification that is calculated by the SPSS 27.0 software.

(Line 198-213.)

L 248 "previous study results" ï "previous work"

Corrected.

L 257 – 260 this should be in methods, not introduced here. please explain ROC

A receiver operating characteristics (ROC) graph is a technique for visualizing, organizing and selecting classifiers based on their performance (Fawcett, 2006). The accuracies of the models and consensus methods could be calculated using spatially independent test data by the area under the curve (AUC) of the ROC plot. The area under the ROC curve (AUC) is a measure of accuracy, in the sense of the ability of an algorithm to distinguish between two classes or groups. The range of AUC values is from 0.0 to 1.0. A model providing excellent prediction has an

AUC higher than 0.9, a fair model has an AUC between 0.7 and 0.9, and a model is considered poor if it has an AUC lower than 0.7 (Swets, 1988, Marmion *et al.*, 2009).

Therefore, we calculated the AUC to measure the performance of the logistic regression model of the permafrost probability distribution.

L260 "some accuracy" and "closely related" is vague. Not sure what the purpose of l 260 -l 262 is, it does not bring much

Thank you for your suggestions. The original intention of these contents is to prove the reliability of the permafrost prediction model through the results of AUC. We have adjusted this part of the content in the revised manuscript and make supplementary explanations in the method part.

(Line 210-213.)

Discussion

L 264 "on rock glaciers..." ïf something missing here. Rock glacier distribution? Characteristics?

Corrected. (Factors controlling rock glaciers distribution)

L 263 -266 this should be presented as results, and here this decreasing trend should be discussed. However, as I mentioned before, it is not specified if this trend is significant

Thanks for your suggestion. We have added the figure of Scatterplots and fitted curves of the mean altitudinal distribution of rock glaciers versus longitude in the result and further discussed it.

(Line 230-231, 326-340 and Figure 4 in the manuscript.)

L 267 specify the difference with these regions, not just give the studies

Corrected.

(Line 327-331.)

L 273 here and throughout section, use present tense

Corrected.

L 279 "the number of RG increased with precipitation" ïf writing unclear

Corrected.

(Line 337-340.)

L 285 I suggest marking this as a speculation because the link between RG and T and PPT is not clear

We have rewritten this paragraph to discuss the probable controlling factors of rock glaciers distribution.

L 302 – 303 writing is vague

We have written this part.

(Line 330-331.)

L 304 remove "will"; use present tense throughout section

Corrected.

L 305 this strong negative correlation was not specifically presented in results

Removed.

L 310 unlike most ïƒ unlike in the most

Corrected.

L 313 Factor analyses- you mean PCA? Please be consistent

Corrected.

L 320 "450 mm" shows up twice, phrase is circular

Corrected.

L 324 Starting the phrase with "While" is not correct replace with "In contrast,"

Corrected.

L 325 – 330 how do these study results relate to this background information? Please be more clear

Thanks for your suggestion, we have moved these sentences to the 'method' part.

L 333 something missing here too. Consider "Hydrological significant of rock glaciers?"

Corrected.

L 334 "rapid melting" ïƒ reference? What time scale? Rapid melting is at decadal scale but RGs do not form on decadal scales

Corrected.

(5.2 Hydrological significance of rock glaciers)

L 335 "The" ïf "Our"

Corrected.

L 335 – 337 already resented in results, here these should be discussed, rather, without repeating the results

Thanks for your suggestion, we have moved these sentences to the introduction part.

L 349 writing is unclear, if 1:142 then RG store less than clean ice glaciers, except in R2 Here too, use present tense

Corrected. Only in R1 that more water stored in rock glaciers than in clean ice glaciers.

L 340 this is too succinct and lack interpretation. The particularity in R2 is interesting and should be discussed more

Thanks for your suggestion, we have added discussion in this part.

(Line 382-386.)

L 343 "much higher" is vague. Give the % difference. However, it is not correct to just compare an average over the entire region without going a weighted average. This study results are quite consistent with Jones et al for R1 and R3, only R2 differs substamtially, so an average is not adequate

Corrected. We have given more description by using '%' to illustrate the difference.

(Line 380-388.)

L 345 here too, writing is vague "It is pretty similar.." and phase is long

Corrected.

(Line 374-380.)

L 349 unclear which region this is about

Corrected. It is R1 that we discussed here.

L 351 re0write "occurred" ïf was reported; "and the" ïf "where"

Corrected.

L 353 hard to draw any conclusions and the temporal scale is not given

Corrected. We want to illustrate that the high ratio of rock glaciers to clean ice glaciers maybe caused by the absence of clean ice glaciers at present.

L 355 "slightly smaller" is vague

Corrected. We have rewritten this part.

L 362 what do you mean "does not include them in estimation?" estimation of what?

It means that we haven't included the water stored in the relict rock glaciers in our study.

L 375 revise the title of the subsection, it is not clear. Perhaps "RG and permafrost distribution" or as "index to permafrost distribution..? it is not clear in the methods either

Corrected.

(5.3 Rock glaciers can be used to model permafrost probability distribution)

L 376 "very close" – vague

Corrected.

(Line 399-401.)

L 382 "significantly smaller" – idem. Need a statistical test

Corrected.

(Line 409-410.)

L 381 than in other studies

Corrected.

L 382 this is methods, please re-write (what is meant by raster comparison calculation)?

Thanks for your suggestion, we have rewritten this sentence. 'By raster comparison calculation' means that we compare the raster value in the GKLRJ to learn the change between different time periods.

(Line 404-410.)

L 385 use present tense and mark this as a possibility not as certainty

Corrected.

Conclusions

L 398 “Conclusion” –" Conclusions” throughout the section, use present tense for consistency (it is mixed throughout the section)

Corrected.

L 401 “increased and then decreased” – please revise

Corrected.

（Line 423-426.）

L 403 this is contrary to what was stated before, that RGs were favored by increased PPT (l 307) The remaining of the discussion section needs re-writing for ex l

Thank for your suggestion, we have written here.

（Line 421-423.）

L 420 “have a good indication”, etc etc

Thank for your suggestion, we have written the whole section.

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