Responses to the Reviewer's comments:

<u>TO REVIEWER#1</u>

General comments

The authors provide a detailed response to my review. Thanks. Some minor technical remarks are contained in the attached annotated PDF. Special attention should be given to a carefully reflected and precise terminology concerning rock glaciers and what the authors call "ice glaciers" or even "clean ice glaciers". The following basic concepts as related, for instance, to global climate system observation should thereby be considered: Glaciers are simply glaciers. Attributes like "clean" or "ice" are unnecessary if not confusing. Glaciers are by definition surface ice showing signs of flow from an accumulation to an ablation area. There are no other glaciers. The ice in glaciers is never "clean" but always contains impurities. The term "clean glaciers" is therefore fundamentally wrong but nevertheless sometimes used to make a difference between "debris-free" and "debris-covered" glaciers (this would be a correct terminology but is not meant in the present paper). The term permafrost is defined as subsurface material at negative temperatures throughout the year. When such material contains ice - of whatever amount, form or origin – the material is called frozen or perennially frozen.

The key of all this is the difference between surface and subsurface ice as related to the involved physical processes, material properties and time scales.

Glaciers as flowing perennial surface ice are recognizable from visual inspection and primarily depend on surface mass balance. The flowing bodies of what is usually called rock glaciers, in contrast, contain perennial subsurface ice, which is not directly visible and primarily depends on thermal (freezing) conditions below the surface. In order to make these differences clear to readers of scientific publications about comparison between ice volumes, "subsurface ice in rock glacier permafrost" should be opposed to "surface ice in glaciers". I strongly recommend that the authors apply such technically *appropriate terminology.*

In connection with such basic concepts and especially in view of effects from global warming on the water cycle in cold mountains, some other aspects are fundamentally important and could be of interest to the authors.

Both, glaciers as well as creeping frozen materials in rock glaciers only constitute the moving part of surface and subsurface perennial ice. Quasi-static perennial ice patches and ice aprons at the surface, and subsurface ice in frozen bedrock or in deep-reaching permafrost underneath creeping materials also belong to perennial mountain ice. As a consequence, the volumes of ice in glaciers and rock glacier permafrost only constitute a lower limit of the total amount of surface and subsurface ice. The ice contained in creeping permafrost of rock glaciers is thereby very old (millennia; .cf Krainer et al. 2014), i.e. much older than the ice in most glaciers (decades). Permafrost temperatures are currently increasing. Rock glacier permafrost in the region as investigated in the present study is obviously "warm" (not far below 0°C). The corresponding reduction of temperature gradients at depth as documented in borehole observations (Etzelmüller et al. 2020) means that even with near-zero surface temperatures, total permafrost depth can easily be close to 100m or so. Again: there is more permafrost ice in cold mountains than just in the flow structures of rock glaciers. Due to the thermal inertia of permafrost, it will take centuries if not millennia to thaw the frozen material and to melt the corresponding subsurface ice.

The authors should be able to adjust and complete the paper in their own responsibility. They should thereby feel free to use the above explanations.

Thank you again for your careful and professional review of our manuscript. Your valuable suggestions are very important and helpful to us. In the new revised manuscript, we have completely updated the inventory of rock glaciers in this study with reference to the updated inventory guidelines of RGIK (2022b), and re-delineated and reclassified the rock glaciers according to the practical concepts provided by them, which may have resulted in some changes in the revised manuscript compared to the previous one. At the same time, considering the uncertainty of the Google Earth images and climate-topography data from different time period, we decided to remove the section of permafrost probability prediction based on the activity types of rock glaciers, and replace it with a comparative analysis of the extent of the rock glacier distribution with the map of Permafrost Zonation Index (PZI) in GKLRJ (Gruber, 2012) and the map of the thermal stability of permafrost in GKLRJ (Ran *et al.*, 2020). In addition, we have also redesigned some of the figures in the manuscript, and we sincerely hope that these improvements will further enhance the manuscript and welcome any further suggestions you may have.

We have provided a point-by-point response to your comment below, and we will try our best to revise the manuscript according to your kind suggestions. The comments are laid out below in italicized font. Our responses are given in the blue text.

Specific comments

Line 15: What exactly is meant with this? Explain.

Thanks for your suggestions .Based on the result of the below figure we have corrected here to"Under the same ground temperature conditions, increases in precipitation are conducive to rock glaciers forming at lower altitudes."

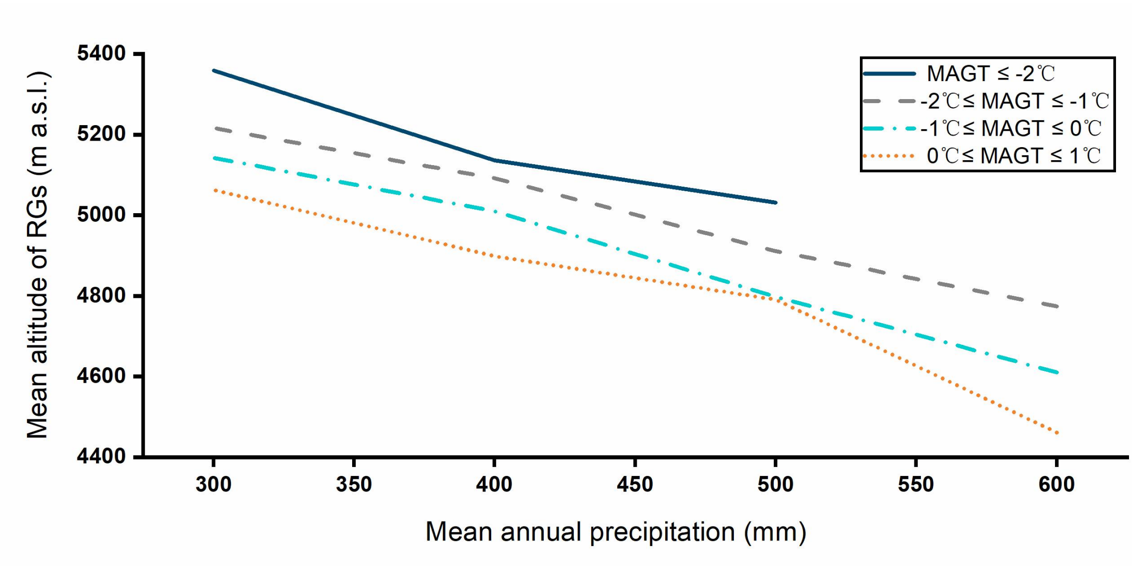

Figure : The variation in rock glacier distribution altitude with changes in precipitation for different MAGT states.

Line 19: Better: " ... the subsurface ice of rock glacier permafrost ... than of surface ice in local glaciers." See the general remarks on apprpriate terminology.

Corrected.

Line 38: add empty space

Corrected.

Line 51: Better - and more modest:" ... it is experiencing rapid geomorphic evolution today (..."

Corrected.

Line 59: Better: "difficult"

Corrected.

Line 68: Better: " ... in light blue ..."

Corrected.

Line 85-87: Are these ranges of temperatures (from -7.7 to 8.8°C)? To what altitude and time period do the numbers refer? The values given here do not seem to correspond to the values given in Table 4. In what sense is the ~ sign used here? Make clear and check throughout the paper for consistency.

The MAAT data in Fig.1(c) and in Table.4 are both provided by Du and Yi (2019), it represents the MAAT in 2015. The range (-7.7 to 8.8℃) reflects the range of variation in MAAT across the study area, while the data in Table. 4 are statistical averages of the MAAT within each rock glacier. In addition, we have checked the ~ sign and corrected it to "–".

Line 109: Better: "perpendicular"

Corrected.

Line 148-149: Better: " ... of the perennially frozen rock glaciers and of surface ice in glaciers ..."See general comments on terminology.

Corrected.

Line 169-170: Better: "The ice content in rock glacier permafrost is spatially variable." The ice content itself is not part of definitions. The definition relates to permafrost, which is a subsurface thermal condition independent of any ice or material properties. The empirical ice contents reported in the literature are based on drilling and geophysical soundings. For long-term viscous flow in rock glaciers, ice-supersaturation or excess ice is needed to induce cohesion and to reduce internal friction. The values used here reflect such conditions.

Thanks for your suggestion. We have corrected it.

Line 179: Better: " ... of surface ice in glaciers."

Corrected.

Line 240: This is important information. It should be noted in the text that such values characterize relatively "warm permafrost". See also the general remarks on subsurface thermal conditions under the effects of continued long-term surface warming

Thanks for your suggestions. In the revised draft, we further discussed the relationship between MAGT, MAP and mean altitude in the distribution area of rock glaciers, and added relevant content in the discussion section. The details are as follows:

- Line 220-226:

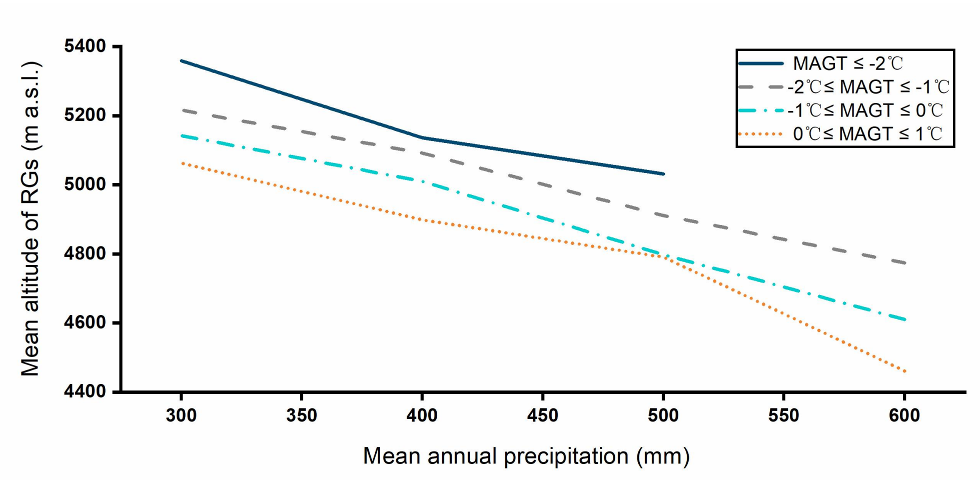

Figure 6: The variation in rock glacier distribution altitude with changes in precipitation for different MAGT states.

Around 90% of the rock glaciers in GKLRJ are found in the region where the MAGT ranges from -2°C to 0°C. Additionally, the MAGT, MAAT and MAP of the rock glaciers vary among the three sub-regions (Table.4). Specifically, the mean MAGT decreases gradually from R1 to R3, while the mean MAP increases gradually. The mean MAAT follows the same order as the regional mean MAAT values listed in Table 1. With the same MAGT, the mean altitude of rock glacier distribution decreases with increasing MAP. Moreover, with the same MAP, the altitude of rock glacier distribution increases with decreasing MAGT (Fig.6).

Table 4: Mean characteristics for rock glaciers.

Type	R1	R2	R3
Number	524	3,447	1,086
Mean altitude (m asl)	5,132	5,117	4,909
Mean MEF (m asl)	5,083	5,051	4,845
Mean area (km^3)	0.06	0.08	0.07
Mean slope range (°)	19.85	19.23	21.43
Mean MAGT (ºC)	-0.02	-0.6	-0.9
Mean MAAT (ºC)	-1.68	-1.94	-1.54
Mean MAP (mm)	343	392	495

MEF: minimum altitude at the rock glacier front

MAGT: mean annual ground temperature

MAAT: mean annual air temperature

MAP: mean annual precipitation

Line 367-374:

With future climate warming, the permafrost located in the eastern part of the Tibetan Plateau with lower ground temperatures may experience a faster warming rate (Cheng *et al.*, 2019). This could result in rapid changes in the movement speed and surface morphology of rock glaciers in GKLRJ over a short period of time (Ikeda *et al.*, 2008; Krainer and Mostler, 2006). However, research has shown that despite the relatively rapid increase in ground temperatures in the deep layers of permafrost, as well as the presence of subsurface ice and geothermal gradients, the thawing of permafrost on the Tibetan Plateau occurs at a slow pace (Cheng *et al.*, 2019). It may take centuries, if not millennia, for the frozen material and corresponding subsurface ice in rock glaciers and permafrost to completely thaw and melt (Krainer *et al.*, 2015).

Line 269: eliminate - unnecessary. See general remarks about terminology

Corrected.

Line 274: Better just "thickness" (without the "ice"). Here is a fundamentally important aspect, which the authors should try to fully understand: The thickness estimates provided in the literature relate to the "flowing" or "creeping" body. The corresponding depth limit often relates to internal shear horizons or bedrock. Permafrost depth and, hence, ice containing perennially frozen subsurface material can reach far beyond such depths (cf. Cicoira et al. as cited in the paper).

Thanks for your suggestions. We have corrected it here as you suggested.

Line 292: "based on the ..."?'

Corrected.

Line 303: In what sense is the ~ sign used here? Make clear and check throughout the paper for consistency.

Thanks to your reminder, we have rechecked the manuscript and corrected the inconsistencies (0.50–0.59).

Line 399: Better: "The minimum front elevation (MFE) of the intact rock glaciers ..."

Corrected.

Line 421: Better make two sentences:" ... R2. The high altitude ... "

Corrected.

Line 427: Better: " ... of the water presently stored in surface ice of glaciers."

Corrected.

Line 428: Better: "perfect plasticity model"

Corrected.

Line 431: Better: " ... ratio of subsurface ice in rock glacier permafrost to surface ice in glaciers may ...

Corrected.

Line 433: Better " ... the lower boundary ..."

Corrected.

Line 435: Better (and more firmly - this result is safely documented in the present study): " ... indicating the high probability of widespread permafrost conditions to occur."

Corrected.

■ Reference:

Cheng, G., Zhao, L., Li, R., Wu, X., Sheng, Y., Hu, G., Zou, D., Jin, H., Li, X., and Wu, B.: Characteristic, changes and impacts of permafrost on Qinghai-Tibet Plateau (in Chinese), Chinese Science Bulletin, 64, 2783-2795, 10.1360/TB-2019-0191, 2019.

Du, Y. Y., Yi, J. W.: Data of climatic factors of annual mean temperature in the Xizang (1990-2015), National Tibetan Plateau Data Center [data set], 2019.

Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, The Cryosphere, 6, 221-233, 10.5194/tc-6-221-2012, 2012.

Ikeda, A., Matsuoka, N., and Kääb, A.: Fast deformation of perennially frozen debris in a warm rock glacier in the Swiss Alps: An effect of liquid water, Journal of Geophysical Research: Earth Surface, 113, https://doi.org/10.1029/2007JF000859, 2008.

Janke, J. and Bolch, T.: Rock Glaciers. Reference Module in Earth Systems and Environmental Sciences, 2021.

Krainer, K., Bressan, D., Dietre, B., Haas, J. N., Hajdas, I., Lang, K., Mair, V., Nickus, U., Reidl, D., Thies, H., and Tonidandel, D.: A 10,300-year-old permafrost core from the active rock glacier Lazaun, southern Ötztal Alps (South Tyrol, northern Italy), Quaternary Research, 83, 324–335, https://doi.org/10.1016/j.yqres.2014.12.005, 2015.

Krainer, K., and Mostler, W.: Reichenkar rock glacier: a glacier derived debris-ice system in the western Stubai Alps, Austria, Permafrost and Periglacial Processes, v. 11, no. 3, p. 267-275, 2000.

Ran, Y., Li, X., Cheng, G., Nan, Z., Che, J., Sheng, Y., Wu, Q., Jin, H., Luo, D., Tang, Z., and Wu, X.: Mapping the permafrost stability on the Tibetan Plateau for 2005–2015, Science China Earth Sciences, 64, 62-79, 10.1007/s11430-020-9685-3, 2020.

RGIK. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp. 2022b.

TO REVIEWER#2

General comments

This manuscript presents the results from a rock glacier inventory of the Guokalariju (GKLRJ) area of the Tibetan Plateau (TP) and integrates the obtained results with assumptions on permafrost distribution and water equivalent. The underlying method is based on the interpretation of satellite images from Google Earth and an ASTER DEM.

It is clear that the authors have made an effort to document rock glaciers from a very remote and poorly documented region. Potentially, the paper would have contributed to understanding rock glacier distribution in the TP. However, the study exhibits some methodological, theoretical and aesthetic shortcomings (most figures are poorly constructed) which deem this work unsuitable for publication in its current form. The authors have not presented a comprehensive analysis of the area, as the data collection is incomplete and the methods of analysis are confusing. Additionally, the lack of clarity in the figures presented makes it difficult to interpret the results, and the aesthetics of the figures are not up to publication standards (illegible legends).

The study is substantially flawed by the classification of rock glaciers into four types. Figure 2 does not clearly indicate that "debris-derived rock glaciers" and "talus-derived rock glaciers" are different from one another. Additionally, the review of the supplementary material (KML file) indicates some inconsistencies among some rock glacier outline styles. Some rock glaciers are mapped using the extended outlines whereas others are mapped using the restricted outlines (see baseline and practical concepts in the RGIK Action Group documents). Using the extended outlines for a rock glacier inventory involves adding mostly ice-free areas (e.g. Talus front and lateral margins). This in turn has implications for the calculation of the water equivalent since the extended outlines add additional areas without significant ground ice to the volumetric calculations (see Mathys et al., 2022).

We feel great thanks for your professional review work on our article. According to your nice suggestions, we have made extensive corrections to our previous draft. Firstly, we inventoried rock glaciers following the inventorying strategy in RGI_PCv2.0 (RGIK, 2022b), and we classified rock glaciers according to their type of activity and upper slope connection. The digital KMZ file has been uploaded to the supplementary material (RGIK, 2022a, 2022b). Secondly, we redraw the images with possible problems to demonstrate our results in a clearer way. We sincerely hope that the improved graph will meet the requirements of the publication. Thirdly, although the study of the extended outline may have caused an overestimation of water reserves for rock glaciers, as most previous studies have used extended outlines for rock glacier delineation (Hausmann et al., 2012; Rangecroft et al., 2015; Jones et al., 2018b, 2021;), we have chosen to continue to use this criterion in this manuscript in order to facilitate comparison with existing results. In order to reduce the overestimation of the subsurface ice of rock glacier permafrost, we have chosen the thickness of the rock glacier obtained from the perfect plasticity model calculations (Cicoira *et al.*, 2021). Compared to the empirical area-thickness formula (Brenning, 2005a), the thickness results obtained by the 'Cicoira' method (Cicoira *et al.*, 2021) are closer to the actual thickness of rock glaciers in GKLRJ, which can reduce the overestimation of rock glacier water storage to a certain extent. Moreover, considering the uncertainty of the Google Earth images and climate-topography data from different time period, we decided to remove the section of permafrost probability prediction based on the activity types of rock glaciers, and replace it with a comparative analysis of the extent of the rock glacier distribution with the map of Permafrost Zonation Index (PZI) in GKLRJ (Gruber *et al.*, 2012) and the map of the thermal stability of permafrost in GKLRJ (Ran *et al.*, 2020).

We have provided a point-by-point response to your comment below, and we will try our best to revise the manuscript according to your kind suggestions. The comments are laid out below in italicized font. Our responses are given in the blue text.

Specific comments

Line 36: This is not supported by the associated references.

Thanks for your suggestion, we have rechecked this reference and removed it from here.

Line 45: This reference is unrelated to the topic of this sentence.

Thanks for your suggestion, we have rechecked this reference and removed it from here.

Line 73-75: This is very vague and unclear. Please provide more support for this statement about why periglacial geomorphology is seminal to the study

Thank for you helpful suggestion, we have corrected this sentence. The study of periglacial geomorphology in GKLRJ is of great significance because it is not only characterized by extensive Quaternary glacial landforms and periglacial landforms but also located in a transitional zone between semi-arid and semi-humid climates regions (Zheng *et al.*, 2010). This provides an opportunity to investigate the influence of different climate conditions on landscape evolution and distribution. Additionally, GKLRJ is an important agricultural area in Tibet with a dense population. Therefore, enhancing our understanding of periglacial landforms in this region is crucial for ensuring ecological security, water resource management, and socioeconomic development (Yao *et al.*, 2022).

Line 89: This is unclear. does the MAGT represent one or more sites in the region? where did this data come from?

The source of data for MAGT is Ran *et al.* (2020), and we calculated the mean MAGT of each sub-region here in ArcGIS 10.7.

Line 98: What do you mean by paleoglacial erosion? Do you have an estimate of when this erosion was active?

'Paleoglacial erosion' here refers to the erosion of glaciers that once existed but have now melted in this area. Although we have carried out fieldwork in this area, the specific dating results have not yet been obtained.

Line 108: Do you mean one of the criteria?

Line 116-117: This is not always the case. Especially if you are quoating the work of the RGIK Action Group this criterion is optional.

Line 121-122: This is a tautology.

Thanks for your suggestions. We have re-detected, located, characterized and delineated the rock glaciers in the study area according to the updated standard guidelines for inventorying rock glaciers (RGIK, 2022a). The revised part in the manuscript is as follows:

"We used high-resolution ©Google Earth Pro remote sensing images from March 2004 to August 2020 to manually and visually interpret and compile a rock glaciers inventory for the GKLRJ (Selley *et al.*, 2018; Magori *et al.*, 2020; Hassan *et al.*, 2021). The inventorying strategy follows the RGI_PCv2.0 (RGIK, 2022b). According to the technical definition of rock glaciers, we conducted the detection of rock glacier landforms in the study area and confirmed the relevant landforms (system/unit). For areas with missing clear imagery and those covered by snow, we simultaneously used the ©Map World for comparison and verification, ensuring that all outline segments can be labeled with certainty. Each cataloged rock glacier system/unit was assigned a primary ID and delineated according to the extended standards, with the outline encompassing the entire rock glacier up to the rooting zone, including its external parts such as the front and lateral margins (RGIK, 2022b). We followed as closely as possible the specific rules for delineating the upper boundaries of the rock glacier and provided information on their upslope connection type in the attribute table. Due to the limited availability of accurate field observations and related data on rock glacier dynamics, their activity states were determined solely based on geomorphological criteria. The activity type of each rock glacier was recorded in the attribute table."

Line 131: If you are working with a UTM projection, these angular values become metric values (northing and easting).

Corrected.

"All shapefiles were fed into the WGS 1984 coordinate system to extract their topographic attributes using ArcGIS 10.7 software."

Line 158: Be aware that the mean aspect cannot be meaningfully described by ordinary arithmetic means such as those available in ArcGIS Zonal Statistics.

Thanks for your suggestions. We feel sorry for our carelessness. This led us to find that there are a large number of rock glaciers distributed on the north-facing aspect in the study area, but they were misclassified in the previous analysis. In the revised manuscript, we have used the 'majority aspect' of each rock glacier to reflect their real aspects. We also confirmed and corrected them in Google Earth images. The relevant results and discussions were both revised in the manuscript.

Line 192: This is kind of perplexing. Delugi et al, 2017 used three classification algorithms and showed that the support vector machine approach outperformed the more conventional ones.

Thanks for your suggestions. We re-examined this reference and revised it.

Line 224: Please specify the mean area unit in the graph.

Corrected.

Line 244: rock glacier front

Corrected.

Line 322: Please check the terminology used here. I think ecological niche does not apply here.

Corrected.

"Compared with R3, which has a lower ELA (mean ELA = 5,292 m asl), and R1, which has a higher MAAT, R2 exhibits a broader range of the cryogenic belt to meet the development and distribution of more rock glaciers."

Line 349-350: This came out of the blue. The calculation of PISR should be in the methods section.

Thanks for your suggestions. We have moved this sentence to the methods section.

Line 370: This reference is unrelated to the topic of this sentence.

Thanks for your suggestions. We re-examined this reference and removed it.

Line 379: This reference is unrelated to the topic of this sentence.

Thanks for your suggestions. We re-examined this reference and removed it.

■ Reference:

Brenning, A.: Climatic and geomorphological controls of rock glaciers in the Andes of Central Chile: Combining Statistical Modelling and Field Mapping. Humboldt-Universität zu Berlin, Berlin, Germany, 2005a.

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.

Gruber, S.: Derivation and analysis of a high-resolution estimate of global permafrost zonation, The Cryosphere, 6, 221-233, 10.5194/tc-6-221-2012, 2012.

Hassan, J., Chen, X., Muhammad, S., and Bazai, N. A.: Rock glacier inventory, permafrost probability distribution modeling and associated hazards in the Hunza River Basin, Western Karakoram, Pakistan, Sci Total Environ, 782, 146833, 10.1016/j.scitotenv.2021.146833, 2021.

Hausmann, H., Krainer, K., Brueckl, E., and Ullrich, C.: Internal structure, ice content and dynamics of Ölgrube and Kaiserberg rock glaciers (Ötztal Alps, Austria) determined from geophysical surveys, Austrian Journal of Earth Sciences, 105, 12-31, 2012.

Jones, D. B., Harrison, S., Anderson, K., Selley, H. L., Wood, J. L., and Betts, R. A.: The distribution and hydrological significance of rock glaciers in the Nepalese Himalaya, Global and Planetary Change, 160, 123-142, 10.1016/j.gloplacha.2017.11.005, 2018b.

Jones, D. B., Harrison, S., Anderson, K., Shannon, S., and Betts, R. A.: Rock glaciers represent hidden water stores in the Himalaya, Sci Total Environ, 793, 145368, 10.1016/j.scitotenv.2021.145368, 2021.

Magori, B., Urdea, P., Onaca, A., and Ardelean, F.: Distribution and characteristics of rock glaciers in the Balkan Peninsula, Geografiska Annaler: Series A, Physical Geography, 102, 354-375, 10.1080/04353676.2020.1809905, 2020.

Ran, Y., Li, X., Cheng, G., Nan, Z., Che, J., Sheng, Y., Wu, Q., Jin, H., Luo, D., Tang, Z., and Wu, X.: Mapping the permafrost stability on the Tibetan Plateau for 2005–2015, Science China Earth Sciences, 64, 62-79, 10.1007/s11430-020-9685-3, 2020.

Rangecroft, S., Harrison, S., and Anderson, K.: Rock glaciers as water stores in the Bolivian

Andes: an assessment of their hydrological importance, Arctic Antarctic and Alpine Research, 47, 89-98, 10.1657/aaar0014-029, 2015.
RGIK. Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp, 2022a.
RGIK. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp. 2022b.
Selley, H., Harrison, S., Glasser, N., Wündrich, O., Colson, D., and Hubbard, A.: Rock glaciers in central Patagonia, Geografiska Annaler: Series A, Physical Geography, 101, 1-15, 10.1080/04353676.2018.1525683, 2018.
Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G., and Zhao, P.: The imbalance of the Asian water tower, Nature Reviews Earth & Environment, 3, 618–632, https://doi.org/10.1038/s43017-022-00299-4, 2022.
Zheng J, Yin Y, Li B. A New Scheme for Climate Regionalization in China, ACTA GEOGRAPHICA SINICA, 65, 3-12, 10.11821/xb201001002, 2010.