Assessment of rock glaciers and their water storage in Guokalariju, Tibetan Plateau

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Abstract. Rock glaciers are important hydrological reserves in arid and semi-arid regions. Their activity states can indicate the existence of permafrost. To help explore further the development mechanisms of rock glaciers in semi-arid and humid transition regions, this paper provides a detailed rock glacier inventory of the Guokalariju area of the Tibetan Plateau (TP) using a manual visual interpretation of Google Earth Pro remote sensing imagery. We also estimated the water volume equivalent (WVEQ) in the study area for the first time. Approximately 5,057 rock glaciers were identified, covering a total area of ~404.69 km^2. Rock glaciers are unevenly distributed within the three sub-regions from west to east, with 80% of them concentrated in the central region, where climatic and topographic conditions are most favorable. Under the same ground temperature conditions, increases in precipitation are conducive to rock glaciers forming at lower altitudes. Indeed, the lower limit of rock glaciers' mean altitude decreased eastward, with increasing precipitation. Estimates of the water storage capacity of rock glaciers obtained by applying different methods varied considerably, but all showed the potential hydrological value of rock glaciers. The possible water storage in the subsurface ice of rock glacier permafrost was 1.32-3.60 km^3. The ratio between the amount of subsurface ice stored in rock glaciers and surface ice stored in local glaciers fall within the range of 1:2.32 to 1:1.26, with an average ratio of 1:1.69. In the west region, where the climate is the driest, the water storage capacity of rock glaciers was estimated to be up to twice as large as that of the sub-region's glaciers. Changes in water resources and permafrost stability in the area where rock glaciers occur will have implications for regional water resource management, disaster prevention, and sustainable development strategies.

1 Introduction

Rock glaciers are periglacial landforms often observed above the timberline in alpine mountains. They are formed by rocks and ice that move down a slope, driven by gravity (French, 2007; RGIK, 2022a). As striking features of viscous flow in perennially frozen materials, they can reflect permafrost conditions in mountainous areas. Their lowest altitudes are often considered to represent the lower limit of discontinuous regional permafrost occurrence (Giardino and Vitek, 1988; Barsch, 1992, 1996; Kääb *et al.*, 1997; Schmid *et al.*, 2015; Selley *et al.*, 2018; Baral *et al.*, 2019; Hassan *et al.*, 2021); their states (active or relict) can be used in Permafrost Zonation Index (PZI) models to predict the probability of permafrost occurrence where field observation data are scarce (Cao *et al.*, 2021; Boeckli *et al.*, 2012a). The large-scale distribution of active rock glaciers is influenced by the complex interaction of climatic and topographic factors (Schrott, 1996; Millar and Westfall, 2008; Pandey, 2019). Global climate change may result in permafrost thawing and ice melting in rock glaciers, thus impacting slope stability, runoff patterns, and water quality, with possible consequences for

periodic landslides, debris flows, floods, and other geological disasters (Barsch, 1996; Schoeneich *et al.*, 2015; Blöthe *et al.*, 2019; Hassan *et al.*, 2021; Yao et al., 2022). Exploring their spatial distribution and evolution is therefore significant for paleoclimatic modeling, disaster risk assessment, and infrastructure maintenance (Arenson and Jakob, 2010; Colucci *et al.*, 2016; Selley *et al.*, 2018; Alcalá-Reygosa, 2019). Furthermore, the

40   slow thawing process through heat diffusion with latent heat exchange at depth, combined with the cooling effect of the ventilated coarse blocks at the surface of rock glaciers, make them a long-term hydrological reserve in high mountain systems (Bolch and Marchenko, 2009; Berthling, 2011; Bonnaventure and Lamoureux, 2013; Millar and Westfall, 2013). The presence and abundance of rock glaciers can therefore affect the quantities and properties of runoff from high mountain watersheds over extended time periods (Jones *et al.*, 2019b).

45   The Tibetan Plateau (TP) is among the key high-altitude areas of periglacial landform worldwide and is a region highly sensitive to climate change (Cui *et al.*, 2019; Yao *et al.*, 2019). Detailed rock glacier inventories have previously been constructed for the Gangdise Mountains (Zhang *et al.*, 2022), the Daxue Mountains (Ran and Liu, 2018), the Nyainqêntanglha Range (Reinosch *et al.*, 2021), and the Nepalese Himalaya (Jones *et al.*, 2018b). The Yarlung Zangbo River Basin (YZRB) is one of the regions with the highest concentrations of

50   modern glaciers on the TP; it is experiencing rapid geomorphic evolution today (Ji *et al.*, 1999; Korup and Montgomery, 2008; Yu *et al.*, 2011; Long *et al.*, 2022). Although Guo (2019) characterized the spatial distribution of rock glaciers in the YZRB using manual visual interpretation, there remains a lack of any systematic and detailed rock glacier inventory, and the regional occurrence characteristics and indicative environmental significance of these rock glaciers are still unclear. Even though ground-penetrating radar (GPR),

55   seismic refraction tomography (SRT), electrical resistivity tomography (ERT), and other geophysical techniques are widely used today and can provide new insights into understanding the ice volumes of rock glaciers and permafrost (Janke *et al.*, 2015; Emmert and Kneisel, 2017; Bolch *et al.*, 2019; Buckel *et al.*, 2021; Halla *et al.*, 2021; Mathys *et al.*, 2022), it remains difficult to apply such methods to large-scale field-based research on the TP. The distribution of permafrost and the hydrological contributions made by rock glaciers on the TP need

60   more research.

        To address this, our study aims to: (i) compile a more comprehensive and systematic inventory of rock glaciers in the Guokalariju; (ii) explore the regional occurrence characteristics and indicative environmental significance of these rock glaciers; (iii) assess the regional hydrological significance of rock glaciers and glaciers; and (iv) compare the distribution of the Guokalariju's rock glaciers to the regional permafrost maps.

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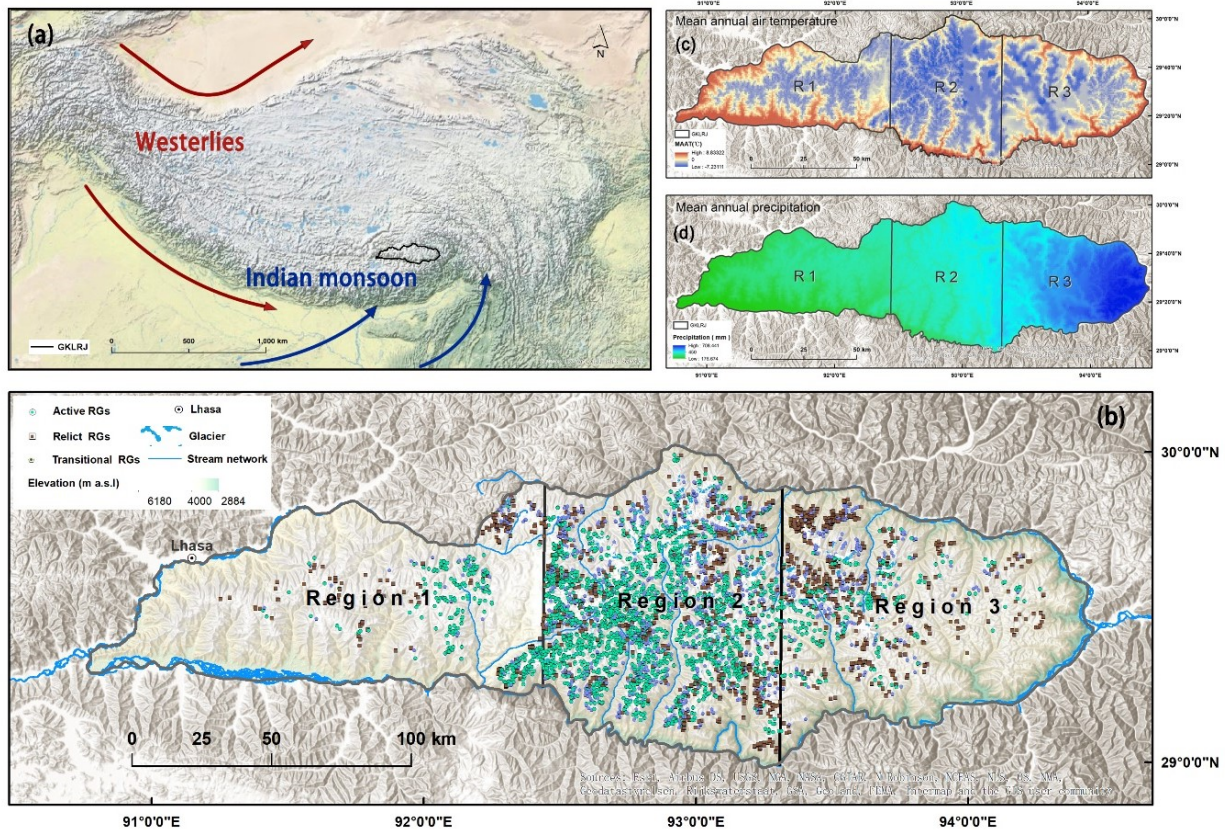
Figure 1: (a) The location of Guokalariju on the TP; (b) The three sub-regions and the spatial distribution of streams. Rock glaciers are categorized as green (active rock glaciers), purple (transitional rock glaciers), and brown (relict rock glaciers), and glaciers are shown in light blue and white;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

The Guokalariju is located between 92.916°N–93.276°N and 29.287°E–29.438°E, on the southeastern TP, adjacent to the Himalayas to the south and the Nyainqêntanglha Range to the north (Fig.1a). It forms the eastern extension of the Gangdise Mountains as well as the watershed of the Yarlung Zangbo River and its tributary, the Niyang-Lhasa River, and belongs to the high mountain plateau-lake basin-wide valley area of the middle and upper reaches of the Yarlung Zangbo and Nujiang rivers (Xiang *et al.*, 2013). The region is also within the world's largest irrigated agricultural area and has a dense population (Yao *et al.*, 2022).

Tectonically, the study area is located in the eastern part of the Ladakh-Kailas-Xiachayu magmatic arc of the Gangdise-Himalayan collisional orogen; from the Late Paleozoic to the Mesozoic, it has experienced the same evolutionary tectonic processes as the Gangdise-Himalayan archipelagic arc-basin systems, *i.e.*, back-arc spreading, arc-arc collision and arc-continental collision (Pan *et al.*, 2013). The main rock types in the study area include Late Cretaceous quartz monzonite, Eocene monzonite, and Eocene biotite granite. It is located in the transition belt between the TP's semi-arid and humid regions (Zheng *et al.*, 2010), mainly dominated by the Indian Summer Monsoon (ISM). The middle and western parts of the study area belong to the TP's temperate, semi-arid zone, while the eastern part belongs to the plateau's temperate humid region (Zheng *et al.*, 2010). The mean annual air temperature (MAAT) reaches from -7.2 to 8.8ºC (Du and Yi, 2019) (Table 1 and Fig.1c), and the mean annual ground temperature (MAGT) reaches from -3.2 to 4.3ºC (Ran *et al.*, 2020) (Table 1). The mean annual precipitation (MAP) is 177–708 mm, decreasing from east to west across the study area (Du and Yi, 2019)

(Table 1 and Fig.1d). Changes in the imbalance between glaciers, permafrost, lakes, and rivers in this region under the influence of climate change may lead to spatial and temporal changes in local ecosystems and changes in water resources in downstream areas (Yao *et al.*, 2022).

Table 1: MAAT (Du and Yi, 2019), MAGT (Ran *et al.*, 2020), MAP (Du and Yi, 2019), mean altitude (ASTER GDEM v3) and mean glacier ELA (RGI Consortium, 2017) for the Guokalariju and its three sub-regions.

Region	MAAT (ºC)	MAGT (ºC)	MAP (mm)	Mean altitude (m asl)	Mean glacier ELA (m asl)
All	0.69	0.53	469	4,623	5,433
Western	1.78	1.65	385	4,589	5,527
Central	-0.63	-0.06	489	4,893	5,478
Eastern	0.91	0.01	534	4,398	5,265

MAGT: mean annual ground temperature
MAAT: mean annual air temperature
MAP: mean annual precipitation

We divided the study areas into the western, central, and eastern sub-regions. These divisions were geospatially based (Fig.1b), where the western and central regions are bounded by the east marginal rift valley of the Oiga Basin, and the central and eastern regions are bounded by Niang River, a tributary of the Niyang River. Each sub-region displays unique characteristics in terms of its topography and climate (Table 1). The whole of the western region is a semi-arid region, and the terrain is more complex here. The west side of the western region is composed of a deep alpine valley landscape formed by glacial-fluvial erosion cutting through the undulating terrain, while the east side is a basin formed by paleo-glacial and fluvial erosion and cutting through less undulating mountainous hills with relatively gentle tops (Wu *et al.*, 2010). The central region is a semi-arid and semi-humid transition zone where the dividing line is located in its northeastern part; the mean altitude here is higher than in the other regions. The main peaks of glacier-carved mountains occur mostly above 5,500 m asl. The east region is located in a semi-humid zone where precipitation is more abundant and the terrain is on average ~500 m lower than that of the central region.

3 Material and methods

3.1 Rock glacier inventory, classification, and database

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 study area (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. Following the baseline concepts, the rock glacier without any (significant) headwall is classified as the "debris-mantled slope-connected" (Fig. 2a), the rock glacier unit subjacent and connected to a talus slope unit is classified as the "talus-connected" (Fig. 2b), and the rock glacier developed within or from a (formerly) glaciated area is classified as the "glacier forefield-connected" (RGIK, 2022a) (Fig. 2c). In addition, any

125 landform consisting of a single rock glacier unit or multiple spatially connected units is classified as a rock glacier system (RGIK, 2022a) (Fig. 2d). We also provided information on their morphological system and units as well as their upslope connection type in the attribute table (RGIK, 2022a, 2022b). 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 (RGIK, 2022a). In general, the "active" rock glacier has a

130 steep front and freshly exposed material on top, indicating current movement (Fig.2e), the "transitional" rock glacier has less distinct evidence of current movement compared to active ones in the same region (Fig.2f), while the "relict" rock glacier shows no recent movement and has a subdued topography, smooth lateral and frontal slopes/margins, and may have developed vegetation and soil cover (RGIK, 2022a) (Fig. 2g). The activity type of each rock glacier was recorded in the attribute table. Furthermore, we applied One Way ANOVA in

135 SPSS27® software based on the F-test method to analyze the differences between groups of different types of rock glaciers in terms of mean altitude, mean area, and mean slope. The significance was evaluated at the level $p < 0.05$.

Figure 2: Example images of different upslope boundary types of rock glaciers in Guokalariju. (a) a debris-mantled
140 **slope-connected rock glacier; (b) a talus-connected rock glacier; (c) a glacier forefield-connected rock glacier; (d) a rock glacier system; (e) an active rock glacier; (f) a transitional rock glacier; (g) a relict rock glacier. Images from ©Google Earth.**

3.2 Estimating the hydrological storage

To calculate more accurately the water content (water volume equivalent, WVEQ [km^3]) of the perennially frozen rock glaciers and surface ice in glaciers in the study area (Jones *et al.*, 2018b), we chose two different methods derived from Brenning (2005a) and Cicoira *et al.* (2021). The previous studies mostly treated active and transitional rock glaciers collectively as intact rock glaciers with the same ice content to calculate the water storage. Therefore, for comparison with the results of other studies, we also did not consider relict rock glaciers when calculating the hydrological storage of rock glaciers by using the methods of Brenning (2005a) and Cicoira *et al.* (2021). Meanwhile, we also provided calculations based on the Janke *et al.* (2015) proposal in the Supplement (Table S1).

The method for calculating the subsurface ice volumes of rock glaciers permafrost provided by Brenning (2005a) requires multiplying the mean thickness, surface area, and ice content of each rock glacier as in Eq. (1), then converting them to the WVEQ by assuming an ice density conversion factor of 0.9 g cm^{-3} ($\equiv 900$ kg m^{-3}) (Paterson, 1994; Jones *et al.*, 2018b), thus:

$$V_{RG} = \text{Area} \times \text{Mean thickness} \times \text{Ice Content} \tag{1}$$

Based on field data from Brenning (2005a) and a rule-of-thumb given by Barsch (1977c) for the Swiss Alps, the rock glacier thickness was modeled empirically as Eq. (2), thus:

$$\text{Mean thickness [m]} = 50 \times (\text{Area [km}^2])^{0.2} \tag{2}$$

The method provided by Cicoira *et al.* (2021), based on the analysis of a dataset of 28 rock glaciers from the Alps (23) and the Andes (5), estimated rock glacier thickness using a perfectly plastic model arrived at by solving Eq. (4) for *H*, assuming a yield stress of $\tau = 92$ kPa (taking the mean driving stress from the dataset as a given), thus:

$$H = \frac{\tau}{\rho g \sin\alpha} \pm 3.4\text{m} \tag{3}$$

where τ is the shear stress ($\tau = 92$ kPa), g is the gravitational acceleration, H is the thickness of the moving rock glacier, α is the angle of the surface slope 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 ($\rho_i = 910$ kg m^{-3} and $\rho_d = 2700$ kg m^{-3}), thus:

$$\rho = \rho_d w_d + \rho_i w_i \tag{4}$$

The ice content in rock glacier permafrost is spatially variable. We therefore used global estimates of ice content within rock glaciers to further calculate their lower (40%), mean (50%) and upper (60%) ice volumes (Hausmann *et al.*, 2012; Krainer and Ribis, 2012; Rangecroft *et al.*, 2015; Jones *et al.*, 2018b; Wagner *et al.*, 2021). In this study, the results of the calculations that used a 50% ice content were used for subsequent comparisons with the surface ice in glaciers.

The ice volume of the glacier was calculated using Eq. (5), thus:

$$V = A \times H \tag{5}$$

where *V* represents ice volume, *A* is the glacier surface area derived from the Randolph Glacier Inventory (RGI) version 6.0 (RGI Consortium, 2017), and *H* is the ice thickness. We chose to apply Glabtop2 to calculate ice thickness in the study area because it is more sensitive to the accuracy of both elevation and slope of the TP DEM data (Frey *et al.*, 2014; Chen *et al.*, 2022), and we also provide statistical values of the ice thickness results based on the Open Global Glacier Model (OGGM; Maussion *et al.*, 2019) and the result provided by

Farinotti *et al.* (2019) in the Supplement (Table S2).   We assumed a 100% ice content by volume and applied the above ice density conversion factor to calculate the water equivalent volume of the surface ice in glaciers.

To mitigate the additional impact caused by the uneven spatial distribution of glaciers and rock glaciers in the study area, we calculated a ratio of rock glaciers (including active and transitional rock glaciers)' to glaciers' water volume equivalence (WVEQ) by using the weighted average method that employs the following equation:

$$\text{WVEQ ratio}_{Rg:\ Glacier} = \frac{WVEQ\ R1_{Rg} \times \frac{R1_{Rg}}{All_{Rg}} + WVEQ\ R2_{Rg} \times \frac{R2_{Rg}}{All_{Rg}} + WVEQ\ R3_{Rg} \times \frac{R3_{Rg}}{All_{Rg}}}{WVEQ\ R1_{Glacier} \times \frac{R1_{Glacier}}{All_{Glacier}} + WVEQ\ R2_{Glacier} \times \frac{R2_{Glacier}}{All_{Glacier}} + WVEQ\ R3_{Glacier} \times \frac{R3_{Glacier}}{All_{Glacier}}} \tag{6}$$

where WVEQ ratio$_{Rg:\ Glacier}$ is the ratio of rock glaciers' to glaciers' WEVQ; WVEQ Rn$_{Rg}$ (n = 1, 2, 3) are the WVEQ values for rock glaciers in the western, central, and eastern regions, respectively; Rn$_{Rg}$ (n = 1, 2, 3) are the numbers of rock glaciers in the three subregions respectively; All$_{Rg}$ is the number of rock glaciers in the whole study area; WVEQ Rn$_{Glacier}$ (n = 1, 2, 3) are the WVEQ values for glaciers in the three subregions respectively; Rn$_{Glacier}$ (n = 1, 2, 3) are the number of glaciers in the three sub-regions respectively; and All$_{Glacier}$ is the number of glaciers in the whole study area.

4 Results

4.1 Rock glacier inventory analysis
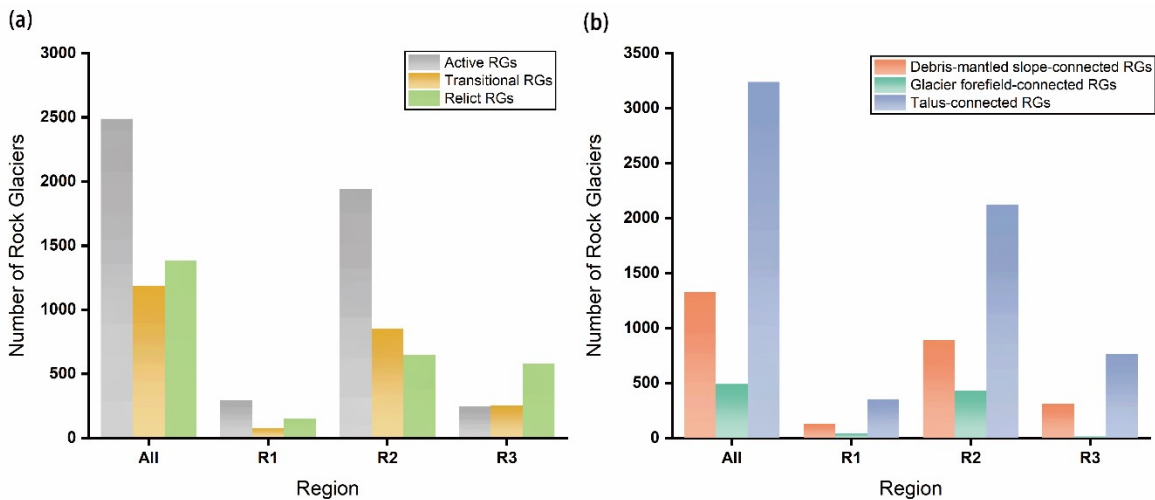
Figure 3: The number of rock glaciers categorized by different(a) activity types and (b) upper slope connection types in the entire study region and its sub-regions.

We identified a total of 5,057 rock glaciers in the Guokalariju, including 2,484 active rock glaciers (49.1%), 1,189 transitional rock glaciers (23.5%), 1,384 relict rock glaciers (27.3%). Active rock glaciers are predominant in the whole study area, except the eastern region where a higher proportion of relict rock glaciers can be found (Fig. 3a). Among the total rock glaciers observed, ~64% of them (n = 3,239) were classified as talus-connected, ~26% (n = 1,327) as debris-mantled slope-connected, and ~10% (n = 491) as glacier forefield-connected, this order of proportions is consistent across three subregions (Fig. 3b). On the whole, rock glaciers are unevenly distributed in three sub-regions, with nearly 70% of rock glaciers (n = 3,447) distributed in the central region (Table 2).

Table 2: Mean characteristics for rock glaciers in three sub-regions.

	RG type	Number	Total area (km³)	Mean altitude (m asl)	Mean MEF (m asl)	Mean area (km³)	Mean slope range (°)	Mean MAGT (ºC)	Mean MAAT (ºC)	Mean MAP (mm)
Western Region	Active	296	18.89	5166	5118	0.06	20.11	-0.1	-1.87	341
	Transitional	78	6.54	5127	5069	0.08	19.85	-0.04	-1.64	350
	Relict	150	8.69	5067	5021	0.06	19.33	0.12	-1.34	341
	Talus-connected	354	19.42	5152	5109	0.05	19.83	-0.06	-1.8	345
	Debris mantled slope-connected	127	6.66	5101	5050	0.05	20.79	0.14	-1.36	338
	Glacier forefield -connected	43	8.05	5064	4968	0.19	17.23	-0.22	-1.7	337
	All	524	34.13	5132	5083	0.06	19.85	-0.02	-1.68	343
Central Region	Active	1,941	155.14	5160	5102	0.08	19.31	-0.59	-2.1	389
	Transitional	856	78.78	5090	5026	0.09	19.07	-0.67	-1.84	394
	Relict	650	57.57	4995	4929	0.09	19.23	-0.58	-1.62	400
	Talus-connected	2,123	181.58	5096	5037	0.09	19.22	-0.61	-1.89	395
	Debris mantled slope-connected	890	59.84	5104	5046	0.07	19.99	-0.47	-1.76	386
	Glacier forefield -connected	434	50.07	5201	5128	0.12	17.73	-0.87	-2.54	393
	All	3,447	291.49	5117	5051	0.08	19.23	-0.6	-1.94	392
Eastern Region	Active	248	13.85	4965	4906	0.06	23.79	-0.96	-1.31	496
	Transitional	255	18.41	4964	4897	0.07	21.99	-0.96	-1.69	495
	Relict	583	46.82	4861	4796	0.08	20.19	-0.86	-1.57	495
	Talus-connected	762	58.81	4930	4867	0.08	20.63	-0.92	-1.75	489
	Debris mantled slope-connected	310	18.58	4850	4785	0.06	23.49	-0.86	-0.99	511
	Glacier forefield -connected	14	1.69	5047	4971	0.12	19.86	-1.15	-2.45	503
	All	1,086	79.08	4909	4845	0.07	21.43	-0.9	-1.54	495

210   MEF: minimum altitude at the rock glacier front
MAGT: mean annual ground temperature
MAAT: mean annual air temperature
MAP: mean annual precipitation
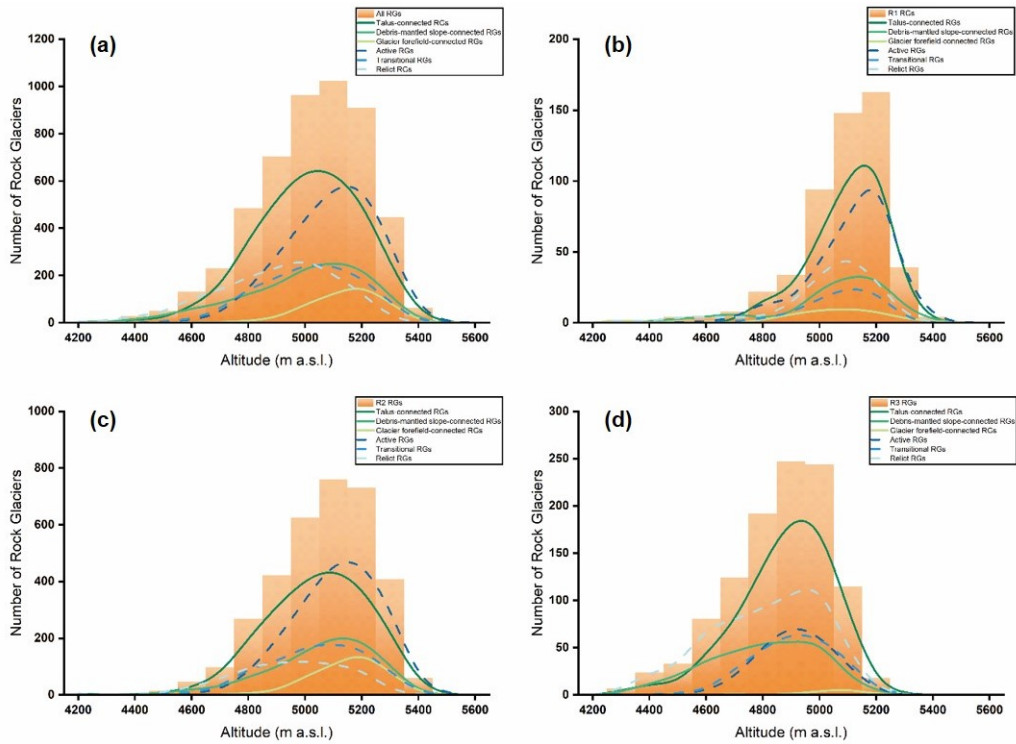
Figure 4: The mean occurrence altitude of rock glaciers categorized by different activity and upper slope connection types in (a) the Guokalariju (b) the western region, (c) the central region, and (d) the western region.

~90% of the rock glaciers are located between 4,800 and 5,400 m asl, with a mean altitude of ~5,070 m asl. Active rock glaciers are statistically distributed at higher altitudes than transitional and relict rock glaciers (Table 3), at ~76 m and ~195 m higher (Fig. 4a). The mean altitude of rock glaciers varies significantly depending on the type of spatial connection to the upper slope (Table 3). Compared to talus-connected (~5,063 m asl) and debris-mantled slope-connected rock glaciers (~5,044 m asl), glacier forefield-connected rock glaciers (~5,185 m asl) are more commonly found at higher elevations (Fig. 4a). The mean altitude of rock glaciers in the western region (~5,132 m asl) is higher than for those in the central (~5,112 m asl) and eastern region (~4,909 m asl) by ~20 m and ~223 m, respectively (Table 2 and Fig. 4b, 4c, 4d). The lower altitudinal limit of rock glaciers declines as longitude increases eastward (Fig. 5).

Table 3: The results of the One Way ANOVA.

Independent variable	Dependent variable	df between groups	df within groups	F-value	p
activity types	mean altitude	2	5,054	544.749	0.000
upper slope connection	mean altitude	2	5,054	102.9	0.000
upper slope connection	mean area	2	5,054	89.814	0.000
sub-regions	mean slope range	2	4,680	81.175	0.000
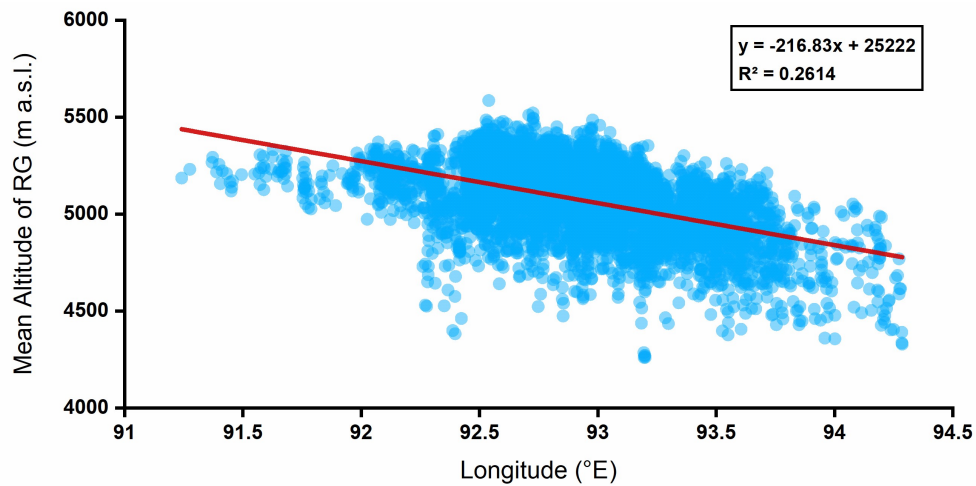
Figure 5: Scatterplots and fitted curves of the mean altitudinal distribution of rock glaciers versus longitude.

230   In Guokalariju, the total area of rock glaciers is 404.69 km2, with active rock glaciers covering 187.88 km^2, transitional rock glaciers covering 103.73 km^2, and relict rock glaciers covering 113.09 km^2, respectively. With the mean area of each rock glacier is 0.08 km^2, the mean area of three different activity types of rock glaciers remain consistent with this value, but there are notable variations in the mean area of rock glaciers depending on their specific type of upper slope connection (Table 3). Glacier forefield-connected rock glaciers (0.12 km^2)

235   generally have a larger mean area than the talus-connected ones (0.08 km^2) and the debris-mantled slope-connected ones (0.06 km^2). The mean area of most types of rock glaciers is the biggest in the central region and smallest in the western region (Table 2). Furthermore, the mean slope range of rock glaciers in the eastern region is significantly steeper compared to that in other sub-regions (Table 3).

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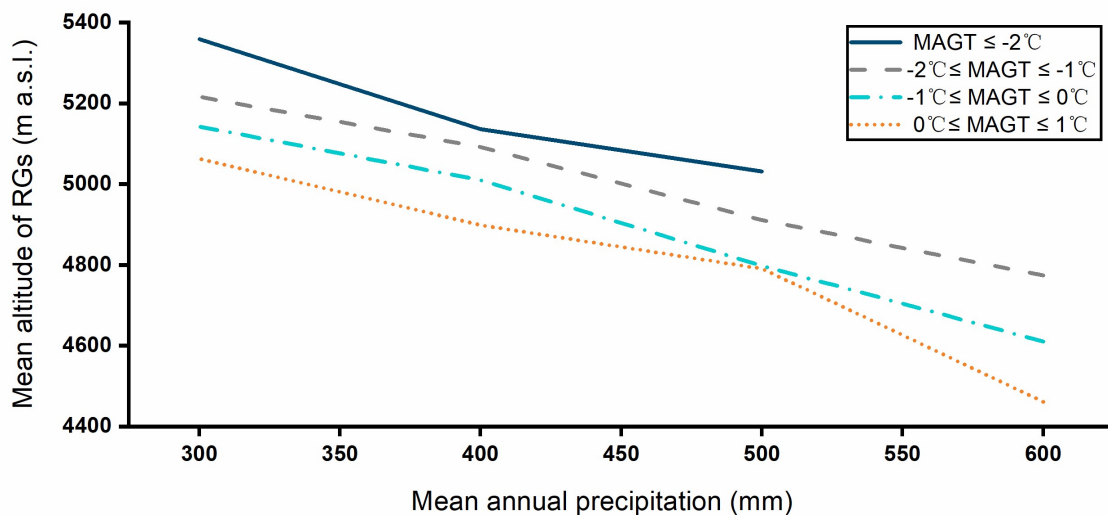


Figure 6: The variation in mean altitude of rock glacier distribution with changes in mean annual precipitation for different mean MAGT states.

    Around 90% of the rock glaciers in Guokalariju 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

245   (Table 2). Specifically, the mean MAGT decreases gradually from the west to the east of the study area, 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

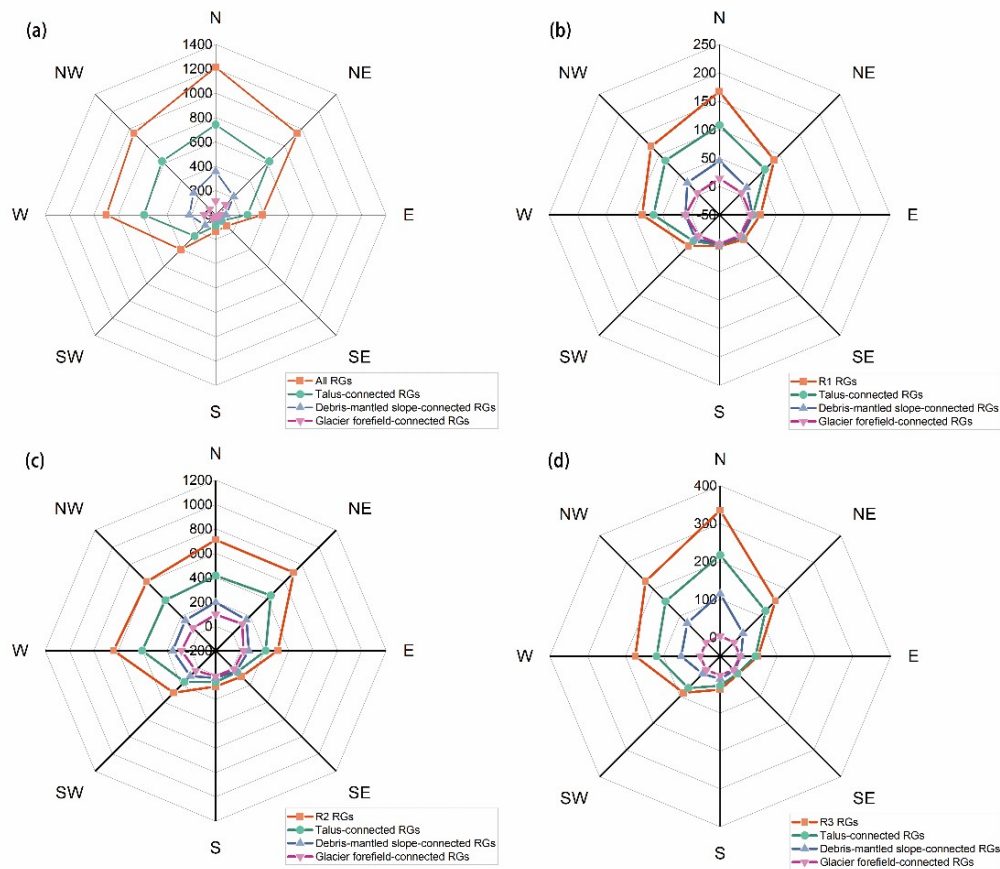
increasing MAP. Moreover, with the same MAP, the altitude of rock glacier distribution increases with decreasing MAGT (Fig. 6).

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Figure 7:   Analysis of abundances of rock glaciers categorized by different upper slope connection types in (a) the Guokalariju, (b) western region, (c) central region, and (d) eastern region. The numbers of rock glaciers for each aspect on the four radar plots are shown as percentages (%).
        Rock glaciers predominantly occur on north-facing slopes (N, 23.9%; NW, 18.7%; NE, 18.7%), with some

255   distributed on the west-facing aspects (W, 17.7%), and fewest on south-facing aspects (S, 2.7%; SE, 2.5%, SW, 7.9%) (Fig. 7a). Compared with the obvious characteristics of the concentrated distribution of rock glaciers in the western and eastern region on the N aspect (Fig. 7b, 7d), rock glaciers in the central region are more evenly distributed on the N, NE, W and NW aspects (Fig. 7c).

4.2 Water equivalent volumes

260   Based on the Randolph Glacier Inventory (RGI) version 6.0 (RGI Consortium, 2017), glaciers in the Guokalariju cover an area of ~183.96 km^2. GlabTop2 provided estimated clean ice glacier thicknesses ranging between ~1 and ~208 m (mean = ~23.87 m) (Frey *et al*., 2014). We estimated the total WVEQ of the region's glaciers to be ~3.95 km^3.

Table 4: Ice volumes (km³) and corresponding WVEQs (km³) calculated using the empirical area-thickness formula (Brenning, 2005a) for sub-regions and Guokalariju-wide (All).

	Brenning, 2005a				
Region	Glacier - WVEQ (km³)	RG - WVEQ (km³)			RG: Glacier WVEQ ratio
		40%	50%	60%	
All	3.95	3.46	4.32	5.19	1.1:1
Western	0.06	0.31	0.38	0.46	6.33:1
Central	2.65	2.78	3.48	4.17	1.31:1
Eastern	1.24	0.37	0.46	0.55	1:2.7

WVEQ = water volume equivalent

The mean thickness of rock glaciers in the Guokalariju estimated using the empirical area-thickness formula (Brenning, 2005a) is ~28.36 m. The WVEQ storage lies between 3.46 and 5.19 km³, of which the central region stores ~80% of the water in the study area (*i.e.*, 2.78 – 4.17 km³). The western region stores 0.31 – 0.46 km³ of water (9% of the whole Guokalariju's reserve). The eastern region stores ~11% of the water, or 0.37 – 0.55 km³ (Table 4). Compared to the WVEQ of glaciers, the result calculated using the weighted method showed that the ratio was 1.1:1, indicating that rock glaciers stored ~1.1 times more water than glaciers.

Table 5: Ice volumes (km³) and corresponding WVEQs (km³) calculated using the perfectly plastic model (Cicoira *et al.*, 2021) for sub-regions and Guokalariju-wide (All).

Region	Glacier - WVEQ (km³)	RG - WVEQ (km³)									RG: Glacier WVEQ ratio		
		40%			50%			60%			40% Mean	50% Mean	60% Mean
		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max			
All	3.95	1.32	1.67	2.03	1.85	2.30	2.74	2.53	3.06	3.60	1:2.32	1:1.69	1:1.26
Western	0.06	0.12	0.15	0.18	0.16	0.20	0.24	0.22	0.27	0.32	2.50:1	3.33:1	4.50:1
Central	2.65	1.08	1.37	1.66	1.52	1.88	2.24	2.08	2.51	2.94	1:1.93	1:1.41	1:1.06
Eastern	1.24	0.12	0.16	0.20	0.16	0.21	0.26	0.23	0.29	0.34	1:7.75	1:5.90	1:4.28

WVEQ = water volume equivalent
The "40%", "50%", and "60%" represent the lower, mean and upper limits of rock glacier ice volume, respectively.
The "Mean" corresponds to the WVEQ calculated based on the mean thickness of the rock glacier calculated in Eq. (2) without the ±3.4 m (Cicoira *et al.*, 2021).
The "Min" and "Max" correspond to the WVEQ calculated based on the mean thickness "-3.4 m" and "+3.4 m", respectively (Cicoira *et al.*, 2021).
The "RG: Glacier WVEQ ratio" is the weighted average ratio calculated on the basis of the "Mean" WVEQ of rock glaciers under different ice content assumptions (40%, 50%, 60%).

The mean thickness of rock glaciers at 50% ice content calculated using a perfectly plastic model (Cicoira *et al.*, 2021) is 16.40±3.4 m, 11.96 m thinner than that estimated using the empirical area-thickness formula. The mean value of the WVEQ estimated using this method is 38 – 69% of the mean value obtained using the 'Brenning' method. As the estimated WVEQ of rock glaciers decreases, the ratio of rock glaciers' to glaciers' WVEQ is also lower than that obtained using the 'Brenning' method (Brenning, 2005a), indicating that the WVEQ of glaciers is ~1.69 times that of rock glaciers (Table 5). However, the results obtained based on both methods reflect clear differences in the water storage of the three sub-regions (ANOVA: *F*-value = 27.930, df within groups = 2, between groups = 3,671, $p \le 0.001$).

5 Discussion

5.1 Factors controlling rock glaciers

Rock glaciers are distributed heterogeneously throughout the Guokalariju, with most concentrated within

the central region. The study area spans a large area from east to west, with variations in topography and climatic conditions between the three sub-regions, thereby providing the basis for a spatially differentiated distribution of rock glaciers. The development of rock glaciers is a complex function of responses to air temperature, insolation, wind, and seasonal precipitation over a considerable period (Humlum, 1998), with the MAAT = -2°C isotherm and the equilibrium line altitude (ELA) for local glaciers forming the lower and upper boundaries of the cryogenic belt where they have developed, respectively (Humlum, 1988; Brenning, 2005a; Rangecroft *et al.*, 2015, 2016; Jones, 2018b). Topographically, the higher terrain in the central region has accommodated the development of more rock glaciers in the area above 4,500 m asl. The central region is located in the transition zone between the TP's semi-arid and sub-humid regions, with a mean ELA of ~5,478 m asl. Compared with the eastern region, which has a lower ELA (mean ELA = 5,265 m asl), and the western region, which has a higher MAAT, the central region exhibits a broader range of the cryogenic belt to meet the development and distribution of more rock glaciers. Additionally, the widespread glacial remains in the central region and the predominance of more easily weathered granite as bedrock in this area could also provide a richer source of material for rock glacier development (Wahrhaftig and Cox, 1959; Haeberli *et al.*, 2006).

The mean and lower altitudinal limits of the rock glacier distribution in the whole study area decrease from west to east, from ~5,200 m asl to ~4,900 m asl. In the Gangdise Mountains, located in the same latitudinal range on the western side of the study area, rock glaciers show a similar trend of gradually decreasing altitude in line with increased moisture; indeed, the characteristics of the changes in the two regions show an overall continuity (Zhang *et al.*, 2022). Limited by the range of the ISM, MAP gradually decreases from west to east from the Gangdise Mountains to the Guokalariju. In the alpine tundra of this region, annual precipitation is dominated by snowfall in summer and autumn. Increases in snowfall in summer and autumn could help to preserve permafrost, allowing permafrost to develop at lower altitudes under similar climatic conditions (Zhou *et al.,* 2000). Additionally, annual regional precipitation values may reflect reductions in short-wave insolation arising from cloud cover, at least to some extent (Boeckli *et al.*, 2012a). Relatively favorable hydrological conditions will be more conducive to freeze-thaw weathering, thereby increasing the generation rate of rock debris, which in turn is conducive to the development of rock glaciers (Hallet *et al.*, 1991; Haeberli *et al.*, 2006; Zhang *et al.*, 2022). Increases in MAP are therefore likely to be conducive to the expansion of the range in the distribution of rock glaciers in semi-arid to sub-humid areas, meaning that the lower altitudinal limit of rock glacier distribution decreases with increases in annual precipitation.

Glacier forefield-connected rock glaciers may have a more abundant source of materials compared to other types of rock glaciers. They occur in regions where glaciers have previously existed, and both glacial moraines and surrounding rock walls can provide debris as their materials. Therefore, they have a more diverse range of material sources, which may contribute to the development of larger-scale rock glaciers. However, debris-mantled slope-connected rock glaciers lack significant headwall, and their debris is primarily produced by in-situ bedrock weathering (RGIK, 2022a). This results in their relatively limited and homogeneous material sources, leading to slower development and smaller scale compared to other types of rock glaciers.

Rock glaciers in the study area are primarily distributed on north-facing and west-facing aspects, which is remarkably similar to the distribution pattern of rock glaciers in the Himalayas (Jones *et al.*, 2018b), Gangdise Mountains (Zhang *et al.*, 2022), Tianshan Mountains (Liu *et al.*, 1995; Bolch and Marchenko, 2009) and the European Alps (Scotti *et al.*, 2013). This is mainly because north-facing slopes receive less solar radiation as

they are shaded, providing favorable conditions for the development and preservation of rock glaciers (Barsch, 1996). Additionally, the ample space and lower potential incoming solar radiation (PISR) on west-facing slopes, influenced by regional topographic conditions, also contribute to the development of rock glaciers here. This is evident in the central region where rock glaciers are more evenly distributed in the W, NW, N, and NE aspects compared to the distinct concentration of rock glaciers on the N aspect in the western and eastern regions.

5.2 Hydrological significance of rock glaciers

In comparison, we found that the thicknesses of rock glaciers calculated using the flow plasticity model (Cicoira *et al.*, 2021) are significantly lower than the corresponding results calculated using the empirical area-thickness formula (Brenning, 2005a). By comparing the thickness of the rock glaciers calculated by both methods with the height of the rock glacier front measured in ©Google Earth, the thickness of the rock glaciers calculated by the 'Cicoira' method (Cicoira *et al*., 2021) seems to be closer to the real value. Therefore, we speculate that the thickness calculated based on the 'Brenning' method (Brenning, 2005a) may be overestimated to a certain extent due to the following reasons. The applicability of different estimation methods may be different across the study area. The mean thickness of the sample rock glaciers in the study of Brenning (2005a) is about 30-50 m, which is higher than the sample of rock glaciers selected in the study of Cicoira *et al.* (2021) (15-30 m). We selected two rock glacier samples from Cicoira *et al.*'s (2021) research and used the 'Brenning' method (Brenning, 2005a) to calculate their thickness (Müller *et al.*, 2016). We observed that the calculated thickness (H=27 m) closely matched the actual thickness for the rock glacier with an area of 45,931 m^2 and a real thickness of 30 m. However, there was a significant discrepancy with the other rock glacier sample (H=25 m), which had an area of 32,356 m^2 and an actual thickness of 12 m. Therefore, the applicability of empirical formulas based on various samples may vary for estimating the thickness of rock glaciers in different areas. As the thickness of rock glaciers in our study area is relatively close to the sample selected by Cicoira *et al.* (2021), the application of the 'Brenning' method (Brenning, 2005a) may lead to an overestimation of rock glacier thickness in this region.

Based on the above discussion, we choose to use the results calculated based on the 'Cicoira' method (Cicoira *et al*., 2021), which may be closer to the actual water reserves in our study area for further comparison and discussion. These estimates indicate that the amount of water stored in rock glaciers in the study area is ~2.4% of the total previously identified rock glacier water reserves globally (95.49 ± 12.40 Gt) (Jones *et al.*, 2018a; Jones *et al.*, 2018b; Millar and Westfall, 2019; Jones *et al.*, 2021a; Jones *et al.*, 2021b; Wagner *et al.*, 2021), and ~4.4% of the existing water reserves in rock glaciers on the TP (50.83 ± 10.17 Gt) (Jones *et al.*, 2021a). The rock glacier to glacier storage ratio in the Guokalariju of 1:1.69 is ~270 times bigger than the global ratio (1:456, excluding the Antarctic and Subantarctic and Greenland Periphery Randolph Glacier Inventory (RGI; Pfeffer *et al.*, 2014; Jones *et al.*, 2021b), ~15 times bigger than that of the Himalayas to its south (1:25) (Jones *et al.*, 2021a), ~18 times bigger than that of the Northern Tien Shan (1:30) (Bolch and Marchenko, 2009), and much closer to that of the Andes in South America (1:3) (Azócar and Brenning, 2010), where glacier presence is also limited/absent (Brenning, 2005b; Azócar and Brenning, 2010; Jones *et al.*, 2019b; Schaffer *et al.*, 2019).

In the Guokalariju, along with the continuous melting of glaciers in the study area, the area of active rock glaciers now exceeds the glacier area, and the estimated water storage of rock glaciers is about 59% of the

glacier water storage, which shows the indispensable hydrological significance of rock glaciers in the study area. Meanwhile, regional differences in the hydrological significance of rock glaciers under different climatic conditions also exist. In the central region, which is located in the transition zone between the semi-arid and semi-humid zones, the higher topography and suitable hydrothermal conditions lead to the highest concentration of glaciers and rock glaciers in this area, with rock glaciers accounting for 82% of the rock glacier water storage in the entire study area, and glaciers accounting for ~67% of the study area's glacial water storage, with a ratio of ~1:1.41 between them. However, in terms of the ratio of rock glaciers to glacial water storage alone, rock glaciers are of greater hydrological significance in the western region which is warmer and drier, despite storing only 8.7% of the total water volume of all rock glaciers. In the context of drought and climate warming, rock glaciers store about three times as large as the water storage of the glaciers in the western region. This partly explains why rock glaciers have a greater hydrological significance and refuge potential as long-term reservoirs in arid regions with small and rapidly vanishing glaciers. Furthermore, the relationship between the proportion of the water cycle occupied by rock glaciers and the water requirements of regional populations should be considered in more detail. More research is needed into the hydrochemical composition of the stored water in rock glaciers and whether it can be used for irrigation and drinking.

5.3 Rock glaciers and permafrost presence
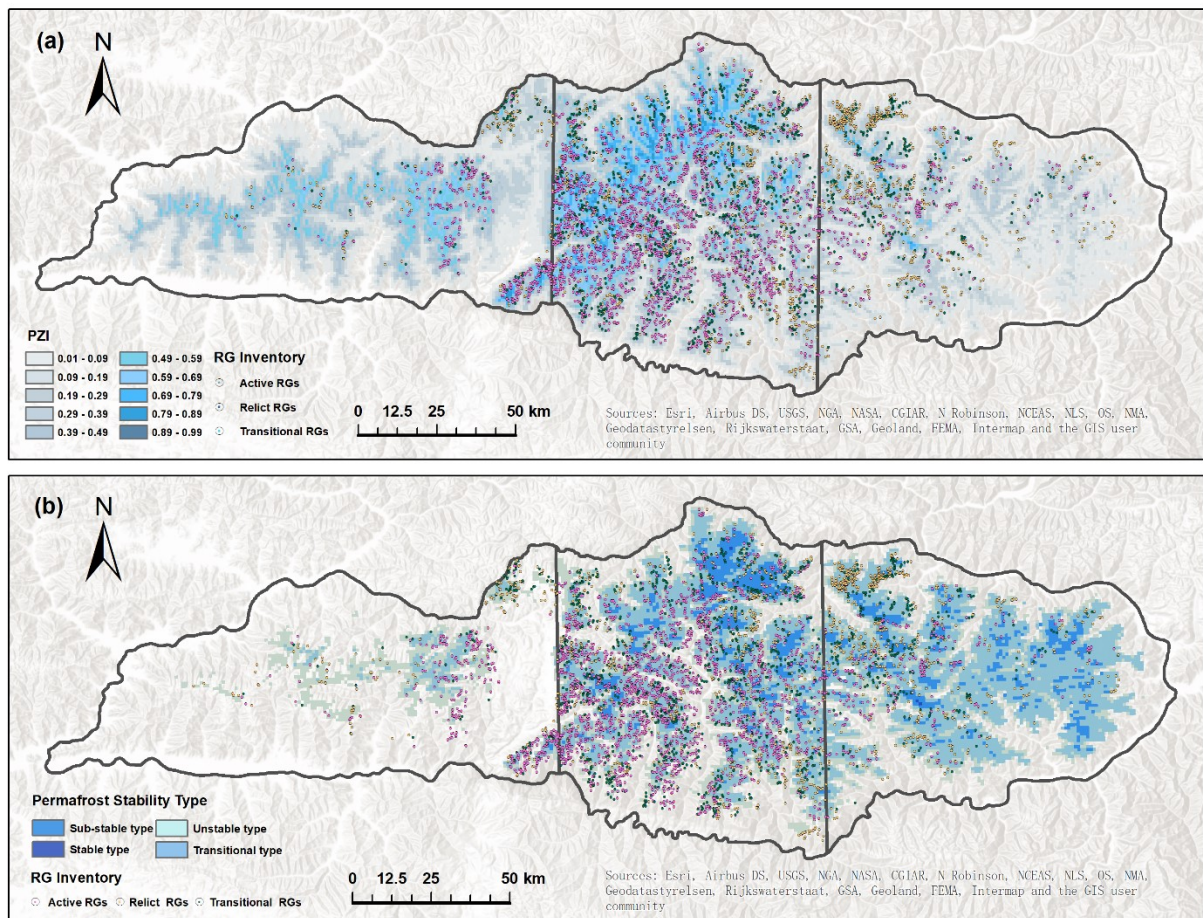
Figure 8: Spatial distribution of rock glaciers vs. (a) Gruber's (2012) Permafrost Zonation Index (PZI) in Guokalariju and (b) Map of the thermal stability of permafrost in Guokalariju (Ran *et al.*, 2020).
The MAGT in Guokalariju is relatively high (Ran *et al.*, 2020; Ni *et al.*, 2020). Approximately 90% of the

rock glaciers are distributed within the MAGT range of -2°C to 0°C, which belong to the regions of sub-stable type (−3°C < MAGT < −1.5°C), transitional type (−1.5°C < MAGT < −0.5°C), and unstable type permafrost (−0.5°C < MAGT < 0.5°C) (Cheng *et al.*, 2019). About 7% of the rock glaciers occur in the seasonal frozen ground area with MAGT > 0°C. Furthermore, we compared the spatial distribution of rock glaciers in the study area to the Permafrost Zonation Index (PZI) which is based on the model of permafrost extent and mainly related to the MAAT (Gruber, 2012). At the same time, we also compared it to the thermal stability of permafrost which mainly depends on the accumulation of the MAGT measurement data and remote sensing big data (Ran et al., 2020). Overall, it aligns well with the regions of PZI ≥ 0.49 (Fig. 8a) and the map of the thermal stability of permafrost (Fig. 8b), especially in the central region and the eastern region's western part.

In the western region, the range of permafrost distribution provided by Ran *et al.* (2020) is significantly smaller than the region with PZI ≥ 0.49 in Gruber (2012), while the difference is larger in the eastern part of the eastern region (Fig. 8). We speculate that these differences may be attributed to variations in the data period used in these studies. When making detailed comparisons between the mean MAAT data from 1961 to 1990 used in the study of Gruber (2012) and MAAT data for the TP in 2015 provided by Du and Yi (2019), we found that, except for a few areas in the eastern part of the eastern region, the mean MAATs of the western and central region increased by ~2°C. Although there may have been some errors in the data, the effect of temperature on the predicted permafrost distribution for the model based on the relationship between air temperature and the occurrence of permafrost may nonetheless be somewhat magnified.

Under the background of global warming, the warming rate of permafrost in the eastern part of the TP is significantly faster than that in the western part (Cheng *et al.*, 2019). This could result in rapid changes in the movement speed and surface morphology of rock glaciers in the study area over a short period (Krainer and Mostler, 2000; Ikeda *et al.*, 2008; Janke and Bolch, 2021). However, research has shown that despite the relatively rapid increase in ground temperatures in the deep layers of permafrost, the degradation of permafrost on the Tibetan Plateau occurs at a slow pace with full consideration of deep ground temperatures, subterranean ice and geothermal gradients in permafrost (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).

6 Conclusions

We constructed an inventory of rock glaciers in the Guokalariju and illustrated their regional distribution characteristics and environmental indications. We employed two methods to estimate and compare the water storage capacity of the region's rock glaciers. The results show that there are 5,057 rock glaciers in the study area, covering an area of about 404.69 km^2 in total. Among them, the area of active rock glaciers is about 187.88 km^2, which exceeds the area of glaciers in the study area. Over 80% of these rock glaciers are located within the central region. The high altitude (~4,900 m asl), low temperatures (MAAT ≤ -2°C), and suitable precipitation (MAP ~400 mm) in the semi-arid and semi-humid transition zone provide the widest cryogenic belt range for rock glacier distribution in the region. The lower altitudinal limit of the distribution of rock glaciers decreases gradually with increasing longitude from the western side of the study area, from the Gangdise Mountains to the interior of the Guokalariju, indicating the positive effect of increased precipitation on the preservation of

permafrost. We used two methods to estimate the thickness of rock glaciers and found that the results calculated based on the perfect plasticity model were more consistent with the actual situation in the study area. Based on the result, we calculated that about 1.32–3.60 km^3 of water is stored in the subsurface ice of rock glacier permafrost, or ~59% of the water presently stored in the surface ice of glaciers. Despite differences from the two

435   methods, both of their results reveal the previously neglected and important hydrological value of rock glaciers in the study area, particularly in the western region, which is the drier sub-region. The WVEQ in rock glaciers and the ratio of subsurface ice in rock glacier permafrost to surface ice in glaciers may continue to increase with global warming and as glaciers retreat in the future. And the stability of permafrost in the area of rock glacier distribution is likely to further decline.

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Data availability. The data associated with this article can be found in the Supplementary Materials. These data include the Google maps of the most important areas described in this article, as well as a tabulation of the parameters of the rock glaciers found in the Guokalariju.

445   *Author contributions.* ML and GL designed the research. ML performed the analysis and wrote the paper. YY and ZP provided overall supervision and contributed to the writing.

Competing interests. The authors declare that they have no conflict of interest.

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