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Permafrost activity and atmospheric warming in the Argentinian Andes

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ABSTRACT

Rock glaciers are permafrost or glacial landforms of debris and ice that deform under the influence of gravity. Recent estimates hold that, in the semiarid Chilean Andes for example, active rock glaciers store more water than glaciers. However, little is known about how many rock glaciers might decay because of global warming and how much this decay might contribute to water and sediment release. We investigated an inventory of >6500 rock glaciers in the Argentinian Andes, spanning the climatic gradient from the Desert Andes to cold-temperate Tierra del Fuego. We used active rock glaciers as a diagnostic of permafrost, assuming that the toes mark the 0 °C isotherm in climate scenarios for the twenty-first century and their impact on freezing conditions near the rock glacier toes. We find that, under future worst case warming, up to 95% of rock glaciers in the southern Desert Andes and in the Central Andes will rest in areas above 0 °C and that this freezing level might move up more than twice as much (~500 m) as during the entire Holocene (~200 m). Many active rock glaciers are already well below the current freezing level and exemplify how local controls may confound regional prognoses. A Bayesian Multifactor Analysis of Variance further shows that only in the Central Andes are the toes of active rock glaciers credibly higher than those of inactive ones. Elsewhere in the Andes, active and inactive rock glaciers occupy indistinguishable elevation bands, regardless of aspect, the formation mechanism, or shape of rock glaciers. The state of rock glacier activity predicts differences in elevations of toes to 140 m at best so that regional inference of the distribution of discontinuous permafrost from rock-glacier toes cannot be more accurate than this in the Argentinian Andes. We conclude that the Central Andes—where rock glaciers are largest, cover the most area, and have a greater density than glaciers—is likely to experience the most widespread disturbance to the thermal regime of the twenty-first century.

1. Motivation

Rock glaciers are perennial frozen periglacial or glacial bodies of debris and various forms of subsurface ice like interstitial ice, ice lenses, or buried massive ice (mainly from snow patches or avalanche cones, sometimes from glaciers) that deform through cohesive flow under gravity (Haeberli and Vonder Mühll, 1996). Depending on topographic location, rock glaciers abound mainly in cold and continental dry climates, where they form in unconsolidated cryogenic (talus rock glaciers) or glacial (debris rock glaciers) materials (Brenning, 2003). Rock glaciers depend on the supply of debris, ground freezing with subsurface ice forming in excess of the pore volume, and are common in mountains where sediment production from rock slopes dominates over input from snowfall (Corte, 1978). Rock glaciers can be intact, meaning active or inactive, or relict (Haeberli, 1985; Barsch, 1992). Active rock glaciers have a distinct, steep (>35°) frontal slope and well-defined longitudinal or transverse flow lines resulting from movement (0.1–1 m/yr; Fig. 1). Under atmospheric warming, flow velocities can be higher (Wirz et al., 2016). The bodies have a characteristic inverse graded sorting with coarser material on the surface (Trombotto and Borzotta, 2009) and often a thin apron of rocks tumbling off the steep advancing toe. Active rock glaciers are diagnostic of discontinuous permafrost: their toes are widely assumed to be near the mean annual 0 °C isotherm (Barsch, 1978, 1996; Garleff and Stingl, 1986; Schrott, 1994; Janke, 2005). Active rock glaciers can contain 40–60% or more of ice (Bolch and Schröder, 2001; Azócar and Brenning, 2010). Inactive rock glaciers have frontal slopes <35° some have vegetation cover and minimal ice, but can be reactivated given sufficient growth in ice content and the resulting increasing load. Once the entire ice content has melted, an inactive rock glacier becomes relict (Barsch, 1996; Trombotto, 2002; Brenning, 2003, 2005).

A first global estimate emphasised that rock glaciers in some regions, e.g. the semiarid Chilean Andes, might store more water than glaciers (Jones et al., 2018) and calls for an appraisal of how current and projected atmospheric warming affects this storage. Mountain regions are particularly sensitive to climate change, which may affect rates of

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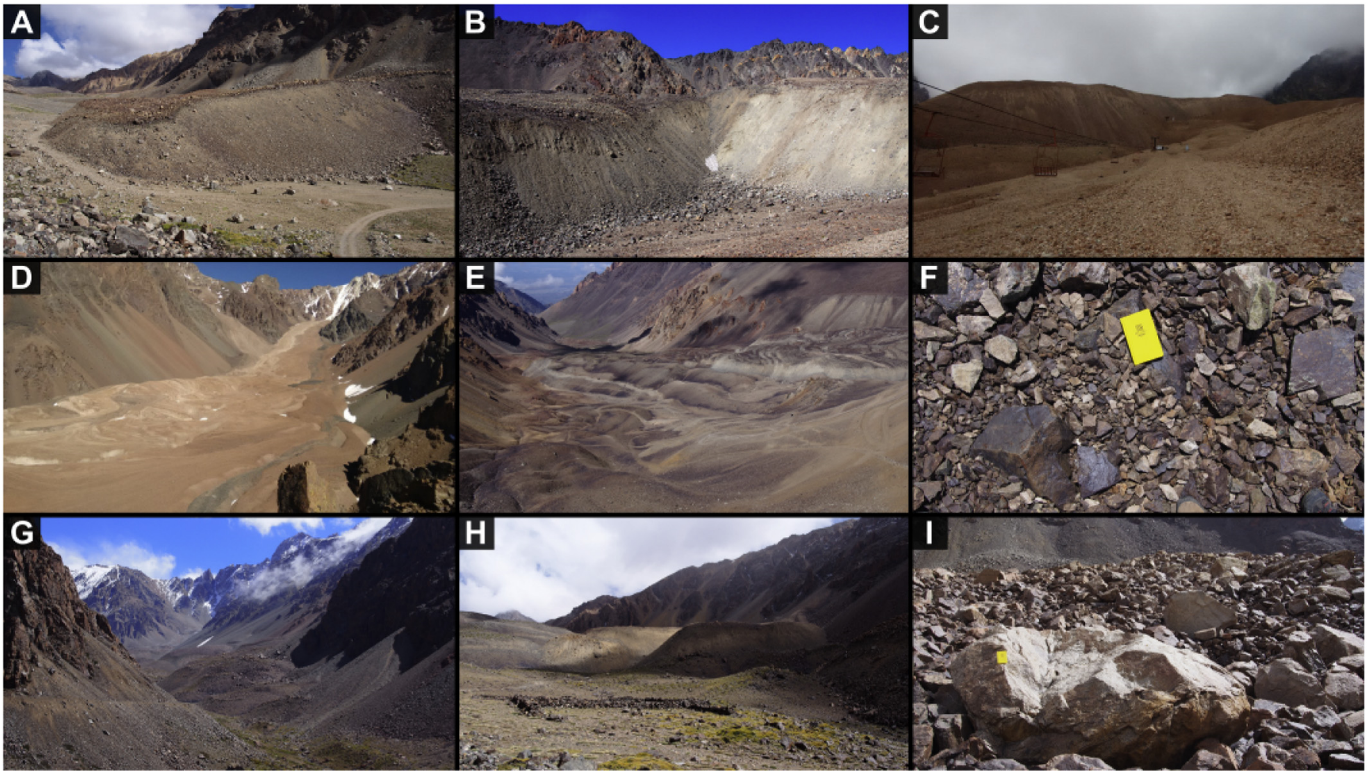

Fig. 1. Active rock glaciers with steep fronts (A–C, G, H), well-defined ridges, and furrows from cohesive flow (D, E), and debris cover (F, I) that is inverse graded sorted with coarse material on the surface (A, B). Photos (A), (B) and (E–I) are near Paso de los Piuquenes, Mendoza Province, March 2017; photos (C) and (D) show Morenas Coloradas, Cordon del Plata, Mendoza Province, February 2016.

erosion, sediment transport, and deposition and eventually the portfolio of natural hazards (Haeberli and Beniston, 1998; Chiarle et al., 2007; Vuille et al., 2008). Thus, under global warming, rock glaciers might also play an important role as an important transporter of sediment. Numerous studies have investigated past and likely future effects of atmospheric warming on glaciers in mountains around the world (Kääb et al., 2007), but the possible impacts on rock glaciers have been largely neglected (Salzmann et al., 2007). Yet rock glaciers have drawn more research attention in recent decades (Jones et al., 2018).

With this study we intend to focus on the latitudinal and vertical distribution of rock glaciers in the Argentinian Andes and to explore possible effects of atmospheric warming on this pattern, drawing on an inventory of >6500 rock glaciers (glacier inventories: Castro et al., 2014; IANIGLA, 2017; see Section 2.1). Our objective is, based on climate variables of the WorldClim data set (Hijmans et al., 2005) and digital topographic data, to estimate current and future predictors of the vertical distribution of rock glaciers in four climatically distinct parts of the Andes. We quantify the number and area of rock glaciers below the isotherm of 0 °C mean annual air temperature as a first-order metric of the potential effects of atmospheric warming on these permafrost landforms.

2. Data

2.1. Rock-glacier inventory

Chile and Argentina have most of the Andean glaciers and periglacial landforms (Williams and Ferringo, 1998; Milana and Maturano, 1999; IANIGLA, 2017). Yet studies of rock glaciers in the Argentinian Andes are highly selective in regional coverage (Schrott, 1996, 1998; Trombotto et al., 1997; Milana and Maturano, 1999; Trombotto, 2000, 2002, 2003; Ahumada, 2002; Croce and Milana, 2002; Angillieri, 2009, 2010; Trombotto and Borzotta, 2009; Perucca and Angillieri, 2011; Falaschi et al., 2014, 2015). The first systematic cryospheric inventory was compiled by Corte and Espizua (1981) for the Mendoza River catchment in the Central Andes. Together with other studies by IANIGLA, this laid the foundation for a database of glacial and periglacial landforms. By mid-2017, this inventory contained >6500 intact rock glaciers in four regions (Fig. 2): the Desert Andes (22°–31°S); the Central Andes (31°–36°S); the Andes of Patagonia (36°–52°S); and Tierra del Fuego (52°–55°S); the inventory is one of the largest of its kind in the Americas and also worldwide. IANIGLA (2017) used topographic data from the SRTM and ASTER missions and LANDSAT, TERRA, ALOS, and CBERS 3B satellite images to automatically detect ice cover; whereas rock glaciers, debris-covered glaciers, and transitional forms were mapped manually following the guidelines and terminology of the Global Land Ice Measurements from Space Initiative (GLIMS; http://www.glims.org). Only landforms >0.01 km^2 are included, some checked locally in the field (http://www.glaciaresargentinos.gob.ar; Castro et al., 2014; IANIGLA, 2017; Tables 1, 2).

2.2. Study area

IANIGLA (2017) divided the Argentinian Andes into four distinct regions for their inventory, following the outlines by Lliboutry (1999): the Desert Andes (22°–31°S) cover the entire northwest of Argentina including the northern San Juan province. In the Desert Andes we took in the three areas where rock glaciers were mapped (Fig. 3). The Desert Andes extend to 6200 m asl; estimated mean annual air temperatures (MAAT) range from −11 to 11 °C, and annual average precipitation totals (MAP) are 130 to 350 mm (Hijmans et al., 2005; Table 3). Vegetation is sparse and mostly herbaceous with some shrubs. The Central Andes (31°–36°S; Fig. 3) extend from the southern San Juan Province to the Río Colorado basin in Neuquén Province and host the highest peaks of the Andes, including Aconcagua (6958 m asl), and one of the highest concentrations of rock glaciers worldwide (IANIGLA, 2017). This transition zone between the arid northern Andes and humid southern Andes has MAP totals of 70 to 900 mm and a MAAT range of −15 to

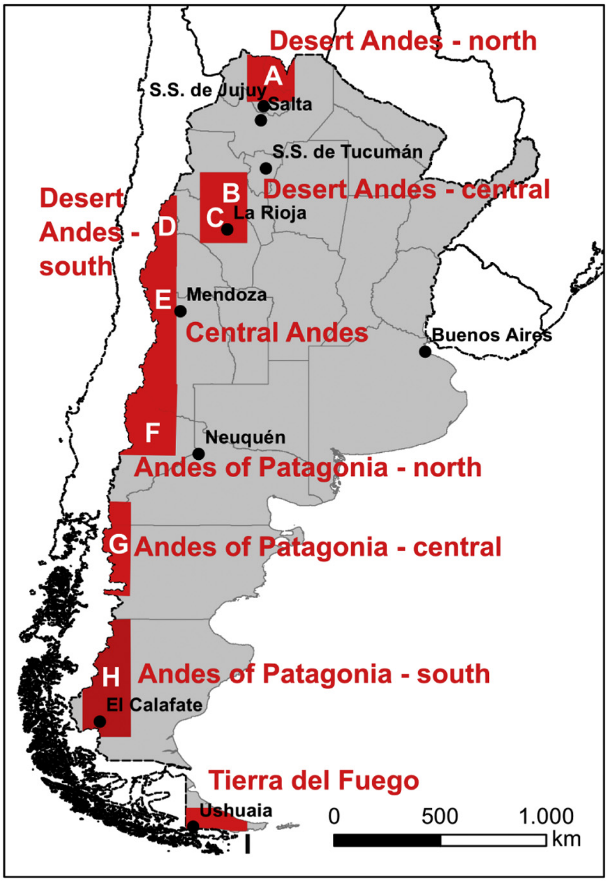

Fig. 2. Overview of the subregions studied in the Argentinian Andes. (A) Desert Andes (north), (B) Desert Andes (central), (C) Desert Andes (south), (E) Central Andes, (F) Andes of Patagonia (north), (G) Andes of Patagonia (central), (H) Andes of Patagonia (south), and (I) Tierra del Fuego.

Table 1
Data fields in the inventory of IANIGLA (Castro et al., 2014).

Parameters		Subdivision
All forms	Province	
	Catchment	
	Subbasin	
	Used satellite imagery	
	Slope	
	Aspect	
	Area	
	Length	
	Elevation	Minimum, maximum, mean
Glacial forms (such as glaciers, covered glaciers, snow patches, and transition forms)	Planform	
	Frontal shape	
	Longitudinal profile	
	Feeding source	
	State of activity	
	Type of moraines	
	Percentage of debris coverage	
Rock glacier	Type	• Active • Inactive
	Formation mechanism	• Cryogenic (no causal connection to glaciers and formed by talus) • Glacial (in connection with small glaciers, usually mixtures of talus- and moraine- or debris derived material) • Combination of cryogen and glacial • Unspecified
	Planform	• Lobate • Tongue-shaped • Spatula-shaped • Coalescent • Uncertain • Others
	Structure	• Single • Multiform • Uncertain
	Source area	• Single • Various • Uncertain

9 °C (Table 3). The vegetation reaches from broadleaved evergreen trees and croplands to sparse herbaceous plants and shrub cover. Farther south are the Andes of Patagonia (36°–52°S; Fig. 3), where elevation drops from 4700 to 3300 m asl. This area has a MAAT range of −7 to 8 °C, and 200 to 1900 mm MAP. The southern Andes of Patagonia (45°–52°S) include the Southern Patagonian Ice Field (12,100 km^2, of which 2662 km^2 are in Argentina). There, rock glaciers are mapped between Lagos Buenos Aires, Pueyrredon, Burmeister, and San Martin (Fig. 3). Tierra del Fuego (52°–55°S) marks the southernmost extension of the Argentinian Andes, where they change the north-south orientation to west-east and lose elevation. Only small rock glaciers and glaciers are limited to peaks reaching 1500 m asl around Ushuaia (IANIGLA, 2017; Fig. 3). Annual mean air temperatures are −1.5 to 5 °C, and precipitation totals are below 860 mm. Dense cool temperate rainforests cover much of the Andes of Patagonia and Tierra del Fuego in lower areas, and sparse herbaceous plants and shrub cover areas higher up.

2.3. Climate data

Few studies explored the possible impacts of climate change on rock glaciers (Haeberli and Beniston, 1998; Rangecroft, 2015). From the analysis of past, current, and projected future conditions, we seek to gain insights into how climate change may affect the activity status of rock glaciers, acknowledging that the ice content in a rock glacier and permafrost have a delayed response to global warming (Haeberli, 1985; Krainer et al., 2014). We used the WorldClim data set (version 1.4, Hijmans et al., 2005), which is a topography-based interpolation of average monthly climate data from weather stations around the world at 30 arc-second resolution. This coarse resolution is suitable for a regional analysis of rock-glacier distributions along the distinct climatic gradient of the Argentinian Andes but may be too coarse for detailed local climatic conditions. WorldClim supplies monthly climate data on precipitation and temperature and on some derivatives and 19 bioclimatic variables averaged over weather stations between 1961 and 1990, estimated conditions for the Last Interglacial Maximum (120–140 ka), Last Glacial Maximum (22 ka), and mid-Holocene (6 ka), as well as four future scenarios for 2050 (averaged from 2041 to 2060) and 2070 (averaged from 2061 to 2080). The data for past

Table 2
Definitions taken from the inventory of IANIGLA (Castro et al., 2014).

Form	Description
Rock glacier	Periglacial landforms of frozen debris and ice that move under the influence of gravity in permafrost areas.
Glacier	Body of permanent ice generated by compaction and recrystallization of snow and ice, which is visible for at least two years and without any significant debris cover. Glaciers move under the influence of gravity and have crevasses and moraines.
Covered glacier	Same as glaciers, though with debris cover.
Snow patch	Shows, compared to glaciers, no evidence of flow.
Covered glacier with rock glacier	Landform that has debris-covered ice grading into a rock glacier.

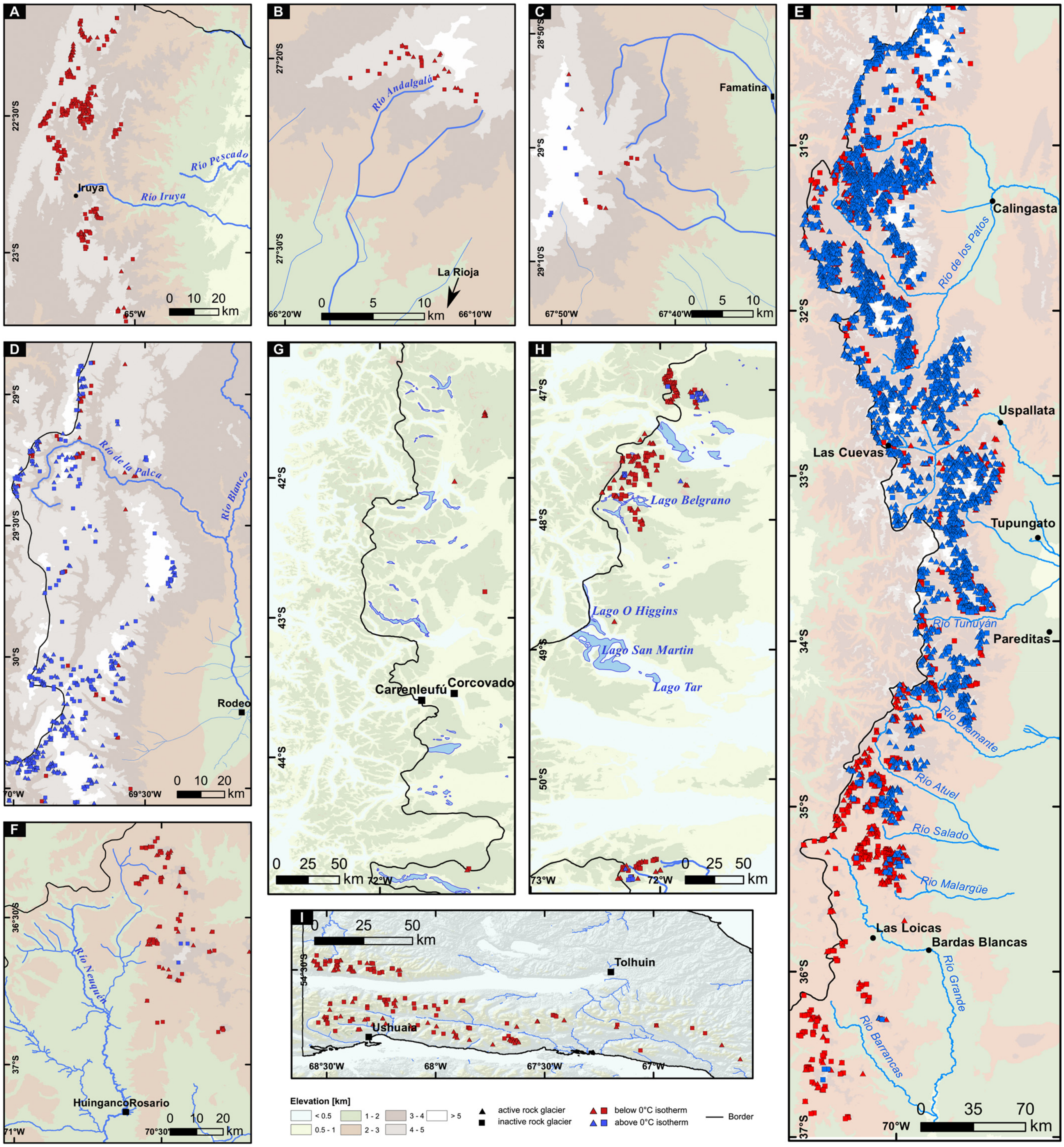

Fig. 3. Maps of the subregions studied. (A) Desert Andes (north), (B) Desert Andes (central), (C) Desert Andes (south), (E) Central Andes, (F) Andes of Patagonia (north), (G) Andes of Patagonia (central), (H) Andes of Patagonia (south), (I) Tierra del Fuego. Active (triangle) and inactive (rectangle) rock glaciers lie above (blue) and below (red) the local 0 °C isotherm elevation defined for the period 1960–1990. Cities, lakes, and rivers serving as orientation are from www.openstreetmap.org.

and future conditions are the downscaled output of the global climate model (Coupled Model Intercomparison Project Phase 5 (CMIP 5)) from the 5th Assessment report of the IPCC (IPCC, 2005). The data include four representative concentration pathways (RCP 2.6, 4.5, 6, and 8.5, Table 4) that simulate future radiative forcing (Wayne, 2013).

The CMIP 5 is a framework of various global climate models focusing on different climate aspects, but it uses standardised boundary conditions to make the results comparable. For a consistent analysis between past and future climate conditions, we considered climate models with data for the Last Glacial Maximum, Last Interglacial Maximum, mid-Holocene, and future in the WorldClim data. We chose the coupled global model CCSM 4 (community climate system model version 4), which includes an atmospheric, land-surface, ocean, and a sea-ice component (Gent et al., 2011). We only show here the results

Table 3
Topographic and climatic characteristics of the subregions studied here; data are from the SRTM mission and estimated by Hijmans et al. (2005).

Study area	Elevation [m]		MAAT [°C]		MAP [mm]	
	Min	Max	Min	Max	Min	Max
Desert Andes (north)	3570	5200	1.22	11.4	138	376
Desert Andes (central)	3870	6100	−6.7	8.7	78	334
Desert Andes (south)	3020	6270	−11	7.8	48	307
Central Andes	2370	6960	−15.4	9.9	72	910
Andes of Patagonia (north)	2340	4700	−6.9	8.2	267	1291
Andes of Patagonia (central)	1530	3430	−3.4	8.0	348	1931
Andes of Patagonia (south)	1070	3300	−7.4	6.9	168	1554
Tierra del Fuego	470	1570	−1.5	5.6	426	867

for the Last Interglacial Maximum, the twentieth century, and the worst-case scenario RCP 8.5 for 2070 to investigate how climate developed from past conditions, which were comparable to current ones.

3. Methods

From the WorldClim data set, we compiled zonal statistics for all bioclimatic variables and timesteps with TopoToolbox in Matlab (Schwanghart and Scherler, 2014). We calculated for each rock-glacier polygon the minimum, maximum, median, mean, and standard deviation of each bioclimatic variable. For topographic metrics, we used the SRTM 30-m digital elevation model available from the USGS Earth Explorer (https://earthexplorer.usgs.gov/). We defined our study areas by subtracting from the minimum elevation of the lowest rock-glacier toe a 10% buffer in elevation to minimise bias in our interpretations in areas devoid of rock glaciers. We estimated the elevation range of the mean annual 0 °C isotherm (or freezing level) by using the mean annual temperatures of the WorldClim data set for the Last Interglacial Maximum, twentieth century period, and worst case scenario RCP 8.5 2070. We used the mean 0 °C isotherm elevation for the twentieth century and for the RCP 8.5 scenario as a threshold to estimate the percentage of rock-glacier toes that fell below the 0 °C isotherm.

To find suitable predictors of rock-glacier toe elevation, we used a Bayesian Multifactor Analysis of Variance that can reveal credible differences in the toe elevations of active and inactive rock glaciers across groups defined by geographic position, type, aspect, formation mechanism, and planform. This method learns from the data the deviation of a group-level variable from the common mean or baseline. An ANOVA assumes that the data are independent and normally distributed, that the variances are equal, and that the groups have the same size. This is not required for a Bayesian approach:

$$p(\theta|D) = \frac{p(D|\theta)\, p(\theta)}{p(D)} \tag{1}$$

Table 4
Overview of representative concentration pathways with radiative forcing in different climate scenarios (Wayne, 2013).

Scenario	Description
RCP 2.6 – best case	• 3.1 W/m^2 by 2050 • 2.6 W/m^2 by 2100 • Equivalent to an atmospheric CO_2 concentration of 490 ppm
RCP 4.5	• Stabilization shortly after 2100 by 4.5 W/m^2 • Equivalent to an atmospheric CO_2 concentration of 650 ppm
RCP 6.0	• Stabilization shortly after 2100 by 6.5 W/m^2 • Equivalent to an atmospheric CO_2 concentration of 850 ppm
RCP 8.5 – worst case	• Rising greenhouse gas emissions until 2100 with 8.5 W/m^2 • Equivalent to an atmospheric CO_2 concentration of 1370 ppm

where $p(\theta|D)$ is the posterior distribution of model parameters θ given observed data D; $p(D|\theta)$ is the likelihood that these data were generated from a model built on θ; $p(\theta)$ is the prior knowledge about these parameters; and $p(D)$ is the evidence irrespective of this prior. Compared to statistical methods based on point estimates, Bayesian inference offers full probability distributions, reallocating the credibility of the model parameters based on observed data and prior knowledge that is also encoded in probability distributions (Kruschke et al., 2012). We use a hierarchical model of a Bayesian ANOVA to predict from categorical inputs a numeric target variable y with Gaussian likelihood: $y \sim \mathcal{N}(\mu, \tau)$. This Gaussian has a mean generated by a linear model $\mu = b_0 + \sum_{i=1}^{I_1} b_{1,i} x_{1,i} + \sum_{j=1}^{J_2} b_{2,j} x_{2,j}$, and precision τ, which is the reciprocal of the variance σ^2. This example has two categorical inputs x_1 and x_2 with i and j states, respectively, and that we encode as 1-of-k vectors, labelling the observed state as 1, and all other levels as 0. The constraint for an ANOVA is that the contrasts $b_{1,\,i}$ and $b_{2,\,j}$ express deviations from the baseline b_0, and, thus, must add to zero: $\sum_{i=1}^{I_1} b_{1,i} = 0$ and $\sum_{j=1}^{J_2} b_{2,j} = 0$. Our prior knowledge assumes that standardised $b_0 \sim \mathcal{N}(0, 0.001)$ and that σ is uniformly distributed, $\sigma \sim U(0,10)$. We further assume that contrasts b_1 and b_2 are Gaussian distributed with zero mean and precision τ_b drawn from a Gamma distribution with a mode = 1 and standard deviation = 10. This model can be

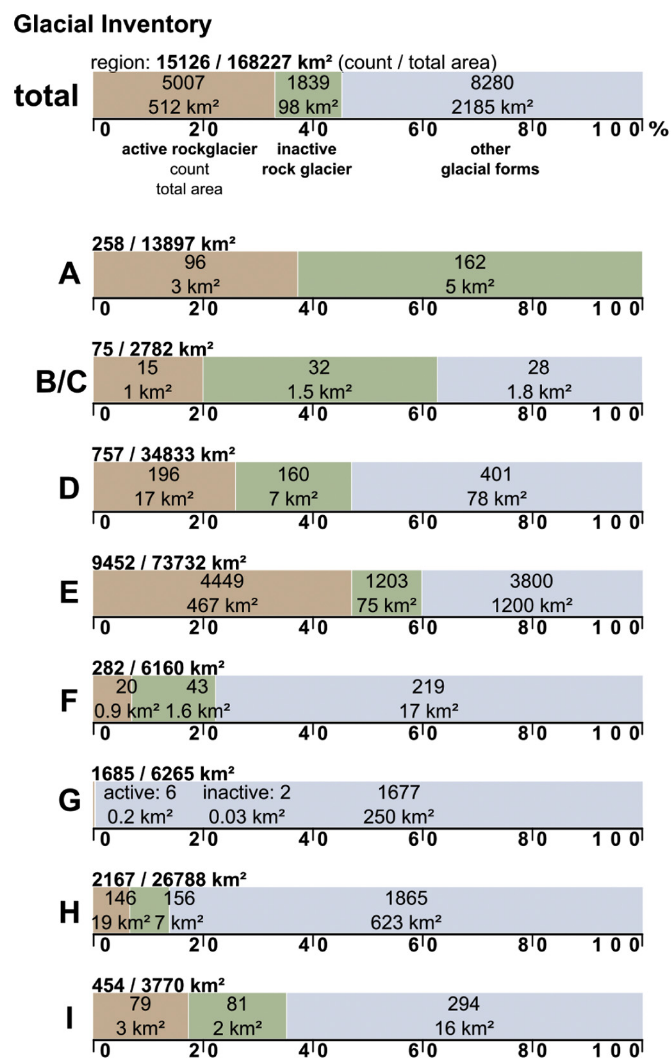

Fig. 4. Bar plots showing the count (in %) and total area of active (brown) and inactive (green) rock glaciers compared to other glacial landforms (blue) in the inventory in subregions A-I (see Fig. 2).

Table 5
Mean minimum toe elevation of active and inactive rock glaciers and mean 0 °C isotherm elevation for the study areas under twentieth century conditions and worst case scenario RCP 8.5 (2070) on the regional scale with their deviations, derived from the probability density.

Region	Mean minimum toe elevation [m]		Deviation between active and inactive [m]	Mean 0 °C isotherm [m] ± SD					
	Active	Inactive		20th century	Difference [m] to		RCP 8.5 2070	Difference [m] to	
					Active	Inactive		Active	Inactive
Desert Andes (north)	4560	4500	60	–	–	–	–	–	–
Desert Andes (central)	4662	4507	155	4901 ± 219	239	394	5411 ± 156	749	904
Desert Andes (south)	4496	4435	61	4151 ± 269	−355	−284	4906 ± 219	410	471
Central Andes	3954	3750	204	3735 ± 197	−219	−15	4414 ± 244	460	664
Andes of Patagonia (north)	2959	2908	51	3377 ± 159	418	469	3990 ± 138	1031	1082
Andes of Patagonia (central)	1984	1901	82	2335 ± 211	351	434	3109 ± 144	1125	1208
Andes of Patagonia (south)	1646	1718	−72	1873 ± 161	227	155	2445 ± 240	799	727
Tierra del Fuego	865	875	−10	1134 ± 100	269	259	–	–	–

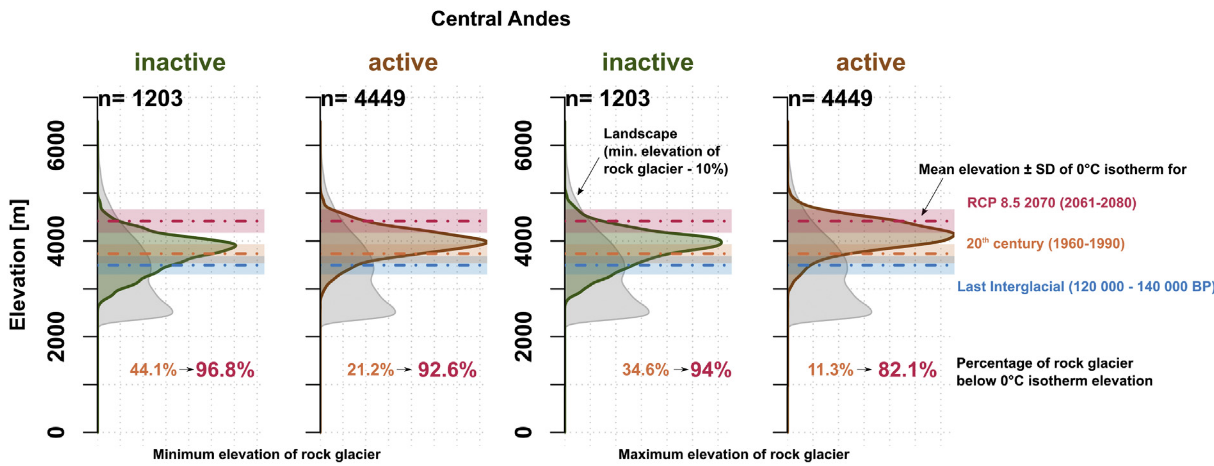

Fig. 5. Estimated distributions of approximate maximum and minimum toe elevations of inactive (green) and active (brown) rock glaciers in the Central Andes of Argentina. Dashed lines and rectangles enclose the approximate 0 °C isotherm elevations during the Last Interglacial (blue), twentieth century (orange), and climate scenario RCP 8.5 (red). Grey shades show distribution of elevation in the study area. Percentages refer to number of rock glaciers below the 0 °C isotherm elevation under current and future (2070) conditions.

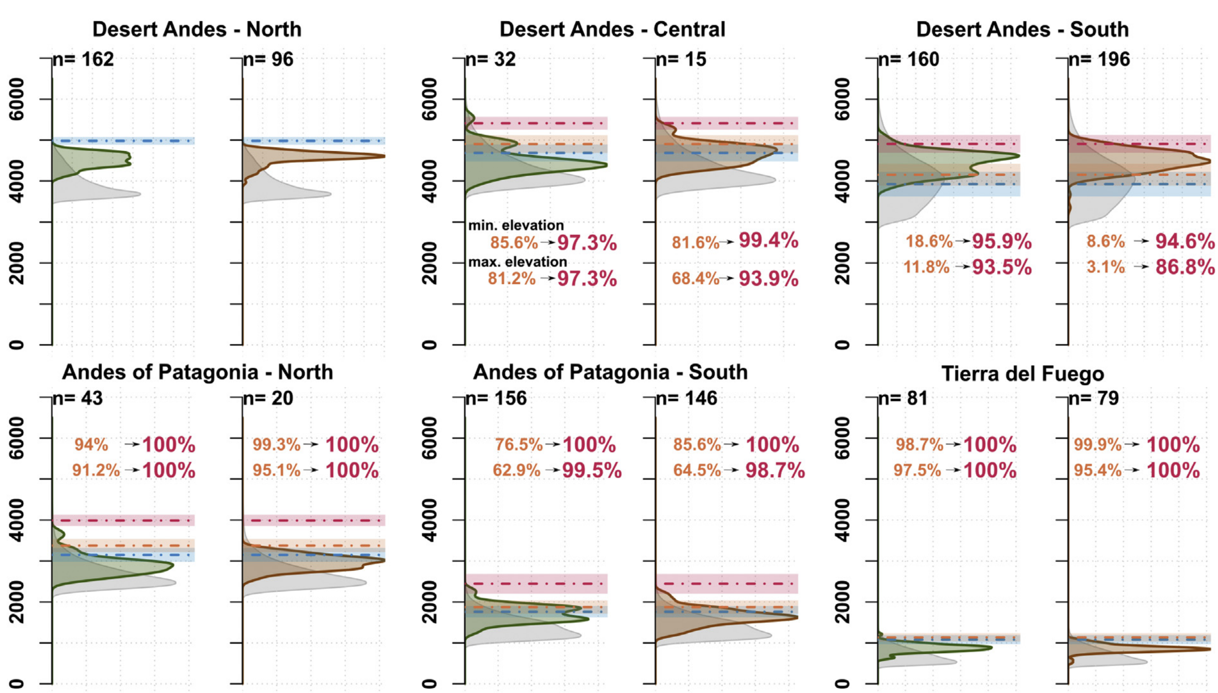

Fig. 6. Estimated distributions of approximate maximum and minimum toe elevations of inactive (green) and active (brown) rock glaciers. The Central Andes of Patagonia are omitted because of insufficient data. See Fig. 5 for explanation.

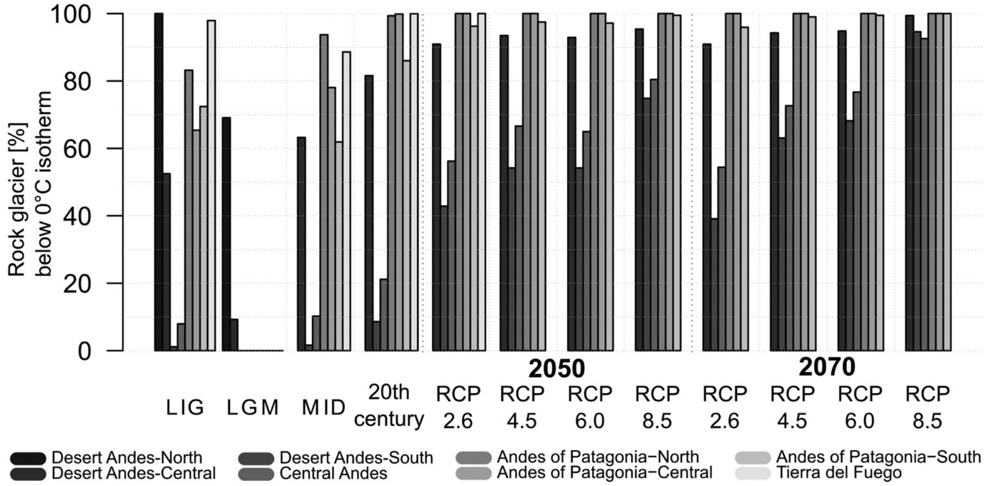

Fig. 7. Percentage of active rock-glacier toes below the mean 0 °C isotherm elevation under past (LIG – Last Interglacial, LGM – Last Glacial Maximum, MID – mid-Holocene), current twentieth century, and projected future climatic conditions (scenarios RCP 2.6, 4.5, 6.0, 8.5 for the years 2050 and 2070).

extended for multiple categorical inputs and interaction terms. Whereas the likelihood and prior information are easy to compute, the evidence or marginal likelihood, $p(D) = \int p(D|\theta)p(\theta)d\theta$, requires most computational effort, especially if integrating over many parameters. Using Markov Chain Monte Carlo (MCMC) and a collection of numerical sampling algorithms implemented in the JAGS language, we estimate the joint posterior distribution from random samples from the standardised parameter space. We ran five parallel MCMC chains with 100,000 steps each to approximate the joint posterior, allowing for 2000 burn-in steps. Given successful convergence, the output of the MCMC provides the marginal posteriors for each model parameter. We use the highest-density interval (HDI) that contains 95% of the probability density in each marginal posterior distribution to summarise the range of credible parameter values (Kruschke et al., 2012). We use the term *credible* here to identify those parameters that do not contain zero in 95% HDIs.

4. Results

The inventory contains 5007 active and 1839 inactive rock glaciers covering an area of >500 km^2 and 100 km^2 respectively. More than 85% of all Argentinian rock glaciers in terms of numbers and area are in the arid to semiarid southern Desert Andes and Central Andes, which make up 60% of the study area (Fig. 4).

On average, rock glaciers terminate <350 m below the mean 0 °C isotherm elevation in the southern Desert Andes and the Central Andes (Table 5). About 21% (44%) of (in)active rock-glacier toes in the Central Andes are below the freezing level at 3730 m asl. This percentage is even higher in the central Desert Andes and in the southern Andes of Patagonia (>75%) and highest in the northern Desert Andes, the northern Andes of Patagonia, and in Tierra del Fuego (>95%). We note that in the northern Desert Andes, the 0 °C isotherm elevation does not

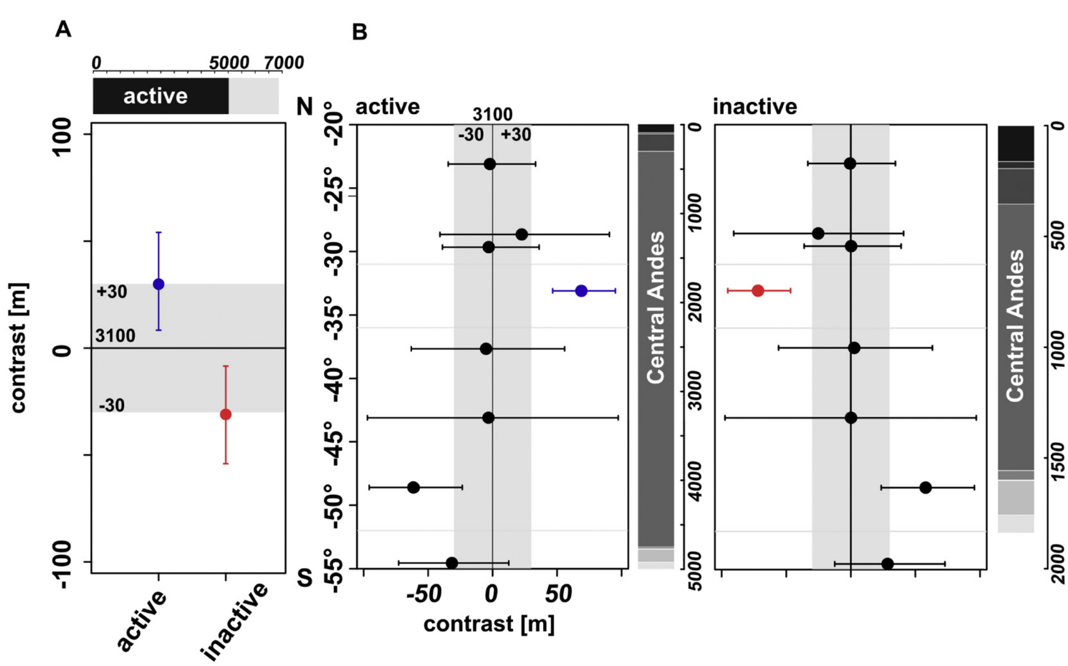

Fig. 8. (A) Deviations (contrasts) from the overall mean toe elevation grouped by state of rock-glacier activity; and (B) also grouped by subregion; red (blue) colours indicate a credible negative (positive) deviation, whereas black colours show no credible contrast; bars show rock-glacier count per subregion; see Fig. 7 for legend.

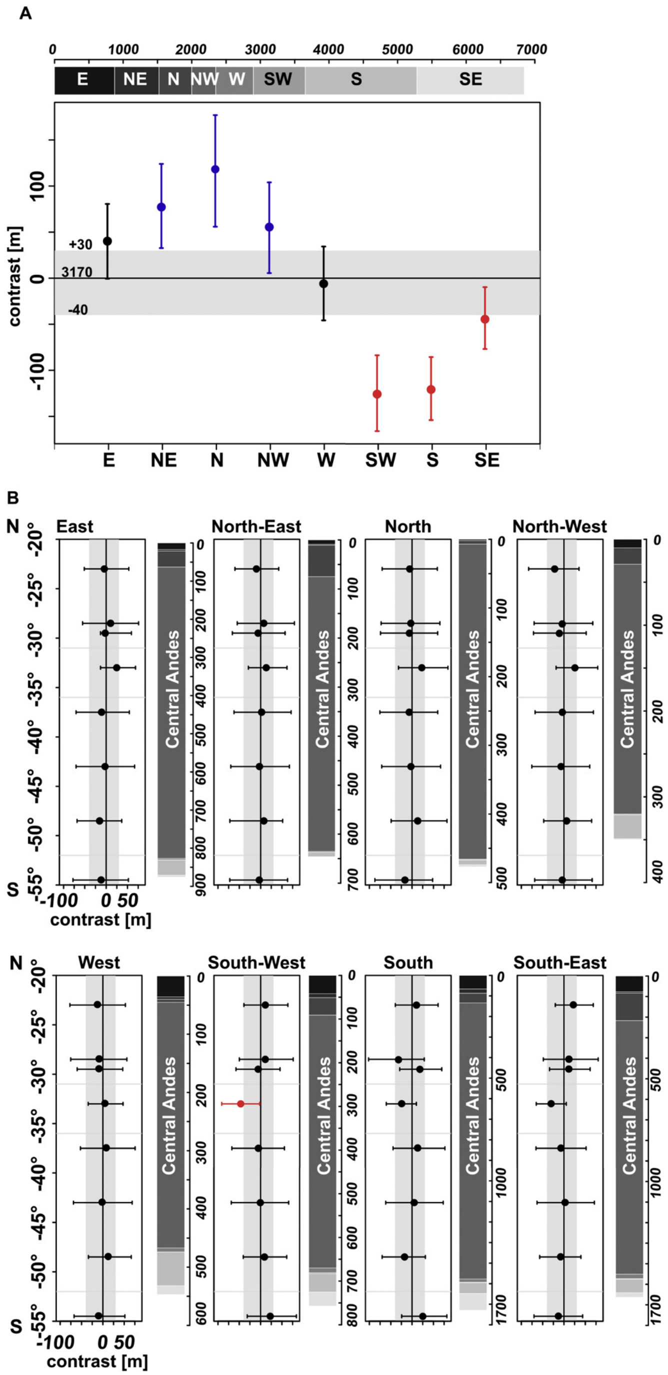

Fig. 9. (A) Deviations (contrasts) from the overall mean toe elevation of rock glaciers grouped by aspect; and (B) aspect and subregion; see Fig. 8 for explanation.

intersect with the topography, though this subregion has nearly 100 active rock glaciers (Figs. 5, 6). We find that active and inactive rock glaciers occupy nearly identical elevation bands along the Argentinian Andes. Inactive rock glacier toes are mostly only 50–80 m lower than those of active rock glaciers (Table 5; Figs. 5, 6). In the Central Andes, most active rock glacier toes are below ~3950 m asl, whereas inactive rock glaciers are about 200 m lower. The southern Andes of Patagonia and Tierra del Fuego have an opposite trend, with inactive rock glacier toes lying up to 70 m higher than active rock glaciers.

All climate scenarios that we considered for 2050 and 2070 involve upward shifts of the 0 °C isotherm by at least 500 m (Table 5; Figs. 5, 6). With future atmospheric warming, the mean 0 °C isotherm elevation in the Central Andes is likely to rise to ~4400 m asl. In the worst case (RCP 8.5), 93% of currently active rock glaciers would terminate below the mean 0 °C isotherm elevation by 2070. We obtain similar results for the southern Desert Andes, where 8.6% of all active rock glaciers are already below this level; this percentage could be as high as 95% by 2070 (Table 5; Figs. 5, 6).

Regardless of climate scenario or region, more than half of all active rock glaciers will lie below the 0 °C isotherm by 2050. Active rock glaciers in the southern Desert Andes and Central Andes might be prone to the most dramatic changes in this regard (Fig. 7), and we obtain similar results, if instead using the estimated maximum elevation of the rock-glacier bodies (Figs. 5, 6).

The results from our Bayesian Multifactor ANOVA show that toe elevations of active and inactive rock glaciers differ credibly in the Argentinean Andes as a whole. If considering activity and subregion, however, only the Central Andes offer a credible distinction (Fig. 8), whereas the elevation contrasts in all other combinations are too low to be credible. Effects of hillslope aspect have a similarly subordinate influence on rock-glacier toe elevation: whereas the elevation contrasts are even smaller, SW-exposed rock-glacier toes in the Central Andes are the only ones that are credibly below the overall mean. Generally speaking, rock glaciers with a SW to SE aspect have moved farther in the landscape than those with a NW to NE aspect (Fig. 9).

Similarly, grouping rock glaciers by region, planform shape, and formation mechanism (Figs. 10, 11) offers little insights as to credibly predicting toe elevations from the activity of rock glaciers alone. Only rock glaciers mapped as having an *uncertain planform* are credibly lower in the Central Andes, as are those with a glacier origin in this area.

5. Discussion

5.1. Changing freezing level

Numerous, and in some regions all, the toes of rock glaciers lie credibly below the 0 °C isotherm elevation in warmer parts, contrary to the general assumption that toes mark the 0 °C isotherm of mean annual air temperature (Garleff and Stingl, 1986; Schrott, 1994; Barsch, 1996; Janke, 2005). Only in the southern Desert Andes and Central Andes are rock glaciers toes >350 m above the 0 °C isotherm elevation on average in colder regions (Table 5; Figs. 5, 6). These are also the subregions with the largest projected atmospheric warming: whereas currently 10–20% of active rock glaciers are below the average freezing level, this percentage could rise to 95% by 2070 in these parts of the Argentinian Andes (Figs. 5, 6). This projection is similar to that by Rangecroft (2015) for the Bolivian Andes, where 34% of the active rock glaciers would terminate below the 2 °C isotherm by 2050. Azócar et al. (2017) observed that, in the semiarid Chilean Andes, 60–80% of the rock glaciers they mapped were below the present 0 °C isotherm elevation and argued that most rock glaciers were in areas with mean annual air temperatures above 0 °C owing to their delayed response of permafrost to atmospheric warming and to the advance of rock glaciers into nonpermafrost regions and favourable climate conditions (Azócar et al., 2017).

Such predictions contain several uncertainties, especially with regard to extrapolating isotherms. Our estimates of the 0 °C isotherm elevation are based on the WorldClim data set, but are largely consistent with other studies (Brenning, 2005; Azócar and Brenning, 2010). Nonetheless, permafrost can occur during a more variable air temperature regime, and rock glaciers can have a locally colder thermal regime that is out of equilibrium with regional climatic conditions so that fast-moving rock-glacier lobes enter permafrost-free elevations (Azócar et al., 2017; Bolch and Gorbunov, 2014). Brenning and Trombotto (2006), for example, reported intact rock glaciers in the Central Andes as low as 3000 m asl, where mean annual air temperatures are around 4 °C. To this end, we also considered the maximum elevation of rock glaciers as a more conservative proxy of the permafrost limit. The initiation zones of many rock glaciers are more diffuse and difficult to discern than the more pronounced toes, though we obtained very similar results for

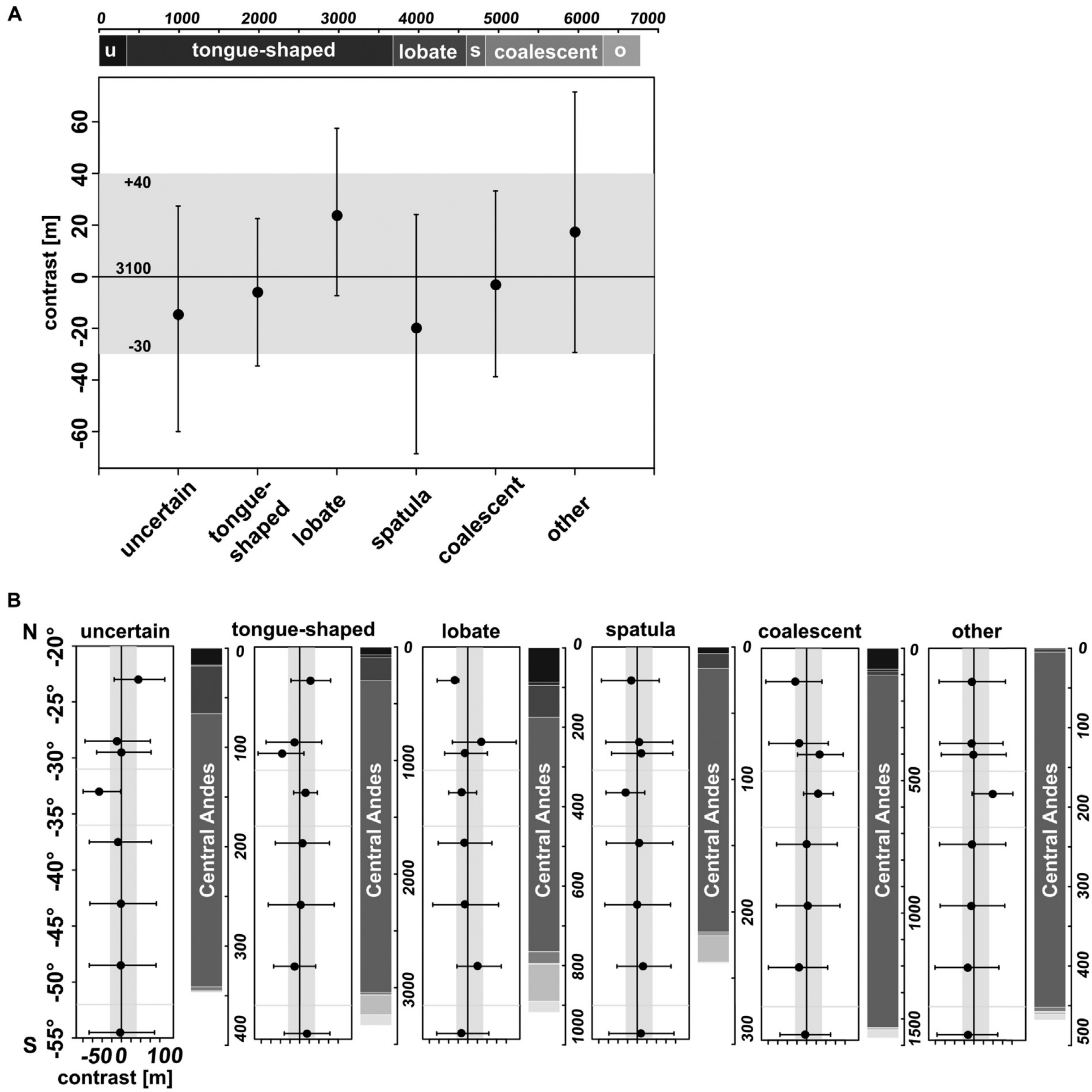

Fig. 10. (A) Deviations (contrasts) from the overall mean toe elevation grouped by planform shape; and (B) planform shape and subregion; see Fig. 8 for explanation.

the different climate scenarios, mainly because 75% (90%) of all (in)active rock glaciers span <200 vertical metres.

5.2. Activity of rock glaciers

The topographic gradient along the Andes is the first-order control on the vertical distribution of rock glaciers (Fig. 12A), and hillslope aspect modifies this pattern such that north-exposed rock glaciers receiving higher solar radiation lie higher (Fig. 9). Rock glaciers terminate on average some 500 m lower than glaciers in the northern Argentinian Andes; but this tendency reverses, and rock glacier toes are higher on average in the south (Fig. 12B). This vertical difference is mimicked by apparent shifts in the snowline since the 1980s, at least judging from World Glacier Inventory (http://nsidc.org/data/glacier_inventory/index.html) data, which indicate average advances (retreats) of glaciers in the north (south) of the Argentinean Andes. This pattern was described by Haeberli (1983), who found that the permafrost boundary in the Swiss Alps, was >400 m lower than today during the Würm glaciation (10,000–15,000 YBP).

Active and inactive rock glaciers occupy nearly identical elevation bands in nearly all subregions (Fig. 8), which contradicts the idea that inactive rock-glacier toes generally lie noticeably lower (e.g., Angillieri, 2010). The Bayesian Multifactor ANOVA demonstrates that an elevation difference of at least 140 m is required to credibly (in a Bayesian sense) distinguish active from inactive rock glaciers in each Andean subregion (Fig. 8). Therefore, inferences about the regional distribution of discontinuous permafrost based on the toe elevations of active rock glaciers (e.g., Monnier and Kinnard, 2015) cannot be more precise than 140 vertical metres on average, at least in the Argentinian Andes. Predictors such as aspect, rock-glacier formation mechanism, and planform do not improve results here. We note that the mean 0 °C isotherm elevation during the mid-Holocene was only ~200 m below its current position (within error) in the Argentinean Andes. Yet, the climate scenarios we considered involve expected upward shifts of the 0 °C isotherm of >500 m by 2070, thus, likely constraining the formation of new, if any, rock glaciers to higher parts of the landscape and promoting new generations of rock-glacier toes to override older bodies. Such projected warming may not necessarily mean that all active rock glaciers thus affected will become

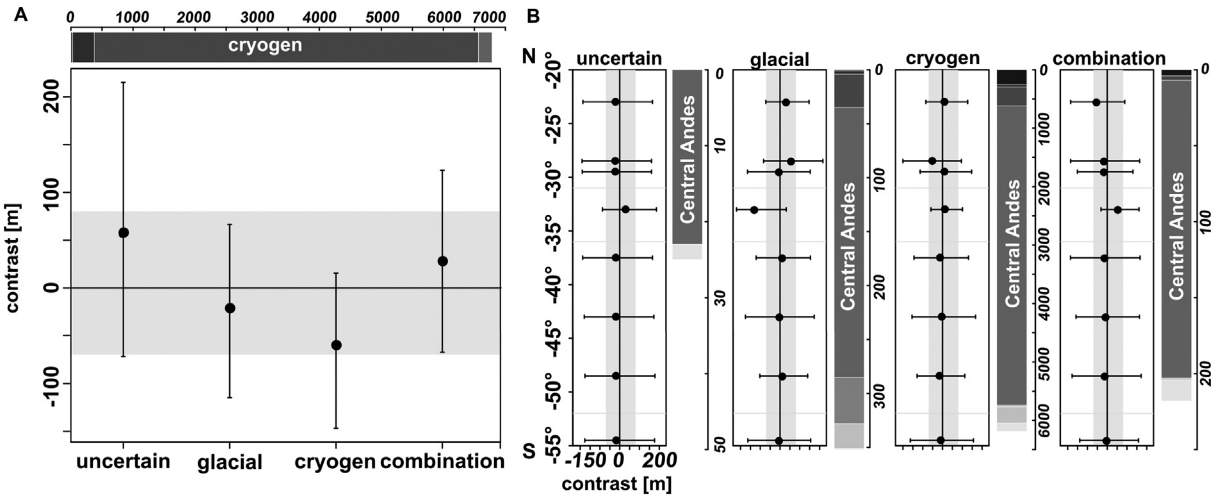

Fig. 11. (A) Deviations (contrasts) from the overall mean toe elevation grouped by formation mechanism; and (B) formation mechanism and subregion; see Fig. 8 for explanation.

inactive (Rangecroft et al., 2014): the northern Desert Andes sustain many active rock glaciers, even though the 0 °C isotherm is above the topography in that subregion (Martini et al., 2017). Yet ice-rich permafrost may respond very slowly to atmospheric warming. Haeberli (1985) pointed out that ice in an alpine rock glacier will take ~1000 years to melt completely given a temperature increase of 3 K. Permafrost cores of inactive rock glaciers may be up to 10,000 years old (Krainer et al., 2014) and indicate that complete ice decay may happen on timescales that are much longer than rapid atmospheric warming. In essence, the activity of rock glaciers represents its current deformation whereas topography and climate set the longer-term extent and activity of permafrost.

5.3. A cluster of rock glaciers

The Central Andes stand out in all our analyses: the area between 28°S and 34°S has the greatest density of rock glaciers (>80% of rock glaciers in the inventory) and also one of the highest in the world in terms of elevation (Brenning and Trombotto, 2006). There, rock glaciers also dominate large parts in terms of total area, outweighing that of glaciers, which become more prominent south of 36°S, where rock glaciers become rare (Fig. 12C, D). Janke et al. (2017) reported a similar pattern for the Aconcagua River basin, where glaciers and debris-covered glaciers were the largest but had a small total area, whereas rock glaciers were most abundant and covering a greater area. We also observe that active rock glaciers are credibly higher than inactive ones only in this part of the Andes. Similarly, it is only in the Central Andes that rock glaciers with a SW aspect are credibly lower; the same applies for rock glaciers with an *uncertain planform* and those connected to glaciers. There, rock glaciers also span more vertical metres and are larger than elsewhere in the Andes so that differences in activity stand out more clearly. Our Bayesian Multifactor ANOVA caters for unbalanced sample size (Kruschke et al., 2012) so that we can disregard the high abundance of rock glaciers in this part of the Andes. Operator bias could play a role: the subregions have been mapped by different people and, although all these experts used the same guidelines, telling apart active from inactive rock glaciers using satellite image interpretation can be problematic and introduce uncertainties (Jones et al., 2018).

The Central Andes is also among the coldest subregions with −10 °C of mean annual air temperatures and mean annual precipitation totals of up to 900 mm. South of the Central Andes, glaciers dominate likely in response to the shift from arid to (per-)humid climate. Rock-mass strength can influence the rates of debris production that nourish rock-glacier growth. For example, Krainer and Ribis (2012) and Lieb (1991) reported that rock glaciers in the Alps are mostly concentrated in metamorphic rocks. Onaca et al. (2017) noted that in the southern carpathian, rock glaciers were concentrated in areas with granites and granodiorites. Angillieri (2010) mentioned that in the San Juan Province, southern Desert Andes, most of the rock glaciers are within the Permo-Triassic volcanic rocks, which also crop out in other parts of the Andes. Brenning (2005) noted that more weathering-resistant Quaternary volcanic rocks provided little debris to nourish rock glaciers. To check whether rock glaciers are rare also in areas with volcanic rocks in the Argentinian Andes, we used locations of Holocene volcanoes from the Global Volcanism Program. The regional pattern is indeed such that rock glaciers distinctly cluster in the gap between the Andean Central Volcanic Zone and the Southern Volcanic Zone (Fig. 12C, D), where flat-slab subduction prevails (e.g., Ramos and Folguera, 2009). Orogen-scale links between Andean geomorphology, tectonics, and climate indicate that erosion potential is also among the lowest in the Central Andes (Montgomery et al., 2001), judging from the distribution of deeply exhumed crystalline rocks and volcanic complexes. Greater rates of erosion driven by higher humidity may explain the decline in rock glaciers south of 36°S. The southern Desert Andes and Central Andes seem to offer optimal conditions for developing thousands of rock glaciers, being cold, semiarid, and resistant to erosion, partly perhaps because of largely absent weathering-resistant Quaternary volcanic rocks. Nonetheless, these two subregions are also the ones most susceptible to atmospheric warming, as a result we expect the most pronounced and also widespread changes to rock glaciers there. The geomorphic fate of rock glaciers in a warmer climate remains largely unknown, though many may gradually become relict and immobile once terminating below the freezing level; some may potentially collapse catastrophically and release debris flows (Bodin and Iribarren Anacona, 2012; Iribarren Anacona et al., 2014). Giardino and Vitek (1988) view rock glaciers as forms shaped by glacial and periglacial processes. A glacier may become debris-covered and transform progressively into a rock glacier, where the ice cores may melt with rising temperatures, leaving only till or colluvium (Giardino and Vitek, 1988). Often it is difficult to define the shape of a rock glacier, and Monnier et al. (2011) argued that the Thabor rock glacier in the northern French Alps, for example, is neither a debris-covered glacier nor a moraine nor a rock glacier in a sense of creeping permafrost. This clearly underlines the need to better understand the dynamics of rock glaciers under global warming.

6. Conclusions

We provided a regional assessment of how atmospheric warming and the associated rise of the freezing level might impact on several thousand active rock glaciers in the Argentinian Andes. We investigated the elevation of toes of rock glaciers as an indicator of local permafrost conditions.

- Future atmospheric warming will raise the 0 °C isotherm by about 500 m under a worst case scenario, more than during the entire Holocene. We expect that in the southern Desert Andes and Central Andes up to 95% of currently active rock glaciers will terminate below the 0 °C isotherm by 2070; these two high-elevation, cold, semiarid, and volcanically inactive subregions also have the largest and most densely clustered rock glaciers in the Argentinian Andes, locally even exceeding the total area of glaciers.
- The number and area of rock glaciers below the freezing line is a first-order measure of potential impacts of atmospheric warming on these permafrost landforms. Several subregions in the Argentinian Andes, however, have active rock glaciers below the 0 °C isotherm. Under future atmospheric warming, not all active rock glaciers below the 0 °C isotherm elevation will necessarily become inactive. Clearly, rock glaciers respond differently depending on the thermal regime, microclimate conditions, debris supply, and topographic and geological settings (Arenson et al., 2010). Our analysis affords some first insights into how many rock glaciers may become inactive or lose ice under atmospheric warming.
- Active and inactive rock glaciers occupy very similar elevation bands and can hardly be distinguished based on toe elevations. The results of a Bayesian Multifactor ANOVA show the state of rock-glacier activity can predict credible differences in toe elevations only if >140 m, which is, thus, the minimum vertical resolution limit to infer the regional distribution of discontinuous permafrost from rock-glacier locations in the Argentinian Andes.

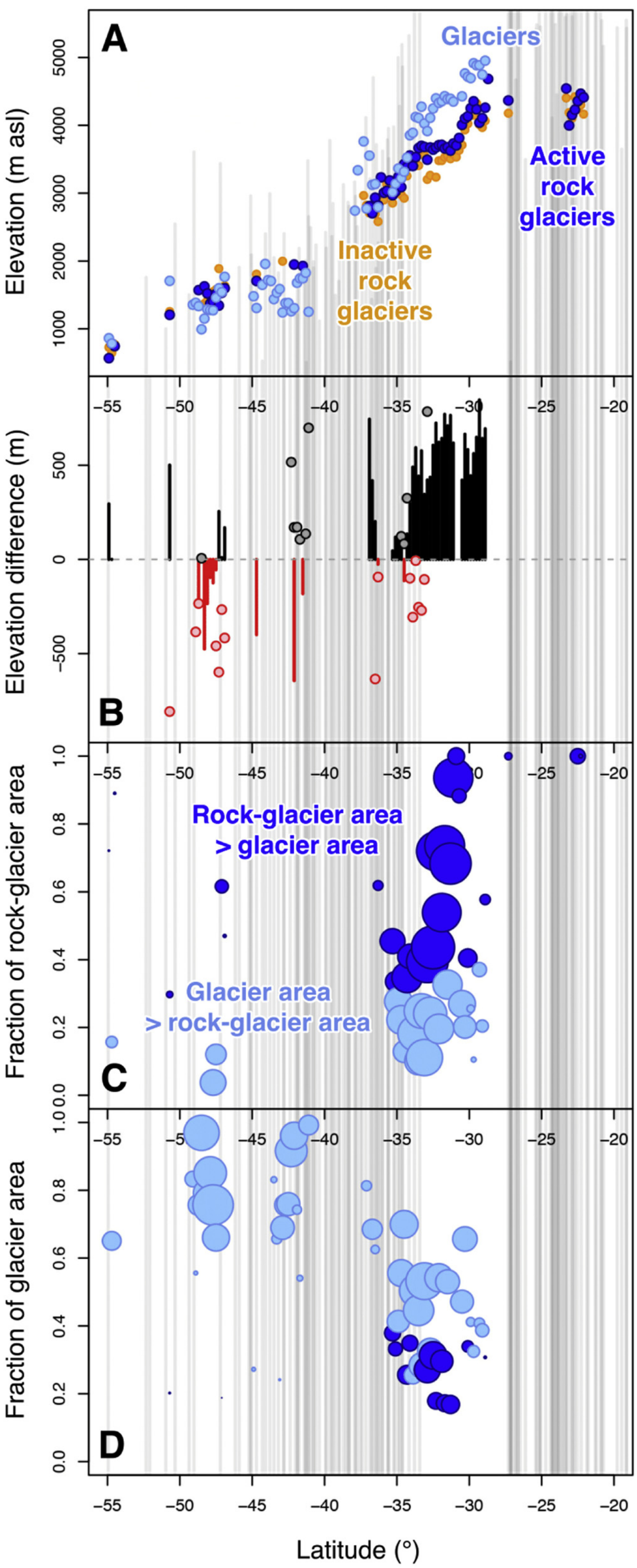

Fig. 12. Distribution of glaciers, rock glaciers, and volcanoes that erupted in the Holocene (vertical grey lines; data from the Global Volcanism Program, http://www.volcano.si.edu/) along the Argentinian Andes in 0.1° bins of latitude. (A) Circles are 5th percentiles of toe elevations. (B) Binned differences of toe elevations in (A); black and red lines are differences between glacier and active rock glaciers, while black and red circles are differences between glacier toes and WGI snowline data from the 1980s. (C) Fraction of binned rock-glacier total area of the total landform area mapped in the inventory; bubble size scaled to total rock-glacier area; dark blue (light blue) shows where rock glaciers have a higher (lesser) total area than glaciers. (D) Fraction of binned glacier total area of the total landform area mapped in the inventory; bubble size scaled to total glacier area; bubble colour as in (C).

Declaration of interest

None.

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