Tropical glacier reconstructions during the Last Glacial Maximum in Costa Rica

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ABSTRACT

Numerous high elevation tropical mountains around the world show evidence of past glacial activity during the Last Glacial Maximum (LGM). Cerro Chirripó in Costa Rica exhibits paleoglacial landforms such as glacial cirques, moraine deposits and polished and striated bedrock surfaces. We used aerial imagery (1:25000) and contour lines to develop a Digital Elevation Model (DEM) for the LGM. We determined paleo-equilibrium line altitudes (paleo-ELAs) using Area-Altitude Balance Ratio (AABR) during the LGM for Cerro Chirripó in Costa Rica. Additionally, a Generalized Linear Model (GLM) was performed to statistically analyze the paleoglacier volumes and ice thickness combined with ten land surface parameters (LSP). Our results identified thirty-one paleoglaciers covering an area of 28.26 km^2 during the global LGM, with a maximum ice thickness of 178 meters in Cerro Chirripó, a total volume of 13863 × 10^5 m^3 and a mean paleo-ELA of 3490 meters. In addition, Area and Slope were the LSP with the highest statistical correlation to explain the paleoglacier volumes, while Area and Diurnal Anisotropic Heating were best for the paleoglacier ice thickness. As one of the first studies in the tropical high mountain environments, this work expands the geographic scope of glacier volume and thickness reconstructions during the maximum expansion of the LGM.

Key words: glacier reconstruction; paleoglacier; ice thickness; equilibrium line altitude; Geomorphometry; Chirripó National Park, Costa Rica.

RESUMEN

Numerosas altas montañas tropicales muestran evidencia de actividad glacial durante el Último Máximo Glacial (UMG) y han sido documentadas alrededor del mundo. El Cerro Chirripó, en Costa Rica, presenta formas de relieve paleoglaciares como circos glaciares, depósitos de morrenas, así como superficies de roca pulida y estriada. Utilizamos imágenes aéreas (1:25000) y curvas de nivel para obtener un Modelo Digital de Elevación (MDE) del UMG. Determinamos las altitudes de las líneas de paleoequilibrio (paleo-ELAs) usando el Area-Altitude Balance Ratio (AABR) durante el UMG para el Cerro Chirripó en Costa Rica. Además, se realizó un Modelo Lineal Generalizado (MLG) para analizar estadísticamente los volúmenes de los paleoglaciares y el espesor del hielo combinados con diez parámetros de superficie terrestre (PST). Nuestros resultados determinaron treinta y un paleoglaciares que cubrían un área de 28.26 km^2 durante el UMG global, con un espesor máximo de hielo de 178 metros en el Cerro Chirripó, un volumen total de 13863 × 10^5 m^3 y un paleo-ELA medio de 3490 metros. Además, Área y Pendiente fueron los PST con mayor correlación estadística para explicar los volúmenes paleoglaciares, mientras que Área y Calentamiento Anisotrópico Diurno (CAD) fueron los mejores parámetros para el espesor del hielo paleoglaciar. Como uno de los primeros estudios en los ambientes tropicales de alta montaña, este trabajo expande el alcance geográfico de las reconstrucciones de glaciares durante la máxima expansión del UMG.

Palabras clave: reconstrucción glaciar; paleoglaciar; grosor de hielo; altitud de la línea de equilibrio; Geomorfometría; Parque Nacional Chirripó, Costa Rica.

INTRODUCTION

Glacier reconstructions as a paleoclimatic information source has an important role in analyzing the relationships between glaciers and climate (Campos *et al.*, 2019). Interpretations of glacial relict landforms can be used to deduce climatic conditions at the time of glaciation, implying that prior glaciers may be useful paleoclimatic proxy records (Carr and Coleman, 2007). In addition, glacial reconstructions can provide crucial information about past glacial changes over much longer timescales than the observational record permits (Carr *et al.*, 2010; Pearce *et al.*, 2017). Moreover, tropical glaciers are highly sensitive to changes in regional and global climate (Chen *et al.*, 2018). Glacial landforms associated with the Last Glacial Maximum (LGM; between ~26.5–19 ka as defined by Clark *et al.*, 2009) persist in tropical regions of Africa, Asia, Oceania, and America (Porter, 2000; Mark *et al.*, 2005). In America, several tropical regions in Costa Rica, Guatemala, Mexico, and the Andes have reported glacial relict landforms created during the LGM (Palacios *et al.*, 2020).

In Costa Rica, Cerro Chirripó's past glacial dynamics have been studied several times (Weyl, 1955; Hastenrath, 1973; Bergoeing, 1977; Barquero and Ellenberg, 1983). Lachniet and Seltzer (2002) mapped

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35 km^2 of the Cerro Chirripó area and mentioned that the local equilibrium line altitude (ELA) was located at 3500 m a.s.l. More recently, the glacial geomorphology of the Chirripó National Park was described in more detail even expanding previous mapped areas (Li *et al.*, 2019; Quesada-Román and Zamorano-Orozco, 2019a). Earlier works suggest paleo-ELAs between 3500 and 3550 m a.s.l. and a mean temperature ranging from 6 to 8 °C colder than the present during the LGM (Islebe and Hooghiemstra, 1997; Orvis and Horn, 2000; Lachniet and Roy, 2011). Moraine sequences have been dated using ^{10}Be and ^{36}Cl cosmic ray exposure (CRE), confirming a peak development period between 21–18 ka BP (Cunningham *et al.,* 2019; Potter *et al.*, 2019). Recently, Quesada-Román *et al.* (2020c) determined an average paleo-ELA around 3490 m a.s.l. for 31 paleoglaciers during the LGM, and obtained paleotemperatures even 10 °C lower than today.

Glacial geomorphological mapping provides parameters to constrain and test numerical simulations of alpine ice masses, such as cirque glaciers or valley glaciers (Chandler *et al.*, 2018). Recently, Quesada-Román *et al.* (2019) performed a detailed glacial and periglacial mapping of Cerro Chirripó that showed a detailed distribution of lateral moraines, which illustrated the maximum probable extent of glaciers during the LGM. With the presently available high-resolution digital information, geomorphometric assessments can revolutionize the way paleogeography is analyzed (Sofia, 2020). Despite the existence of several glacial geomorphology studies in Cerro Chirripó and Chirripó National Park since the 1950s, there are no studies aimed at estimating the volumes and thicknesses paleoglaciers or at understanding the variables that controlled their response during the LGM. We hypothesize that glacial development during the LGM in the highest mountains of Costa Rica was conditioned by global and regional climatic variability and locally by topographic control. As far as we know, this work is one of the first studies of paleoglacial volume and ice thickness reconstruction in the tropics. Therefore, our aims are to (i) reconstruct the volume and the ice thickness distribution of the Chirripó paleoglacial system and, (ii) to make a Generalized Linear Model using ten land surface parameters to explain the paleoglacial volumes and ice thickness.

GEOGRAPHICAL SETTING

Cerro Chirripó is the highest peak in Costa Rica with a summit at 3820 m.a.s.l. It is situated within the Chirripó National Park, which is part of the Cordillera de Talamanca (Figure 1). The highlands of the Chirripó National Park are the product of the subduction processes

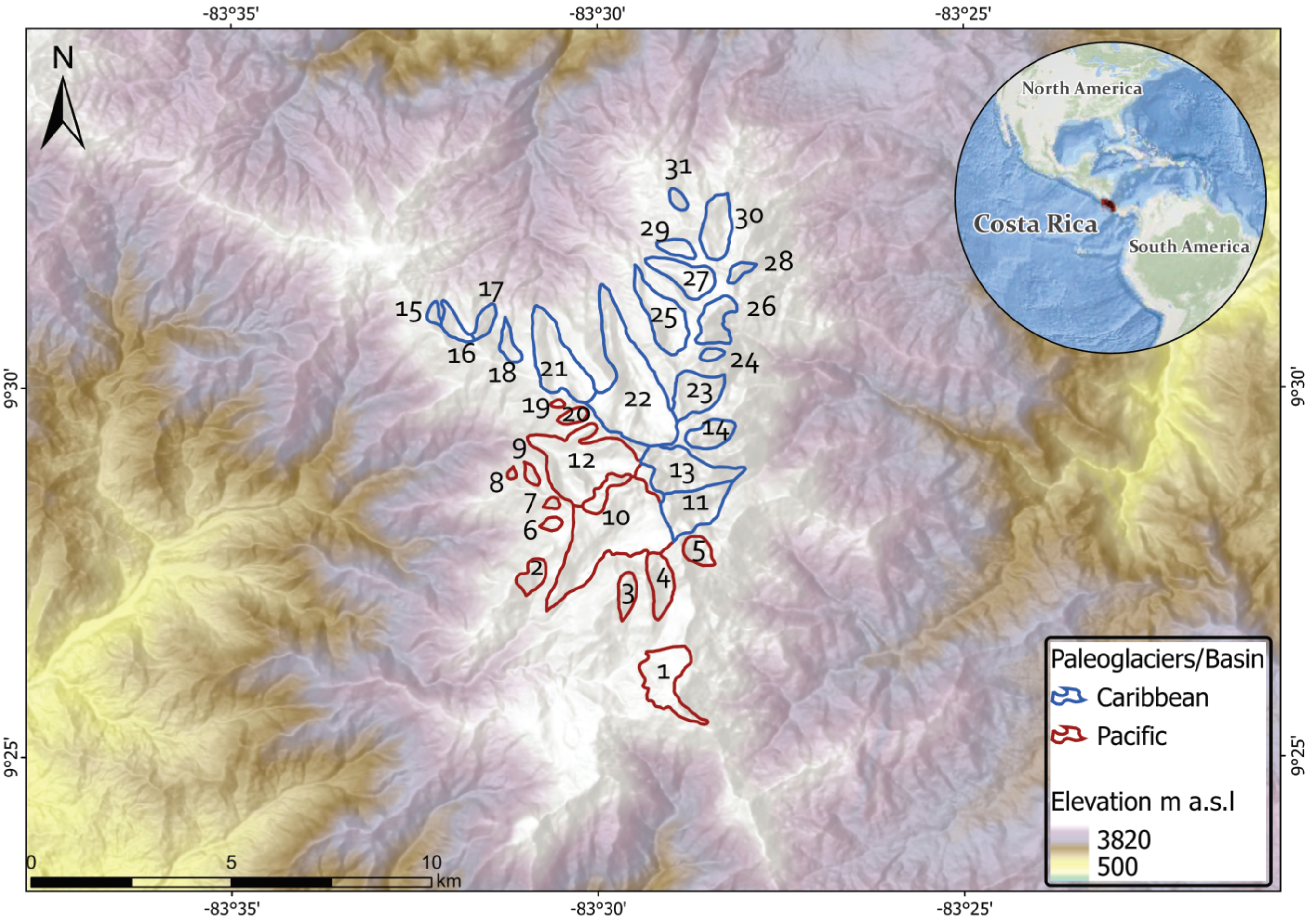

Figure 1. Chirripó National Park location and reconstructed paleoglaciers: 1) Cerro Amó; 2) Los Arrepentidos; 3) Cerro Terbi 1; 4) Cerro Terbi 2; 5) Pico Sureste; 6) Bosin; 7) Cerro Ventisqueros 1; 8) Cerro Ventisqueros 2; 9) Cerro Ventisqueros 3; 10) Valle Talari; 11) Pico Noreste; 12) Lagos Chirripó; 13) Cerro Pirámide; 14) Cerro Truncado; 15) Cerro Urán 1; 16) Cerro Urán 2; 17) Cerro Urán 3; 18) Cerro Urán 4; 19) Río Chirripó Pacífico 1; 20) Río Chirripó Pacífico 2; 21) Río Chirripó; 22) Valle Las Morrenas; 23) Cerro Laguna; 24) Chirripó Grande 1; 25) Chirripó Grande 2; 26) Chirripó Grande 3; 27) Fila Norte 1; 28) Fila Norte 2; 29) Fila Norte 3; 30) Fila Norte 4; 31) Fila Norte 5. Glaciers named by Quesada-Román *et al.* (2020c).

of the Cocos and Caribbean plates with influences from regional volcanism and seismicity (*e.g.*, DeMets *et al.*, 2010). The impact of the Cocos Ridge on SE Costa Rica, an arrangement of oceanic crust originating from the Galapagos hotspot, caused uplift of the Cordillera de Talamanca. Volcanism in the Cordillera de Talamanca ceased approximately 2 Ma ago (Morell *et al.*, 2012). The predominant lithology of the Cordillera is composed of three phases: 1) Vulcanism before the upper Miocene, about 17 to 11 Ma ago; 2) Plutonism during the middle-upper Miocene, between 12.5 and 7.5 million years ago, known as the Talamanca Intrusive Group or Talamanca Granite-Gabbro; 3) Post-intrusive magmatic pulses from the Neogene to the Quaternary, whose time range extends between 5 and 2 million years (Alfaro *et al.*, 2018). Regional tectonics are controlled by extreme uplift rates oscillating from 1.7 to 8.5 m/ka (Gardner *et al.*, 2013; Quesada-Román and Zamorano-Orozco, 2019b), as well as faulting with NW-SE and N-S alignments (Camacho *et al.*, 2020). Volcanic slopes molded by glacial or periglacial activity comprise the paleo-glaciated highlands (Quesada-Román and Zamorano-Orozco, 2019b). The remains of these processes include cirques, moraines, till deposits, arêtes, and glacial lakes over 3000 m a.s.l. (Quesada-Román *et al.*, 2019). Currently the summits of Chirripó National Park are not glaciated.

The latitudinal movement of the Intertropical Convergence Zone (ITCZ), trade winds, cold fronts, and tropical cyclones (Alfaro *et al.*, 2010; Campos-Durán and Quesada-Román, 2017) control the climatic conditions of the high Costa Rican mountains. These processes favor two rainfall peaks, one in May and another in October accumulating around 1800 mm of rain annually. These are intermittent with a minimum in July and August known as the Mid-Summer Drought (Maldonado *et al.*, 2016), however, the dry season generally occurs from December to April with average temperatures of 9.7 °C (Figure 2; Quesada-Román 2016, 2017). The temporal and spatial variability of rainfall in the country is heavily influenced by the El Niño-Southern Oscillation (ENSO; Méndez *et al.*, 2019; Quesada-Román and Pérez-Briceño, 2019). According to Waylen and Laporte (1999), complex and contrasting responses (*i.e.*, warm or wet) vary in terms of their signs, magnitude, duration, and seasonality between catchment areas draining to the Pacific and those flowing into the Caribbean Seas. At present, páramo, a grass and/or shrub dominated ecosystem in the neotropics, dominate the Costa Rican highlands over 3100 m a.s.l., providing important hydrological and ecological functions (Esquivel-Hernández *et al.*, 2018; Quesada-Román *et al.*, 2020a). This ecosystem is threatened by projected warming conditions in the following decades (Veas-Ayala *et al.*, 2018). Recently, a dendrochronological study reported the ENSO signal in a páramo endemic shrub of Chirripó National Park (Quesada-Román *et al.*, 2020b).

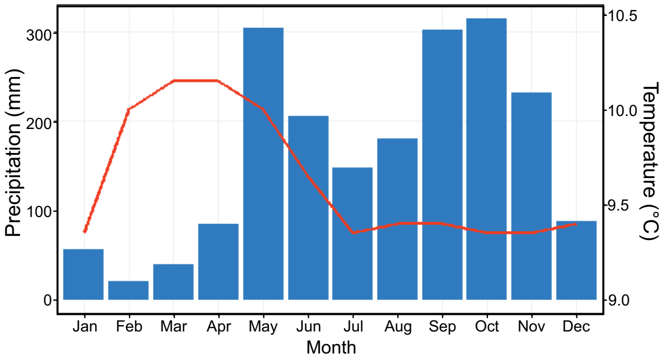

Figure 2. Average precipitation and temperature conditions of Chirripó National Park between 1995 and 2009 (IMN, 2009; Veas-Ayala *et al.*, 2018).

METHODS

Paleoglacier reconstruction

We created a digital elevation model (DEM) using a Geographic Information System (ArcGIS 10.3) (Table 1) to allow calculation of glacial volumes. The DEM was obtained by subtracting the actual DEM of the area, created from contour lines with 10 m interval provided by CARTA - Costa Rica Airborne Research and Technology Applications (2005). Quesada-Román *et al.* (2020c) transformed the lines from the LGM based on previous studies (Lachniet and Seltzer, 2002; Lachniet and Vázquez-Selem, 2005). In order to obtain the LGM DEM, the contour lines were converted into a triangulated irregular network (TIN) and transformed into a raster. Due to a lack of high-resolution sources, a by-product of the difficult access to the area, the calculations have been made with the best topographic information existing for the region. Therefore, the reconstruction, although it shows reasonable and logical results considering the current topography, is bound to a number of uncertainties and should be considered with this in mind. The new DEM allowed us to calculate the volume of each glacier. The limits of the paleoglaciers were obtained by Quesada-Román *et al.* (2020c) on the basis of the limits proposed by Lachniet and Seltzer (2002). Table 1 shows the ELA values for each glacier. We used the values obtained by Quesada-Román *et al.* (2020c) using the Area-Altitude Balance Ratio (AABR) method, which considers the hypsometry of the glacier, with BR=2. This method assumes that the mass balance gradient consists of approximately two linear segments, normally with different slopes above and below the ELA, and uses a balance ratio (BR) for the estimate (Osmaston, 2005). We chose BR=2 because tropical glaciers had high ablation ratios and tend to have small ablation areas (Rea, 2009).

Morphometric and statistical analysis

First, we calculated and extracted the mean value of seven land surface parameters (LSP) for each paleoglacier. We considered Area (A), Basin location (B), Analytical Hillshading (AH; Tarini *et al.*, 2006), Aspect (ASP), Area Surface Radiation (ASR; Boehner and Antonic, 2009), Diurnal Anisotropic Heating (DAH; Cristea *et al.*, 2017), Slope (SLO), Terrain Ruggedness Index (TRI; Riley *et al.*, 1999), and Wind Exposition (WE; Boehner and Antonic, 2009) using SAGA software (Conrad *et al.*, 2015). Second, we applied a Pearson correlation equation (Vinod, 2017), and performed a generalized linear model (GLM) to describe statistically significant linkages between obtained paleoglacier volumes (VOLUME) as well as paleoglacier ice thickness (ICE) with LSP. Based on the Akaike Information Criterion (AIC) (Anderson and Burnham, 2004), we used a backward selection to contrast the two models (VOLUME/ICE~ AREA+B+AH+ASP+ASR+DAH+SLO+TRI +WE) against the alternative model (VOLUME~ AREA+SLOPE) and (ICE~ AREA+DAH). All co-variables were first standardized using z-score (regression coefficient divided by standard error). Finally, model parameters were used to evaluate the weight of each LSP interaction explaining the paleoglacier volumes and ice thickness.

RESULTS

Glacier reconstruction

The 31 reconstructed paleoglacier volumes yield a total of 13862.76 $\times 10^5$ m^3 (Table 1). Nonetheless, paleoglacier average volumes were restricted to 447.18 $\times 10^5$ m^3. The Caribbean basin comprised 62 % of the total volumes, but the distribution of large volumes was located in both basins (Figure 1). Ice thickness varied from 12.85 m to 178.14 m (Table 1; Figure 3), however, ice thickness during the LGM in the highest mountains of Costa Rica had an average thickness of 76.76 m,

Table 1. Summary of the spatial measurements of the studied paleoglaciers. Length, altitude and equilibrium line altitude (ELA) data taken from Quesada-Román *et al.* (2020c). AABR: Area-Altitude Balance Ratio method.

Number	**Glacier**	**Basin**	**Length** (m)	**Area** (km^2)	**Altitude** (m a.s.l.)		**ELA AABR**	**Volume+** ($\times 10^5$ m^3)	**Max. ice thickness** (m)
					Max	Min	(2.0)		
1	Cerro Amó	Pacific	2340	1.488	3410	3295	3389	137.043	53.37
2	Los Arrepentidos	Pacific	985	0.413	3524	3195	3326	11.564	25.43
3	Cerro Terbi 1	Pacific	1238	0.400	3700	3397	3580	113.563	58.36
4	Cerro Terbi 2	Pacific	1710	0.759	3610	3393	3502	189.212	81.65
5	Pico Sureste	Pacific	945	0.418	3573	3360	3499	94.322	52.94
6	Bosin	Pacific	580	0.129	3680	3579	3652	8.948	12.85
7	Cerro Ventisqueros 1	Pacific	404	0.081	3696	3585	3679	4.575	16.6
8	Cerro Ventisqueros 2	Pacific	300	0.045	3556	3293	3411	10.548	38.28
9	Cerro Ventisqueros 3	Pacific	680	0.134	3683	3535	3583	40.689	63.17
10	Valle Talari	Pacific	4050	4.333	3700	3198	3560	2736.606	144.3
11	Pico Noreste	Caribbean	1970	1.449	3661	3265	3478	1375.641	178.14
12	Lagos Chirripó	Pacific	2850	2.885	3740	3162	3590	1852.853	150.36
13	Cerro Pirámide	Caribbean	2695	1.778	3705	3148	3530	501.224	91.82
14	Cerro Truncado	Caribbean	1302	0.631	3689	3365	3542	248.840	87.21
15	Cerro Urán 1	Caribbean	584	0.137	3495	3231	3380	75.902	63.89
16	Cerro Urán 2	Caribbean	1225	0.361	3495	3222	3419	125.335	70.12
17	Cerro Urán 3	Caribbean	1005	0.298	3469	3134	3251	184.515	107.34
18	Cerro Urán 4	Caribbean	1165	0.295	3532	3306	3408	53.905	47.03
19	Río Chirripó Pacífico 1	Pacific	355	0.049	3696	3603	3665	9.837	no data
20	Río Chirripó Pacífico 2	Pacific	790	0.208	3698	3584	3633	26.167	31.56
21	Río Chirripó	Caribbean	2808	1.942	3700	3240	3545	893.577	102.63
22	Valle Las Morrenas	Caribbean	4255	4.083	3700	3132	3539	2919.562	163.96
23	Cerro Laguna	Caribbean	1450	1.100	3653	3370	3535	603.031	126.52
24	Chirripó Grande 1	Caribbean	630	0.137	3597	3491	3517	27.569	48.38
25	Chirripó Grande 2	Caribbean	2545	1.350	3650	3251	3515	788.173	121.54
26	Chirripó Grande 3	Caribbean	640	0.773	3514	3293	3394	137.116	54.1
27	Fila Norte 1	Caribbean	1835	0.942	3525	3248	3440	215.016	93.02
28	Fila Norte 2	Caribbean	870	0.191	3530	3354	3499	56.604	62.53
29	Fila Norte 3	Caribbean	1040	0.307	3491	3275	3377	10.751	14.15
30	Fila Norte 4	Caribbean	1730	0.976	3576	3307	3439	379.673	74.6
31	Fila Norte 5	Caribbean	625	0.165	3500	3369	3393	30.408	66.97

which was greater in the Caribbean (87.44) than in the Pacific basin (60.73). The bigger paleoglacier volumes and some of the highest ice thickness values were reported in Lagos Chirripó (Figure 4b) and Valle Talari (Figure 4d) of the Pacific basin, and Valle Las Morrenas in the Caribbean basin (Figure 4c).

Land surface parameters analysis

Statistical analyses of the paleoglacier volumes with LSP based on the AIC criterion supports the null model (AIC=435.51) against the alternative model (AIC=429.55). In addition, the model suggests that the best generalized linear model supports an interaction between Area and Slope (VOLUME ~AREA+SLOPE). Table 2 provides the model parameters, also indicating that the most significant influence on onset probability of paleoglacier volumes are provided by Area and Slope, as shown by z-ratio tests of parameter estimates.

The most influential LSP according to the GLM that show interesting associations were Area and Slope. The glaciers of the Caribbean represent 58 % of the total number of glaciers and 60 % of the entire glacial area (Table 1). Larger paleoglacier volumes and areas were encountered mainly in the Caribbean basin. With the exception of three cases, Pacific paleoglacier volumes tended to be below 0.5 km^2 (Figure 5a). The majority of Slope values are less than 1000 m^3. Larger paleoglacier volumes (1500–3000 m^3), two in each basin, were located on slopes between approximately 15 and 30 slope degrees (Figure 5b). Topographic conditions such as the marked relationship of Area and Slope probably regulated climate responses in Cerro Chirripó. The Caribbean basin has steeper slopes and smaller paleoglaciers while the Pacific basin presented larger paleoglacier volumes.

Morphometric statistical analyses of the determined paleoglacier ice thicknesses (ICE) based on the AIC criterion supports the alternative model (AIC=291.77) against the null model (AIC=293.58). The model suggests that the best generalized linear model supports an interaction between Area and DAH (ICE ~AREA+DAH). Table 3 provides the model parameters, also indicating that the most significant influence on onset probability of paleo-glacier ice thickness are given by Area and DAH, as shown by z-ratio tests of parameter estimates.

The most statistically significant paleoglacier land surface parameters were Area and DAH. Ice thickness values of 80 % of the glaciers were between 12.85 and 107.34 m, with a maximum height of 178.14 m. Even so, there was a slight trend of broader paleoglaciers in the Caribbean basin (Figure 5c). Another LSP with a strong statistical relationship to explain the paleoglacier ice thickness of Cerro Chirripó was DAH. This index shows the spatial terrain variation as a function of slope and aspect. Both basin's paleoglaciers had flatter slopes. The

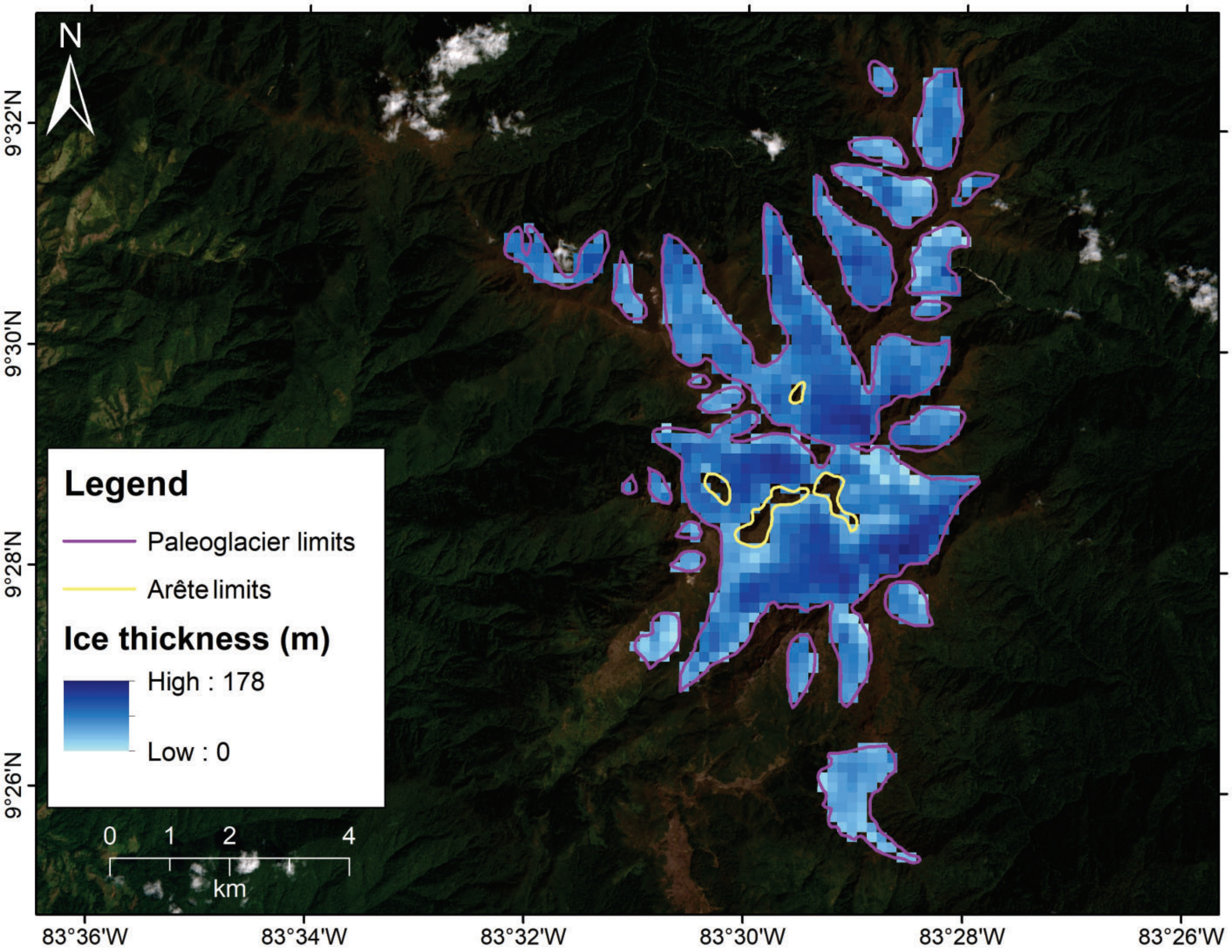

Figure 3. Reconstruction and distribution of the ice thickness (m).

Pacific basin paleoglacier aspects tended more to the SW (-0.2 to 0.3) with ice thickness around 10 and 150 m, while the Caribbean paleoglaciers had an eastern orientation and thicker ice (Figure 5d). The greater thickness of Caribbean basin paleoglaciers could be related to differential warming due to dissimilar slope aspects that produced asymmetric topographic heat budget distributions. This likely exerted the principal control on glacier ice thickness during the LGM.

DISCUSSION

We performed the Chirripó paleoglacier system reconstruction, which determined its volumes, ice thickness distributions and significant land surface parameter analyses using its ELA with the AABR method during the LGM. We focused upon 31 paleoglaciers summing up a total area of 28.2 km^2 at 1:25000 scale. This result agrees with Quesada-Román *et al.* (2019) who determined 29.7 km^2 of landscapes impacted by ice masses and 51.6 km^2 of periglacial processes using 1:25000 aerial imagery. Other studies with less resolution (1:50000 aerial photos or 30 m spaceborne imagery) reported 35 km^2 (Lachniet and Seltzer, 2002), and 22.1 km^2 (Li *et al.*, 2019) of glacial areas around the Cerro Chirripó area. The results showed that the paleo-ELA based on the AABR (2.0) method for Cerro Chirripó is ~3490 m a.s.l, which is likely similar to previous paleo-ELA reconstructions in Costa Rica, Guatemala, and Venezuela (Lachniet and Seltzer, 2002; Lachniet and Vázquez-Selem, 2005; Stansell *et al.*, 2007; Roy and Lachniet, 2010; Lachniet and Roy, 2011). Quesada-Román *et al.* (2020c) calculated a LGM paleotemperature ~10 °C lower than today in Chirripó National Park, which is consistent with reconstructions in Guatemala, Mexican volcanoes, and Venezuela (Stansell *et al.*, 2007; Roy and Lachniet, 2010; Vázquez-Selem and Lachniet, 2017). Moreover, Mexican speleothem reconstructions and magnetic susceptibility measurements suggested wet conditions in the Pacific and Atlantic coasts of Central America during the LGM due to a Mesoamerican monsoon establishment motivated by a ITCZ proximal to Mexico (Hodell *et al.*, 2008; Lachniet *et al.*, 2009; Escobar *et al.*, 2012; Lachniet *et al.*, 2013; Oster *et al.*, 2019). These wet and cold conditions prevailed in the circum-Caribbean region during the LGM and agreed with global sea surface temperature reconstructions (Ganeshram *et al.*, 2000; Annan and Hargreaves, 2015).

During the LGM, tropical American paleoglaciers descended below 4000 m. In other tropical and subtropical latitudes on different continents, several other glaciated mountains have been reported in Oceania with Mt. Wilhelm, Star Mts, and Mt. Giluwe in Papua New Guinea (3400–3600 m); Asia in Taiwan Shan, Taiwan (3450 m), Mt Kinabulu in Malaysia (3665 m), and Mt Jaya in Indonesia (3590 m). This has also been noted in Africa in Ayachi and Toubkalin in Morocco (3250-3450 m), Aberdare in Kenya (3600 m), Mt Kecha in Ethiopia (3600 m), as well as in Elgon N and numerous mountains in Uganda (~3500 m) (Porter, 2001; Mark *et al.*, 2005; Osmaston and Harrison, 2005). It must be noted that cooling during the LGM was amplified

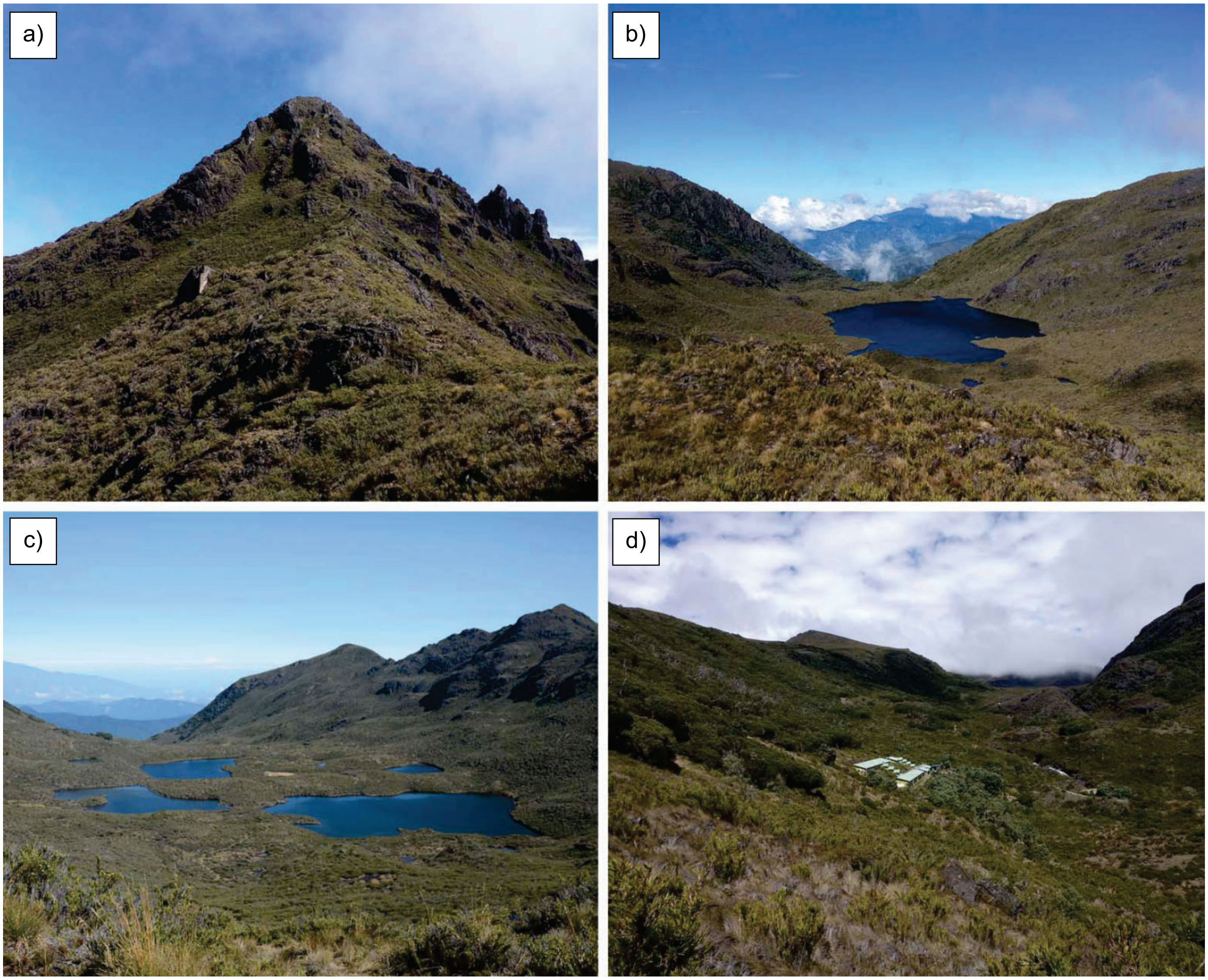

Figure 4. (a) Cerro Chirripó peak 3820 m a.s.l., (b) Lagos Chirripó (Pacific), (c) Valle Las Morrenas (Caribbean), (d) Valle Talari (Pacific).

by elevation and hence the lapse rate was significantly steeper than today (Loomis *et al.*, 2017). Different studies indicate that the retreat of tropical glaciers was synchronous or even earlier than that seen in temperate latitudes (Clark *et al.*, 2009). Recently, Jackson *et al.* (2019) found that tropical glacial recession was ongoing by 20 ka, preceding the rapid CO_2 rise at ~18.2 ka influenced by rising high-latitude insolation and parallel with the ice-sheet recession in both polar regions.

Most studies of tropical glacier volumes in South America focus on modern glaciers, since the relevance of the glaciers located in the tropics to society is primarily reflected in their provision of water supplies in parts of South America, mainly during the dry season (Mölg *et al.*, 2008). According to Favier *et al.* (2004) tropical climate is characterized by homogeneous temperature conditions during the year, with a slight seasonality of air temperature in the outer tropics (higher temperatures during the austral wet summer). However, we can deduce the similarities with other tropical glaciers by looking at the altitude of the moraines. In Chirripó National Park, the frontal moraines from the LGM are located at an average altitude of ~3295 m a.s.l. Our result is comparable with other studies of tropical glaciers during the LGM in regions such as in Mexico, South America along the Andes, East Africa, Indonesia and Papua New Guinea (Mark *et al.*, 2005).

Costa Rica highland paleoglacier volumes and ice thickness during the LGM were controlled by local land surface parameters. Topographic conditions regulate climate responses in the Chirripó National Park. Its climate is defined by the interaction of the Intertropical Convergence Zone migration, north-east trade winds, cold fronts, and tropical

Table 2. Parameters used to model paleoglacier areas.

Model terms	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**	
(Intercept)	-439.25	197.05	-2.229	0.034	*
Area	682.57	40.62	16.806	3.68E-16	***
Slope	959.74	638.19	1.504	0.144	

Note: Null deviance is 17587324 on 30° and residual deviance is 1461220 on 28° degrees of freedom, AIC is 429.55. Pr(>jzj) is the probability of finding the observed Z-ratio in the normal distribution of Z with a critical point of jzj. ***P=0.

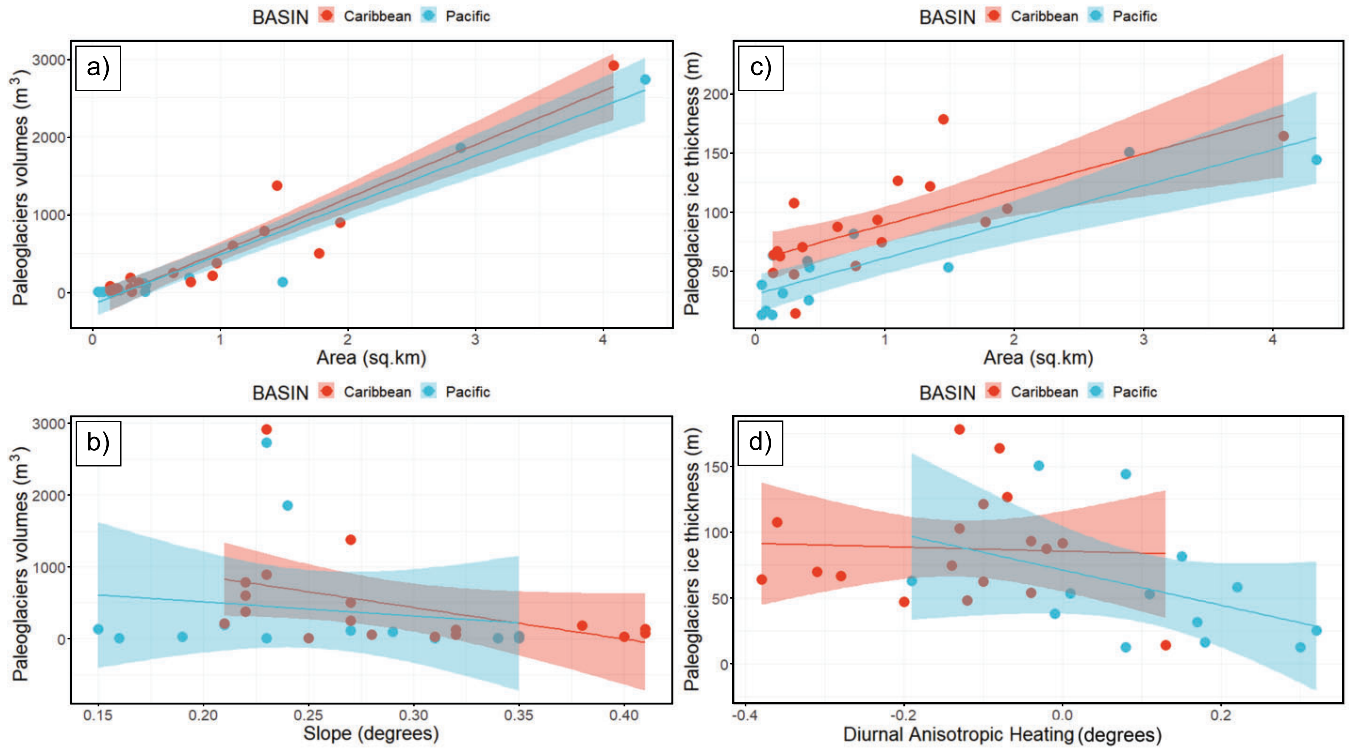

Figure 5. Relationship between paleoglacier volume and (a) Area, and (b) Slope, as well as paleoglacier ice thickness with Area (c) and Diurnal Anisotropic Heating (d), for the Caribbean (red) and Pacific (blue) basins.

cyclones (Esquivel-Hernández *et al.*, 2019). Recently, Quesada-Román *et al.* (2020c) reported that Wind Exposition and Terrain Ruggedness Index were the LSPs with significant statistical relationships with the paleoglacier areas. Our results demonstrated other LSP that explain the paleoglacier volumes and thickness reconstructions. Area and Slope showed a significant statistical relationship with the paleoglacial volumes, while Area and Diurnal Anisotropic Heating are responsible for paleoglacier ice thickness. Paleoglacier volumes certainly had a direct relationship with its accumulative area, but Slope can significantly impact its stability. Higher slopes are intrinsically linked with bed roughness, which applies a major control on an ice mass's basal motion (Li *et al.*, 2010). The higher slope values in the Caribbean basin can be related to the continuous orographic precipitation on the windward side which generates more erosion, as previously reported by Quesada-Román *et al.* (2020c). Rock surface weathering often leads to increased rock surface roughness, which is strongly linked with slope inclination (McCarrol and Nesje, 1996). Otherwise, the Pacific basin had larger paleoglaciers and lower slopes.

Paleoglacial ice thickness depends directly on its area, but Diurnal Anisotropic Heating accounted for differential warming on different aspects, which were important for spatial snow variability during the ablation season (Cristea *et al.*, 2017). Moreover, more pronounced rain shadows probably generated topographic east-west asymmetry that strengthen the primary control on glacier ice thickness (Kessler *et al.*, 2006). Paleoglaciers with broader thickness favored wind characteristics, such as wind direction (mostly from NE), velocity, seasonality and temperature, which can affect the processes that control ablation of glaciers, so there was a connection amid local wind fields and snow accumulation (Dadic *et al.*, 2010). Local wind associated with the DAH dynamics possibly permeated the heat budget distribution thru air temperature variability, causing glacier fragmentation and impacts on mass balance during the LGM (Carturan *et al.*, 2015).

CONCLUSIONS

We completed the reconstruction of thirty-one paleoglacier volumes and ice thickness distribution in the highest summits of Costa Rica during the LGM. We found a maximum paleoglacier ice thickness of 178 meters in Cerro Chirripó and a total volume of 13862.768 × 10^5 (m^3). The land surface parameters that had stronger relationships and better explained the paleoglacier volumes were Area and Slope, while for paleoglacier ice thickness the parameters were Area and Diurnal Anisotropic Heating. Our results agree with the projected climatic conditions that prevailed in the circum-Caribbean region through the LGM and with global sea surface temperature reconstructions. The synchronous effect of the LGM along the tropics also affected the surfaces over 3000 m in Costa Rica. We provide new insights into LGM activity in tropical high-altitude landscapes as one of the first paleoglacier volume and thickness reconstruction studies in the tropics. Glacier reconstructions not only provide valuable information on the past climatic dynamics in the tropics, but also are important assets to the country's geoheritage in order to promote geotourism in the surrounding rural communities (Quesada-Román and Pérez-Umaña, 2020a, 2020b).

Table 3. Parameters used to model paleoglacial ice thickness.

Model terms	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	43.613	5.854	7.45	4.09E-08	***
Area	30.803	4.082	7.547	3.21E-08	***
DAH	-95.357	25.215	-3.782	0.000752	***

Note: Null deviance is 60659 on 30° df, residual deviance is 17157 on 27° df, and the AIC is 291.77. Pr(>jzj) is the probability of finding the observed Z-ratio in the normal distribution of Z with a critical point of jzj. ***P=0.

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