

REVISITING THE ANDEAN TROPICAL GLACIER BEHAVIOR DURING THE ANTARCTIC COLD REVERSAL

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ABSTRACT. *The sensitivity of tropical glaciers to paleoclimatic conditions that prevailed during the Antarctic cold reversal (ACR, ca. 14.5-12.9 ka) has been the subject of a wide debate. In 2014 a paper suggested that tropical glaciers responded very sensitively to the changing climate during the ACR (Jomelli et al., 2014). In this study, we reexamine the conclusions from this study by recalculating previous chronologies based on 226 ¹⁰Be and 14 ³He ages respectively, and using the most up-to date production rates for these cosmogenic nuclides in the Tropical Andes. 53 moraines from 25 glaciers were selected from the previous analysis provided by Jomelli et al. (2014) located in Colombia, Peru and Bolivia. We then focused on two distinct calculations. First we considered the oldest moraine and its uncertainty for every glacier representing the preserved evidence of the maximum glacier extents during the last deglaciation period, and binned the results into 5 distinct periods encompassing the Antarctic cold reversal and Younger Dryas (YD) chronozones: pre-ACR, ACR, ACR-YD, YD and post-YD respectively. Results revealed a predominance of pre-ACR and ACR ages, accounting for 60% of the glaciers. Second we counted the number of moraines per glacier according to the different groups. 21 moraines (40%) of the selected glaciers belong to the pre-ACR-ACR chronozones while 3 moraines only (5%) were dated to the YD and YD-Holocene groups. The rest was assigned mostly to the Holocene. These results suggest that moraine records are a very good proxy to document the ACR signal in the Tropical Andes.*

Revisando el comportamiento de los glaciares tropicales andinos durante la inversión fría Antártica

RESUMEN. La sensibilidad de los glaciares tropicales a las condiciones de temperatura fría durante la Inversión Fría Antártica (ACR, por sus siglas en inglés, 14.5-12.9 miles de años AP aprox.) ha sido ampliamente discutida. En 2014, un artículo científico revelaba una respuesta de los glaciares tropicales a la tendencia climática de la ARC (Jomelli et al., 2014); sin embargo, en 2015 nuevas producciones científicas cuestionaron la relevancia de tal conclusión. A partir de las nuevas producciones se procedió a re-examinar las conclusiones previas, recalculando los resultados basados en cronologías ^{226}Be y ^{14}He . Para esta revisión, se seleccionaron 53 morrenas de 25 glaciares localizados en Colombia, Perú y Bolivia, entre los analizados por Jomelli et al. (2014) y se procedió a realizar dos cálculos diferentes. En primer lugar, se tuvo en cuenta la morrena más antigua y su incertidumbre para cada glaciar, de acuerdo con cinco períodos distintos abarcando ACR y Younger Dryas (YD): pre-ACR, ACR, ACR-YD, YD y post-YD respectivamente. Los resultados revelaron el predominio de señales pre-ACR, ACR en el 60% de los casos. Posteriormente, se contaron el número de morrenas por glaciar, teniendo en cuenta los diferentes grupos. 21 morrenas (40%) de los glaciares seleccionados corresponden con las cronozonas pre-ACR y ACR mientras que solo tres morrenas (5%) fueron datadas en los grupos YD y YD-Holoceno. El resto fue asignado principalmente al Holoceno. Estos resultados sugieren que las morrenas son un proxy muy bueno para analizar la señal de ACR en los Andes Tropicales.

Key words: Tropical glaciers, ACR, Younger Dryas, Cosmogenic nuclides.

Palabras clave: Glaciares tropicales, ACR, Younger Dryas, nucleidos cosmogénicos.

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1. Introduction

Climatic-induced glacier fluctuations during the last deglaciation (18.0-11.5 ka) have been recognized at several localities in the southern hemisphere (Thompson *et al.*, 2000; 2006; Rodbell *et al.*, 2009). One prominent event, the Antarctic cold reversal (ACR, ca. 14.5-12.9 ka) identified as a cold period in the southern polar latitudes, was contemporaneous with the Bølling-Allerød warm period in the northern hemisphere and ended at the onset of the Younger Dryas stadial (YD, ca. 12.8-11.6 ka). This ACR cold event provoked glacier advances in different regions of the southern mid latitudes. In New Zealand, for instance Putnam *et al.* (2010) documented an advance of the Pukiki

glacier during this cold event. ACR glacier advances were also identified in Patagonia. Glaciers of the Lago Argentino basin, Southern Patagonian Icefield experienced a major glacial stillstand or re-advance at ca. 13 ka (Strelin *et al.*, 2014). After the ACR period the large ice lobes that filled the eastern reaches of Lago Argentino retreated and separated into individual outlet glaciers. Interestingly, this recession was interrupted only by a stillstand or minor re-advance during the YD at 12.2 ka. However the impacts of the ACR cooling event on glaciers located at lower latitudes of the southern hemisphere remained unclear in particular in the tropics. Recently Jomelli *et al.* (2014) established the chronology of Ritacuba Negro glacier located in the northern tropics of Colombia. The data revealed that the ACR extent of the glacier was larger than during the YD. The analysis was complemented by a synthesis of different published moraine chronologies from the Tropical Andes for the last 15 ka. On the basis of a homogenized chronology of all ^{10}Be and ^3He moraine ages across the southern Tropical Andes, the authors showed that their behavior of ACR glacier extents exceeding those of the YD was common to the northern and southern Tropical Andes. Since this publication new ^{10}Be and ^3He production rates have been published for the tropical Andes (Martin *et al.*, 2015; Delunel *et al.*, 2016). This could induce possible shifts in the chronologies which may question the accuracy of the conclusions published by Jomelli *et al.* (2014). Within the scope of this study, we evaluate the impact of these updated production rates on the conclusions of Jomelli *et al.* (2014).

Thus the main goal of this paper is to revisit the behavior of tropical Andean glaciers during the ACR and YD events. In other words, we investigate if tropical glaciers experienced an advance during the ACR and/or during YD periods and determine when the maximum glacial extent occurred between 14.5 and 11.6 ka ago, and whether it was synchronous between the northern and southern tropical Andes.

To achieve this goal our approach consisted in recalculating the homogenized chronologies in the tropical Andes published by Jomelli *et al.* (2014) that cover the last 15,000 years using the new regional ^{10}Be and ^3He production rates of Martin *et al.* (2015) and Delunel *et al.* (2016).

2. Data

In this study we used the same database as the one compiled by Jomelli *et al.* (2014), i.e. late glacial cosmogenic ^{10}Be and ^3He moraine chronologies from the Tropical Andes, including data from Venezuela, Colombia, Peru, Bolivia and northern Argentina, but we restrict our dataset to the ages younger than 15 ka (Smith *et al.*, 2005; Farber *et al.*, 2005; Zech *et al.*, 2007, 2009; Glasser *et al.*, 2009; Hall *et al.*, 2009; Licciardi *et al.*, 2009; Rodbell *et al.*, 2009; Smith and Rodbell, 2010; Smith *et al.*, 2011; Jomelli *et al.*, 2011; Bromley *et al.*, 2009, 2011; Blard *et al.*, 2013; Carcaillet *et al.*, 2013) (Table 1 and Fig. 1). The selected glaciers are located in the northern and southern tropics (Kaser, 2001). In the northern tropic, we recalculated the moraine chronologies of two glaciers, Mucubaji located in Venezuela and Ritacuba Negro glacier located in the Sierra Nevada El Cocuy, Cordillera Oriental, Colombia. The Sierra Nevada has twenty summits reaching a maximum elevation of 5300 m above sea level (a.s.l.) covered by glaciers.

Table 1. Description of the selected glaciers.

Name glacier	Latitude	Longitude (W)	Reference Altitude (m a.s.l.)	Cosmogenic nuclide	Reference
Mucubaji	N 8.77	70.81	3804	10Be	Carcaillet <i>et al.</i> , 2014
Ritacuba	N 6.50	72.33	4209	10Be	Jomelli <i>et al.</i> , 2014
Laguna Bara	S 9.65	77.36	4045	10Be	Farber <i>et al.</i> , 2005
Quenua Ragra	S 10.01	77.25	4330	10Be	Smith and Rodbell, 2010
Jeullesh	S 10.01	77.27	4290	10Be	Glasser <i>et al.</i> , 2009; Smith and Rodbell, 2010
Tuco	S 10.05	77.21	4310	10Be	Glasser <i>et al.</i> , 2009; Smith and Rodbell, 2010
Mitococha East	S 10.17	76.8	3829	10Be	Hall <i>et al.</i> , 2009
Mitococha	S 10.21	76.9	4384	10Be	Hall <i>et al.</i> , 2009
Jahuacocha	S 10.24	76.97	4095	10Be	Hall <i>et al.</i> , 2009
Carhuacocha	S 10.24	76.86	4189	10Be	Hall <i>et al.</i> , 2009
Gashapampa	S 10.27	77.00	4569	10Be	Hall <i>et al.</i> , 2009
Huanacpatay	S 10.38	76.9	4541	10Be	Hall <i>et al.</i> , 2009
Tucarhuay	S 13.38	72.58	4307	10Be	Licciardi <i>et al.</i> , 2009
Rio Blanco	S 13.38	72.56	4047	10Be	Licciardi <i>et al.</i> , 2009
Sisaypampa	S 13.34	72.51	4506	10Be	Licciardi <i>et al.</i> , 2009
San Franc	S 15.97	68.53	4752	10Be	Zech <i>et al.</i> , 2007
Zongo	S 16.13	68.17	3489	10Be	Smith <i>et al.</i> , 2005
Telata	S 16.26	68.11	4529	10Be	Jomelli <i>et al.</i> , 2011
Illimani	S 16.57	67.79	4052	10Be	Smith <i>et al.</i> , 2011
Huara Loma	S 17.21	66.26	4213	10Be	Zech <i>et al.</i> , 2007
Riosutiru	S 17.23	66.44	3930	10Be	Zech <i>et al.</i> , 2007
Wara wara	S 17.28	66.11	4330	10Be	Zech <i>et al.</i> , 2009
Tres lagunas	S 22.2	65.11	4563	10Be	Zech <i>et al.</i> , 2009
Coropuna	S 15.55	72.62	4830	3He	Bromley <i>et al.</i> , 2009, 2011
Tunupa	S 19.82	67.64	4252	3He	Blard <i>et al.</i> , 2013

In this Colombian region, a very short dry season is observed from December to March while the maximum precipitation occurs from April to November with a mean value of about 920 mm (1970-2000) at 3750 m a.s.l. The wet season over the northern tropics is associated with the latitudinal shift of the Inter Tropical Convergence Zone (ITCZ) toward its northern most position. The mean annual temperature is about 6°C at 3716 m a.s.l. (1970-2000). The current Equilibrium Line Altitude (ELA) in Cordillera de Cocuy is about 4915 m a.s.l. (Jomelli *et al.*, 2014).

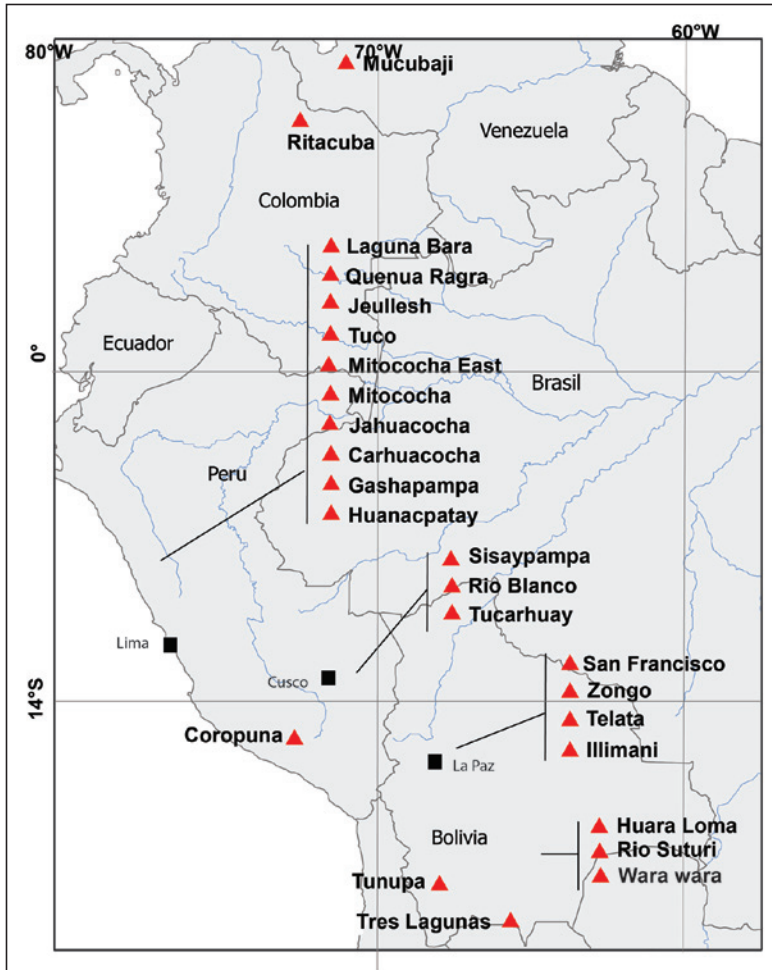


Figure 1. Location of the selected glaciers.

In the southern tropic twenty-one glaciers were selected in different cordilleras (Figs. 1 and 2). Ten glaciers were selected in the Peruvian Blanca and Huayhuash Cordilleras and three other glaciers in the Peruvian Vilcanota Cordillera near Cusco city. The White Cordillera ($9^{\circ}10' S, 77^{\circ}35' W$) is the highest tropical mountain range in the world where e.g. Quenua Ragra is located. It extends over 180 km in length and comprises 35 peaks with an altitude greater than 6000 m. The Huayhuash Cordillera is located in the south of the White Cordillera in Peru. It extends about 25 km long. Six summits of the Huayhuash mountain range exceed 6000 m a.s.l. and seven others are over 5500 m a.s.l. (e.g. Gashapampa glacier). Further south eight glaciers were selected along the Bolivian Oriental Cordilleras. Four glaciers were selected in the Cordillera Real with six peaks higher than 6000 m a.s.l. including Nevado Illimani

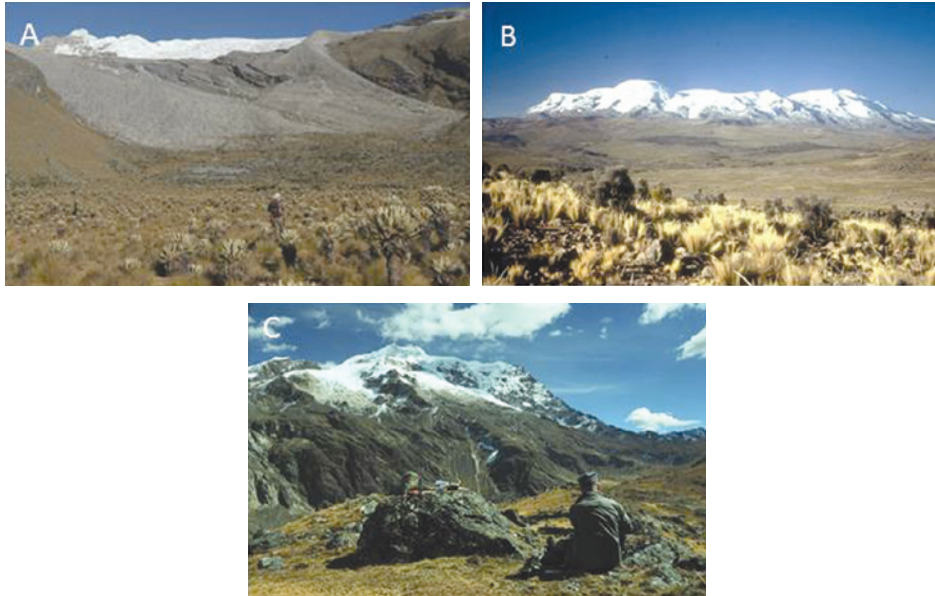


Figure 2. Ritacuba, Coropuna and Zongo glaciers selected in this paper.

summit (6400 m) near La Paz city. In these outer tropical cordilleras one wet season occurs, with tropical conditions prevailing from October to March, followed by a dry season with subtropical conditions prevailing from April to September. In the city of Cusco (3219 m) the average temperature varies from 12°C to 14°C during the warm season and from 9°C to 11°C during the cold season. Total annual precipitation ranges from 550 to 850 mm with more than 80% falling in the rainy season. In the Cordillera Blanca, the current ELA is at about 4950 m a.s.l., while it is at about 5240 m on Zongo glacier in the Bolivian Cordillera Real (Rabatel *et al.*, 2013).

Finally we also recalculated ^3He moraine chronologies from two glaciers in the western Peruvian and Bolivian cordilleras. Here, the climate is drier with less than 500 mm of precipitation per year. On Coropuna volcano the current ELA oscillates around 5700 m but it is above 6000 m in southern Bolivia around Atacama Desert.

3. Methods

3.1. Ages re-calculation

The determination of an accurate CRE (Cosmic Ray Exposure) age relies on a priori knowledge of the production rate of the measured cosmogenic nuclide in a specific mineral (Balco *et al.*, 2008). Because of the spatial and temporal variability of terrestrial cosmogenic nuclide production, the CRE age calculation requires transformation of a production rate value from its standard expression (i.e. for present sea level and high

latitude conditions, SLHL) to a value that is adapted to the site of the CRE dating. This step relies on using one of the available scaling models (e.g. Dunai, 2001; Lal, 1991; Lifton *et al.*, 2014; Stone, 2000), the choice of which introduces a model dependency on the final results and a related uncertainty that is difficult to assess. This dependency on the scaling model is reduced if the calibration site (from which the production rate is derived) and the dating site are close in space and time (Licciardi *et al.*, 2009; Martin *et al.*, 2015).

Jomelli *et al.* (2014) homogenized and recomputed 477 published ^{10}Be and $14\ ^3\text{He}$ surface exposure ages in the tropical Andes covering the last 21,000 years. For the ^{10}Be ages, the process of homogenization was done as follow (Jomelli *et al.*, 2014): first, ^{10}Be concentrations measured by accelerator mass spectrometry were all normalized to the assigned value of the 07KNSTD (Nishiizumi *et al.*, 2007; Balco *et al.*, 2008); second, existing ^{10}Be ages were recalculated using a production rate calibrated on the Altiplano (Blard *et al.*, 2013a) and the Lal/Stone time dependent scaling factor (Stone, 2000; Balco *et al.*, 2008). For ^3He , the concentrations measured at CRPG Nancy were calibrated using the reference value of the ‘CRONUS-Earth pyroxene intercomparison material’ (Blard *et al.*, 2015). Finally, the ^3He ages were computed using the production rate calibrated on the Altiplano (Blard *et al.*, 2013b).

However, since the publication of Jomelli *et al.* (2014) new ^{10}Be and ^3He local production rates have been published (Martin *et al.*, 2015; Delunel *et al.*, 2016). The new ^{10}Be production rate in quartz used in this study, is from Martin *et al.* (2015). These authors made a weighted mean of the three recently published rates from three Andean sites ranging from 3800 m to 4900 m (Blard *et al.*, 2013a; Kelly *et al.*, 2015; Martin *et al.*, 2015). These high tropical Andes production rates are very well clustered (Fig. 3). Similarly, the new ^3He production rate in the pyroxenes is based on the calibration studies of Blard *et al.* (2013b) and Delunel *et al.* (2016).

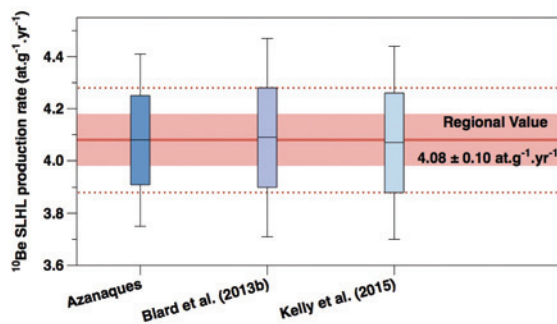


Figure 3. ^{10}Be production rates in the high tropical Andes from 3 calibration studies, with their values represented by box plots (modified from Martin *et al.* [2015]). The scaling has been conducted using the “Lal modified” model (Balco *et al.*, 2008), for a standard atmosphere and using the Muscheler *et al.* (2005) geomagnetic reconstruction. The body of the box and the whiskers indicate the 1σ and 2σ uncertainties respectively. The red shaded area and the red dotted lines show the 1σ and 2σ uncertainties of the regional value (weighted mean).

For the integral re-calculation of the CRE ages, the scaling procedure is based on the *Lal modified* time dependant scaling scheme (Lal, 1991; Stone, 2000; Balco et al., 2008) using the ERA-40 standard atmosphere (Uppala et al., 2005) and the Muscheler et al. (2005) Virtual Dipolar Moment (VDM) reconstruction. Borchers et al. (2015) showed that the *Lal modified* model and the LSD model (Lifton et al., 2014) were the most efficient models presently available to reduce discrepancies between the different calibration studies at the SLHL conditions. With the same type of approach Martin et al. (2015) showed that the *Lal modified* scheme yielded slightly better performance in the high Tropical Andes, especially when combined with the ERA-40 atmosphere and the Muscheler et al. (2005) VDM reconstruction. With this parameterization, we derived SLHL *in situ* production rates of 4.08 ± 0.10 at.g⁻¹.yr⁻¹ and 136 ± 5 at.g⁻¹.yr⁻¹ for ¹⁰Be and ³He, respectively, using the three ¹⁰Be calibration sites (Martin et al., 2015) and the two ³He calibration sites Blard et al. (2013b) and Delunel et al. (2016).

3.2. Moraines selected in this study

After the recalculation of the 477 published ¹⁰Be and ³He surface exposure ages from Jomelli et al. (2014), we excluded all moraines that yield exposure ages older than 14.5 ka, with the aim to focus on the ACR and YD-Holocene period (assuming that the ACR began at 14.5 kyr). This filtering retained 240 ¹⁰Be and ³He surface exposure ages from 25 different glaciers. To facilitate the comparison with the previous studies, moraine notation was strictly the same as the one used by authors in their original studies (Table 2). When the name was missing, we arbitrarily assigned an alphabetic letter to each of the documented moraines with A corresponding to the moraine located closest to the current glacier front position (for example, see Glasser et al., 2009). This classification was based on our analysis of maps or aerial photos shown in the papers. We then calculated the age of each moraine following two distinct approaches. In the first approach, we strictly used or excluded the same samples as the authors did in their own analyses for the mean age moraine calculation. In a second approach, we applied a chi-square (χ^2) test for the calculation of the moraine ages.

4. Results

In order to document the number of glaciers with a maximum extent at the ACR or during a younger period, we distinguished 6 different chronozones. The first group corresponds to glaciers with a moraine possibly included in the ACR age bracket (14.5-12.9 ka), or older if we account for the uncertainty range, hereafter referred to as “pre ACR” (whose nominal values are older than 14.5 ka, but the uncertainties overlap with 14.5 ka) (orange in Fig. 4 and Tables 2-4), as is the case for Jeullesh glacier with a moraine dated to 14.5 ± 0.3 ¹⁰Be ka ago. The second group corresponds to glaciers with a moraine dated during the ACR chronozone *sensu stricto* (red in Fig. 4). We applied the same principle for the four other groups named “ACR-YD”, “YD” (*sensu stricto* 12.9-11.6 ka) (blue in Fig. 4) YD-Holocene (dark blue in Fig. 4) and Holocene with a documented moraine younger than 11.6 ka ago (green in Fig. 4).

Table 2. Sample characteristics and associated moraine ages. The Mucubaji glacier moraine chronology was excluded because of too large uncertainties and discrepancies with the stratigraphic order. We also chose to differentiate the left lateral moraine M3 of Jeulleth glacier dated to 13.3 ± 0.3 ¹⁰Be ka ago from the right lateral moraine which was dated to 16.5 ± 0.2 ¹⁰Be ka ago (Smith and Rodbell, 2010) assuming this difference may reflect two distinct advances.

Each age was based on all the samples used by the authors and defined in column "ID"

Reference	Name glacier	Name moraine	Nb samples	ID sample	Age (ka)	$\pm 1\sigma$	Option 1 (ka) χ^2	Rejected	Option 2 (ka) χ^2	Rejected
Carcaillet <i>et al.</i> , 2013	Mucubaji	Level 8	1	Mu14	11.73	1				
Carcaillet <i>et al.</i> , 2013	Mucubaji	Level 9	1	Mu13	11.54	0.4				
Carcaillet <i>et al.</i> , 2013	Mucubaji	Level10	1	Mu10	10.89	0.4				
Carcaillet <i>et al.</i> , 2013	Mucubaji	Level11	1	Mu11	12.58	0.5				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M18	5	B35, B36; B42, B43, B45	13.8	0.3				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M17	4	B48, B50-B52	13.5	0.4				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M16	7	B31, B32, B34, B54-57	13.1	0.3				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M15	4	B25, B27, B28, B29	11.3	0.3				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M14	9	B21- B23bis, B59, B59bis-62	10.9	0.3				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M13	4	B15-B17, B19	10.9	0.2				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M12	2	B7M6, B8M6	1.1	0.1				
Jomelli <i>et al.</i> , 2014	Ritacuba negro	M4	3	B1M2, B1M2bis, B5M2	0.3	0.0				
Farber <i>et al.</i> , 2005	Laguna Bara	LB 1	2	Hu41,43	13.5	0.4				
Farber <i>et al.</i> , 2005	Laguna Bara	LB 2	6	Pe98R043a,b, C41-42,44-45	13.5	0.2	14.5 \pm 0.5	C41,42,45	12.3 \pm 0.3	43a, b, 44
Smith & Rodbell, 2010	Quenua Ragra	M7	2	PE07-QUE-22,23	14.6	0.5				
Smith & Rodbell, 2010	Jeulleth	M5	5	PE07-Jeu-5,6,7,8,9	14.4	0.3	13.5 \pm 0.4	PE07, 8	15.6 \pm 0.4	PE 06, 9
Smith & Rodbell, 2010	Jeulleth	left M3*	5	PE07-Jeu-10,13,15	13.3	0.3	13.5 \pm 0.3	13, 15		
Glasser <i>et al.</i> , 2009	Jeulleth	A	5	jeu9,10-13	11.0	0.2				
Glasser <i>et al.</i> , 2009	Jeulleth	B	2	jeu14,15	13.3	0.4				
Glasser <i>et al.</i> , 2009	Jeulleth	C	3	jeu4,5,6	14.7	0.3				
Glasser <i>et al.</i> , 2009	Tuco	A	2	Tuco8,9	14.5	0.4				
Hall <i>et al.</i> , 2009	Mitococha East	Feature M	1	Quer9	13.4	0.5				
Hall <i>et al.</i> , 2009	Mitococha	Feature J	2	Mit3,4	0.3	0.05				
Hall <i>et al.</i> , 2009	Mitococha	Feature K	1	Mit9	13.0	0.5				
Hall <i>et al.</i> , 2009	Mitococha	Feature L	3	Mit12,13,14	13.3	0.3				
Hall <i>et al.</i> , 2009	Jahuacocha	Feature A	3	Jah9,10,11	9.9	0.2	11 \pm 0.3	JAH-11		
Hall <i>et al.</i> , 2009	Jahuacocha	Feature B	4	Jah12,13,14,15	13.0	0.3				

Reference	Name glacier	Name moraine	Nb samples	ID sample	Age (ka)	$\pm 1\sigma$	Option 1 (ka) χ^2	Rejected	Option 2 (ka) χ^2	Rejected
Hall et al., 2009	Jahuacocha	Feature C	2	Jah1,5	12.4	0.3	10.8 ± 0.4	JAH-05	14.9 ± 0.5	JAH-01
Hall et al., 2009	Jahuacocha	Feature E	3	Jah18,19,21	12.7	0.3				
Hall et al., 2009	Carhuacocha	Feature N	2	Car24,25	9.8	0.3	8.9 ± 0.4	CAR-24	10.8 ± 0.4	CAR-25
Hall et al., 2009	Carhuacocha	Feature O	3	Car28,29,30	10.3	0.2				
Hall et al., 2009	Carhuacocha	Feature S	3	Car36,37,38	10.8	0.2	10.4 ± 0.3	CAR-37		
Hall et al., 2009	Carhuacocha	Feature T	3	Car2,4,5	13.6	0.3				
Hall et al., 2009	Carhuacocha	Feature U	4	Quer1,2,3,4	14.7	0.2	14.2 ± 0.3	QUER-01		
Hall et al., 2009	Gashapampa	Feature G	3	Gas 1,2,3	13.9	0.3				
Hall et al., 2009	Huanacpatay	Feature I	4	Hua 7,8,9,10	10.2	0.3				
Licciardi et al., 2009	Tucarlhuay	A	2	Pe08-2,3	0.3	0.0				
Licciardi et al., 2009	Tucarlhuay	B	1	Pe08-13	5	0.1				
Licciardi et al., 2009	Rio Blanco	A	7	Pe06-8,9,10,11,12,13,14	0.3	0.0	0.3 ± 0.1	Pe06-8,14,12		
Licciardi et al., 2009	Rio Blanco	B	6	Pe06-1,2,3,4,6,7	9.9	0.1	10.3 ± 0.1	PE06-1		
Licciardi et al., 2009	Sisaypampa	A	3	Pe08-4,5,6	0.2	0.0				
Licciardi et al., 2009	Sisaypampa	B	2	Pe08-11,12	9.8	0.3				
Licciardi et al., 2009	Sisaypampa	C	4	Pe08-7,8,9,10	11.1	0.1				
Zsch et al., 2007	San Francisco	A	2	SF21, 23	14.1	0.5				
Smith et al., 2005	Zongo	Moraine 5	5	Zongo00-1,2,3,4,5	13.6	0.3				
Smith et al., 2005	Zongo	Moraine 4	3	Zongo00-10,11,12	15.0	0.3				
Jomelli et al., 2011	Telata	MG1	2	B1,2	12.5	0.8				
Jomelli et al., 2011	Telata	MG2	24	B7, until 33 without 13,22,29	10.5	0.2				
Jomelli et al., 2011	Telata	MG3	21	B35 until 57 without 37,46	10.0	0.1				
Jomelli et al., 2011	Telata	M4	2	B58,59	0.2	0.0				
Smith et al., 2011	Ilimani	A2	5	BV 44,45,50,56,58	11.2	0.3	10.9 ± 0.3	BV58		
Smith et al., 2011	Ilimani	B	4	BV 37,38,39,52	11.0	0.3	10.6 ± 0.3	BV52		
Smith et al., 2011	Ilimani	C	4	BV47, 49, 60,61	2.6	0.3				
Zsch et al., 2007	Huara Loma	A	2	HH31,32	14.2	0.4				
Zsch et al., 2007	Rio Suturi	A	2	RM13,14	14.9	0.6	16.0 ± 0.9	RM13	13.6 ± 0.9	RM14
Zsch et al., 2009	Wara wara	WW5	2	ww51,52	11.0	0.4				
Zsch et al., 2009	Wara wara	WW3	2	ww31,32	14.0	0.5				
Zsch et al., 2009	Wara wara	WW4	2	ww41,42	13.7	0.5				
Zsch et al., 2009	Tres lagunas	A	2	LG72,73 without outlier 76	13.5	0.4				
Zsch et al., 2009	Tres lagunas	B	2	LG92,93 without outlier 95	13.4	0.4				
Bromley et al., 2009, 2011	Coropuna	C-II	12	NC17 to NC20, NC32 to NC39	11.8	0.2				
Blard et al., 2009, 2013	Tunupa	M3	2	TU-3A(1-2), TU-3B	12.5	0.3				

*interpreted here as asynchronous with the right side, in italic: moraine rejected when the χ^2 test is considered in the analysis. In the case of different rejected sample solutions we tested the different options.

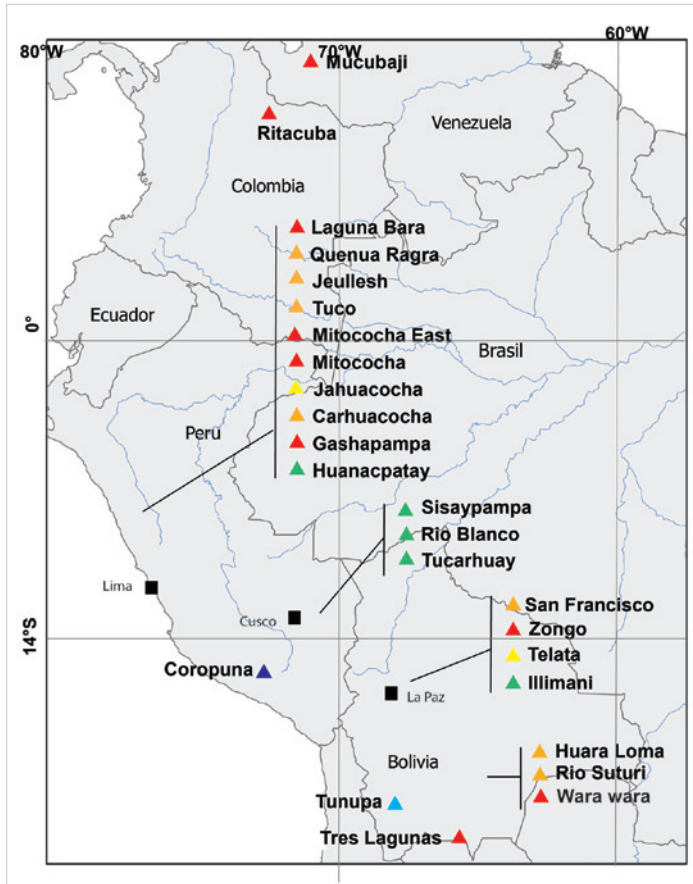


Figure 4. Location of the ^{10}Be and ^3He moraine record sites covering the northern and southern tropical Andes with the largest glacial advance dated to the ACR or possibly older (considering uncertainties) in orange, during the ACR in red, during the ACR or the YD (considering uncertainties) in yellow, during the YD in blue, during the YD or during the Holocene in dark blue, during the Holocene in green and rejected chronology in black without applying a χ^2 test.

To determine the behavior of tropical glaciers, we next focused on two different calculations. First we considered the oldest dated moraine in the valley since the ACR period in order to document the timing of maximum extent per valley glacier over the last 14.5 ka. In the case of a glacier having a larger YD advance (compared to the ACR), this analysis should yield a YD signature only. Each glacier was classified in a single chronozone according to the age of the maximum extent moraine and its uncertainty. The number of glaciers (Tables 3-4) was then counted with and without applying a chi-square (χ^2) moraine age analysis. We excluded moraine ages when the χ^2 test results were ambiguous yielding two possible moraine ages, which fall in different chronozones (this is detailed in options 1 and 2 in Table 2, see for instance moraine A of Río Suturi glacier).

Among the 24 glaciers (excluding Mucubaji glacier with moraine ages that do not respect the stratigraphic order) retained in this study, 15 glaciers (60%) recorded their oldest moraine during the ACR or pre-ACR chronozone without chi-square (χ^2) moraine analysis (Table 3). 8 glaciers (32%) recorded their oldest moraine dated to the ACR chronozone and 2 other glaciers showed their largest moraine belonging to the ACR-YD group. Conversely only 4 glaciers showed their maximum extent dated to one of the three ACR-YD, YD and YD-Holocene groups. The application of the χ^2 test does not change the predominance of the pre ACR-ACR moraine population. The number of glaciers showing the oldest ACR moraine is much larger than glaciers with their oldest moraines belonging exclusively to the YD (Table 4).

Table 3. Ages of maximum glacier extent without applying a χ^2 test.

Name glacier	Pre-ACR	ACR	ACR-YD	YD	YD-HOL	HOL
Mucubaji	rejected	rejected	rejected	rejected	rejected	rejected
Ritacuba		1				
Laguna Bara		1				
Quenua Ragra	1					
Jeullesh*	1					
Tuco	1					
Mitococha East		1				
Mitococha		1				
Jahuacocha			1			
Carhuacocha	1					
Gashapampa		1				
Huanacpatay						1
Tucarhuay						1
Rio Blanco						1
Sisaypampa						1
San Franc	1					
Zongo		1				
Telata			1			
Illimani						1
Huara Loma	1					
Rio Suturi	1					
Wara wara		1				
Tres lagunas		1				
Coropuna					1	
Tunupa				1		
Total	7	8	2	1	1	5

* Jeullesh is either Pre-ACR according to chronology in Glasser et al. (2009) or ACR according to chronology in Smith and Rodbell (2010).

Table 4. Ages of maximum glacier extent when applying a χ^2 test.

Name glacier	Pre-ACR	ACR	ACR-YD	YD	YD-HOL	HOL
Mucabaji	rejected	rejected	rejected	rejected	rejected	rejected
Ritacuba		1				
Laguna Bara		1				
Quenua Ragra	1					
Jeullesh*	1					
Tuco	1					
Mitococha East		1				
Mitococha		1				
Jahuacocha			1			
Carhuacocha	1					
Gashapampa		1				
Huanacpatay						1
Tucarhuay						1
Rio Blanco						1
Sisaypampa						1
San Franc	1					
Zongo		1				
Telata			1			
Illimani						1
Huara Loma	1					
Rio Suturi	rejected	rejected	rejected	rejected	rejected	rejected
Wara wara		1				
Tres lagunas		1				
Coropuna					1	
Tunupa				1		
Total	6	8	2	1	1	5

* based on the chronology of Glasser et al. (2009), but excluded if one considers the chronology in Smith and Rodbell (2010).

We then proceeded to the second calculation counting, this time counting the number of moraines dated to each of the different chronozone groups. Ages for which uncertainties are too large for a firm chronozone attribution were rejected from the analysis. 21 moraines (39%) from the selected glaciers belong to the pre ACR-ACR chronozones while 8 moraines (15%) only were dated to the ACR-YD, YD and YD-Holocene groups (Table 5-6). Again the application of the χ^2 test does not change the predominance of a pre-ACR-ACR chronozones signal. The highest number of moraines synchronous with the ACR was found on Ritacuba glacier located in Colombia, suggesting at least 3 distinct advances and/or stillstands during this period.

Table 5. Number of moraines dated to each chronozone without applying a χ^2 test.

Name glacier	Pre-ACR	ACR	ACR-YD	YD	YD-HOL	HOL
Mucabaji	rejected	rejected	rejected	rejected	rejected	rejected
Ritacuba		3			1	4
Laguna Bara	2					
Quenua Ragra	1					
Jeullesh	1	1*				1*
Tuco	1					
Mitococha East		1				
Mitococha		1	1			1
Jahuacocha			2	1		1
Carhuacocha	1	1				3
Gashapampa	1					
Huanacpatay					1	1
Tucarhuay						2
Rio Blanco						2
Sisaypampa						3
San Franc	1					
Zongo		1				
Telata			1			3
Illimani						3
Huara Loma	1					
Riosuturi	1					
Wara wara		2				1
Tres lagunas		2				
Coropuna					1	
Tunupa				1		
Total	7	14	4	2	2	24

* Based on the chronology in Glasser et al. (2009) exclusively.

Table 6. Number of moraines dated to each chronozone when applying a χ^2 test.

Name glacier	Pre-ACR	ACR	ACR-YD	YD	YD-HOL	HOL
Mucabaji	rejected	rejected	rejected	rejected	rejected	rejected
Ritacuba		3			1	4
Laguna Bara		1				
Quenua Ragra	1					
Jeullesh	1	1*	1			1
Tuco	1					
Mitococha East		1				

Mitococha	1	1				1
Jahuacocha			2			1
Carhuacocha	2					3
Gashapampa		1				
Huanacpatay						1
Tucarhuay						2
Rio Blanco						2
Sisaypampa						3
San Franc	1					
Zongo		1				
Telata			1			3
Illimani						3
Huara Loma	1					
Riosuturi						
Wara wara		2				1
Tres lagunas		2				
Coropuna					1	
Tunupa				1		
Total	5	15	5	1	2	25

1* Based on the chronology in Smith and Rodbell (2010).

5. Discussion

A recent paper based on 84 high-resolution terrestrial and marine southern hemisphere palaeoclimate time series revealed a progressive decrease of the intensity of the ACR signal from Antarctica to the northern regions (Pedro *et al.*, 2016). A strong ACR signal is most common in the Antarctic, whereas a mixture of strong and weak ACR signals are seen in the Southern Ocean, South Atlantic and terrestrial lower latitudes. Lowland regions in the subtropics and tropics of South America do not show a clear trend. For instance, speleothems from western Amazonia show hydrologic variations that are highly correlated with North Atlantic climate signals expressed in Greenland ice cores (Mosblech *et al.*, 2012; Cheng *et al.*, 2013). Lake level fluctuations in Bolivia support a strong impact of the North Atlantic events on the hydrology of the Southern Tropical Andes (Sylvestre *et al.*, 1999; Placzek *et al.*, 2006; Blard *et al.*, 2011). In South African regions, lacustrine records (7° S) also suggest millennial-scale hydrologic variability in phase with the North Atlantic rather than with Antarctica (Schefuss *et al.*, 2011).

Our meta-analysis of the Tropical Andes glaciers chronologies with the most up-to-date production rates of Martin *et al.* (2015) and Delunel *et al.* (2016) do not change the main conclusions of Jomelli *et al.* (2014): over the last 15 ka, tropical Andean glaciers predominantly reached their maximum extent during the ACR. These findings

raise the question of the latitudinal and longitudinal boundaries within which glaciers significantly advanced as response to the ACR signal, and their significance relative to the other paleoclimatic proxies from the same regions.

In South America, moraine records selected along different cordilleras from Patagonia to high-altitude glacier records in Bolivia-Peru (this study) revealed glacier advances during the ACR, whatever the latitude. Event in the northern tropics of Colombia (6°N) our study showed that at least one glacier exhibited moraines formed during the ACR. Further north, a recent study conducted in Mexico (Vázquez-Selem and Lachniet, 2017) revealed, on the other hand, that glaciers expressed a North Atlantic climate signal with a major glacier advance during the YD chronozone.

Other moraine records selected in other southern mid latitude mountain regions such as in the South Island of New Zealand revealed a re-advance of glaciers during the ACR period (Putnam *et al.*, 2010). All together these results suggest that moraine records are a very good proxy to document the ACR signal in the southern hemisphere.

The difference of pattern of change between glacier records and other proxies during the ACR period may be related to their respective sensitivity to temperature and precipitation changes. Recent papers (Jomelli *et al.*, 2011; 2014; Shakun *et al.*, 2016) revealed that long term glacier fluctuations including those in the tropical Andes are mostly driven by temperature changes which may explain the homogeneous glacier behavior during the ACR-YD period and the sensitivity of tropical glaciers to the ACR signal. Yet this overall trend can be challenged at a regional scale due to peculiarities of the hydrological cycle, as for the Altiplano.

6. Conclusion

This paper reevaluates the Andean tropical glacier behavior during the time span between the ACR and the Holocene. Based on a recalculation of 226 ages from 53 moraines from 24 glaciers, we examined the maximum glacier extent of the last 14,500 years and the most frequent occurrences of preserved moraines in the five groups of ages from the pre ACR to the Holocene, respectively. Results show that about 60% of glaciers recorded at least one advance during the pre-ACR-ACR periods. 21 moraines (40%) of the selected glacier belong to the pre-ACR-ACR chronozones, while 3 moraines only (5%) were dated to the YD and YD-Holocene groups. Several other moraine records selected in other southern mid latitudes mountain regions also revealed glacier re-advances during the ACR period and demonstrate that moraine records are a very good proxy to document the ACR signal in the southern hemisphere.

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