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Toward an imminent extinction of Colombian glaciers?

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ABSTRACT
This study documents the current state of glacier coverage in the Colombian Andes, the glacier shrinkage over the twentieth century and discusses indication of their disappearance in the coming decades. Satellite images have been used to update the glacier inventory of Colombia reflecting an overall glacier extent of about 42.4 ± 0.71 km^2 in 2016 distributed in four glacierized mountain ranges. Combining these data with older inventories, we show that the current extent is 36% less than in the mid-1990s, 62% less than in the mid-twentieth century and almost 90% less than the Little Ice Age maximum extent. Focusing on Nevado Santa Isabel (Los Nevados National Park), aerial photographs from 1987 and 2005 combined with a terrestrial LiDAR survey show that the mass loss of the former ice cap, which is nowadays parceled into several small glaciers, was about −2.5 m w.e. yr^{-1} during the last three decades. Radar measurements performed on one of the remnant glaciers, La Conejeras glacier, show that the ice thickness is limited (about 22 m in average in 2014) and that with such a mass loss rate, the glacier should disappear in the coming years. Considering their imbalance with the current climate conditions, their limited altitudinal extent and reduced accumulation areas, and in view of temperature increase expected in future climate scenarios, most of the Colombian glaciers will likely disappear in the coming decades. Only the largest ones located on the highest summits will probably persist until the second half of the twenty-first century although very reduced.

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Glaciers; surface area changes; tropical Andes; Colombia

1. Introduction

Glaciers in Colombia are more than ice on mountains: they indeed are key components of the landscapes lived by the Colombian society (Ceballos et al. 2012). For peasants, indigenous, mountain climbers, artists, scientists and city dwellers, glaciers in Colombia fulfill different functions within their territories and are part of their daily practices in different ways: from sentinels of global climate changes, local water resources, unique ecosystems, to local-to-regional sources of mass flow hazards from glaciers on active volcanoes in the Cordillera Central (Jordan et al. 1989; Thouret 1990; Linder 1991, 1993; Linder et al. 1994; Huggel et al. 2007). The large ice loss in Colombian glaciers since the late 1970s (Ceballos et al. 2006; Morris et al. 2006; Poveda and Pineda 2009), like in most part of the tropical Andes (Rabatel et al. 2013a), has strengthened the necessity of a glacier monitoring

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combining repeated inventories at the national scale and *in situ* measurements on benchmark glaciers located in the two mostly glacierized mountain ranges of Colombia (e.g. Ceballos et al. 2012; Mölg et al. 2017). Such a monitoring strategy is in line with the international strategy for glacier monitoring defined by the Global Terrestrial Network for Glaciers (GTN-G, gtn-g.org).

In situ measurements were initiated after the eruption event of Nevado del Ruiz in 1985 and are nowadays conducted by the *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM). These activities have been part of different international programs: started by the *Instituto Geográfico Agustín Codazzi* (IGAC, Bogota) in 1988 supported by Deutsche Forschungsgemeinschaft (DFG) and Volkswagen Foundation, IDEAM has taken over the task, presently cooperating with the joint international laboratory GREAT-ICE (Sicart et al. 2015) financed by the French *Institut de Recherche pour le Développement* (IRD), the World Glacier Monitoring Service (wgms.ch) and the CATCOS project (Capacity Building and Twinning for Climate Observing Systems) financed by the Swiss Agency for Development and Cooperation (SDC).

The aims of this paper are (1) to present and analyze the current state of glaciers in Colombia, with the results of a new glacier inventory from 2016; (2) to draw a multi-decadal perspective of changes in glacier surface area using repeated glacier inventories since the mid-twentieth century and Little Ice Age maximum extent; and (3) to estimate the future evolution of glaciers in Colombia on the basis of the up-to-date inventory, current surface area and mass loss rates, as well as future possible changes (until 2100) in air temperature according to climate scenarios.

2. Study area

Glaciers in Colombia are located in four main areas (Figure 1): from North to South: Sierra Nevada de Santa Marta (about 10°50′ N; 73°40′ W); Sierra Nevada de El Cocuy (about 6°25′ N; 72°20′ W); Cordillera Central: Los Nevados National Park (Ruiz-Santa Isabel-Tolima, about 4°45′ N; 75°20′ W) and Nevado Huila (about 2°55′ N; 76°00′ W). In the two northernmost areas, small slope glaciers can be found, whereas in the two southernmost areas, small ice caps lying on more or less active volcanoes with significant different slope angles (e.g. Nevados del Ruiz, de Santa Isabel, de Tolima and del Huila) are the dominant glacier types.

Table 1 lists the main characteristics of the glacierized areas of Colombia, with the glacier cover in 2016, the maximum ice thickness estimate – where it exists – together with the year of the estimate. One can note that the averaged maximum elevations of the glacierized summits range in most parts between 5100 and 5400 m a.s.l., which is rather low in comparison with the other glacierized areas in the tropical Andes of Ecuador, Peru and Bolivia where the highest elevations frequently exceed 6000 m a.s.l. (Rabatel et al. 2013a).

2.1. Climatic settings

From a climatological point of view, Colombia belongs to the inner tropics (Troll 1941) with continued humidity, homogeneous temperature (daily amplitude > annual amplitude) and almost constant incident solar radiation throughout the year. At the seasonal scale, the displacement of the intertropical convergence zone (ITCZ) strongly controls the annual regime of precipitation, which results to be contrasted from one region to the other at the country scale (e.g. Poveda et al. 2011). The central and western parts of Colombia (glacierized areas C and D in Figure 1) experience a bimodal precipitation regime with two periods of high precipitation (April–May and October–November) and two periods of less precipitation (December–February and June–August). On the other hand, the Caribbean coast (glacierized area A in Figure 1) and the Pacific coast of the isthmus with Panama show a unimodal precipitation regime (May–October), resulting from the northernmost position of the ITCZ. The easternmost glacierized mountain range (glacierized area B on Figure 1) also experiences a single precipitation peak occurring during June–August, which results from deep convection of the moisture transported from the Amazon basin due to the orographic barrier of the Andes.

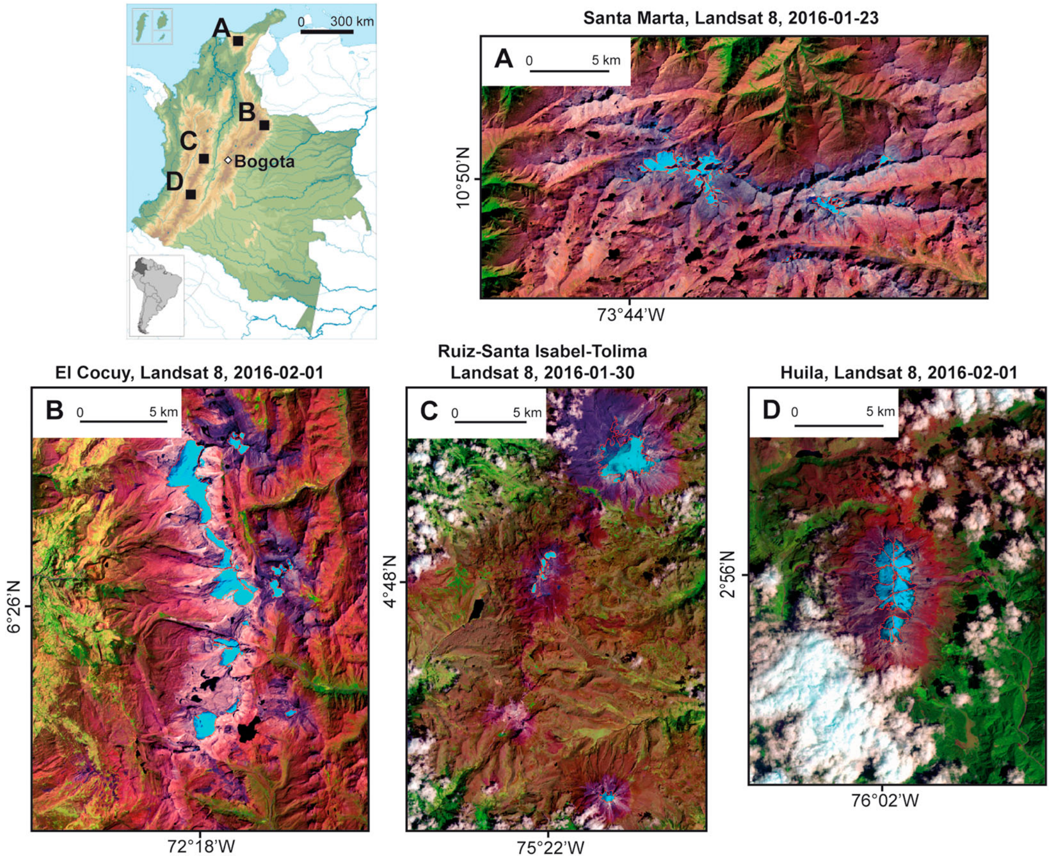

Figure 1. Glacierized areas in Colombia. The spectral bands combination used for the Landsat-8 images provided by USGS-EDC involves the bands #6 (middle infra-red: MIR), #5 (short-wave infra-red: SWIR) and #3 (green).

The IDEAM maintains automatic weather stations (AWS) in the glacierized areas B and C (at elevations up to 4700 m a.s.l.). Mölg et al. (2017) presented the data from the AWS located on the Nevado Santa Isabel (glacierized area C), which show that over the monitoring period (2009–2016), the average 0°C isotherm was located at 4980 m a.s.l., which is higher than the summit located at 4940 m a.s.l. In Sierra Nevada de El Cocuy (glacierized area B), the average 0°C isotherm over the period 2007–2016 was located at 5045 m a.s.l. It is worth noting that these average 0°C isotherm

Table 1. Colombian glacierized areas with the most up-to-date glacier cover surface area and topographic features of the glaciers.

Glacierized area	Glacier cover (km^2) in 2016	Highest elevation of the area (m a.s.l.)	Average max. elevation of glaciers (m a.s.l.)	Average mean elevation of glaciers (m a.s.l.)	Average min. elevation of glaciers (m a.s.l.)	Max thickness (m) and year of estimate
S.N. de Santa Marta	7.2 ± 0.27	5678	5340	5170	5000	//
S.N. de El Cocuy	15.5 ± 0.33	5346	5055	4910	4750	//
Los Nevados National Park	11.8 ± 0.52	5314	5170	5060	4900	190, 1999
V.N. del Huila	8.0 ± 0.23	5390	5250	5020	4710	//

Note that the elevation data are computed from ASTER GDEM V2 and may differ from other sources due to differences in the accuracy of used data. Maximum thickness estimates are taken from Huggel et al. (2007) and Ceballos et al. (2012), but the original data have been provided by J. Ramirez (Servicio Geologico de Colombia).
S.N.: Sierra Nevada; V.N.: Volcán Nevado. //: no data are available.

estimates may slightly vary within the considered glacierized areas and in the other glacierized areas of Colombia due to local site effects.

The interannual variability of atmospheric conditions is dominated by the El Niño–Southern Oscillation (ENSO). Although the climate characteristics of La Niña/El Niño events are not uniform at the scale of a country, El Niño years (warm phase of ENSO) tend to be warmer and drier, while La Niña years (cold phase of ENSO) are typically associated with colder and wetter conditions in the mountains (e.g. Poveda et al. 2011). Poveda et al. (2011) underlined that the ENSO effects are phase locked to the above-described seasonal cycle: i.e. stronger during more intense precipitation months and vice versa.

2.2. Glacier surface processes

In terms of surface mass balance regime, the Colombian glaciers belong to the inner tropics (Kaser and Osmaston 2002) as precipitation may occur all year long with one or two periods of more intense precipitation depending on the glacierized region concerned.

Using the longest Colombian surface mass balance time series (since 2006) on the La Conejeras glacier on the Nevado Santa Isabel, Mölg et al. (2017) showed that there is no seasonal cycle with ablation/accumulation processes that can occur all year long, covering parts of or the entire glacier surface area. They also mentioned that the impact of temperature and precipitation on the surface mass balance relies on the phase of precipitation and the subsequent albedo effect. This is in line with the former studies made on another glacier of the inner tropics located in the Ecuadorian Andes: Antizana 15 glacier, where both surface mass and energy balance studies (Favier et al. 2004; Francou et al. 2004) revealed the strong relationship between glacier surface albedo and melting. These studies showed that the frequency and intensity of snowfalls, which can occur all year long, play a major role in attenuating the melting processes and consequently, both precipitation and temperature are crucial for the annual surface mass balance.

In a review paper about the state of glaciers in the tropical Andes, Rabatel et al. (2013a) concluded that the sensitivity of inner tropical glaciers to climate is closely linked to the absence of temperature seasonality and to the fact that the 0°C isotherm constantly oscillates through the glaciers. As a consequence, a minor variation in air temperature can influence the melting processes by determining the phase of precipitation and consequently affect the surface albedo and mass balance.

3. Methods and data

3.1. Quantification of glacier surface area

Former studies have documented the glacier surface area changes since their maximum extent during the Little Ice Age and until the early 2000s (e.g. Jordan et al. 1989; Florez 1992; Pulgarin et al. 1996; Ceballos et al. 2006; Herrera and Ruiz 2009; Poveda and Pineda 2009). Note that the Little Ice Age maximum extent has not been so systematically dated in the Colombian Andes as it was the case in the other countries of the tropical Andes (e.g. Rabatel et al. 2005, 2008; Jomelli et al. 2009), even if the link between moraines and reliably dated Ruiz eruptions on 12 March 1595 and 18 February 1845 locally provides good indicators (Jordan et al. 1987; Jordan and Mojica 1987). The former studies on the extent of Colombian glaciers in the past are based on moraines (reflecting the Little Ice Age maximum extent), aerial photographs from the late 1940s to the mid-1990s, and Landsat TM and ETM from the mid-1990s to the early 2000s. In the current study, an update of the glacial coverage across all Colombian glacierized mountain ranges has been realized using images from the following satellites: QuickBird (2007, spatial resolution of 2.5 m in multispectral mode = visible + near-IR), ALOS (2007, 2008, 2009, spatial resolution of 10 m in multispectral mode = visible + near-IR), RapidEye (2010, spatial resolution of 5 m in multispectral mode = visible + near-IR) and Landsat-8 OLI (2016, Figure 1).

On the basis of Landsat-8 images from late January to early February 2016, a detailed inventory was produced and a database was generated according to the design of the GLIMS glacier relational database. For an extensive description of the database content, the reader should refer to the GLIMS website (http://www.glims.org/MapsAndDocs/db_design.html). The 2016 Landsat-8 images provide the perfect conditions for a glacier inventory: no snow cover outside the glaciers and no cloud cover on the mountains, a particular challenge in Colombia due to often persistent cloudy weather conditions. These images have a spatial resolution of 30 m in multispectral mode and 15 m in the panchromatic mode (the spectral bands 'green', 'NIR-IR' and 'MIR' available at 30 m have been pansharpened at 15 m). Due to the small size of the glaciers and their limited number, the delineation of the glacier outlines has been made manually. Manual delineation can have advantages over automatic detection of glacier ice in shadowed areas (Gardent et al. 2014). Note that debris-covered glacier areas are limited in Colombia, either because the glaciers are small ice caps, or remnants of ice caps, or slope glaciers; and in every case, rock walls overhanging the glaciers are limited or absent. However, ashes resulting from eruptions can cover some parts of the ice caps located on active volcanoes. On the 2016 satellite images, it was the case on the north-western side of the Nevado del Ruiz, but because the ash cover was not homogeneous and ice-free areas can be seen, it did not prevent an accurate delineation of the glacier margin. For older data sources, aerial photographs from 1959, 1987 and 2005 used on Nevado del Ruiz allowed an accurate delineation of glacier contour due to their high spatial resolution.

Regarding the uncertainties, they largely depend on the data sources (moraines, aerial photos, satellite images). It is noteworthy that the estimated values for the Little Ice Age are probably associated with the highest uncertainty compared with inventories performed using aerial photos or satellite images. Indeed, for the Little Ice Age, the surface area reconstruction is based on the moraine ridges, which are not always continuous over the glacier foreland. However, the uncertainty is not given in all the related studies. Regarding the aerial photos and the satellite images, to compute a margin of uncertainty on the delineation of the glacier outline, Rabatel et al. (2011) considered different sources related to:

(i) the pixel size of the image or digital photograph, which has an influence on the digitization;
(ii) the process of geometric correction and georeferencing of the images, ortho-photos and numerical maps, which affect the geometry of the used data source;
(iii) the errors associated with visual identification and manual delineation of the glacier outline, which depend on the ability and experience of the operator. After a test of multiple digitization, this error was set a ±1 pixel for the Landsat satellite images used for 2016, and ±2 pixels for the ortho-photos or very high-resolution satellite images such as Quickbird used for 2007 and RapidEye used for 2010;
(iv) the possible residual snow cover, which compromises the accurate visual identification of the border of the glacier. This error has a huge spatial variability, but is always limited in our case because the images were selected to have a minimum snow cover outside the glaciers.

The total uncertainty is the root of the quadratic sum of the different independent errors. Uncertainty in surface area can be considered as the horizontal uncertainty of the position of the margin times its length (Rabatel et al. 2011).

3.2. Quantification of glacier volume

Ice thickness measurements have been acquired on La Conejeras glacier (Nevado Santa Isabel) using an ice penetrating radar (IPR) during field campaigns in January–February 2014. Our IPR is a geophysical instrument specially designed by the Canadian company Blue System Integration Ltd in collaboration with glaciologists to measure the thickness of glacier ice (Mingo and Flowers 2010). It comprises a pair of transmitting and receiving 5 MHz antennas that allow continuous acquisition, georeferenced with a GPS receiver.

Fourteen cross profiles and two longitudinal profiles have been acquired on this small glacier (0.19 km² in 2014, Figure 2), which is a remnant of the Santa Isabel ice cap (Figure 3). From the *in situ* IPR continuous acquisitions, 200 measurements have been selected (Figure 2) representing points with clear reflection signal with an average density of 1 pt/100 m². Note that these data have been integrated to the glacier thickness database GLATHIDA 2.0 (WGMS 2016).

The main uncertainty in the ice thickness measurements comes from the analysis of the radar signal and results from the manual picking on the radargram of the signal reflected by the bedrock. The analysis of the radar data has been made using the software IceRadarAnalyzer 4.1 (Mingo and Flowers 2010), and the uncertainty on each individual ice thickness measurement was estimated at 2 m, resulting in a uncertainty of the total glacier volume of about 10%.

3.3. Quantification of surface elevation changes

Changes in glacier surface elevation can be computed by the difference of digital elevation models (DEMs) realized by topography (DGPS, LiDAR) or using aerial photographs or satellite stereo-images from high spatial resolution data (e.g. SPOT 5–7, Pléiades, Ikonos, Worldview). However, such accurate DEMs are not available for all the Colombian glaciers. Nevado del Ruiz and Santa Isabel are two of the exceptions with photogrammetric restitutions performed on the basis of 1959, 1987 and 2005 aerial photographs. All the technical details about these restitutions as well as more results and interpretation can be found in Linder (1991, 1993), Braitmeier (2003) and González et al. (2010). Figure 3(A and B) show the ortho-photos from 1987 and 2005, respectively. The ortho-photo from 2005 shows the extent of the Santa Isabel ice cap in 1987, 2005 and 2016 (Figure 3(B)).

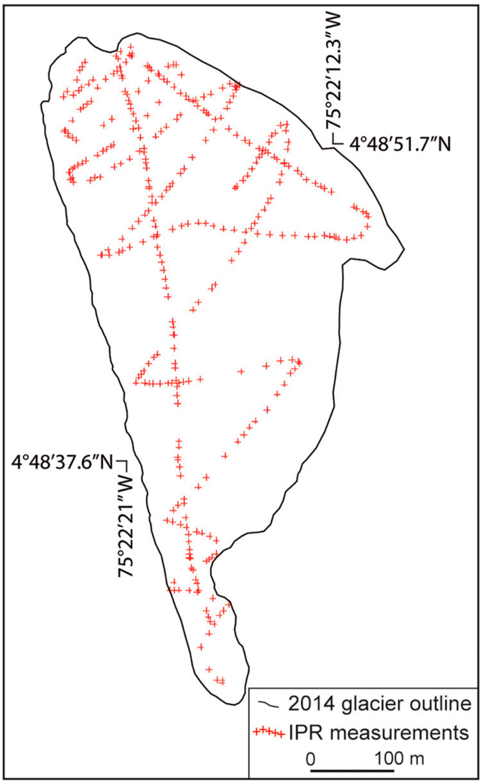

Figure 2. IPR measurements acquired in Jan-Feb 2014 on La Conejeras glacier.

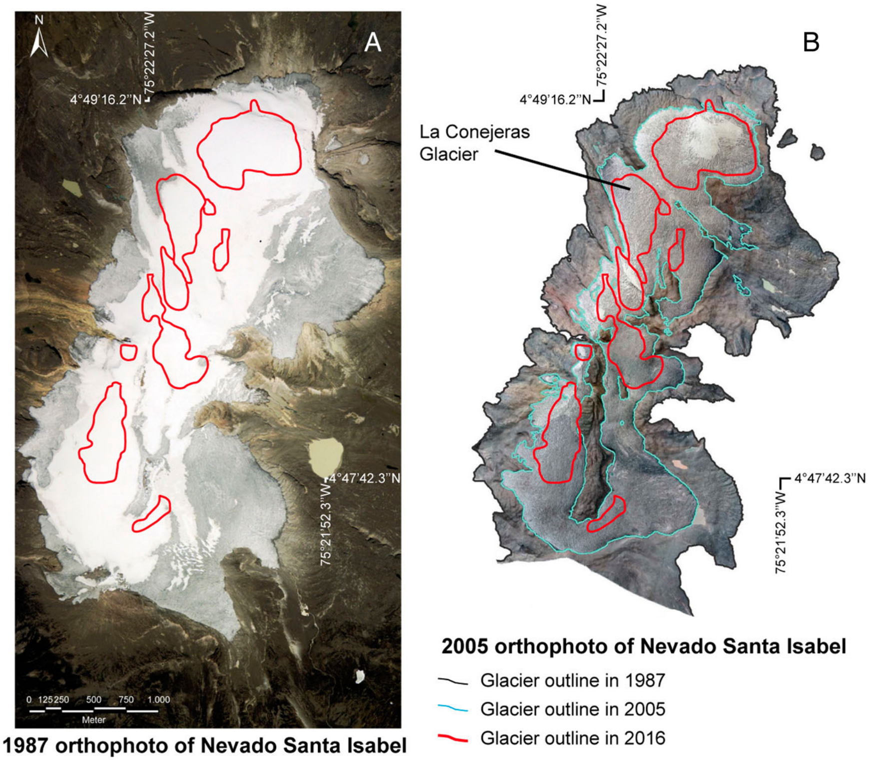

Figure 3. Ortho-photo of Nevado Santa Isabel with glacier extent in 1987 and 2016 (A) and Ortho-photo from 2005, with the outline of the ice cap in 1987 (in dark grey) and the outline of the remnant glaciers in 2005 and 2016 (light blue and red respectively) (B). The horizontal scale shown on A is the same for B. Sources: Braitmeier (2003) for the 1987 ortho-photos and González et al. (2010) for the 2005 ortho-photos.

During the January–February 2014 field campaign for glacier thickness measurements on La Conejeras glacier (a remnant of Santa Isabel ice cap, Figure 3(B)), a complete topography of the glacier surface was generated using a terrestrial LiDAR (an ultra-long-range RIEGL VZ-6000 device, Figure 4(A)). This system emits a near-infrared laser beam at 1064 nm ideal for glaciological studies (e.g. Gabbud et al. 2015; Fischer et al. 2016). Ten reflector targets with 5 cm diameter were fixed on stakes or rocks around the glacier for georeferencing purposes. Their position has been measured using differential GPS. Three distinct scan positions were set to achieve good coverage of the whole glacier and its surroundings. The LiDAR data were processed using the software RiSCAN PRO. The main processing steps included a filtering of points (e.g. due to atmospheric reflections caused by dust or moisture), a merge of the point clouds from the different scan positions and the georeferencing of the final grid using the target reference points. Figure 4(B) provides an illustration of the final point cloud. The resulting DEM has a homogeneous resolution of 0.5 m and was reprojected to MAGNA Colombia Bogotá (EPSG 3116), the current official georeference system of Colombia.

The changes in glacier surface elevation have been quantified by subtracting the different DEMs. This was possible at the scale of the entire Santa Isabel ice cap as published by Linder (1991) for the period from 1959 to 1987; now with more details for the period 1987–2005, and additionally for La Conejeras glacier only for the periods 1987–2005 and 2005–2014 using the 2014 LiDAR data.

From these surface elevation changes, the geodetic average annual mass balance has been quantified considering the average surface area between the two considered dates, the time between the

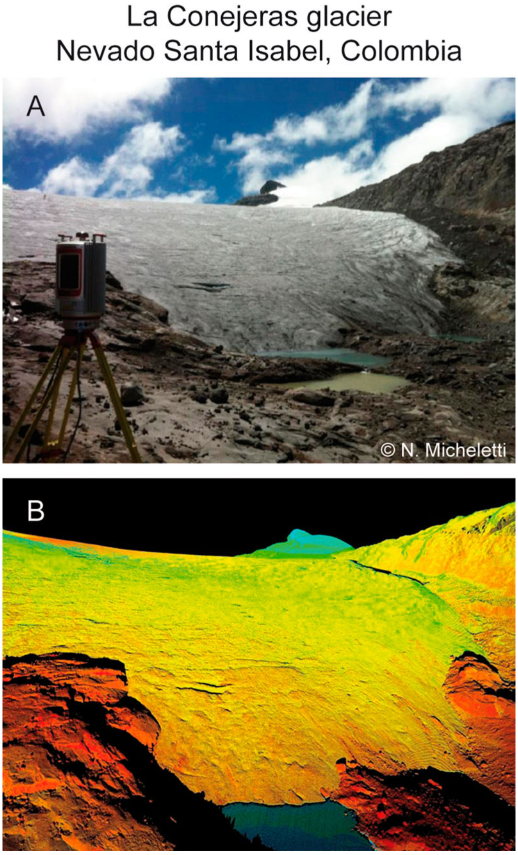

Figure 4. RIEGL VZ-6000 operating at the front of La Conejeras glacier (A) and Scanned point cloud of La Conejeras glacier (B).

two DEMs and an average ice density of 900 kg m^{-3}. For more details about the geodetic method, the reader may refer to the literature (e.g. Rabatel et al. 2006; Cogley 2009; Basantes-Serrano et al. 2016).

3.4. In situ *glacier surface mass balance data*

Two glaciers in Colombia are monitored with *in situ* measurements to quantify their surface mass balance: La Conejeras glacier on the Nevado Santa Isabel and Ritacuba glacier in the Sierra Nevada de El Cocuy (Ceballos et al. 2012). Accumulation and ablation measurements are performed at a monthly scale with the classical glaciological method (snow pits and ablation stakes) since 2006 for La Conejeras and 2008 for Ritacuba glacier. Recently, the entire monthly surface mass balance data series of La Conejeras glacier has been reanalyzed by Mölg et al. (2017), where more details on the monitoring network and the results of this 10-yr monitoring program are provided.

4. Results and discussion

4.1. 2016 Colombian glaciers inventory

Table 2 gives an overview of the distribution of glaciers according to size classes for the 2016 inventory for the whole Colombian Andes and considering the four main glacierized areas: Sierra Nevada de Santa Marta, Sierra Nevada de El Cocuy, Los Nevados National Park (including los Nevados del Ruiz, de Santa Isabel and de Tolima) and Nevado del Huila.

Table 2. Summary statistics (number and area) on glaciers in Colombia for the 2016 inventory.

Size class (km^2)	Colombia	Sta Marta	El Cocuy	P.N. Los Nev.	Huila	
<0.1	Number	30	13	6	11	
	Number (%)	30	46	24	35	
	Area (km^2)	1.73	0.74	0.37	0.62	
	Area (%)	4	10	2	5	
0.1–0.5	Number	40	11	11	10	8
	Number (%)	40	39	44	32	53
	Area (km^2)	10.02	2.70	2.54	2.00	2.77
	Area (%)	24	38	16	17	35
0.5–1	Number	19	3	3	7	6
	Number (%)	19	11	12	23	40
	Area (km^2)	13.72	2.61	2.28	4.74	4.10
	Area (%)	32	36	15	40	51
1–5	Number	10	1	5	3	1
	Number (%)	10	4	20	10	7
	Area (km^2)	16.92	1.13	10.28	4.39	1.12
	Area (%)	40	16	66	37	14
Total	Number	99	28	25	31	15
	Area (km^2)	42.4	7.2	15.5	11.8	8.0

Glaciers of the Colombian Andes covered 42.42 ± 0.71 km^2 in early 2016, with 7.2 ± 0.27 km^2 in the Sierra Nevada de Santa Marta, 15.5 ± 0.33 km^2 in the Sierra Nevada de El Cocuy, 11.8 ± 0.52 km^2 in Los Nevados National Park and 8.0 ± 0.23 km^2 for the Nevado del Huila. At the scale of the Colombian Andes, the mean glacier size was 0.43 km^2 (median = 0.22 km^2, indicating that the distribution is clearly dissymmetric toward small-sized glaciers); glaciers <0.5 km^2 represented 70% of all glaciers and 28% of the total glacierized area. Glaciers >1 km^2 accounted for 66%, 37%, 16% and 14% of the glacierized area in Sierra Nevada de El Cocuy, Los Nevados National Park, Sierra Nevada de Santa Marta and Nevado del Huila, respectively.

Glacier minimum, maximum, and mean altitudes have been computed from the ASTER GDEM V2. This global DEM was generated from ASTER images dating from the period 2000 to 2010. The exact dating for each region is unknown, but it can be considered that the elevation provided by this DEM is representative of the 2000s. The mean altitude has been computed from the area-altitude distribution. Indeed, such mean altitude can be considered as a proxy of the balanced-budget equilibrium-line altitude corresponding to the glacier extent (Jordan 1991; Machguth et al. 2012; Rabatel et al. 2013b; Braithwaite 2015). Considering the different glacierized regions, the average values of the mean altitude of each individual glacier are 5170, 4910, 5140 and 5020 m a.s.l. for Sierra Nevada de Santa Marta, Sierra Nevada de El Cocuy, Los Nevados National Park and Nevado del Huila, respectively.

The maximum altitude of the glacier is an interesting variable, because when compared to the equilibrium-line altitude it allows computing the altitudinal extent of the accumulation zone, and together with the glacier area distribution the accumulation area ratio. The highest altitudes of glaciers' top can be found in the Sierra Nevada de Santa Marta, where they reach 5678 m a.s.l. On the Nevado del Huila, the altitude of glaciers' top ranges between 5160 and 5390 m a.s.l. In the two other glacierized areas, the uppermost elevations are lower, ranging between 4785 and 5346 m a.s.l. for the Sierra Nevada de El Cocuy and between 4925 and 5314 m a.s.l. for the Los Nevados National Park. Assuming that the current elevation of the 0°C isotherm at ~5000 m a.s.l. in glacierized areas B and C (see Section 2.1) can be representative of the two other glacierized areas, about 20% of the glaciers in Colombia have their uppermost elevation located below.

In terms of altitudinal extent (difference between the minimum and maximum elevations of the glacier), the Colombian glaciers span over limited altitudinal ranges: in average (max.) 550 m (770 m) on the Nevado del Huila, 340 m (870 m) in the Sierra Nevada de Santa Marta, 300 m (600 m) in the Sierra Nevada de El Cocuy and 280 m (700 m) in Los Nevados National Park.

Table 3. Surface area changes since the Little Ice Age maximum.

	Santa Marta (km²)	El Cocuy (km²)	Ruiz (km²)	Santa Isabel (km²)	Tolima (km²)	Huila (km²)	Total (km²)
LIA max	82.60[c,*]	148.70[c,*]	47.50[c,*]	27.80[c,*]	8.60[c,*]	33.70[c,*]	348.9 + 23.7[c,*]
1939	21.40[c,*]						
1946				10.80[c,*]	3.10[c,*]		
1954	19.40[c,*]						110.6
1955		38.90[g]					
1958					2.7[c,*]		
1959			21.40[a,+] 20.70[b,+] 21.00[c,*]	9.78[a,+] 9.50[b,+] 9.40[c,*]	2.22[a,+]		
1961						18.86[d,+]	
1965						19.77[a,+] 16.30[c,*] 19.06[d]	
1970						18.21[d]	
1973	14.1[e,°°]	28.0[e,°°]					
1974	16.26[a,+]						
1975			19.60[c,*]				
1976			21.3[e,°°]	10.8[e,°°]	3.8[e,°°]	26.0[e,°°]	
1978		39.12[a,+] 38.80[c,*]					
1981	16.10[c,*]					15.40[c,*]	87.95
1985		35.70[c,*]	18.70[c,*]				
1986		31.45[g]	17.00[c,*]				
1987			17.70[b,+]	6.50[b,+] 6.40[f,+] 6.56[h,+]	2.10[c,*] 1.60[g]		
1989	12.00[c,*]					14.72[d,+]	
1990			14.10[c,*]				
1994		23.70[g]					66.43
1995	11.10[g]					13.39[d,+]	
1996				5.30[g]			
1997			11.76[g]		1.18[g]		
2001						12.95[g]	
2002	8.40[g]		10.32[g]	3.33[g]	1.03[g]		53.33
2003		19.8[g]					
2005				2.78[h,+]			
2007	7.70[°,+]	18.60[°,+]		2.60[°,+]	0.93[°,+]	10.80[°,+]	
2008		17.70°					
2009	7.40°	17.40°					
2010		16.00°		1.80°	0.74°	9.70°	
2016	7.20 ± 0.27°	15.46 ± 0.33°	10.11 ± 0.26°	1.0 ± 0.08°	0.65 ± 0.06°	8.00 ± 0.23°	42.42 ± 0.71
~2005–2016	−6%	−17%	−2%	−62%	−30%	−25%	−20%

~1995–2016	−35%	−35%	−14%	−81%	−45%	−40%	−36%
~1985–2016	−55%	−51%	−46%	−84%	−59%	−48%	−52%
~1955–2016	−63%	−60%	−53%	−90%	−71%	−58%	−62%
LIA-2016	−91%	−90%	−79%	−96%	−92%	−76%	−88%

Notes: For each glacierized area the surface area (km^2) for each date is presented as well as the loss for different periods (in % of the initial surface area for the considered period). Data before 2007 were taken from previous studies, the letter indicates the original study: [a]Jordan et al. (1989); [b]Linder (1991, 1993); [c]Florez (1992); [d]Pulgarin et al. (1996); [e]Hoyos Patiño (1998); [f]Braitmeier (2003); [g]Ceballos et al. (2006); [h]González et al. 2010. Symbols indicate the method: *Planimetry on aerial photos; +Photogrammetric restitution with uncertainty estimate; °Planimetry on satellite ortho-images (pixel size between 0.5 and 15 m); °°Planimetry on Landsat MSS (pixel size of 79 m). Regarding the total glacier cover computed for the gray shaded lines, when several surface areas are available for a glacierized area, the average is considered. The uncertainty for the 2016 inventory have been computed from the quadratic sum of the uncertainties of each glacier of the considered area.

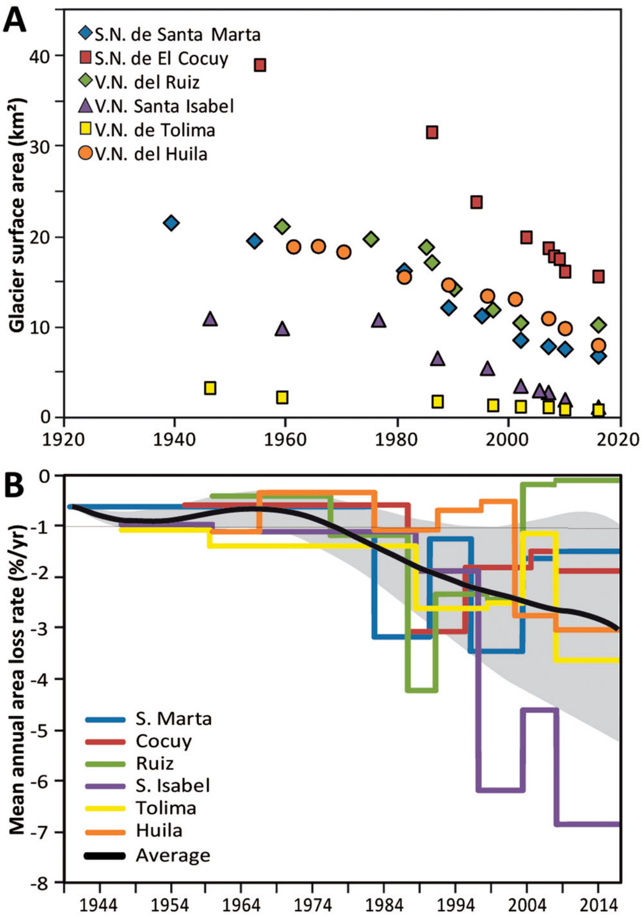

Figure 5. Glacier surface area changes in the different glacierized areas of Colombia since the 1940s (A) and Rates of mean annual area loss in percentage per year for each glacierized area. The black curve and grey area represent the average with 1 st-dev interval. The average has been smoothed using a polynomial fit (B).

4.2. Historical glacier surface area changes

Table 3 presents the surface area changes in the different glacierized areas of the Colombian Andes. Note that Los Nevados National Park encompasses three volcanoes Ruiz, Santa Isabel and Tolima (Figure 1(C)). These changes are also illustrated in Figure 5(A and B), including the rates of mean annual surface area loss in percentage per year for each glacierized area since the mid-twentieth century.

The overall glacierized surface area in the Colombian Andes decreased by ~90% since the Little Ice Age maximum extent (undated). Note that in addition to the 349 km^2 in the six glacierized areas, eight other areas in Colombia presented glaciers during the Little Ice Age (with an estimated surface area of 23.7 km^2) and are currently without glaciers (Florez 1992; Baumann 2006).

Considering the glacierized surface area in the mid-twentieth century (about 110 km^2), the 2016 extent is about 62% smaller. In the last two decades (i.e. since 1995), the glacierized surface area has decreased by about 36%.

However, Figure 5 illustrates that the trend has not been homogeneous since the mid-twentieth century, both temporally and spatially. Indeed, the mean annual surface area loss rate (black curve in Figure 5(B)) has remained close to −1% per year from the 1940s till the mid-1970s, with a slightly reduced loss rate between the mid-1960s and the mid-1970s. Since the mid-1970s, the mean annual surface area loss rate has increased continuously, reaching −3% per year during the current decade in average for all the Colombian glacierized areas. On the other hand, this retreating trend is spatially highly contrasted, with the most important loss rate found for Santa Isabel and Tolima volcanoes, which is in agreement with their lowest elevations and the very small glaciers. Glaciers of the Sierra Nevada de Santa Marta show a slightly lower surface area loss rate over the last decades. This has to be related with the higher elevation of this mountain range: glaciers' top ranges between 4970 and 5678, and only five of the 28 glaciers have a median elevation located below 5000 m a.s.l. (approximately the elevation 0°C isotherm in the other glacierized areas of Colombia).

It is noteworthy that for some ice masses located on active volcanoes such as on the Nevado del Ruiz, Nevado del Tolima and Nevado del Huila, the glacier shrinkage is not only influenced by changes in climatic conditions but also due to eruptions increasing the geothermal flux and depositing ashes at the glacier surface. This leads to an increase in snow and ice melt. Such an event occurred in 1985 on the Nevado del Ruiz, leading to an important ablation and surface area shrinkage from the mid-1980s to the late 1990s (Thouret 1990; Linder 1991, 1993; Linder and Jordan 1991; Linder et al. 1994; Borrero et al., 1996). This important shrinkage (~1.5 times the country scale average) during more than a decade mainly related to the eruption (i.e. not exclusively climate related) is probably at the origin of the observed lower shrinkage rate observed for the Nevado del Ruiz during the last decade.

4.3. Glacier volume estimation from field data at La Conejeras glacier

The 2014 ice thickness data from the 14 cross profiles and two longitudinal ones acquired on La Conejeras glacier (Figure 2) have been interpolated using the software PCI-Geomatica (MQSINT: multiquadratic spline interpolation). Figure 6 presents the resulting raster with a spatial resolution of 15 m (pixel size). The maximum ice thickness located in the central part of the glacier was slightly above 50 m in 2014. The total ice volume was estimated to 4.325×10^6 m^3, which corresponds to 3.893×10^6 m^3 of water equivalent (using an ice density of 0.9). Considering a surface area of 0.199 km^2, the average ice thickness of La Conejeras glacier was about 22 m in 2014.

4.4. Decadal mass balances

In situ mass balance measurements over the last decade on La Conejeras and Ritacuba glaciers in Los Nevados National Park – Nevado Santa Isabel and in the Sierra Nevada de El Cocuy, respectively, have shown a clear unbalanced situation (Ceballos et al. 2012). Indeed, the balanced-budget equilibrium-line altitude (ELA$_0$, *cf.* Cogley et al. 2011) derived from the surface mass balance measurements for La Conejeras glacier is about 4920 m a.s.l., thus 160 m above its mean altitude computed from the area-altitude distribution (i.e. 4760 m a.s.l.), and 120 m above the mean altitude of the glaciers located on the Nevado Santa Isabel. This is the same for the Sierra Nevada de El Cocuy, where the mean altitude of the glaciers is 4910 m a.s.l., 120 m below the ELA$_0$ derived from *in situ* measurements on Ritacuba glacier.

Reanalyzing the 10-yr monthly mass balance time series of La Conejeras glacier, Mölg et al. (2017) have shown that the mean annual mass balance has been close to −3 m w.e. yr^{-1} over the period 2006–2015 (*cf.* Figure 7 where annual mass balance are plotted). Mölg et al. (2017) also showed that the annual ELA was on average close to the glacier maximum altitude during the monitoring period, with an accumulation area ratio of about 4%, i.e. almost no accumulation zone.

On the other hand, the comparison between the 2014 Lidar DEM and the photogrammetric DEM from 1987 (see Section 3.3) showed that the glacier surface elevation has lowered by 80 m at 4700 m a.s.l. (altitude of the glacier surface close to the front of the glacier in 2014) between the two dates, 50 m between 1987 and 2005 (Figure 6). The geodetic mass balance was −2.56 m w.e. yr^{-1} for the period 1987–2005 and −2.46 m w.e. yr^{-1} for the period 2005–2014 (Figure 7). Note that the *in situ* surface mass balance averaged over the closest period (i.e. 2007–2014) was −2.45 m w.e. yr^{-1}. This

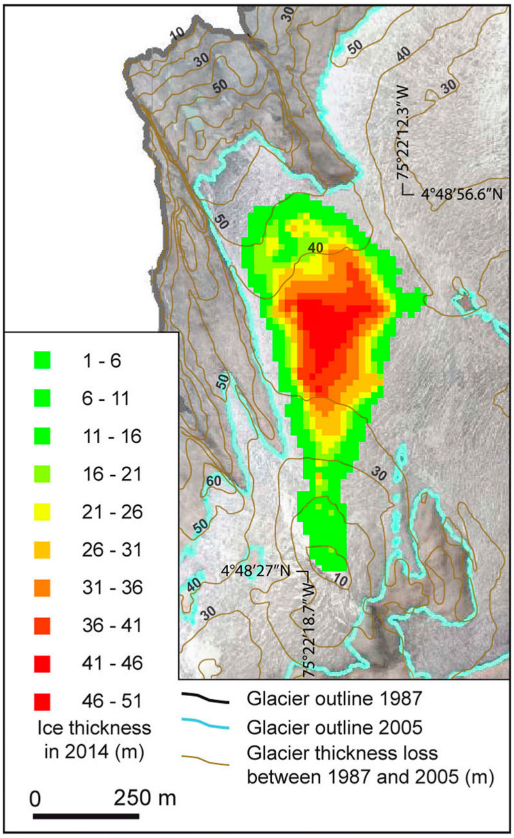

Figure 6. Map of ice thickness in 2014 at La Conejeras glacier. The image in the background is the ortho-photo from 2005 with the outlines for 1987 and 2005 (see Fig. 3 for the glacier extents of the entire ice cap). The brown contour lines show the ice thickness loss (in m) between 1987 and 2005 from González et al. (2010).

very good agreement between the two independent methods shows that the well-distributed network of *in situ* measurements at the surface of La Conejeras glacier allows an accurate quantification of the mass balance using the glaciological method. Computed at the scale of the entire Santa Isabel ice cap, the geodetic mass balance between 1987 and 2005 was −2.69 m w.e. yr^{-1}, i.e. slightly more negative than considering La Conejeras glacier only.

4.5. Future changes of Colombian glaciers

The strong shrinkage of the Colombian glaciers since the mid-twentieth century and in particular the constant increase in the rate of shrinkage at the country scale over the past four decades is an indication of the strong imbalance of glaciers with current climate. Figure 7 shows the volume loss of La Conejeras glacier computed on the basis of the ice thicknesses measured in 2014, the annual changes in surface area and the surface mass balances *in situ* measured since 2006. A linear extrapolation of the glacier volume changes of the last decade for the future would result in the disappearance of La Conejeras glacier in the first years of the 2020s, likely in concert with the other remaining glaciers of Nevado Santa Isabel.

The mass balances measured on La Conejeras and Ritacuba glaciers cannot be directly extrapolated to the scale of all other glaciers in Colombia, as neighboring glaciers under similar climate conditions can show different mass balances in relation with the dynamic response of glaciers to a change in climate forcing (e.g. Rabatel et al. 2016). Estimates of future changes and disappearance

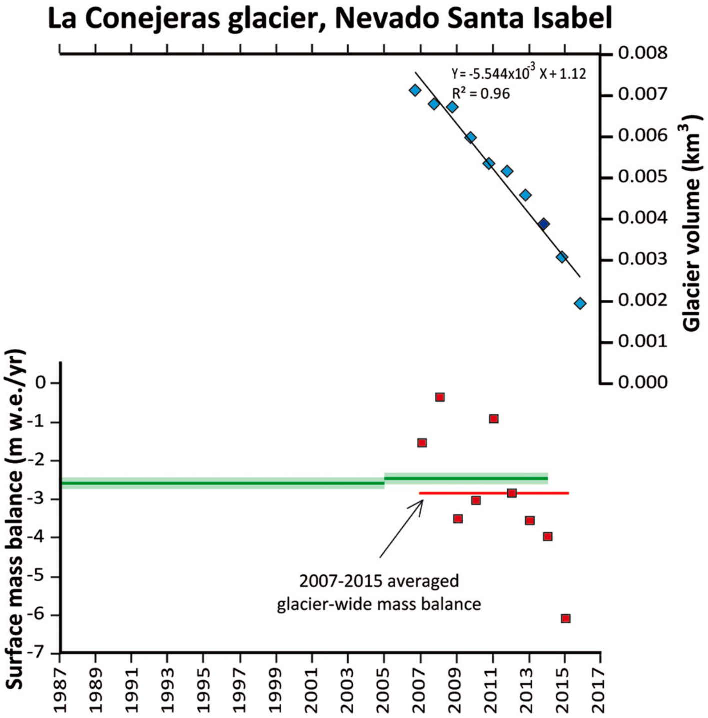

Figure 7. Surface mass balance and volume changes of La Conejeras glacier. Red squares show the annual surface mass balance with the average for the period 2006–2015 (red line) from Mölg et al. (2017). The green lines illustrate the average glacier-wide annual mass balance computed from the difference between the 1987, 2005 and 2014 DEM. The blue diamonds show the annual glacier volume computed on the basis of 2014 estimate (dark blue diamond) using thickness measurements; the black line shows the linear regression.

of Colombian glaciers based on decadal trends in glacier surface area loss therefore imply some uncertainty. Nevertheless, as a first approximation, a linear trend extrapolation from the observed glacier surface area shrinkage rates in the different glacierized areas of Colombia during the last decades (Figure 5(A)) allows a rough estimation of their future changes and disappearance. Accordingly, glaciers on the Nevado de Tolima will likely disappear before 2030, and most of the glaciers in the Sierra Nevada de Santa Marta and Sierra Nevada de El Cocuy before 2050. Only the few largest glaciers with the highest maximum elevations on Nevado del Huila, Nevado del Ruiz and in the Sierra Nevada de Santa Marta and Sierra Nevada de El Cocuy will probably persist after the mid-twenty-first century although strongly reduced. Our results suggest that glacier extinction in Colombia happens much faster than the corresponding estimates in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Magrin et al. 2007: ‘within the next 100 years’), but not as dramatic as suggested by Poveda and Pineda (2009: ‘by the late 2010–20 decade’). The latter estimates are based on Landsat TM and ETM+ images from 1989 to 2007 and result in slightly smaller total areas for 2004–2007, and correspondingly higher loss rates, than the present study.

Taking into account the influence of temperature changes on glacier surface processes (see Section 2.2), an alternative to the extrapolation of surface area changes can be made from the relationship between the 0°C isotherm and the maximum elevation and/or the ELA of the glaciers, and considering the future projections of temperature using different climate scenarios. Figure 8 shows the HadCRUT4 observations (Morice et al. 2012) as well as historical and future CMIP5 experiments following the two extreme radiative concentration scenarios (RCPs) RCP 2.6 and 8.5 (Taylor et al. 2012) for the near-surface air temperature. Data from different global climate models (see Figure 8 caption) are averaged over the region defined as the box 2°–10°N, 72°–77°W to

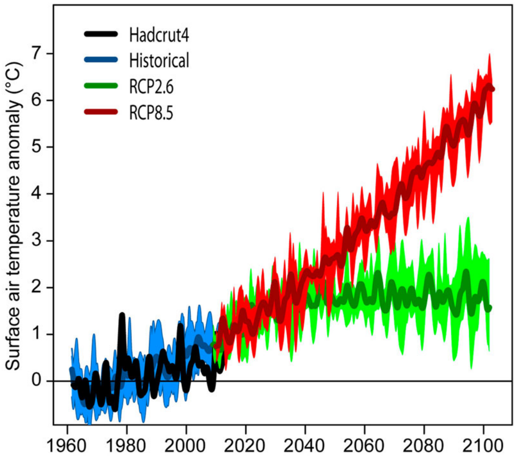

Figure 8. Near-surface air temperature anomalies computed with respect to the average 1961–1991: Hadcrut4 observations (black, Morice et al. 2012; historical CMIP5 simulations (blue); CMIP5 scenarios based on low GHG emissions (RCP2.6, green) and high GHG emissions (RCP8.5, red). A 12-month running mean has been applied to the anomalies computed as an average over 2°–10°N, 72°–77°W to encompass all the glacierized areas in Colombia. Shading indicate the maximum-minimum range across three CMIP5 models (GFDL-CM3 (4 members); IPSL-CM5A-LR (5 members); MPI-ESM-LR (3 members). See Taylor et al. (2012) for the description of the CMIP5 experiment.

encompass the different glacierized areas in Colombia. Over the reference period extended from 1961–1990, both model and observations show a temperature increase within the range of 0.5°C, an increase smaller than the interannual variability over this period. The scenarios RCP 2.6 and 8.5 show an increase in air temperature reaching respectively 1.6°C (0.5–2.7°C) and 6.3°C (5.4–7.2°C) by the end of the twenty-first century, considering a 10-yr average of the multi-model ensemble experiments.

Assuming that the current vertical gradient of air temperature remains unchanged, such an increase in temperature would raise the 0°C isotherm by 320 m (ranging from 100 to 540 m) for RCP 2.6 and by 1260 m (ranging from 1080 to 1440 m) for RCP 8.5, i.e. reaching the elevation of 5320 and 6260 m a.s.l., respectively. Note that these estimates are in close agreement with the results found by Schauwecker et al. (2017) for the Peruvian Andes. In such conditions, 75% (100%) of the Colombian glaciers would be entirely located below the 0°C isotherm by the end of the twenty-first century, considering RCP 2.6 (8.5).

In addition, although the time series are short (~10 yr), the meteorological and glaciological data from La Conejeras glacier (Mölg et al. 2017) allow quantifying the sensitivity of the ELA to air temperature and elevation of the 0°C isotherm. The significant correlation between the ELA and the 0°C isotherm ($r = 0.9$, $p < .002$) shows that a 100-m increase in the 0°C isotherm leads to an increase in the ELA by 160 m. As a consequence, the above-mentioned increases in the 0°C isotherm by the end of the twenty-first century would place the ELA 500 and 2000 m above its current location for the RCP 2.6 and 8.5, respectively. Assuming that these estimates made from the data available on La Conejeras glacier can be transposed to the other glacierized areas in Colombia, the projected ELA would be above the maximum elevation of 80% (100%) of the Colombian glaciers. In such conditions, glaciers in Colombia would constantly be in ablation over most or the totality of their surface area (very limited or no accumulation zone would persist) and their shrinkage/disappearance looks ineluctable.

It is worth noting that considering the RCP 2.6, the increase in air temperature during the coming decades would mainly occur before 2040–2050, meaning that the remaining glacierized surface areas in Colombia would stabilize during the second half of the twenty-first century.

Finally, it must be reminded that even with the use of 'anomaly' approaches applied to remove the biases in climate models, large uncertainties remain when using CMIP5 scenarios, in particular, because of the potential non-stationarity of the model bias. Global climate models show also weaknesses to simulate regional atmospheric circulation changes (Shepherd 2014), and their coarse resolution does not allow to simulate correctly the feedbacks strengthening the warming with the altitude (MRIEDW 2015) and the local impact of particle deposition on glacierized areas (Hansen and Nazarenko 2004). Even with significant improvements in terms of ENSO modeling from CMIP3 to CMIP5 (Bellenger et al. 2014), it is very challenging to anticipate the potential ENSO changes over the next decades, and these ones may have strong impacts on the Colombian climate. Nevertheless, the use of CMIP5 model projections is currently one of the unique ways to anticipate the future changes in temperature and precipitation. Retrospective validations show that CMIP models reproduce the main features of the current climate in Southern America (e.g. Vera et al. 2006; Sillmann et al. 2013) and can be used to estimate the future trends of temperature over this continent, whereas the uncertainties in terms of precipitation are very high (Blázquez and Nuñez 2013). By setting up calibration approaches, Marzeion et al. (2014) and Réveillet et al. (2015) demonstrated the possibility to use CMIP outputs to simulate glaciers' future evolution. We describe here a potential evolution for the Colombian glaciers that follows two scenarios based on different societal evolutions. A limitation of our study relies on the regional or local forcing and feedbacks described previously that could modulate these future evolutions.

4.6. Potential impacts of future glacier changes

In other regions of the tropical Andes, glaciers represent an important source of water for domestic, agricultural or industrial use, for example in La Paz, Bolivia, where the water from the glaciers represents up to 30% of the runoff during the dry season (Soruco et al. 2015), and recent studies have shown the negative impacts of current glacier shrinkage on the biodiversity of the proglacial areas (e.g. Dangles et al. 2017; Zimmer et al. 2017). In Colombia, the potential impact of glacier shrinkage mainly relates to the Páramo ecosystems (Brown et al. 2007), as well as for local agriculture and tourism. However, the glacierized volcanoes in Colombia remain – at least for the next few decades – a natural hazard, as dramatically shown with the example of the post-eruption lahars of the Nevado del Ruiz in 1985 (e.g. Jordan et al. 1987; Thouret 1990). Because the Nevado del Ruiz presents the largest single ice coverage in Colombia (10.11 km^2 in 2016) with an estimated ice volume of 484 $\times 10^6$ m^3 back in 2003 (measured maximum and mean thickness of 190 and 47 m in 1999, respectively, Huggel et al. 2007), the risk of lahars generated from the interaction of volcanic activity and snow and ice will still persist for several decades. As a consequence, to better estimate the potential water release resulting from an eruption of the Nevado del Ruiz and to prepare potential impact scenarios, an accurate mapping to the ice thickness and distribution, as we presented here for La Conejeras glacier, is urgently recommended. A similar mass of ice (8.0 km^2 in 2016 and 648 $\times$ 10^6 m^3 of ice estimated for 2001) persists on Nevado del Huila, which produced several far-reaching (up to 150 km) lahars in 2007 and 2008 when Nevado del Huila erupted and large amount of water was produced (Worni et al. 2012).

5. Conclusion

In this study, we presented the results of a new glacier inventory of the Colombian Andes using 2016 Landsat images, in combination with *in situ* measurements of glacier thickness using radar and of glacier surface topography using LiDAR and aerial photogrammetry on the well-studied La Conejeras glacier located on the Nevado Santa Isabel in Los Nevados National Park.

The main results showed that:

- The glacier surface area is nowadays very reduced in Colombia, with a total ice-covered area of 42.4 km^2 in 2016. The mean glacier size was 0.43 km^2, and small-size glaciers largely predominate (70%, <0.5 km^2).

- The glacier shrinkage is strong since the mid-1970s and, remarkably, almost constantly increasing, reaching a mean annual area loss rate of $-3\%\ \mathrm{yr}^{-1}$ during the last years, which points to a continued climatic forcing, possibly in addition to local topographic and geometric effects.
- Mass loss on the Santa Isabel ice cap has been strong over the last three decades with an average annual mass balance of about -2.5 m w.e. yr^{-1} since 1987 quantified using aerial photogrammetry and terrestrial LiDAR.

Considering the imbalance of the glaciers in Colombia with the current climate conditions, the relatively low altitude of the Colombian glaciers and the expected changes in air temperature for the twenty-first century, most of them will most likely disappear in the coming decades and only the largest ones located on the highest summits will persist until the second half of the twenty-first century.

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