

Toward an imminent extinction of Colombian glaciers?

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30 **ABSTRACT.**

31 This study documents the current state of glacier coverage in the Colombian Andes, the
32 glacier shrinkage over the 20th century and discusses indication of their disappearance in the
33 coming decades. Satellite images have been used to update the glacier inventory of Colombia
34 reflecting an overall glacier extent of about $42.4 \pm 0.71 \text{ km}^2$ in 2016 distributed in four
35 glacierized mountain ranges. Combining these data with older inventories, we show that the
36 current extent is 36% less than in the mid-1990s, 62% less than in the mid-20th Century, and
37 almost 90% less than the Little Ice Age maximum extent.

38 Focusing on Nevado Santa Isabel (Los Nevados National Park), aerial photographs from 1987
39 and 2005 combined with a terrestrial LiDAR survey show that the mass loss of the former ice
40 cap, which is nowadays parceled into several small glaciers, was about $-2.5 \text{ m w.e. yr}^{-1}$ during
41 the last three decades. Radar measurements performed on one of the remnant glaciers, La
42 Conejeras glacier, show that the ice thickness is limited (about 22 m in average in 2014) and
43 that with such a mass loss rate, the glacier should disappear in the coming years.

44 Considering their imbalance with the current climate conditions, their limited altitudinal
45 extent and reduced accumulation areas, and in view of temperature increase expected in future
46 climate scenarios, most of the Colombian glaciers will likely disappear in the coming decades.
47 Only the largest ones located on the highest summits will probably persist until the second
48 half of the 21st century although very reduced.

49

50 **KEY WORDS.** Glaciers, surface area changes, tropical Andes, Colombia

51

52 1. INTRODUCTION

53 Glaciers in Colombia are more than ice on mountains: they indeed are key components of the
54 landscapes lived by the Colombian society (Ceballos *et al.*, 2012). For peasants, indigenous,
55 mountain climbers, artists, scientists and city dwellers, glaciers in Colombia fulfill different
56 functions within their territories and are part of their daily practices in different ways: from
57 sentinels of global climate changes, local water resources, unique ecosystems, to local-to-
58 regional sources of mass flow hazards from glaciers on active volcanoes in the Cordillera
59 Central (Jordan *et al.*, 1989; Thouret, 1990; Linder, 1991, 1993; Linder *et al.*, 1994; Huggel *et*
60 *al.*, 2007). The large ice loss of Colombian glaciers since the late 1970s, (Ceballos *et al.*,
61 2006; Morris *et al.*, 2006; Poveda and Pineda, 2009), like in most part of the tropical Andes
62 (Rabatel *et al.*, 2013a), has strengthened the necessity of a glacier monitoring combining
63 repeated inventories at the national scale and *in-situ* measurements on benchmark glaciers
64 located in the two mostly glacierized mountain ranges of Colombia (e.g., Ceballos *et al.*,
65 2012; Mölg *et al.*, 2017). Such a monitoring strategy is in line with the international strategy
66 for glacier monitoring defined by the Global Terrestrial Network for Glaciers (GTN-G, [gtn-
g.org](http://gtn-
67 g.org)).

68 *In-situ* measurements were initiated after the eruption event of Nevado del Ruiz in 1985 and
69 are nowadays conducted by the *Instituto de Hidrología, Meteorología y Estudios Ambientales*
70 (IDEAM). These activities have been part of different international programs: started by the
71 *Instituto Geográfico Agustín Codazzi* (IGAC, Bogota) in 1988 supported by Deutsche
72 Forschungsgemeinschaft (DFG) and Volkswagen-Foundation, IDEAM has taken over the
73 task, presently cooperating with the joint international laboratory GREAT-ICE (Sicart *et al.*,
74 2015) financed by the French *Institut de Recherche pour le Développement* (IRD), the World
75 Glacier Monitoring Service (wgms.ch), and the CATCOS project (Capacity Building and

76 Twinning for Climate Observing Systems) financed by the Swiss Agency for Development
77 and Cooperation (SDC).

78 The aims of this paper are: 1) to present and analyze the current state of glaciers in Colombia,
79 with the results of a new glacier inventory from 2016; 2) to draw a multi-decadal perspective
80 of changes in glacier surface-area using repeated glacier inventories since the mid-20th
81 Century and Little Ice Age maximum extent; and 3) to estimate the future evolution of
82 glaciers in Colombia on the basis of the up-to-date inventory, current surface-area and mass
83 loss rates, as well as future possible changes (until 2100) in air temperature according to
84 climate scenarios.

85

86 **2. STUDY AREA**

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

95 **Table 1** lists the main characteristics of the glacierized areas of Colombia, with the glacier
96 cover in 2016, the maximum ice thickness estimate -where it exists- together with the year of
97 the estimate. One can note that the averaged maximum elevations of the glacierized summits
98 range in most parts between 5,100 and 5,400 m a.s.l. which is rather low in comparison with
99 the other glacierized areas in the tropical Andes of Ecuador, Peru and Bolivia where the
100 highest elevations frequently exceed 6,000 m a.s.l. ([Rabatel et al., 2013a](#)).

101 2.1. Climatic settings

102 From a climatological point of view, Colombia belongs to the inner tropics (Troll, 1941) with
103 continued humidity, homogeneous temperature (daily amplitude > annual amplitude) and
104 almost constant incident solar radiation throughout the year. At the seasonal scale, the
105 displacement of the inter-tropical convergence zone (ITCZ) strongly controls the annual
106 regime of precipitation which results to be contrasted from one region to the other at the
107 country scale (e.g., Poveda *et al.*, 2005). The central and western parts of Colombia
108 (glacierized areas C and D on Fig. 1) experience a bimodal precipitation regime with two
109 periods of high precipitation (April-May and October-November) and two periods of less
110 precipitation (December-February and June-August). On the other hand, the Caribbean coast
111 (glacierized area A on Fig. 1) and the Pacific coast of the isthmus with Panama show a
112 unimodal precipitation regime (May-October), resulting from the northernmost position of the
113 ITCZ. The easternmost glacierized mountain range (glacierized area B on Fig. 1) also
114 experiences a single precipitation peak occurring during June-August which results from deep
115 convection of the moisture transported from the Amazon basin due to the orographic barrier
116 of the Andes.

117 The IDEAM maintains automatic weather stations (AWS) in the glacierized areas B and C (at
118 elevations up to 4700 m a.s.l.). Mölg *et al.* (2017) presented the data from the AWS located
119 on the Nevado Santa Isabel (glacierized area C) which show that over the monitoring period
120 (2009-2016), the average 0 °C isotherm was located at 4980 m a.s.l., higher than the summit
121 located at 4940 m a.s.l. In Sierra Nevada de El Cocuy (glacierized area B) the average 0 °C
122 isotherm over the period 2007-2016 was located at 5045 m a.s.l. It is worth noting that these
123 average 0 °C isotherm estimates may slightly vary within the considered glacierized areas and
124 in the other glacierized areas of Colombia due to local site effects.

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

132 **2.2. Glacier surface processes**

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

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

148 In a review paper about the state of glaciers in the tropical Andes, [Rabatel et al. \(2013a\)](#)
149 concluded that the sensitivity of inner tropical glaciers to climate is closely linked to the

150 absence of temperature seasonality and to the fact that the 0 °C isotherm constantly oscillates
151 through the glaciers. As a consequence, a minor variation in air temperature can influence the
152 melt processes by determining the phase of precipitation and consequently affects the surface
153 albedo and mass balance.

154

155 **3. METHODS AND DATA**

156 **3.1. Quantification of glacier surface-area**

157 Former studies have documented the glacier surface-area changes since their maximum extent
158 during the Little Ice Age and until the early 2000s (*e.g.*, [Jordan *et al.*, 1989](#); [Florez, 1992](#);
159 [Pulgarin *et al.*, 1996](#); [Ceballos *et al.*, 2006](#); [Poveda and Pineda, 2009](#); [Herrera and Ruiz,](#)
160 [2009](#)). Note that the Little Ice Age maximum extent has not been so systematically dated in
161 the Colombian Andes as it was the case in the other countries of the tropical Andes (*e.g.*,
162 [Rabatel *et al.*, 2005, 2008](#); [Jomelli *et al.*, 2009](#)), even if the link between moraines and
163 reliably dated Ruiz eruptions on 1595/03/12 and 1845/02/18 locally provides good indicators
164 ([Jordan *et al.*, 1987](#); [Jordan and Mojica, 1987](#)). The former studies on the extent of Colombian
165 glaciers in the past are based on moraines (reflecting the Little Ice Age maximum extent),
166 aerial photographs from the late 1940s to the mid-1990s, and Landsat TM and ETM from the
167 mid-1990's to the early 2000s. In the current study, an update of the glacial coverage across
168 all Colombian glacierized mountain ranges has been realized using images from the following
169 satellites: QuickBird (2007, spatial resolution of 2.5 m in multispectral mode = visible + near-
170 IR), ALOS (2007, 2008, 2009, spatial resolution of 10 m in multispectral mode = visible +
171 near-IR), RapidEye (2010, spatial resolution of 5 m in multispectral mode = visible + near-IR)
172 and Landsat-8 OLI (2016, [Fig. 1](#)).

173 On the basis of Landsat-8 images from late January-early February 2016, a detailed inventory
174 was produced and a database was generated according to the design of the GLIMS glacier

175 relational database. For an extensive description of the database content, the reader will refer
176 to the GLIMS website (http://www.glims.org/MapsAndDocs/db_design.html). The 2016
177 Landsat-8 images provide the perfect conditions for a glacier inventory: no snow cover
178 outside the glaciers and no cloud cover on the mountains, a particular challenge in Colombia
179 due to often persistent cloudy weather conditions. These images have a spatial resolution of
180 30 m in multispectral mode and 15 m in the panchromatic mode (the spectral bands “green”,
181 “NIR-IR” and “MIR” available at 30 m have been pansharpened at 15 m). Due to the small
182 size of the glaciers and their limited number, the delineation of the glacier outlines has been
183 made manually. Manual delineation can have advantages over automatic detection of glacier
184 ice in shadowed areas ([Gardent et al., 2014](#)). Note that debris-covered glacier areas are
185 limited in Colombia, either because the glaciers are small ice caps, or remnants of ice caps, or
186 slope glaciers; and in every case, rock walls overhanging the glaciers are limited or absent.
187 However, ashes resulting from eruptions can cover some parts of the ice caps located on
188 active volcanoes. On the 2016 satellite images, it was the case on the north-western side of the
189 Nevado del Ruiz, but because the ash cover was not homogeneous and ice free areas can be
190 seen, it did not prevent an accurate delineation of the glacier margin. For older data sources,
191 aerial photographs from 1959, 1987 and 2005 used on Nevado del Ruiz allowed an accurate
192 delineation of glacier contour due to their high spatial resolution.

193 Regarding the uncertainties, they largely depend on the data sources (moraines, aerial photos,
194 satellite images). It is noteworthy that the estimated values for the Little Ice Age are probably
195 associated with the highest uncertainty compared with inventories performed using aerial
196 photos or satellite images. Indeed, for the Little Ice Age the surface area reconstruction is
197 based on the moraine ridges which are not always continuous over the glacier foreland.
198 However, the uncertainty is not given in all the related studies. Regarding the aerial photos

199 and the satellite images, to compute a margin of uncertainty on the delineation of the glacier
200 outline Rabatel *et al.* (2011) considered different sources related to:

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

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

217 **3.2. Quantification of glacier volume**

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

224 14 cross profiles and two longitudinal profiles have been acquired on this small glacier (0.19
225 km² in 2014, [Fig. 2](#)), which is a remnant of the Santa Isabel ice cap ([Fig. 3](#)). From the *in-situ*
226 IPR continuous acquisitions, 200 measurements have been selected ([Fig. 2](#)) representing
227 points with clear reflection signal with an average density of 1 pt / 100 m². Note that these
228 data have been integrated to the glacier thickness database (GLATHIDA 2.0, [WGMS, 2016](#)).
229 The main uncertainty in the ice thickness measurements comes from the analysis of the radar
230 signal and results from the manual picking on the radargram of the signal reflected by the
231 bedrock. The analysis of the radar data has been made using the software IceRadarAnalyzer
232 4.1 ([Mingo and Flowers, 2010](#)) and the uncertainty on each individual ice thickness
233 measurement was estimated at 2 m resulting in a uncertainty of the total glacier volume of
234 about 10%.

235 **3.3. Quantification of surface elevation changes**

236 Changes in glacier-surface elevation can be computed by the difference of digital elevation
237 models (DEMs) realized by topography (DGPS, LiDAR) or using aerial photographs or
238 satellite stereo-images from high spatial resolution data (e.g. SPOT 5-7, Pléiades, Ikonos,
239 Worldview). However, such accurate DEMs are not available for all the Colombian glaciers.
240 Nevado del Ruiz and Santa Isabel are two of the exceptions with photogrammetric restitutions
241 performed on the basis of 1959, 1987 and 2005 aerial photographs. All the technical details
242 about these restitutions, as well as more results and interpretation can be found in Linder
243 ([1991, 1993](#)) Braitmeier ([2003](#)) and González *et al.* ([2010](#)). [Figures 3A](#) and [3B](#) show the
244 ortho-photos from 1987 and 2005 respectively. The ortho-photo from 2005 shows the extent
245 of the Santa Isabel ice cap in 1987, 2005 and 2016 ([Fig. 3B](#))
246 During the January-February 2014 field campaign for glacier thickness measurements on La
247 Conejeras glacier (a remnant of Santa Isabel ice cap, [Fig. 3B](#)), a complete topography of the
248 glacier surface was generated using a terrestrial LiDAR (an ultra-long-range RIEGL VZ-6000

249 device, Fig. 4A). This system emits a near-infrared laser beam at 1064 nm ideal for
250 glaciological studies (e.g., Gabbud *et al.*, 2015; Fischer *et al.*, 2016). Ten reflector targets
251 with 5 cm diameter were fixed on stakes or rocks around the glacier for georeferencing
252 purposes. Their position has been measured using differential GPS. Three distinct scan
253 positions were set to achieve good coverage of the whole glacier and its surroundings. The
254 LiDAR data were processed using the software RiSCAN PRO. The main processing steps
255 included a filtering of points (e.g., due to atmospheric reflections caused by dust or moisture),
256 a merge of the point clouds from the different scan positions, and the georeferencing of the
257 final grid using the target reference points. Figure 4B provides an illustration of the final point
258 cloud. The resulting DEM has a homogeneous resolution of 0.5 m and was reprojected to
259 MAGNA Colombia Bogotá (EPSG 3116), the current official georeference system of
260 Colombia.

261 The changes in glacier surface elevation have been quantified by subtracting the different
262 DEMs. This was possible at the scale of the entire Santa Isabel ice cap as published in Linder
263 (1991) for the period from 1959 to 1987; now with more detail for the period 1987-2005, and
264 additionally for La Conejeras glacier only for the periods 1987-2005 and 2005-2014 using the
265 2014 LiDAR data.

266 From these surface elevation changes, the geodetic average annual mass balance has been
267 quantified considering the average surface area between the two considered dates, the time
268 between the two DEMs and an average ice density of 900 kg m^{-3} . For more details about the
269 geodetic method the reader may refer to the literature (e.g. Rabatel *et al.*, 2006; Cogley, 2009;
270 Basantes Serrano *et al.*, 2016).

271 **3.4. *In situ* glacier surface mass balance data**

272 Two glaciers in Colombia are monitored with *in-situ* measurements to quantify their surface
273 mass balance: La Conejeras glacier on the Nevado Santa Isabel and Ritacuba glacier in the

274 Sierra Nevada de El Cocuy (Ceballos *et al.*, 2012). Accumulation and ablation measurements
275 are performed at monthly scale with the classical glaciological method (snow pits and ablation
276 stakes) since 2006 for La Conejeras and 2008 for Ritacuba glacier. Recently, the entire
277 monthly surface mass balance data series of La Conejeras glacier has been reanalyzed by
278 Mölg *et al.* (2017) where more details on the monitoring network and the results of this 10-yr
279 monitoring program are provided.

280

281

282 **4. RESULTS AND DISCUSSION**

283 **4.1. 2016 Colombian glaciers inventory**

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

288 Glaciers of the Colombian Andes covered 42.42 ± 0.71 km² in early 2016 with 7.2 ± 0.27 km² in
289 the Sierra Nevada de Santa Marta, 15.5 ± 0.33 km² in the Sierra Nevada de El Cocuy,
290 11.8 ± 0.52 km² in Los Nevados National Park and 8.0 ± 0.23 km² for the Nevado del Huila. At
291 the scale of the Colombian Andes the mean glacier size was 0.43 km² (median = 0.22 km²,
292 indicating that the distribution is clearly dissymmetric toward small-sized glaciers); glaciers <
293 0.5 km² represented 70% of all glaciers and 28% of the total glacierized area. Glaciers > 1
294 km² accounted for 66%, 37%, 16% and 14% of the glacierized area in Sierra Nevada de El
295 Cocuy, Los Nevados National Park, Sierra Nevada de Santa Marta and Nevado del Huila,
296 respectively.

297 Glacier minimum, maximum, and mean altitudes have been computed from the ASTER
298 GDEM V2. This global DEM was generated from ASTER images dating from the period

299 2000-2010. The exact dating for each region is unknown but it can be considered that the
300 elevation provided by this DEM is representative of the 2000s. The mean altitude has been
301 computed from the area-altitude distribution. Indeed, such mean altitude can be considered as
302 a proxy of the balanced-budget equilibrium-line altitude corresponding to the glacier extent
303 (Jordan, 1991; Machguth *et al.*, 2012; Rabatel *et al.*, 2013b; Braithwaite, 2015). Considering
304 the different glacierized regions, the average of the mean altitude of each individual glacier
305 are 5170 m a.s.l., 4910 m a.s.l., 5140 m a.s.l. and 5020 m a.s.l. for Sierra Nevada de Santa
306 Marta, Sierra Nevada de El Cocuy, Los Nevados National Park, and Nevado del Huila,
307 respectively.

308 The maximum altitude of the glacier is an interesting variable, because when compared to the
309 equilibrium-line altitude it allows computing the altitudinal extent of the accumulation zone,
310 and together with the glacier-area distribution the accumulation-area ratio. The highest
311 altitudes of glaciers' top can be found in the Sierra Nevada de Santa Marta where they reach
312 5678 m a.s.l. On the Nevado del Huila, the altitude of glaciers' top ranges between 5160 and
313 5390 m a.s.l. In the two other glacierized areas, the uppermost elevations are lower, ranging
314 between 4785 and 5346 m a.s.l. for the Sierra Nevada de El Cocuy and between 4925 and
315 5314 m a.s.l. in Los Nevados National Park. Assuming that the current elevation of the 0 °C
316 isotherm at ~5000 m a.s.l. in glacierized areas B and C (see 2.1) can be representative of the
317 two other glacierized areas, about 20% of the glaciers in Colombia have their uppermost
318 elevation located below.

319 In terms of altitudinal extent (difference between the minimum and maximum elevations of
320 the glacier), the Colombian glaciers span over limited altitudinal ranges: in average (max.)
321 550 m (770 m) on the Nevado del Huila, 340 m (870 m) in the Sierra Nevada de Santa Marta,
322 300 m (600 m) in the Sierra Nevada de El Cocuy and 280 m (700 m) in Los Nevados National
323 Park.

324 4.2. Historical glacier surface area changes

325 **Table 3** presents the surface area changes in the different glacierized areas of the Colombian
326 Andes. Note that Los Nevados National Park encompasses the three volcanoes Ruiz, Santa
327 Isabel and Tolima (**Fig. 1C**). These changes are also illustrated in **Figures 5A** and **5B**
328 including the rates of mean annual surface area loss in percentage per year for each
329 glacierized area since the mid-20th century.

330 The overall glacierized surface area in the Colombian Andes decreased by ~90% since the
331 Little Ice Age maximum extent (undated). Note that in addition to the 349 km² in the six
332 glacierized areas, eight other areas in Colombia presented glaciers during the Little Ice Age
333 (with an estimated surface area of 23.7 km²) and are currently without glaciers (**Florez, 1992**;
334 **Baumann, 2006**).

335 Considering the glacierized surface area in the mid-20th Century (about 110 km²), the 2016
336 extent is about 62% smaller. In the last two decades (*i.e.* since 1995) the glacierized surface
337 area has decreased by about 36%.

338 However, **Figure 5** illustrates that the trend has not been homogeneous since the mid-20th
339 century, both temporally and spatially. Indeed, the mean annual surface area loss rate (black
340 curve in **Fig. 5B**) has remained close to -1% per year from the 1940s till the mid-1970s, with a
341 slightly reduced loss rate between the mid-1960s and the mid-1970s. Since the mid-1970s, the
342 mean annual surface area loss rate has increased continuously, reaching -3% per year during
343 the current decade in average for all the Colombian glacierized areas. On the other hand, this
344 retreating trend is spatially highly contrasted, with the most important loss rate found for
345 Santa Isabel and Tolima volcanoes, which is in agreement with their lowest elevations and the
346 very small glaciers. Glaciers of the Sierra Nevada de Santa Marta show a slightly lower
347 surface area loss rate over the last decades. This has to be related with the higher elevation of
348 this mountain range: glaciers' top ranges between 4970 and 5678, and only five of the 28

349 glaciers have a median elevation located below 5000 m a.s.l. (approx. the elevation 0 °C
350 isotherm in the other glacierized areas of Colombia).

351 It is noteworthy that for some ice masses located on active volcanoes like on the Nevado del
352 Ruiz, Nevado del Tolima and Nevado del Huila, the glacier shrinkage is not only influenced
353 by changes in climate conditions but is also due to eruptions increasing the geothermal flux
354 and depositing ashes at the glacier surface. This leads to an increase in snow and ice melt.
355 Such an event occurred in 1985 on the Nevado del Ruiz leading to an important ablation and
356 surface-area shrinkage from the mid-1980s to the late 1990s (Thouret, 1990; Linder 1991,
357 1993; Linder and Jordan, 1991; Linder *et al.*, 1994; Borrera *et al.*, 1996). This important
358 shrinkage (~1.5 times the country scale average) during more than a decade, mainly related to
359 the eruption (*i.e.* not exclusively climate related) is probably at the origin of the observed
360 lower shrinkage rate observed for the Nevado del Ruiz during the last decade.

361 **4.3. Glacier volume estimation from field data at La Conejeras glacier**

362 The 2014 ice thickness data from the 14 cross profiles and two longitudinal ones acquired on
363 La Conejeras glacier (Fig. 2) have been interpolated using the software PCI-Geomatica
364 (MQSINT: multiquadratic spline interpolation). Figure 6 presents the resulting raster with a
365 spatial resolution of 15 m (pixel size). The maximum ice thickness located in the central part
366 of the glacier was slightly above 50 m in 2014. The total ice volume was estimated to $4.325 \times$
367 10^6 m^3 , which corresponds to $3.893 \times 10^6 \text{ m}^3$ of water equivalent (using an ice density of 0.9).
368 Considering a surface area of 0.199 km², the average ice thickness of La Conejeras glacier
369 was about 22 m in 2014.

370 **4.4. Decadal mass balances**

371 *In-situ* mass balance measurements over the last decade on La Conejeras and Ritacuba
372 glaciers in Los Nevados National Park – Nevado Santa Isabel and in the Sierra Nevada de El
373 Cocuy, respectively, have shown a clear unbalanced situation (Ceballos *et al.*, 2012). Indeed,

374 the balance-budget equilibrium line altitude (ELA_0 , cf. Cogley *et al.*, 2011) derived from
375 the surface mass balance measurements for La Conejeras glacier is about 4920 m a.s.l., thus
376 160 m above its mean altitude computed from the area-altitude distribution (*i.e.* 4760 m a.s.l.),
377 and 120 m above the mean altitude of the glaciers located on the Nevado Santa Isabel. This is
378 the same for the Sierra Nevada de El Cocuy where the mean altitude of the glaciers is 4910 m
379 a.s.l., 120 m below the ELA_0 derived from *in situ* measurements on Ritacuba glacier.

380 Reanalyzing the 10-yr monthly mass balance time series of La Conejeras glacier, Mölg *et al.*
381 (2017) have shown that the mean annual mass balance has been close to -3 m w.e. yr^{-1} over
382 the period 2006-2015 (cf. Fig. 7 where annual mass balance are plotted). Mölg *et al.* (2017)
383 also showed that the annual ELA was on average close to the glacier maximum altitude
384 during the monitoring period, with an accumulation-area ratio of about 4%, *i.e.* almost no
385 accumulation zone.

386 On the other hand, the comparison between the 2014 Lidar DEM and the photogrammetric
387 DEM from 1987 (see section 3.3) showed that the glacier-surface elevation has lowered by 80
388 m at 4700 m a.s.l. (altitude of the glacier surface close to the front of the glacier in 2014)
389 between the two dates; 50 m between 1987 and 2005 (Fig. 6). The geodetic mass balance was
390 -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
391 (Fig. 7). Note that the *in situ* surface mass balance averaged over the closest period (*i.e.* 2007-
392 2014) was -2.45 m w.e. yr^{-1} . This very good agreement between the two independent methods
393 shows that the well distributed network of *in situ* measurements at the surface of La Conejeras
394 glacier allows an accurate quantification of the mass balance using the glaciological method.

395 Computed at the scale of the entire Santa Isabel ice cap, the geodetic mass balance between
396 1987 and 2005 was -2.69 m w.e. yr^{-1} , *i.e.* slightly more negative than considering La
397 Conejeras glacier only.

398

399 **4.5. Future changes of Colombian glaciers**

400 The strong shrinkage of the Colombian glaciers since the mid-20th century and in particular
401 the constant increase in the rate of shrinkage at the country scale over the past four decades is
402 an indication of the strong imbalance of glaciers with current climate. [Figure 7](#) shows the
403 volume loss of La Conejeras glacier computed on the basis of the ice thicknesses measured in
404 2014, the annual changes in surface-area and the surface mass balances *in situ* measured since
405 2006. A linear extrapolation of the glacier volume changes of the last decade for the future
406 would result in the disappearance of La Conejeras glacier in the first years of the 2020s, likely
407 in concert with the other remaining glaciers of Nevado Santa Isabel.

408 The mass balances measured on La Conejeras and Ritacuba glaciers cannot be directly
409 extrapolated to the scale of all other glaciers in Colombia, as neighboring glaciers under
410 similar climate conditions can show different mass balances in relation with the dynamic
411 response of glaciers to a change in climate forcing (*e.g.*, [Rabatel et al., 2016](#)). Estimates of
412 future changes and disappearance of Colombian glaciers based on decadal trends in glacier
413 surface-area loss therefore imply some uncertainty. Nevertheless, as a first approximation a
414 linear trend extrapolation from the observed glacier surface-area shrinkage rates in the
415 different glacierized areas of Colombia during the last decades ([Fig. 5A](#)) allows a rough
416 estimation of their future changes and disappearance. Accordingly, glaciers on the Nevado de
417 Tolima will likely disappear before 2030, and most of the glaciers in the Sierra Nevada de
418 Santa Marta and Sierra Nevada de El Cocuy before 2050. Only the few largest glaciers with
419 the highest maximum elevations on Nevado del Huila, Nevado del Ruiz and in the Sierra
420 Nevada de Santa Marta and Sierra Nevada de El Cocuy will probably persist after the mid-21st
421 century although strongly reduced. Our results suggest that glacier extinction in Colombia
422 happens much faster than the corresponding estimates in the 4th Assessment Report of the
423 Intergovernmental Panel on Climate Change (IPCC) ([Magrin et al., 2007](#): “within the next

424 100 years”), but not as dramatic as suggested by [Poveda and Pineda \(2009\)](#): “by the late 2010-
425 20 decade”). The latter estimates are based on Landsat TM and ETM+ images from 1989-
426 2007 and result in slightly smaller total areas for 2004-07, and correspondingly higher loss
427 rates, than the present study.

428 Taking into account the influence of temperature changes on glacier surface processes (see
429 2.2.), an alternative to the extrapolation of surface-area changes can be made from the
430 relationship between the 0 °C isotherm and the maximum elevation and/or the ELA of the
431 glaciers, and considering the future projections of temperature using different climate
432 scenarios. [Figure 8](#) shows the Hadcrut4 observations ([Morice et al., 2012](#)) as well as historical
433 and future CMIP5 experiments following the two extreme radiative concentration scenarios
434 (RCPs) RCP 2.6 and 8.5 ([Taylor et al., 2012](#)) for the near-surface air temperature. Data from
435 different global climate models (see [Fig. 8](#) caption) are averaged over the region defined as
436 the box 2°-10°N, 72°-77°W to encompass the different glacierized areas in Colombia. Over
437 the reference period extended from 1961-1990, both model and observations show a
438 temperature increase within the range of 0.5 °C, an increase smaller than the inter-annual
439 variability over this period. The scenarios RCP 2.6 and RCP 8.5 show an increase in air
440 temperature reaching respectively 1.6 °C [0.5 to 2.7 °C] and 6.3 °C [5.4 to 7.2 °C] by the end
441 of the 21st century considering a 10-year average of the multi-model ensemble experiments.

442 Assuming that the current vertical gradient of air temperature remains unchanged, such an
443 increase in temperature would raise the 0 °C isotherm by 320 m (ranging from 100 to 540 m)
444 for RCP 2.6 and by 1260 m (ranging from 1080 to 1440 m) for RCP 8.5; *i.e.* reaching the
445 elevation of 5320 and 6260 m a.s.l., respectively. Note that these estimates are in close
446 agreement with the results found by [Schauwecker et al. \(2017\)](#) for the Peruvian Andes. In
447 such conditions, 75% (100%) of the Colombian glaciers would be entirely located below the 0
448 °C isotherm by the end of the 21st century considering RCP 2.6 (8.5).

449 In addition, although the time-series are short (~10 years) the meteorological and
450 glaciological data from La Conejeras glacier (Mölg *et al.*, 2017) allow quantifying the
451 sensitivity of the ELA to air temperature and elevation of the 0 °C isotherm. The significant
452 correlation between the ELA and the 0 °C isotherm ($r = 0.9$, $p < 0.002$) shows that a 100-m
453 increase in the 0 °C isotherm leads to an increase in the ELA by 160 m. As a consequence, the
454 above mentioned increases in the 0 °C isotherm by the end of the 21st century would place the
455 ELA 500 and 2000 m above its current location for the RCP 2.6 and 8.5. Assuming that these
456 estimates made from the data available on La Conejeras glacier can be transposed to the other
457 glacierized areas in Colombia, the projected ELA would be above the maximum elevation of
458 80% (100%) of the Colombian glaciers. In such conditions, glaciers in Colombia would
459 constantly be in ablation over most or the totality of their surface-area (very limited or no
460 accumulation zone would persist) and their shrinkage/disappearance looks ineluctable.

461 It is worth noting that considering the RCP 2.6, the increase in air temperature during the
462 coming decades would mainly occur before 2040-2050, meaning that the remaining
463 glacierized surface areas in Colombia would stabilize during the second half of the 21st
464 century.

465 Finally, it must be reminded that even with the use of "anomaly" approaches applied to
466 remove the biases of climate models, large uncertainties remain when using CMIP5 scenarios,
467 in particular because of the potential non-stationarity of the model bias. Global climate
468 models show also weaknesses to simulate regional atmospheric circulation changes
469 (Shepherd, 2014) and their coarse resolution does not allow to simulate correctly the
470 feedbacks strengthening the warming with the altitude (MRIEDW, 2015) and the local impact
471 of particle deposition on glacierized areas (Hansen and Nazarenko, 2004). Even with
472 significant improvements in terms of ENSO modeling from CMIP3 to CMIP5 (Bellenger *et*
473 *al.*, 2014), it is very challenging to anticipate the potential ENSO changes over the next

474 decades, and these ones may have strong impacts on the Colombian climate. Nevertheless, the
475 use of CMIP5 model projections is currently one of the unique ways to anticipate the future
476 changes in temperature and precipitation. Retrospective validations show that CMIP models
477 reproduce the main features of the current climate in Southern America (e.g., [Vera et al.,](#)
478 [2006](#); [Sillmann et al., 2013](#)) and can be used to estimate the future trends of temperature over
479 this continent, whereas the uncertainties in terms of precipitation are very high ([Blazquez et](#)
480 [al., 2013](#)). By setting up calibration approaches, [Marzeion et al. \(2014\)](#) and [Réveillet et al.](#)
481 [\(2015\)](#) demonstrated the possibility to use CMIP outputs to simulate glaciers future evolution.
482 We describe here a potential evolution for the Colombian glaciers that follows two scenario
483 based on different societal evolutions. A limitation of our study relies on the regional or local
484 forcing and feedbacks described previously that could modulate these future evolutions.

485 **4.6. Potential impacts of future glacier changes**

486 In other regions of the tropical Andes glaciers represent an important source of water for
487 domestic, agricultural or industrial use, for example in La Paz - Bolivia where the water
488 coming from the glaciers represents up to 30% of the runoff during the dry season ([Soruco et](#)
489 [al., 2015](#)), and recent studies have shown the negative impacts of current glacier shrinkage on
490 the biodiversity of the proglacial areas (e.g., [Dangles et al., 2017](#); [Zimmer et al., 2017](#)). In
491 Colombia, the potential impact of glacier shrinkage mainly relates to the páramo ecosystems
492 ([Brown et al., 2007](#)), as well as for local agriculture and tourism. However, the glacierized
493 volcanoes in Colombia remain – at least for the next few decades – a natural hazards, as
494 dramatically shown with the example of the post-eruption lahars of the Nevado del Ruiz in
495 1985 (e.g., [Jordan et al., 1987](#); [Thouret, 1990](#)). Because the Nevado del Ruiz presents the
496 largest single ice coverage in Colombia (10.11 km² in 2016) with an estimated ice volume of
497 $484 \times 10^6 \text{ m}^3$ back in 2003 (measured maximum and mean thickness of 190 and 47 m in 1999,
498 [Huggel et al., 2007](#)), the risk of lahars generated from the interaction of volcanic activity and

499 snow and ice will still persist for several decades. As a consequence, to better estimate the
500 potential water release resulting from an eruption of the Nevado del Ruiz and to prepare
501 potential impact scenarios, an accurate mapping to the ice thickness and distribution, as we
502 presented here for La Conejeras glacier, is urgently recommended. A similar mass of ice (8.0
503 km² in 2016 and 648 x10⁶ m³ of ice estimated for 2001) persists on Nevado del Huila which
504 produced several far-reaching (up to 150 km) lahars in 2007 and 2008 when Nevado del Huila
505 erupted and large amount of water were produced (Worni *et al.*, 2012).

506

507 **5. CONCLUSION**

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

513 The main results showed that:

514 - The glacier surface area is nowadays very reduced in Colombia, with a total ice covered
515 area in 2016 of 42.4 km². The mean glacier size was 0.43 km², and small size glaciers
516 largely predominate (70 % < 0.5 km²).

517 - The glacier shrinkage is strong since the mid-1970s and, remarkably, almost constantly
518 increasing reaching a mean annual area loss rate of -3 % yr⁻¹ during the last years, which
519 points to a continued climatic forcing, possibly in addition to local topographic and
520 geometric effects.

521 - Mass loss on the Santa Isabel ice cap has been strong over the last three decades with an
522 average annual mass balance of about -2.5 m w.e. yr⁻¹ since 1987 quantified using aerial
523 photogrammetry and terrestrial LiDAR.

524 Considering the imbalance of the glaciers in Colombia with the current climate conditions, the
525 relative low altitude of the Colombian glaciers, and the expected changes in air temperature
526 for the 21st century, most of them will most likely disappear in the coming decades and only
527 the largest ones located on the highest summits will persist until the second half of the 21st
528 century.

529

530 **AUTHOR CONTRIBUTION STATEMENT**

531 A. Rabatel conducted the GPR monitoring on La Conejeras glacier, realized the 2016 glacier
532 inventory, analyzed the data, wrote the manuscript and produced the figures and tables. N.
533 Micheletti conducted the LiDAR measurements on La Conejeras glacier and produced the
534 DEM. J.L. Ceballos (with colleagues from IDEAM) performed ten years of mass balance *in-*
535 *situ* measurements on La Conejeras glacier and analyzed the data with N. Mölg. J.L. Ceballos
536 and C. Huggel made the glacier mapping from the satellite images from 2007 to 2010. E.
537 Jordan, M. Braitmeier and J. González realized the photogrammetric DEMs of Nevado Santa
538 Isabel for 1987 and 2005 and completed the sources in Table 3. M. Ménégoz analyzed the
539 CMIP5 temperature data. M. Zemp led the Andean part of the CATCOS project and together
540 with J.L. Ceballos managed the 2014 field campaign. All the co-authors revised the
541 manuscript.

542

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561

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766

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	//

767

768 **Table 1:** Colombian glacierized areas with the most up-to-date glacier cover surface-area and
769 topographic features of the glaciers. Note that the elevation data are computed from ASTER
770 GDEM V2 and may differ from other sources due to differences in the accuracy of used data.
771 Maximum thickness estimates are taken from Huggel et al. (2007) and Ceballos et al. (2012),
772 but the original data have been provided by J. Ramirez (Servicio Geologico de Colombia).
773 S.N. = sierra nevada, V.N. = volcán nevado.

774

Size class (km²)		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

775

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

778

	Santa Marta (km ²)	El Cocuy (km ²)	Ruiz (km ²)	Santa Isabel (km ²)	Tolima (km ²)	Huila (km ²)	Total (km ²)
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/*}						
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/+}		110.6
1961						18.86 ^{d/+} 19.77 ^{a/+} 16.30 ^{c/*} 19.06 ^d 18.21 ^d	
1965							
1970							
1973	14.1 ^{e/oo}	28.0 ^{e/oo}					
1974	16.26 ^{a/+}						
1975			19.60 ^{c/*}				
1976			21.3 ^{e/oo}	10.8 ^{e/oo}	3.8 ^{e/oo}	26.0 ^{e/oo}	
1978		39.12 ^{a/+} 38.80 ^{c/*}					
1981	16.10 ^{c/*}					15.40 ^{c/*}	
1985		35.70 ^{c/*}	18.70 ^{c/*}				
1986		31.45 ^g	17.00 ^{c/*}				87.95
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					
1995	11.10 ^g					13.39 ^{d/+}	66.43
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		
2003		19.8 ^g					
2005				2.78 ^{h/+}			53.33
2007	7.70 ^{i/+}	18.60 ^{i/+}		2.60 ^{i/+}	0.93 ^{i/+}	10.80 ^{i/+}	
2008		17.70 ^{i/}					
2009	7.40 ^{i/}	17.40 ^{i/}					
2010		16.00 ^{i/}		1.80 ^{i/}	0.74 ^{i/}	9.70 ^{i/}	
2016	7.20±0.27 ^{i/}	15.46±0.33 ^{i/}	10.11±0.26 ^{i/}	1.0±0.08 ^{i/}	0.65±0.06 ^{i/}	8.00±0.23 ^{i/}	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 %

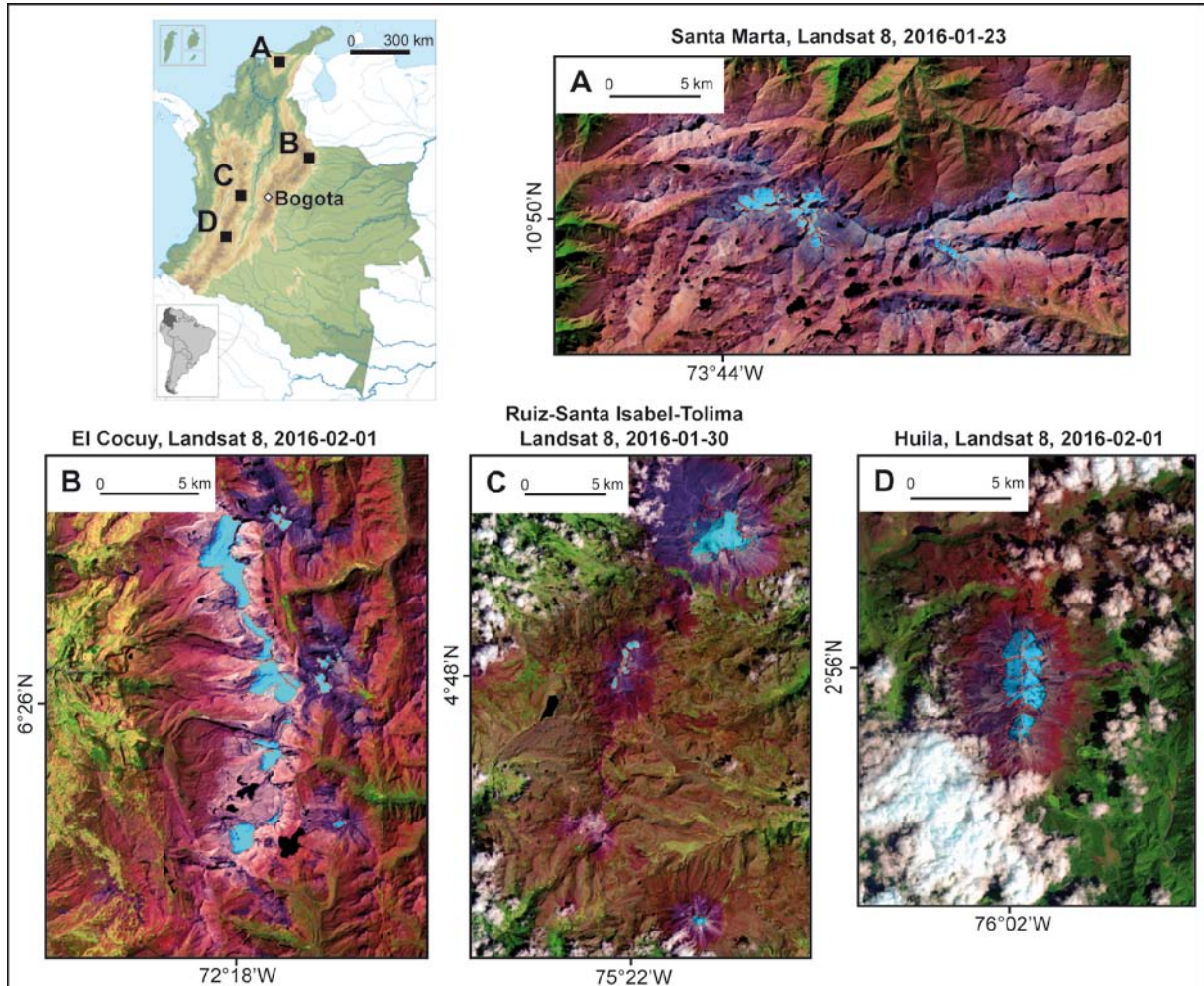
779

780 **Table 3:** Surface area changes since the Little Ice Age maximum. For each glacierized area
781 the surface area (km²) for each date is presented as well as the loss for different periods (in %
782 of the initial surface area for the considered period). Data before 2007 were taken from
783 previous studie, the letter indicates the original study: ^a = Jordan *et al.*, 1989; ^b = Linder 1991,
784 1993; ^c = Florez, 1992; ^d = Pulgarin *et al.*, 1996; ^e = Hoyos-Patino, 1998; ^f = Braitmeier, 2003;
785 ^g = Ceballos *et al.*, 2006; ^h = Gonzalez *et al.*, 2010. Symbols indicate the method: * =

786 planimetry on aerial photos; ⁺ = photogrammetric restitution with uncertainty estimate; [°] =
787 planimetry on satellite ortho-images (pixel size between 0.5 and 15 m); ^{°°} = planimetry on
788 Landsat MSS (pixel size of 79 m). Regarding the total glacier cover computed for the gray
789 shaded lines, when several surface-areas are available for a glacierized area, the average is
790 considered. The uncertainty for the 2016 inventory have been computed from the quadratic
791 sum of the uncertainties of each glacier of the considered area.

792

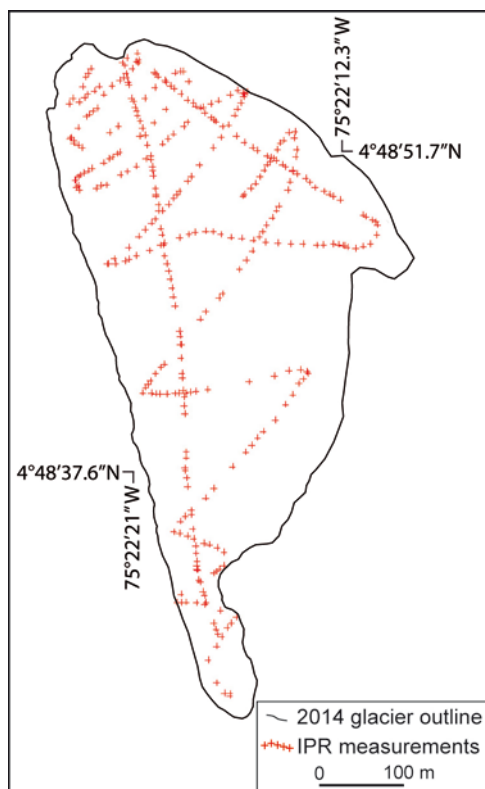
793 **Figure 1:** Glacierized areas in Colombia. The spectral bands combination used for the
794 Landsat-8 images provided by USGS-EDC involves the bands #6 (middle infra-red: MIR), #5
795 (short-wave infra-red: SWIR) and #3 (green).



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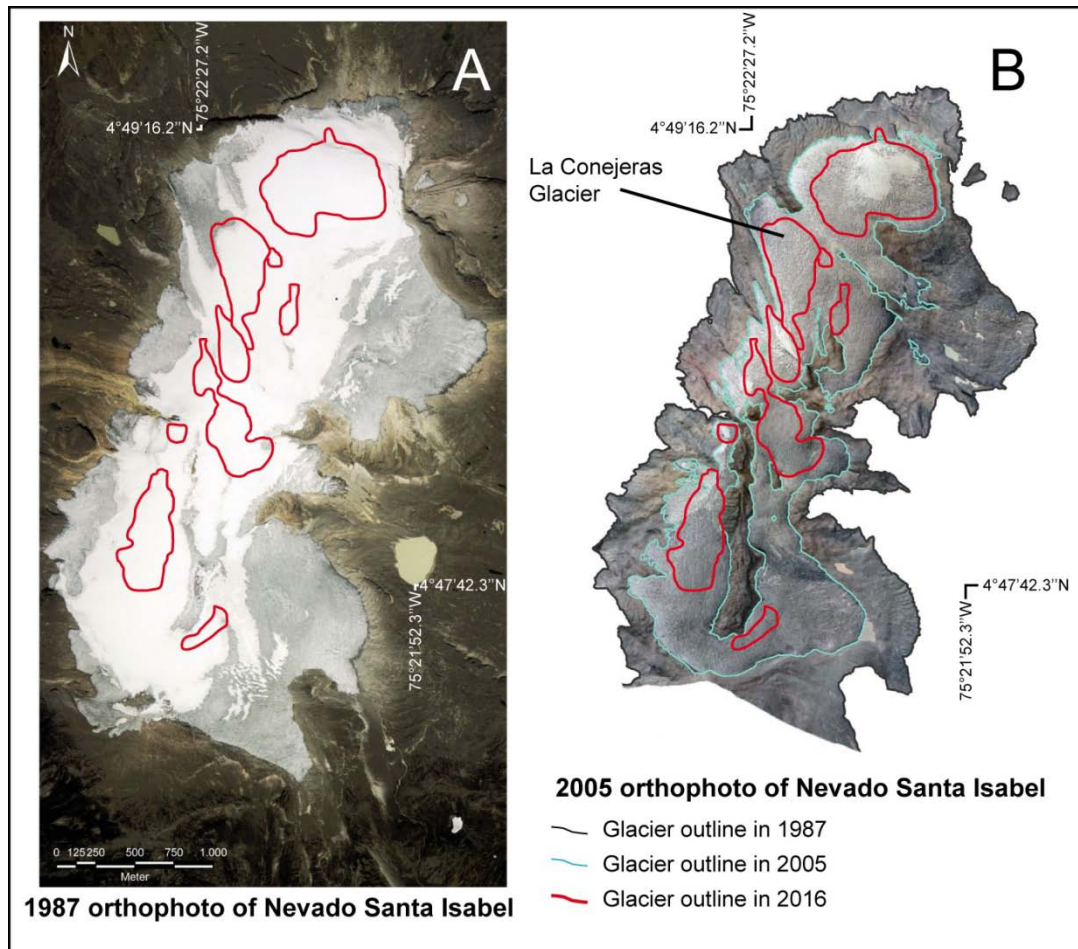
798 **Figure 2:** IPR measurements acquired in Jan-Feb 2014 on La Conejeras glacier.



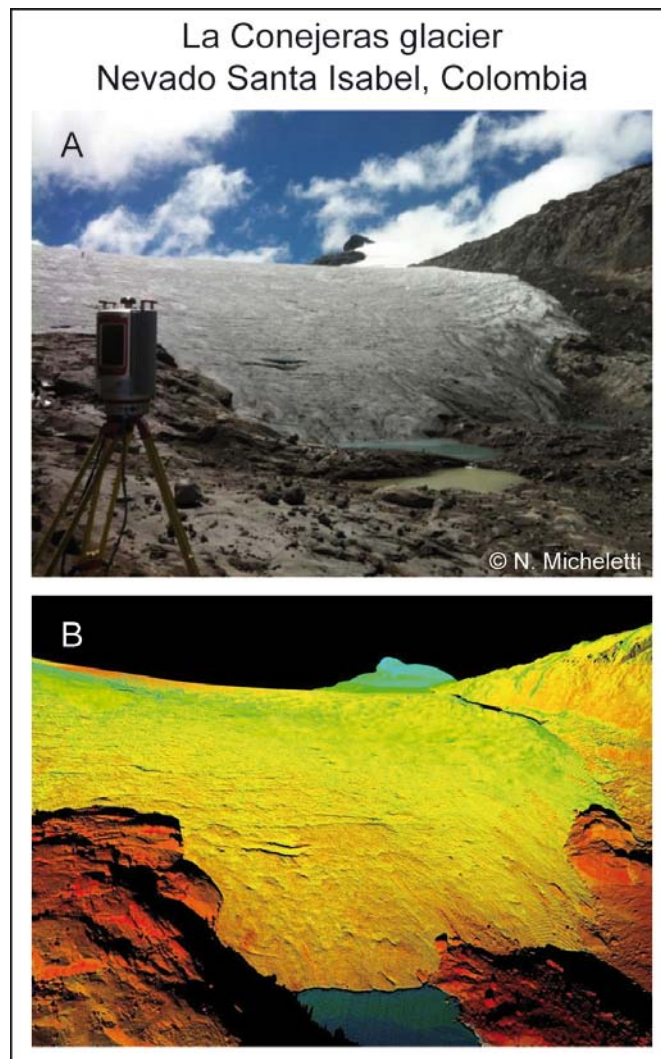
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800

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



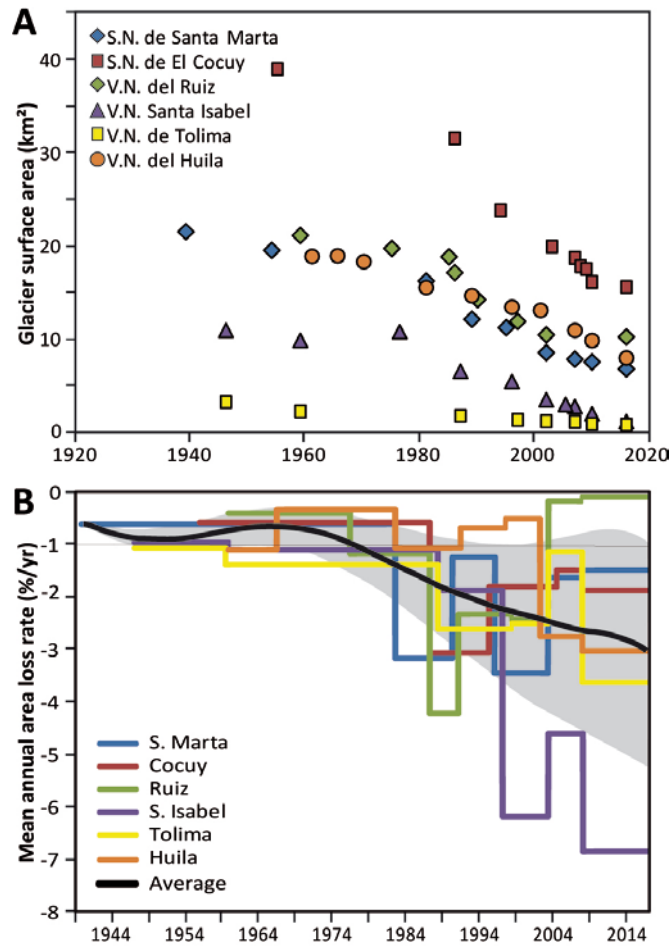
808 **Figure 4:** A) RIEGL VZ-6000 operating at the front of La Conejeras glacier. B) Scanned
809 point cloud of La Conejeras glacier.



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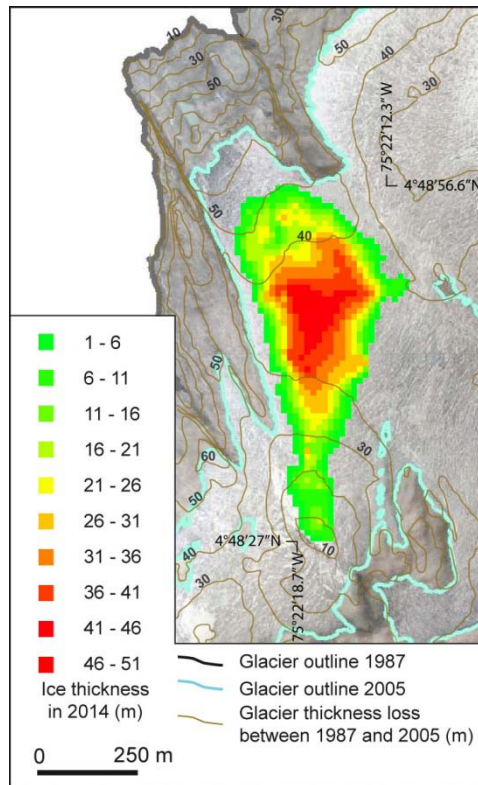
812 **Figure 5:** A) Glacier surface area changes in the different glacierized areas of Colombia since
813 the 1940s. B) Rates of mean annual area loss in percentage per year for each glacierized area.
814 The black curve and grey area represent the average with 1 st-dev. interval. The average has
815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



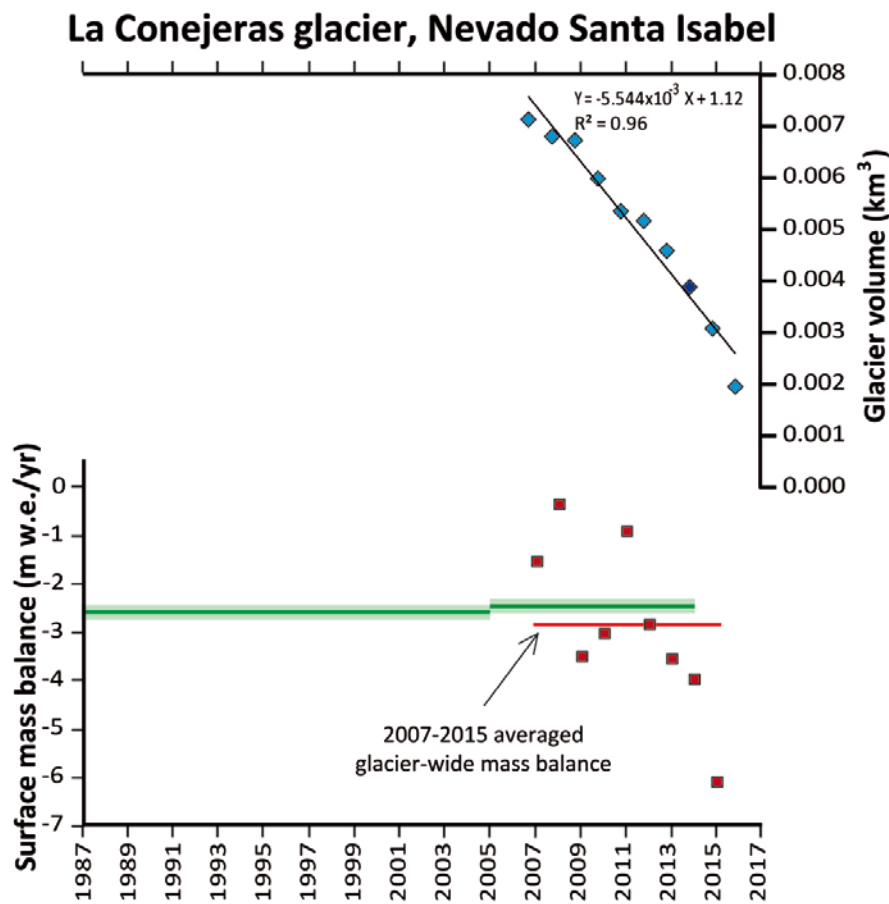
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818 **Figure 6:** Map of ice thickness in 2014 at La Conejeras glacier. The image in the background
819 is the ortho-photo from 2005 with the outlines for 1987 and 2005 (see Fig. 3 for the glacier
820 extents of the entire ice cap). The brown contour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



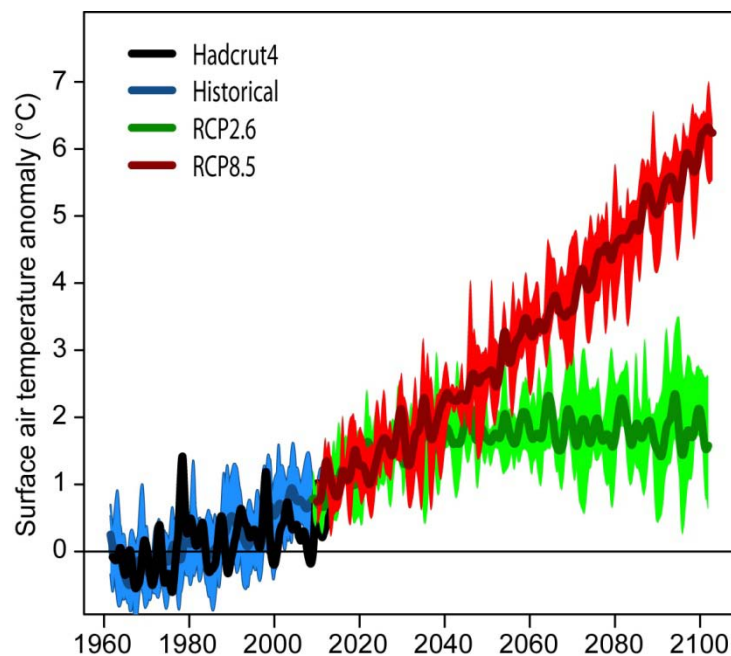
824 **Figure 7:** Surface mass balance and volume changes of La Conejeras glacier. Red squares
 825 show the annual surface mass balance with the average for the period 2006-2015 (red line)
 826 from Mölg *et al.* (2017). The green lines illustrate the average glacier-wide annual mass
 827 balance computed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



830

831

832 **Figure 8:** Near-surface air temperature anomalies computed with respect to the average 1961-
833 1991: Hadcrut4 observations (black, [Morice et al., 2012](#); historical CMIP5 simulations (blue);
834 CMIP5 scenarios based on low GHG emissions (RCP2.6, green) and high GHG emissions
835 (RCP8.5, red). A 12-month running mean has been applied to the anomalies computed as an
836 average over 2°-10°N, 72°-77°W to encompass all the glacierized areas in Colombia. Shading
837 indicate the maximum-minimum range across three CMIP5 models (GFDL-CM3 (4
838 members); IPSL-CM5A-LR (5 members); MPI-ESM-LR (3 members). See Taylor *et al.*
839 ([2012](#)) for the description of the CMIP5 experiments.



840