

Glacier inventory and recent glacier variations in the Andes of Chile, South America

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ABSTRACT. The first satellite-derived inventory of glaciers and rock glaciers in Chile, created from Landsat TM/ETM+ images spanning between 2000 and 2003 using a semi-automated procedure, is presented in a single standardized format. Large glacierized areas in the Altiplano, Palena Province and the periphery of the Patagonian icefields are inventoried.

The Chilean glacierized area is $23\,708 \pm 1185 \text{ km}^2$, including $\sim 3200 \text{ km}^2$ of both debris-covered glaciers and rock glaciers. Glacier distribution varies as a result of climatic gradients with latitude and elevation, with 0.8% occurring in the Desert Andes ($17^{\circ}30' - 32^{\circ} \text{ S}$); 3.6% in the Central Andes ($32 - 36^{\circ} \text{ S}$), 6.2% in the Lakes District and Palena Province ($36 - 46^{\circ} \text{ S}$), and 89.3% in Patagonia and Tierra del Fuego ($46 - 56^{\circ} \text{ S}$). Glacier outlines, across all glacierized regions and size classes, updated to 2015 using Landsat 8 images for 98 complexes indicate a decline in areal extent affecting mostly clean-ice glaciers ($-92.3 \pm 4.6 \text{ km}^2$), whereas debris-covered glaciers and rock glaciers in the Desert and Central Andes appear nearly unchanged in their extent. Glacier attributes estimated from this new inventory provide valuable insights into spatial patterns of glacier shrinkage for assessing future glacier changes in response to climate change.

Keywords: glacier delineation, glacier fluctuations, glacier mapping

INTRODUCTION

A detailed glacier inventory, required to determine the importance of glaciers in the hydrologic cycle, was recommended during the International Hydrological Decade (1965–74) sponsored by UNESCO, who promoted the creation of the World Glacier Inventory (WGI) (UNESCO/IAHS, 1970). Today, one of the recommendations of the Global Terrestrial Network for Glaciers (GTN-G) is the compilation of glacier inventory data from space-borne sensors with a repetition after a few decades, which is the typical response time of glaciers to climate change (e.g. Zemp and others, 2009). Global information on glacier area is used for estimating ice volumes, the contribution of glaciers to sea-level rise and sea-level equivalent in a context of climate change (e.g. Bahr and Radić, 2012; Huss and Farinotti, 2012; Marzeion and others, 2012; Grinsted, 2013).

Remote sensing techniques have proven to be useful for glacier inventories worldwide (e.g. Paul and others, 2009), as well as estimation of glacier changes in large areas. In spite of advances achieved following the Global Land Ice Measurements from Space (GLIMS) initiative (e.g. Raup and others, 2007), or the Randolph Glacier Inventory (RGI) (e.g. Pfeffer and others, 2014; Arendt and others, 2015), the lack of quality-controlled glacier inventories for the Southern Andes

is still a source of uncertainties. Mountain glaciers and ice caps (GIC) react rapidly to climatic forcing, contributing faster than continental ice sheets to sea-level rise (IGOS, 2007, p. 34).

The Chilean glacierized area was estimated to be $\sim 20\,715 \text{ km}^2$ (Casassa, 1995). The glacierized area of the Southern Andes (south of 25° S), covering $\sim 3\%$ of the total area of worldwide GIC, mostly lies in Chile. Despite the importance of Chilean glaciers as representatives of the Southern Andes, the inventory work was up to now still uncompleted. The usefulness of sparse glacier inventories obtained with different data and methods is much less than that of one inventory in a standardized format based on international recommendations (i.e. Paul and others, 2009). Since the use of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) data from the year 2000 (± 5 years) is recommended (i.e. Paul and others, 2009), we selected Landsat images close to late-summer 2003, prior the failure of the Scan-Line Corrector (SLC-Off) for our observation period.

Glacier changes are connected to global warming and contribute to run-off. It is well known that debris-covered glaciers and rock glaciers are less sensitive to ablation than clean-ice glaciers so their changes may alter spatial patterns (e.g. Benn and others, 2012) of mass loss if they predominate in a

certain catchment. Therefore, a quantitative and detailed inventory of these ice masses provides important information needed to assess future area changes in response to global warming.

In this paper, we present the results of the first complete glacier inventory in Chile. The inventory was carried out using Landsat TM and ETM+ images acquired primarily close to late-summer 2003; the Shuttle Radar Topographic Mission (SRTM) DEM; a semi-automatic procedure to define glacier outlines; and an unsupervised classification method (*k*-means) to estimate clean-ice or debris-covered area.

Study area

Chile extends along the Southern Andes over 4000 km ($17^{\circ}30'–56^{\circ}$ S), occupying mostly its western side (Fig. 1). The elevation of the Andes Cordillera decreases southwards from peaks in excess of 6000 m in the Dry Andes ($17^{\circ}30'–36^{\circ}$ S) to mountains dissected by fjords and channels in the Wet Andes ($36–56^{\circ}$ S) (Lliboutry, 1998). This large extent in both latitude and elevation creates a natural diversity for the occurrence of glaciers, which can be classified in the following main zones: (i) Desert Andes; (ii) Central Andes; (iii) Lakes District and Palena Province; and (iv) Patagonian Andes and Tierra del Fuego (Lliboutry, 1998).

The Desert Andes zone extends from the northern boundary of Chile to the Choapa basin ($\sim 17^{\circ}30'–32^{\circ}$ S). The transition in climate from hyper-arid conditions in Norte Grande to semi-arid ones in Norte Chico (Ginot and others, 2006; Favier and others, 2009) is defined by the South American Arid Diagonal ($19–29^{\circ}$ S), hereafter Arid Diagonal, which separates summer precipitation patterns driven from the Tropics to the north, and winter precipitation driven by the westerlies to the south (Garreaud, 2009).

At Norte Grande, an intermountain high plateau so-called Altiplano, a distinct wetter region within the Desert Andes, is characterized by inland drainage (endorheic drainage basin). Surface water discharging to the sea in catchments with a clear perimeter is found only from Norte Chico ($28^{\circ}30'$ S) and southward, which includes Copiapó, Huasco, Elqui, Limarí and Choapa catchments (Favier and others, 2009). Puna de Atacama ($\sim 27^{\circ}$ S) is another inner high and arid plateau containing also inland drainage, a branch of Altiplano found eastward of Atacama Desert.

The Central Andes ($32–36^{\circ}$ S) including Petorca, Aconcagua, Maipo, Rapel, Maule and Mataquito catchments, are characterized by Mediterranean climate with wet winters (April–September) and dry summers (October–March). South of Itata river (36° S), the elevation of the Andes range sharply decreases and a wetter climate prevails at Lakes District, where isolated ice-covered volcanoes can be found down to Petrohué catchment (41° S).

South of Reloncaví inlet, along the so-called Palena Province ($41^{\circ}30'–44^{\circ}$ S), the Andes range is dissected by fjords characterizing a deeply indented glacierized rocky coastline. A series of archipelagos which stretches along the western coast of Patagonia means fewer large catchments such as Puelo, Yelcho, Palena and Aysén.

The Patagonian Andes and Tierra del Fuego, from Río Aysén to Cape Horn ($46–56^{\circ}$ S) are characterized by a larger amount of annual rainfall well distributed throughout the year and a strong west–east gradient (e.g. Ohata and others, 1985; Carrasco and others, 2002). The Northern



Fig. 1. Chile extends along the Southern Andes for over 4000 km ($17^{\circ}30'–56^{\circ}$ S), occupying mostly its western side. Elevation of the Andes Cordillera decreases southwards from peaks in excess of 6000 m in the Dry Andes ($17^{\circ}30'–36^{\circ}$ S) to mountains dissected by fjords and channels in the Wet Andes ($36–56^{\circ}$ S). Main glaciological zones according to Lliboutry (1998): (i) Desert Andes; (ii) Central Andes; (iii) Lakes District and Palena Province; and (iv) Patagonian Andes and Tierra del Fuego.

Patagonia Icefield (NPI) and the Southern Patagonia Icefield (SPI) are the largest temperate ice-bodies of the Southern Hemisphere (Warren and Sugden, 1993).

Although most of the SPI lies in Chile, it is partially shared with Argentina (Casassa and Rivera, 2001), existing within its eastern side a rectangle (Mount Fitz Roy – Cerro Murallón), in which the boundary is not defined yet. In the periphery of the Patagonian icefields, mountain glaciers are found at Baker, Pascua and Serrano catchments, the three main large catchments, which drain meltwater from the east side of the icefields to the Pacific Ocean.

Climatic setting

Meteorological stations from the Dirección General de Aguas (DGA), the official water agency of Chile, are used to characterize the climatic setting of main glaciological zones (Liboutry, 1998). At Visviri station (17°36' S/69°28' W; ~4080 m a.s.l.) located in the Altiplano, the mean annual air temperature (MAAT) is 5 °C and the total precipitation up to 350 mm a⁻¹ is concentrated in summer (January–March) whereas the winter (May–September) is dry. In Norte Chico, at Embalse La Laguna station (30°12' S/70°2' W; ~3150 m a.s.l.), the MAAT is 8 °C and the precipitation is concentrated in winter (July–October) with a lesser amount of 200 mm a⁻¹. At Embalse El Yeso station (33°40' S/70°5' W; ~2400 m a.s.l.), in the Central Andes, the MAAT is 8.3 °C and precipitation, up to 515 mm a⁻¹, is concentrated in winter.

At Puelo station (41°39' S/72°17' W; ~0 m a.s.l.) in the Lakes District, the MAAT is 11.4 °C while the precipitation, evenly distributed throughout the year, greatly increases to 3066 mm a⁻¹. In the Patagonian icefields, at Laguna San Rafael (46°38' S/73°52' W; ~0 m a.s.l.) the MAAT of 6.9 °C indicates a warm climate with a total precipitation of 3144 mm a⁻¹ on the west side because of maritime influence. However, the MAAT of 4.9 °C and lesser precipitation of 1649 mm a⁻¹ at Lake Colonia Station (47°20' S/73°6' W; ~150 m a.s.l.) indicates a cold steppe on the continental east side of the Andes.

Previous glacier inventories

Based upon vertical aerial photographs taken in 1955 and 1961, glacier inventories were carried out in catchments of the Dry Andes (Garín, 1987); Central Andes (Caviedes, 1979; Marangunic, 1979; Valdivia, 1984; Noveroy, 1987); and Lakes District (Rivera, 1989). These studies covered only ca. 1365 km², i.e. ~6% of the total glacierized area, distributed in 1751 individual glaciers inventoried. Rock glaciers inventoried are limited to the Altiplano between 18° S and 29° S (i.e. Kammer, 1998; Payne, 1998). Other catchments with data available are Huasco (Nicholson and others, 2009) and Aconcagua (Bown and others, 2008).

In the Wet Andes, outlet glaciers of Patagonia were inventoried due to their scientific importance such as their location in mid-latitudes and temperate ice conditions. Satellite images acquired in 1986 and after 2000, were used within the NPI (Aniya, 1988; Rivera and others, 2007), the SPI (Aniya and others, 1996), Gran Campo Nevado (Schneider and others, 2007) and Isla Riesco (Casassa and others, 2002).

Existing glacier inventories estimated a glacierized area varying between 20 715 km² (Casassa, 1995) and 20 575 km² (Rivera and others, 2002). These compilations included the catchments inventoried by DGA, the inventories for both the icefields (Aniya, 1988; Aniya and others, 1996), and an estimate of ca. 5300 km² of the total area not inventoried in Palena Province and of mountain glaciers in the periphery

of the Patagonian icefields (i.e. Casassa, 1995; Rivera and others, 2000; Rivera and others, 2002).

DATA AND METHODS

Datasets

We selected 35 Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) images at Level 1 downloaded from the United States Geological Survey (USGS) website spanning between 2000 and 2003 (Table 1). Images with minimum clouds and mostly acquired in late-summer season were selected.

Glacier outlines

To identify clean-ice using multispectral data, the band ratio applied to digital numbers (DN) of bands TM3 (0.63–0.69 µm) and TM5 (1.55–1.75 µm) was used as classification method. Subsequently, a 3 × 3 kernel median filter was applied to remove isolated pixels corresponding to rocks on the glacier or snow-cover nearby glacier outlines. The threshold value was obtained from the histogram of each ratio image to discriminate clean-ice and snow surfaces from surrounding terrain (Fig. 2).

Despite improved algorithms, automatic classification of debris-covered glaciers and rock glaciers is still challenging and a main source of inaccuracies (Paul and others, 2013). While a debris-covered glacier (i.e. valley glacier) has continuous coverage of supra-glacial debris across its width in the ablation zone (Kirkbride, 2011), a rock glacier contains interstitial ice (Müller and others, 1977) or a matrix of ice, showing evidence of past or present flow (Cogley and others, 2011). An important clue to distinguish debris-covered glaciers from rock glaciers is the existence of clean-ice exposed in supraglacial lakes and surface depressions on debris-covered glaciers (e.g. Sakai and others, 2000; Benn and others, 2012) whereas rock glaciers are identified by their steep fronts and distinctive series of ridges and furrows perpendicular to the direction of flow (Giardino and others, 2011). Debris-covered glaciers and rock glaciers were manually digitized on screen using Band 8 at 15 m spatial resolution (Fig. 2). Manual editing was also supported by aerial photographs taken in 1996/97 as well as ground, maritime and aerial observations between Tacora and Lullaillaco volcanoes; the catchments of Copiapó, Elqui, Aconcagua, Maipo, Rapel and Petrohué; and both NPI and SPI.

Minimum threshold

Using Landsat 30 m pixel size images, a minimum threshold of 0.01 km² (1 hectare) has been recommended for the identification of glaciers (Paul and others, 2009). We used the threshold value of 0.01 km², which has been widely used for glacier inventories (e.g. Kääb and others, 2002; Paul and Andreassen, 2009; Bliss and others, 2013; Pfeffer and others, 2014). However, mountain groups located between Aucanquilcha and Lullaillaco volcanoes, in the driest part of the Arid Diagonal, were excluded from the analyses to avoid the inclusion of patchy snow cover in the Dry Andes.

Parameters inventoried

We used the UNESCO classification and description (Müller and others, 1977) to define glacier variables to be inventoried

Table 1. Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI) images used in this study

Catchment	Sensor	Path	Row	Date	Image ID
Altiplánicas – Sillajhuay	ETM+	002	072	2002-11-30	LE70020722002334COA00
	OLI	001	073	2015-12-05	LC80010732015339LGN00
	ETM+	001	073	2002-12-25	LE70010732002359PFS01
	ETM+	001	074	2002-08-19	LE70010742002231PFS00
	OLI	001	074	2015-11-20	LC80010742015323LGN00
Aucanquilcha – Lullailaco	ETM+	233	075	2003-03-08	LE72330752003067COA01
	ETM+	233	076	2003-04-25	LE72330762003115ASN00
	ETM+	233	077	2003-03-24	LE72330772003083EDC00
Puna de Atacama Copiapó	ETM+	233	078	2000-02-12	L72233078_07820000212
	ETM+	233	079	2002-03-21	LE72330792002080EDC00
Huasco	OLI	233	079	2015-05-03	LC82330792015044LGN00
	ETM+	233	080	2003-01-03	LE72330802003003PFS00
Elqui – Limarí	OLI	233	080	2015-03-18	LC82330802015076LGN00
	ETM+	233	081	2003-04-09	L72EDC1103099170300
Choapa Aconcagua – Maipo	OLI	233	081	2015-05-03	LC82330812015044LGN00
	ETM+	233	082	2002-03-21	LE72330822002080EDC00
Rapel – Mataquito	ETM+	233	083	2003-03-24	LE72330832003083EDC00
	ETM+	233	083	2003-04-09	LE72330832003099EDC00
	OLI	233	083	2015-02-13	LC82330832015044LGN01
Maule	ETM+	232	084	2003-03-17	LE72320842003076EDC00
	OLI	232	084	2015-03-10	LC82320842015069LGN01
Itata – Bío-Bío – Toltén	ETM+	233	085	2003-03-24	L72233085_08520030324
	ETM+	232	085	2003-03-17	LE72320852003076EDC00
	OLI	233	085	2015-04-02	LC82330852015092LGN00
Valdivia – Bueno	ETM+	233	086	2003-03-24	L72233086_08620030324
	OLI	233	086	2015-03-18	LC82330862015076LGN00
	ETM+	232	087	2001-02-07	L72232087_08720010207
Petrohué – Puelo – Inexplorado	OLI	233	087	2015-05-03	LC82330872015044LGN00
	ETM+	232	088	2001-04-12	L72232088_08820010412
Yelcho	OLI	232	088	2015-03-26	LC82320882015085LGN00
	ETM+	232	089	2003-03-17	L72232089_08920030317
Palena – Cisnes – Aysén	OLI	232	089	2015-03-26	LC82320892015085LGN00
	ETM+	232	090	2003-02-13	L72232090_09020030213
Aysén – Baker	OLI	232	090	2015-02-22	LC82320902015053LGN01
	ETM+	232	091	2000-03-08	L72232091_09120000308
Northern Patagonia Icefield	OLI	232	091	2015-02-22	LC82320912015053LGN01
	ETM+	232	092	2000-03-08	L72232092_09220000308
	OLI	232	092	2015-03-26	LC82320922015085LGN00
East of Southern Patagonia Icefield	ETM+	231	093	2002-01-18	LE72310932002018EDC00
	OLI	232	093	2001-03-11	L72232093_09320010311
Southern Patagonia Icefield (North)	OLI	232	093	2015-04-11	LC82320932015101LGN00
	ETM+	232	094	2003-04-02	L72232094_09420030402
Southern Patagonia Icefield (Central)	OLI	232	094	2015-05-08	LC82320942015021LGN00
	TM	231	094	2001-03-12	LT52310942001071COA00
Southern Patagonia Icefield (South)	OLI	231	094	2015-05-10	LC82310942015014LGN00
	TM	231	095	2001-03-12	LT52310952001071COA00
Gran Campo Nevado – Isla Riesco	OLI	231	095	2015-05-10	LC82310952015014LGN00
	TM	231	096	2001-03-12	LT52310962001071COA00
	ETM+	231	096	2001-05-07	L72231096_09620010507
	OLI	231	096	2015-09-27	LC82310962015270LGN00
	ETM+	230	097	2002-03-16	L72230097_09720020316
Cordillera Darwin	ETM+	226	098	2003-02-19	LE72260982003050EDC00
	ETM+	228	098	2001-03-31	LE72280982001090EDC00
	ETM+	227	098	2003-03-30	LE72270982003089EDC00
	OLI	229	098	2001-03-28	L71AGS1103087210200
	OLI	227	098	2015-03-23	LC82270982015082LGN01

in line with international recommendations (Paul and others, 2009). The basic information includes: identification code following WGI; name of the glacier; primary classification of WGI; datum; coordinates; catchment code; acquisition date; inventory date; glacier surface area; exposed area (clean-ice); debris-covered area; mean width and length; orientation; and mean elevation.

Glacier catchments

We used the catchment classification data base of DGA (Benitez, 1980) as a hydrographic unit. Because this classification is based on large topographic maps (1:250 000), we improved it by means of the ArcGIS Watershed module. In the absence of surface water, natural regions such as Altiplano and Puna de Atacama were determined

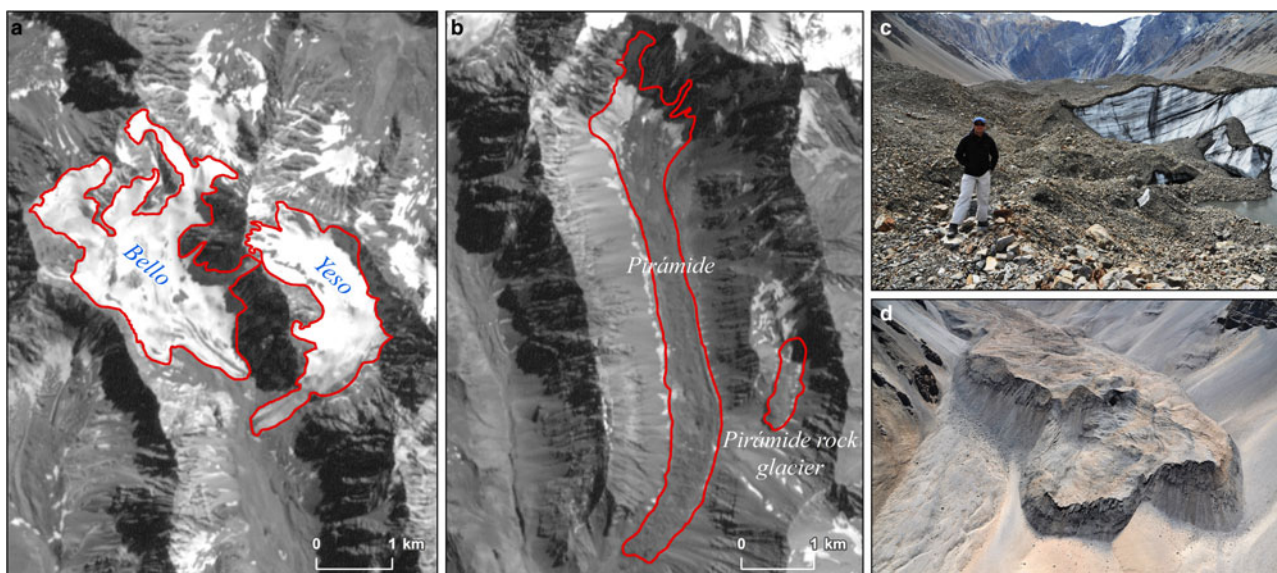


Fig. 2. Glacier outlines for Bello and Yeso (a) glaciers (clean-ice), Pirámide debris-covered glacier and Rocoso Pirámide rock glacier (b) in the Maipo catchment, Central Andes, as seen in Landsat ETM+ image (24 March 2003). The band ratio of bands TM3 and TM5 and a threshold value were used to discriminate clean-ice from surrounding terrain. Supported by ground observations, debris-covered glaciers and rock glaciers were manually digitized on screen using Band 8 at 15-m spatial resolution. Note the existence of clean-ice exposed in the supra-glacial lake and surface depression on the Pirámide debris-covered glacier (c) and the steep front and distinctive series of ridges and furrows of Pirámide rock glacier (d). Location of glaciers is shown in [Figure 3](#).

following distinctive peaks instead of catchments. In cases of very small catchments at the archipelagic west coast of Palena Province and Patagonia, glacier complexes were labeled per specific rivers, peaks or fjords.

Outlet glaciers were labeled according to contiguity to the icefield and size of the drainage area (Aniya and others, 1996). Mountain glaciers other than outlets were grouped as those connected with the icefield but facing away from its main body; and remaining mountain glaciers contributing to a large catchment (e.g. Baker, Pascua and Serrano) but unconnected with its main body were labeled as other than icefields. In the case of SPI, outlets glaciers contributing to the Pacific Ocean were labeled separately from those outlets flowing to the east side, and the rectangle defined by the boundary Agreement of 1998 was excluded. The Strait of Magellan represents a natural division between mainland and the archipelagic area down to Cape Horn.

Glacier classification

The primary morphological classification of UNESCO (Müller and others, 1977; Digit 1) was adopted to distinguish different types of glaciers. However, and beyond Müller and others (1977), the distinction between clean-ice and debris-covered areas as well as land-terminating and calving glaciers is an important issue for mass-balance considerations. A threshold of 0.25 km² (Cogley and others, 2011) was used to further distinguish between glacierets (<0.25 km²) and glaciers (>0.25 km²). We added size intervals ranging between 0.05 and 0.25 km² for discussion and analyses. Ice-bodies smaller than 0.05 km², including rock glaciers, snowfields or snow-patches are considered to be objects made mainly by ice that may or may not be a glacier (Cogley and others, 2011).

Recent glacier variations

Glacier outlines for 98 large representative glacier complexes across all glacierized regions and size classes were updated to 2015 using 21 Landsat 8 Operational Land Imager (OLI) images ([Table 1](#)). Glacier area variations since 2000/03 were determined by comparing changes in terminus position as visible in the imagery for the different periods. The glaciers sampled represent an area of 7461.8 ± 373 km² in 2000/03, which is ~31% of glacierized area, including glaciers of different characteristics such as rock glaciers and debris-covered glaciers as well as land-terminating and calving glaciers (clean-ice).

Error estimation

Since most of the estimated glacierized area was measured for the first time, we estimated a measurement error based upon outline perimeter and the size of the pixel. In case of clean-ice glaciers these measurements yield an error of ~2%. However, assuming a worst case scenario for debris-covered glaciers and rock glaciers, this error was enlarged to 5% as a representative error. In addition to delineation method, other potential error sources are co-registration, scene quality, clouds, seasonal snow, shadow, drainage divides in the accumulation region or glacier terminus with dead ice (e.g. Paul and others, 2009; Bolch and others, 2010; Paul and others, 2013). All these potential errors were minimized by means of manual editing.

RESULTS AND DISCUSSION

Glaciers occur from Tacora volcano in the Altiplano southward to Isla Hoste at Cape Horn ([Figs. 3 and 4](#)). Glacier distribution varies due to topographical factors and climate determined by latitude and the elevation of the Andes. Whereas ice-bodies in the Dry Andes are located at high



Fig. 3. Glacier distribution in the Desert Andes (17°30'–32° S) and Central Andes (32–36° S). Glacier distribution varies as a result of latitudinal climate and elevation gradients, occurring 188.9 km² in the Desert Andes and 869.5 km² in the Central Andes. Mountain groups and individual glaciers are shown.

altitude, glaciers in the Wet Andes reach down to sea-level. Figure 5 depicts the predominance of glaciers of 0.01–1 km² around 3700 m a.s.l. in the Central Andes (30–35° S), while glaciers larger than 10 km² occur between 800 and 2000 m a.s.l. and are concentrated in the Patagonian Andes and Tierra del Fuego (43–56° S).

San Rafael (ca. 724 km²), an outlet glacier of the NPI is the lowest latitude tidewater glacier. Pio XI, an outlet glacier on the west side of the SPI is the largest glacier, with an area of 1246 km². It is the only glacier larger than 1000 km², and accounts alone for 5.2% of the total glacierized area.

Glaciers (ice-bodies) inventoried were morphologically classified into five main types: icefield and outlet, valley, mountain, glacierets and snowfields, and rock glaciers.

Glacier number and areas

The inventory contains 24 005 ice-bodies larger than 0.01 km², covering an area of 23 708 ± 1185 km², which corresponds to ca. 3.1% of the Chilean territory. The results are presented as total number of glaciers and glacierized area

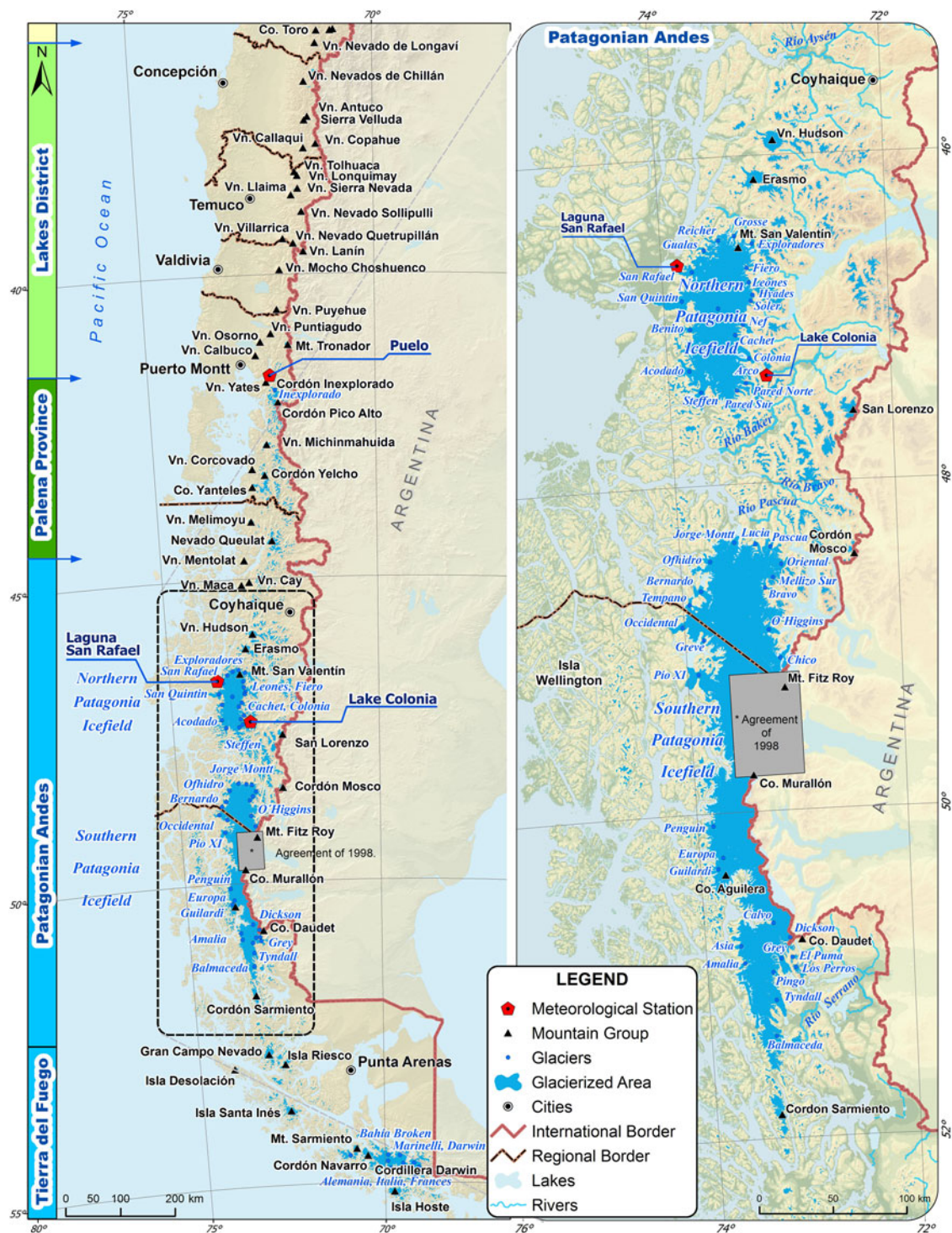


Fig. 4. Glacier distribution in the Lakes District and Palena Province (36–46° S) and Patagonia and Tierra del Fuego (46–56° S). Glaciers from Itata to Cisnes catchments cover 1478.8 km² and 21 171 km² occurs from Aysén catchment southwards, along the Patagonian Andes and Tierra del Fuego. Mountain groups and individual glaciers are shown.

by glaciological zone, region and catchment (Table 2) and as number of glaciers per size class (Table 3).

Uncertainties in the final inventory are due to the occurrence of snowfields that may remain for more than two summer seasons, the absence of ice flow or the lack of current ice in a rock glacier. All these uncertainties are more critical in ice-bodies smaller than 0.05 km². Although misclassification of rock glaciers does not largely alter the total glacierized area (e.g. 259.4 km²), the inclusion of small ice-bodies largely hampers the

number of glaciers inventoried (e.g. 10 707 glaciers are smaller than 0.05 km²). If ice-bodies smaller than 0.05 km² are excluded, the number of ice-bodies decreases to 13 298, with a decrease of 3% in area yielding a glacierized area of 23 448 ± 1172 km².

When all the glacierets are excluded (<0.25 km²), the total number of 5748 glaciers yields a glacierized area of 22 567 ± 1128 km², which lies within the error estimates for satellite-derived inventories. Therefore, a decrease of 75% in number of ice-bodies only implies a decrease of 5% in glacierized

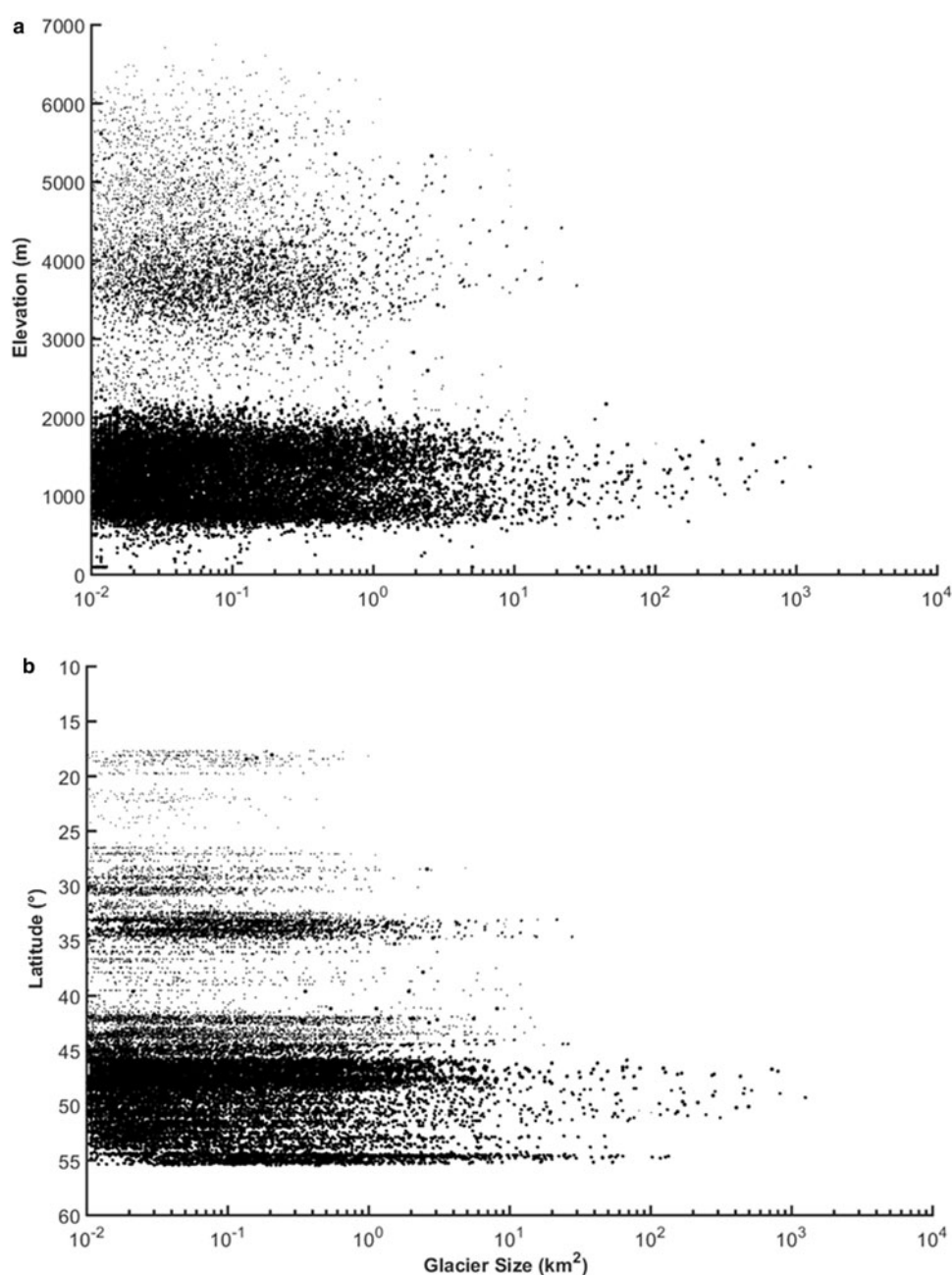


Fig. 5. Glacier size vs mean elevation for glaciers inventoried (a) and glacier size vs southern latitude (b). Smaller ice-bodies are found at high altitude in the Desert Andes over 4000 m a.s.l. whereas the largest glaciers are found in the Patagonian Andes, where outlets reach the sea. X-axes in both figures are plotted in logarithmic scale.

area. Consequently, based on a decadal-scale glacier inventory, a threshold value of 0.01 km² can be misleading and time consuming due to rapid glacier changes, and a threshold value of 0.05 km² is preferable.

Minimum threshold

The minimum threshold used determines the number of small ice-bodies (<0.05 km²). To reduce errors in sea-level rise estimates, a glacier inventory using a threshold down to 0.01 km² is required to consider the significant contribution from very small glaciers (Bahr and Radić, 2012). However, at those scales the difference between glaciers and snowpatches is blurred (Bahr and Radić, 2012).

The minimum threshold varies in existing inventories worldwide depending on objectives and resources available

(Pfeffer and others, 2014). Different threshold values have been used: 0.01 km² at the Antarctic Peninsula (Bliss and others, 2013); 0.02 km² for Western Himalaya (Frey and others, 2012); 0.1 km² (Schiefer and others, 2008) and 0.05 km² for British Columbia (Bolch and others, 2010) and 0.05 km² for northern Patagonia (Paul and Mölg, 2014). The division of an ice-complex into individual glaciers can also significantly make the number of glaciers vary; therefore it can be an arbitrary quantity (Pfeffer and others, 2014) with the glacier surface area being the most important parameter.

Glacier distribution by zones

Desert Andes

Glaciers and rock glaciers of the Desert Andes cover 188.9 km², representing about 0.8% of the Chilean glacierized area,

Table 2. Total number and area of inventoried glaciers by zone, region and catchment using 2000/03 Landsat data

	Zone	Region	Catchment	Number	Area km ²		
Dry Andes	Desert Andes	Norte Grande	Altiplano down to Cerro Sillajhuay (19°45' S)	373	36.2		
			Endorheic basins between Cerro Aucanquilcha (21°28' S) and Vn. Llullaillaco (24°43' S)	93	5.1		
			Puna de Atacama down to Nevado Tres Cruces (27° S)	257	21.0		
	Central Andes Lakes District and Palena Province	Norte Chico Central Andes Lakes District Palena Province	Copiapó – Choapa	1334	126.6		
			Petorca – Maule	2624	869.5		
			Itata – Cochamó	447	193.3		
			Puelo – Cisnes	3474	817.6		
			West coast from Vn. Yate to Vn. Mentolat	687	364.5		
			Nevado Queulat	37	102.8		
			West coast and Aysén	1168	412.2		
			Exploradores other than NPI	294	86.8		
			NPI main (Outlets)	28	3758.9		
			NPI mountain glaciers connected other than Outlets	87	151.6		
Wet Andes	Patagonia and Tierra del Fuego	Northern Patagonia Icefield and surrounding areas	West coast North of Fjord Calén (unconnected)	626	175.0		
			Baker other than NPI	3353	1331.4		
			Bravo and others north of Fjord Calén	646	286.7		
			Pascua other than SPI	1144	302.9		
			SPI main (Outlets to Pacific Ocean)	39	8479.1		
			SPI mountain glaciers connected other than Outlets	287	1465.4		
			West coast of SPI (unconnected)	2647	348.8		
			SPI (Combined East side*)	5	215.6		
			Serrano other than SPI	415	133.1		
			Última Esperanza (Mount Balmaceda and others)	400	61.6		
			Cordillera Sarmiento	288	127.7		
			Southern Patagonia Icefield and surrounding areas	Mainland north of Strait of Magellan	Other mountain glaciers north of Strait of Magellan	737	120.4
					Gran Campo Nevado (Outlets and mountain glaciers)	28	190.8
		Isla Riesco			444	205.8	
		Other Archipelagos			221	72.0	
		Mountain glaciers of Tierra del Fuego			894	826.1	
		Cordillera Darwin (Outlets and mountain glaciers)			172	1794	
		Archipelagos south of Strait of Magellan down to Cape Horn		Isla Desolación	6	13.5	
				Isla Santa Inés (Outlets and mountain glaciers)	283	267.0	
				Isla Hoste (Outlets and mountain glaciers)	467	345.4	
					24.005	23.708	

*A portion of the drainage area of five east side glaciers contributing to the Atlantic Ocean.

of which 105.7 km² (55% of the zone) correspond to 1368 rock glaciers. Twelve glaciers, mostly found at the Altiplano, Copiapó and Huasco catchments, are larger than 1 km².

Tropical glaciers are located north of the Arid Diagonal (Vuille, 2011), as ice-covered volcanoes of northernmost Chilean Altiplano such as Pomerape, Parinacota, Acotango and Guallatire. Cerro Sillajhuay (19°45' S) contains the last glacier prior to the development of hyper-arid conditions further south. Tropical glaciers of the Chilean Altiplano (17°30'–19°45' S) amount to <1% of the total glacierized area.

The driest part of the Desert Andes occurs between Cerro Aucanquilcha (21°28' S), in the Loa catchment, and Llullaillaco volcano (24°43' S) at the high plateau of Puna de Atacama where only rock glaciers can be found. Large rock glaciers have been observed at Cerro Aucanquilcha, San Pedro and San Pablo volcanoes (Payne, 1998).

In the Norte Chico, at the southern tip of the Arid Diagonal, relatively large glacierets appear at Llullaillaco volcano, Nevado Tres Cruces (27°05' S) and Cerro Muerto. Mountain glaciers occur at Cerro El Potro (28°23' S), in the Copiapó catchment, where Del Potro glacier,

4.8 km², is the largest one of the entire Norte Chico. Some other large glaciers of Norte Chico are Tronquitos, Maranceles and Estrecho. Glacier coverage decreases in the Elqui and Choapa catchments, covering altogether 22.3 km².

Garín (1987) estimated 106.8 km² in 92 ice-bodies between the Altiplano and Elqui catchment, which is lower than our estimate of 188.9 km² distributed in 2057 ice-bodies for the same Andean area. In the case of Huasco catchment, 152 ice-bodies covering 23.17 km² were identified using satellite data of 2004 (Nicholson and others, 2009), whereas we identified 334 ice-bodies covering 32.6 km². Although former inventories are not directly comparable with our results, the reduction in glacierized area is interpreted as glacier shrinkage.

Central Andes

The glacierized area of the Central Andes is 869.5 km², ca. 3.6% of the Chilean glacierized area, of which 289.9 km² (33% of the zone) correspond to 1472 rock glaciers. A

Table 3. Number of glaciers per size class inventoried using 2000/2003 Landsat data

Size class km ²	Number	Area km ²
0.01–0.049	10 707	259.4
0.05–0.099	3364	259.5
0.1–0.24	3868	621.8
0.25–0.49	2246	800.7
0.5–0.99	1575	1094.9
1–4.9	1525	3113.9
5–9.9	204	1362.9
10–49	148	3047.3
50–99	31	2011.7
100–499	32	7044
500–999	4	2845.1
>1000	1	1246.9
Total	24 005	23 708

number of 153 glaciers are larger than 1 km², covering 489 km² (57% of the zone) and 627 glaciers are larger than 0.25 km², covering 708 km² (82%). In this zone, glaciers with distinctive tongues reach significant dimensions (>10 km²) at three main catchments. The most glacierized one is Maipo with 388.3 km² of glaciers, followed by Rapel with 292.3 km² and Aconcagua with 135.8 km², and together containing 95% of the glacierized area of the Central Andes. The mean elevation of glaciers is 3700 m, which is relatively low and goes in line with the decrease in the elevation of the Andes southwards. 65% of the glaciers are oriented to the south and southeast.

The Juncal – Olivares glacier complex (ca. 72.8 km²) comprises the watershed between the Aconcagua and Maipo catchments. Other several large complexes located at Maipo catchment are Loma Larga – Morado; Tupungato; Marmolejo – San José; Bello – Pirámide; Argüelles and Maipo volcano. Picos del Barroso mountain complex comprises the watershed of Maipo and Rapel catchments, while the group of Palomo volcano with ca. 92.5 km² is the largest complex of the Central Andes. Located at Rapel catchment, Universidad glacier, with 27.5 km² is one of the largest of the Central Andes. A smaller group at Rapel catchment is the Tinguiririca complex, which contains several unnamed glaciers. Glacier coverage is reduced drastically at Maule and Mataquito catchments. At the Peteroa – Azufre complex, the southernmost large glaciers (>5 km²) of the Central Andes are found. In addition, few isolated ice-covered volcanoes such as Descabezado Grande, Cerro Azul, Nevado Longaví and Nevados de Chillán still have a large coverage of glaciers.

In the Aconcagua catchment, Valdivia (1984) inventoried 267 ice-bodies with an area of 151.2 km² using air photographs, and Bown and others (2008) 159 glaciers covering 121.2 km² using satellite data of 2003. In the Maipo catchment, 647 glaciers were inventoried covering 421.9 km² (Marangunic, 1979), and at Rapel catchment, 507 ice-bodies covering 328 km² were inventoried (Caviedes, 1979; Valdivia, 1984). These earlier inventories also indicate generalized glacier shrinkage in the Central Andes.

Lakes District and Palena Province

Glaciers in the zone from Itata catchment to Cisnes catchment cover 1478.8 km², representing ca. 6.3% of the

Chilean glacierized area. At the northern sector between the catchments of Itata and Petrohué, Lakes District contains 17 large ice-covered volcanoes such as Sierra Nevada, Villarrica, Mocho-Choshuenco and Osorno as well as Mount Tronador, covering together an area of 193.3 km². A total glacierized area of 261.82 km² was previously determined between Bío-Bío and Petrohué catchments (Rivera, 1989) confirming the glacier shrinkage trend also in this area. The largest glacier area, covering 1285 km², is found at the southern sector between Cochamó and Cisnes catchments, including Yate, Michinmahuida, Corcovado and Melimoyu, four ice-covered volcanoes of Palena Province, where many small mountain glaciers also straddle the crest of the coastal range. In addition, Cordón Inexplorado, Cordón Pico Alto, Cordón Yelcho and Nevado Queulat are the largest inner ice-complexes contributing to Blanco, Puelo, Yelcho and Queulat catchments, respectively.

Patagonian Andes and Tierra del Fuego

From Aysén catchment southwards, the Andes range is characterized by a deeply indented glaciated coastline and its inner icefields. The Patagonian Andes represent 89.3% of the total glacierized area, covering ca. 21 171 km². At the western coastal range of Patagonia, the four ice-covered volcanoes Mentolat, Cay, Macá and Hudson and the Erasmo complex are the largest ice masses prior to the extent of the main Patagonian icefields.

The NPI and SPI are the largest ice masses, where the small number of 66 large outlet glaciers predominate. These calving glaciers cover a total area of 12 138 km², representing ~51% of the Chilean glacierized area. In addition, we have to add 87 mountain glaciers connected with the main body of NPI, covering 151.6 km²; 2647 mountain glaciers connected with the main body of the SPI, covering 1465.4 km²; and 2647 mountain glaciers on the west side of SPI, covering 348.8 km². This large number of mountain glaciers located in the periphery of the main icefields and those other than icefields found at Baker, Pascua and Serrano catchments, have never previously been inventoried.

On the west maritime side, outlet glaciers directly reach sea-level in a fjord. On the other hand, east side continental outlets terminate in fresh water lakes and contribute to three large catchments such as Baker, Pascua and Serrano. In addition, smaller icefields with outlet glaciers larger than 100 km² and many mountain glaciers also exist north and south of the Strait of Magellan, such as Gran Campo Nevado, Isla Santa Inés, Cordón Navarro, Cordillera Darwin and Isla Hoste.

Glacier classification

Land-terminating ice masses such as mountain and valley glaciers are widely spread along the country, predominating in number (5687) whereas 79 large calving glaciers of Patagonia and Tierra del Fuego represent 12 848 km² (54% of glacierized area). Meltwater from land-terminating glaciers importantly contributes to run-off if they constitute a large ice-complex. On the other hand, calving glaciers of Patagonia have accounted for a major contribution to sea-level rise per unit area, which is larger than the contribution from Alaska's glaciers (e.g. Aniya, 1999; Rignot and others, 2003).

Identification of rock glaciers is not straightforward when only using optical imagery. Their distinction from debris-covered glaciers is important because rock glaciers contain

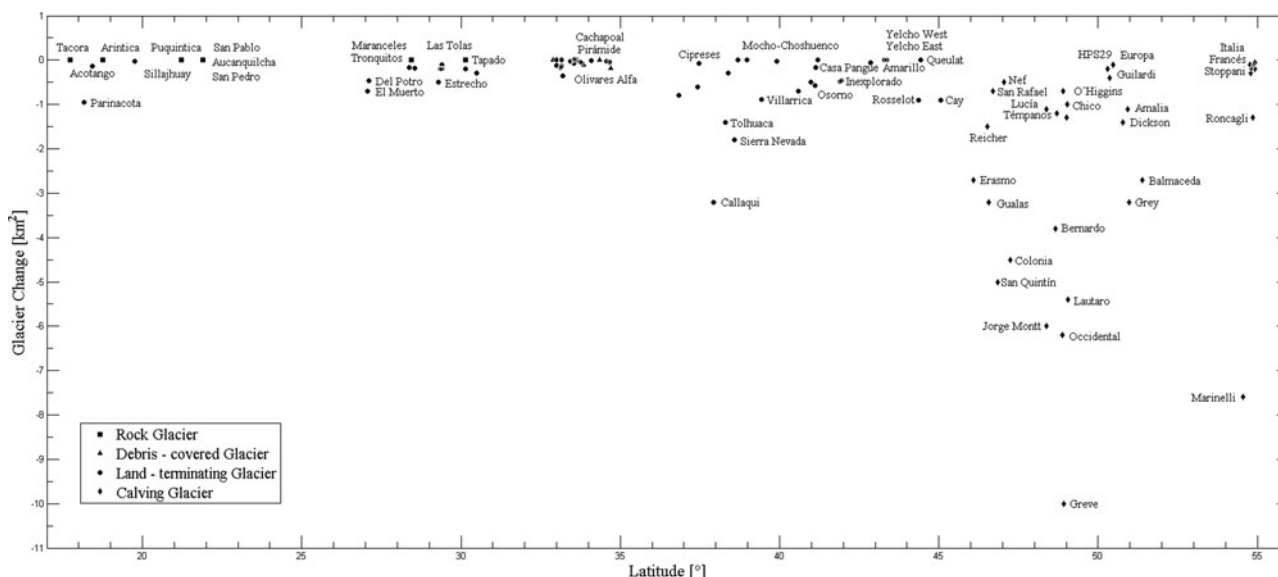


Fig. 6. Area changes between 2000/03 and 2015 for 98 glaciers across all glacierized regions and size classes. Rapid glacier changes have been observed from the Altiplano down to Cordillera Darwin. Decline in glacier area is mostly affecting to clean-ice land-terminating glaciers at different rates whereas debris-covered glaciers and rock glaciers in the Desert and Central Andes appear nearly unchanged in their extent. The uneven recession trend in the Patagonian Andes is explained by the dynamics of calving glaciers.

much less ice per volume thereby the total ice volume and its sea-level equivalent of a catchment can be overestimated. However, only further field-based surveys can investigate both the internal structure and ice content of a rock glacier, which are key factors in its dynamics and evolution (Hausmann and others, 2007).

Despite the fact that Gran Campo Nevado (Schneider and others, 2007) and Cordillera Darwin (Holmlund and Fuenzalida, 1995) have been classified as ice caps, we classified them as icefields (i.e. outlets and mountain glaciers) as well as Isla Santa Inés and Isla Hoste because the threshold of 50 000 km² to classify an ice cap (Benn and Evans, 2010), appears too large even for the entire glacierized area of the Southern Andes. While an ice cap is a dome-shaped ice mass with radial flow, a distinctive feature of an icefield is a large and flat accumulation area in which the catchment area may not be clearly delineated (Müller and others, 1977).

In flat areas where rock outcrops are absent, the location of the ice divides is not straightforward when ice flow data is lacking, so changes in drainage areas reflect trends mainly in ice dynamics rather than surface mass-balance processes alone (Mouginot and Rignot, 2015). Redefined ice-divides and drainage areas from previous studies (e.g. Davies and Glasser, 2012; Casassa and others, 2014) have been reported for both the NPI and the SPI due to enhanced ice flow, meaning that changes in ice dynamics propagate far inside the accumulation areas (Mouginot and Rignot, 2015). However, for inventory purposes those changes take place in the inner accumulation areas, which does not largely alter the main glacierized area.

Glacier surface conditions

The total surface area of clean-ice in Chile reaches 20 508 km², ~86% of the total glacierized area. It is mostly found in Patagonia and Tierra del Fuego as well as in mountain and valley glaciers in Lakes District and Palena Province and partially in the Central Andes. A small amount of clean-ice is found in the Desert Andes. The remaining

15%, including both rock glaciers and debris-covered glaciers, is largely found along the Desert Andes and Central Andes, up to the Maule catchment, where freezing temperatures by elevation and low snow-accumulation rates are characteristics. Due to loss of both continuity and elevation of the Andes, the transition to Mediterranean climate with a wetter summer precludes the occurrence of rock glaciers southwards. However, debris-covered areas can still be found in a wetter climate due to local conditions such as rock-fall and stagnation at Mount Tronador, as the case of Casa Pangue and Blanco glaciers. Large amount of debris coverage also exists in the ablation areas of Grosse, Exploradores, Fiero, Soler, Nef, Colonia, Pared Norte and Pared Sur glaciers within the NPI (46°30'–47° S), or Chico glacier (49° S) within the SPI, all of them flowing to continental east side.

Recent glacier variations (2000/03–2015)

Different data and methods (i.e. aerial photos, satellite images, algorithms, scale) yield different inventory measurements. However, when comparing the former inventories from the Dry Andes to Petrohué catchment with our results, there is a reduction in glacierized area from 1365 to 1200 km² and an increase from 1751 to 4973 in the number of glaciers. Decrease in glacierized area is interpreted as glacier shrinkage and the increase in number is attributed to the fragmentation of ice-bodies. Although the existing inventories are not directly comparable, rapid glacier changes have been observed along the country, from the Altiplano down to Cordillera Darwin between 2000–03 and 2015 (Fig. 6).

Decline in glacier area is mostly affecting clean-ice (both land-terminating and calving) glaciers at different rates resulting in changes in their geometry such as marked ice front retreat (Figs. 7 and 8). The total area loss for 77 glaciers is $\sim -92.3 \pm 4.6$ km². However, 21 rock glaciers and debris-covered glaciers in the Desert and Central Andes appear nearly unchanged in their extent. Even though different type of glaciers can indicate distinct glacier sensitivities to

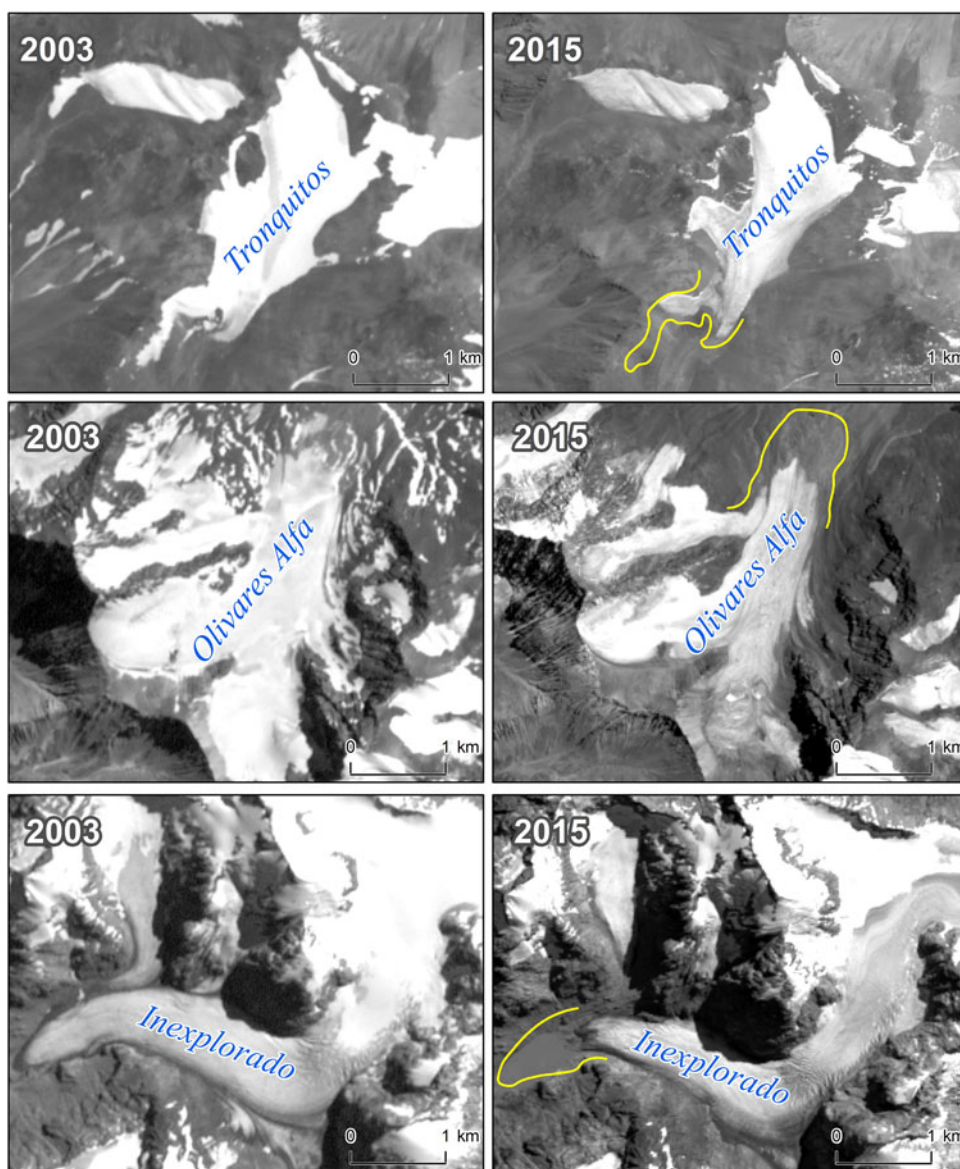


Fig. 7. Changes in terminus position between 2003 and 2015 for glaciers located at different zones. In the Desert Andes, Tronquitos glacier, one of the largest glaciers of Copiapó catchment, retreated -0.18 km^2 . A larger retreat of -0.36 km^2 is observed at Olivares Alfa, a glacier located at the Maipo catchment, Central Andes. An unnamed tongue of the west side of Inexplorado complex at Palena Province retreated -0.48 km^2 .

climatic regimes, local conditions are important in explaining current glacier response, because some large calving glaciers in Patagonia and Tierra del Fuego have been stable in recent years (e.g. Nef, O'Higgins) even in the zone where the largest retreating rates are observed (e.g. Colonia, Jorge Montt, Marinelli).

The glacierized areas of all ice-covered volcanoes of the Altiplano are shrinking. The largest retreat is observed at Parinacota volcano with -0.9 km^2 , whereas at Acotango volcano and Cerro Sillajhuay a more moderate retreat of -0.13 and -0.03 km^2 is observed. However, large rock glaciers of Tacora volcano, Cerro Arintica, Cerro Aucanquincha, San Pedro and San Pablo volcanoes showed no frontal change.

At Norte Chico, a large retreat rate is observed at Del Potro glacier with -0.17 km^2 and Tronquitos glacier with -0.18 km^2 . Between Estrecho glacier and Cerro Volcán the retreat rate is more moderate ($\sim -0.5 \text{ km}^2$). Large rock glaciers such as Maranceles and Las Tolas at Copiapó, and Elqui catchments, respectively, also showed no frontal change.

Larger recession rates in the Central Andes are observed at Olivares Alfa glacier with -0.36 km^2 and Universidad glacier with -0.17 km^2 whereas other large glacier such as Cipreses, Cortaderal and Palomo decreased $< -0.04 \text{ km}^2$. Debris-covered glaciers such as Pirámide and Cachapoal also showed no frontal change.

Ice-covered volcanoes and mountain glaciers of the Lakes District are retreating at contrasting rates. High retreat rates have been observed at Villarrica volcano with -0.56 km^2 , at Mocho-Choshuenco volcano with -0.02 km^2 and at Osorno volcano with -0.58 km^2 . At the northern side of Mount Tronador, the Casa Pangué glacier retreated -0.17 km^2 whereas at its southern side, Blanco glacier showed no change even though they are both covered by debris.

Contrasting retreat rates are also observed at Palena Province as the case of Cordón Inexplorado, where two unnamed glaciers (west side) retreated -0.48 and -0.46 km^2 . However, two unnamed glaciers of Cordón Yelcho (west and east sides) showed no frontal change. A moderate rate is observed at Michinmahuida volcano (Amarillo glacier)

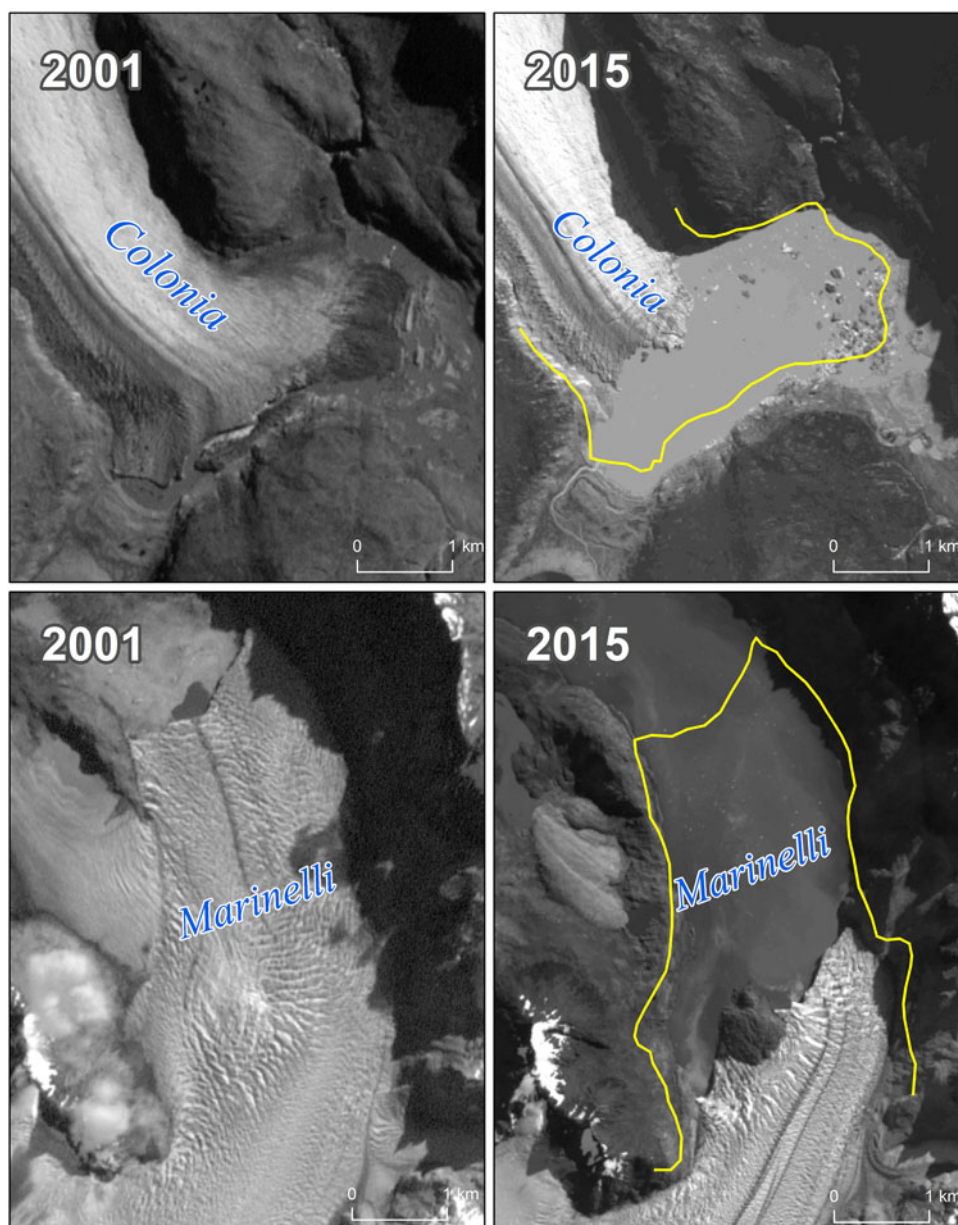


Fig. 8. The largest retreating rate is observed in the Patagonian Andes and Tierra del Fuego. Colonia glacier, one of the five largest outlet glaciers of the Northern Patagonia Icefield (NPI) retreated -4.5 km^2 and Marinelli glacier in the Cordillera Darwin, retreated -7.0 km^2 between 2001 and 2015.

with -0.05 km^2 , whereas the northern tongue of Queulat complex (Rosselot glacier) retreated -0.9 km^2 and contrastingly its southern tongue (Ventisquero Colgante del Queulat), showed no frontal change.

The magnitude of recession in Patagonia and Tierra del Fuego is the largest one in the Chilean Andes because of the large size and dynamics of calving glaciers (e.g. Warren and Aniya, 1999; Rivera and others, 2012). Large recession rates up to -10 km^2 in the case of Greve glacier and -7.6 km^2 for Marinelli in Cordillera Darwin are observed. Other west facing glaciers such as Gualas and San Quintin within NPI retreated -3.2 and -5.0 km^2 , respectively. However, on the east side of NPI, Nef glacier retreated at a more moderate rate of -0.5 km^2 , whereas Colonia glacier retreated at a larger rate of -4.5 km^2 , a contrasting behavior of two neighboring glaciers.

SUMMARY AND OUTLOOK

The first comprehensive glacier inventory of Chile, which will be available to the scientific community, includes a large glacierized area south of 46° S , especially along the Patagonian Andes and Tierra del Fuego. Large glacierized areas along the Altiplano, Palena Province and the periphery of the Patagonian icefields and surrounding areas are inventoried. Chilean glaciers, with an area of $23\,708 \text{ km}^2$, represent nearly 80% of the glacierized area of the entire Southern Andes. This estimate is more than 2000 km^2 larger than previous glacier compilations, and is a large portion of the glacierized area of all countries of South America.

Glaciers across all glacierized regions and size classes are retreating at different rates. The observed warming in Southern South America (Rosenblüth and others, 1997) and the consequent rise in the snowlines (Carrasco and others,

2005) is interpreted as the main reason. However, the spatial pattern of glacier shrinkage across the Andes of Chile is explained by the contrasting response of debris-covered glaciers in the Desert and Central Andes compared to the large recession trend in Patagonia, which is enhanced by the dynamics of calving glaciers.

A recent warming of +0.25 °C per decade in the Andes between 17° S and 37° S has been established on the basis of observational data and modeling (Falvey and Garreaud, 2009). MODIS data indicate a high variability in the snow-covered area and its depletion depending on wet or dry years (i.e. El Niño Southern Oscillation) (Minora and others, 2015). Scant geodetic mass-balance observations in the Central Andes indicate larger thinning rates (ca. -2.2 m a^{-1}) on clean-ice glaciers whereas a debris-covered glacier showed no elevation change between 2009 and 2012 (Barcaza and others, 2015).

AUTHOR CONTRIBUTION STATEMENT

G.B. led the study and wrote the manuscript. S.N. and J.L.G. helped in writing and scientific discussion. All the other co-authors contributed to data processing and analyses.

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