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Accelerating Glacier Area Loss Across the Andes Since the Little Ice Age

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Key Points:

- Little Ice Age (LIA) chronozone extent of >5,500 glaciers mapped from geomorphological evidence
- Overall glacier area change of −25% to year 2000 at a rate of −36.5 km^2 yr^{-1} or −0.11% yr^{-1}
- Up to 10 × acceleration in glacier area loss for Tropical sub-regions comparing LIA to 2,000 with post-2000 rates

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Andean glaciers are losing mass rapidly but a centennial-scale context to those rates is lacking. Here we show the extent of >5,500 glaciers during the Little Ice Age chronozone (LIA; c. 1,400 to c. 1,850) and compute an overall area change of −25% from then to year 2000 at an average rate of −36.5 km^2 yr^{-1} or −0.11% yr^{-1}. Glaciers in the Tropical Andes (Peru, Bolivia) have depleted the most; median −56% of LIA area, and the fastest; median −0.16% yr^{-1}. Up to 10 × acceleration in glacier area loss has occurred in Tropical mountain sub-regions comparing LIA to 2,000 rates to post-2000 rates. Regional climate controls inter-regional variability, whereas local factors affect intra-region glacier response time. Analyzing glacier area change by river basins and by protected areas leads us to suggest that conservation and environmental management strategies should be re-visited as proglacial areas expand.

Plain Language Summary

Andean glaciers are melting fast but how that rate compares in a longer-term context is unknown. In this study we mapped the extent of >5,500 glaciers during the Little Ice Age, which was the last major glacial advance culminating about c. 150 years ago. We analyzed the change in glacier size and computed overall area change of −25% from the LIA to year 2000 at a rate of −36.5 km^2 per year or −0.11% per year. Glaciers within Peru and Bolivia have shrunk the most by median −56% of LIA area, and the fastest by median −0.16% per year. We discuss that these glaciers are depleting and retreating due to climate change but that response is compounded by glacier size, shape and terminus environment effects. As glaciers melt they reveal proglacial landscapes that tend to be highly unstable, impacting water resources, natural hazards and terrestrial and aquatic ecology.

1. Introduction

Glaciers and ice caps (GICs) across South America are depleting and retreating rapidly with climate change. GICs nearest the equator in Venezuela, Colombia and Ecuador have almost entirely disappeared since the last Late Holocene advance, commonly termed the Little Ice Age (LIA) that occurred c. 1,400 to c. 1,850 (Braun & Bezada, 2013; García et al., 2020; Poveda and Pineda, 2009; Rabatel et al., 2005, 2008, 2018; Van Wyk de Vries et al., 2022).

As atmospheric warming proceeds (Nuñez et al., 2009) and as precipitation patterns alter, for example, with snowfall increasingly delivered by fewer, more extreme precipitation events (Grimm, 2011; Vera et al., 2006), Andean GICs are shrinking, thinning and fragmenting (Braun et al., 2019). Glacier loss constitutes an immediate, urgent and profound threat to the ability of some parts of the Andean cryosphere to sustain downstream water usage and river flows especially during dry seasons (Bradley et al., 2006; Cai et al., 2020). Glacier loss also perturbs downstream water usage and water quality (Drenkhan et al., 2015; Immerzeel et al., 2020). Identification of the spatio-temporal variability in Andean GICs change is therefore needed not only for understanding regional factors that force land surface processes, but also for applied environmental, land and human resource management immediately downstream of the emerging proglacial areas.

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Recent decadal-scale changes to Andean GICs (e.g., Aniya et al., 1997; Braun et al., 2019; Dussaillant et al., 2019; Malmros et al., 2016; Rignot et al., 2003; Schneider et al., 2007; Willis et al., 2012) are spatio-temporally variable due to a diverse climatology across the Andes and also due to the variety of glacier types that are present including icefields, ice caps and mountain (valley and cirque) glaciers (Caro et al., 2021; Dussaillant et al., 2019; Sagredo and Lowell, 2012). Understanding of the recent GIC changes is also hindered due to a lack a longer-term centennial-scale context; exceptions being the LIA reconstruction for Patagonia (Davies et al., 2020; Davies and Glasser, 2012) and for some tropical cordilleras (Jomelli et al., 2009; Rabatel et al., 2008, 2013). A longer-term context is important for understanding the pace of changes occurring now. Furthermore, projections of Andean GICs into the future require base line data sets, such as past glacier extents and calibration, such as with hindcasts, over meaningful timeframes (hundreds of years) to inform on future glacier extent and freshwater yield, for example, to year 2,100.

The aim of this study is therefore to assess glacier extent across the Andes during the LIA chronozone and changes since then.

2. Data Sets and Methods

Existing centennial-scale changes of glaciers in South America (e.g., Davies et al., 2020; Davies and Glasser, 2012; Espizua and Pitte, 2009; Fernández-Navarro et al., 2023; García et al., 2020; Koch and Kilian, 2005; Licciardi et al., 2009; Masiokas et al., 2009, 2010; Meier et al., 2018; Rabatel et al., 2005, 2008, 2013; Sagredo et al., 2021) have been of individual regions or mountain massifs and have used a variety of methods of dating, mapping and measurements; for example, of glacier number, length, area and volume, which is prohibitive of robust comparisons between regions. In this study, we sought to implement a coherent and consistent workflow to enable analysis of large numbers of glaciers across the Andes (Figure 1). Specifically, we extended year 2000 glacier outlines (RGI Consortium, 2017) to LIA moraine crests and trimlines using the established workflows of Davies et al. (2020), Davies and Glasser, (2012), Meier et al. (2018), Carrivick and Heckmann et al. (2019), Carrivick and Boston et al. (2019), Carrivick et al. (2020, 2022, 2023) and Lee et al. (2021), and in accordance with many other sub-regional (e.g., Baumann et al., 2009; Weber et al., 2019, 2020) and national-coverage efforts of LIA glacier extent mapping (e.g., Fischer et al., 2015; Hannesdottir et al., 2020; Martín-Moreno et al., 2017).

To map LIA glacier extents, we firstly identified moraine crests and trimlines pertaining to the LIA where they have been directly dated (Figures S1 and S2 in Supporting Information S1). That work included compiling ∼540 published dates from ∼160 moraines (Table S2 in Supporting Information S1) and also obtaining new lichenometry data from sites in Peru and Bolivia for relative dating (Figure S3 in Supporting Information S1; supplementary. xlsx files in Supporting Information S2). After mapping LIA glacier extents at dated sites, we then mapped glacier outlines using morphostratigraphic principles to identify contiguous geomorphological evidence in neighboring valleys. Our mapping was primarily using sub-meter resolution WorldView/Geoeye imagery available from Maxar within ESRI ArcGIS Pro software. Our collective team experience of extensive fieldwork over many years assisted identification of LIA moraines, a few photographs of which are given as exemplars in Figure S4 in Supporting Information S1. For some additional topographic checks, such as for ice divides and shading, and also for elevation attributes, we queried the ALOS "AWD3D" 30 m resolution Digital Elevation Model (DEM), which is a photogrammetric DEM generated from high resolution (2.5 m) stereo images acquired by ALOS-PRISM between 2006 and 2,011.

This mapping protocol means that we did not include glaciers that have disappeared. We made a sensitivity check of this exclusion where we interpreted empty cirques above our estimated regional glaciation limit noting that almost all (98%) were <1 km^2 (Figure S5 in Supporting Information S1). We did not include the glaciers in Venezuela, Colombia and Ecuador, which have almost entirely disappeared since the LIA (Van Wyk de Vries et al., 2022). We identified geomorphological evidence pertaining to LIA glacier advances for all glaciers across Peru and Bolivia. In the Central Andes and across Patagonia we filtered the year 2000 glacier outlines to only include those >1 km^2.

Overall, across the Andes, we mapped 5501 LIA glacier outlines and these are available from Carrivick (2024). That number corresponds to 20% of the total number of glaciers in year 2000 (as inventoried in RGI_v6), and typically to 70% of total glacier area in year 2000 for 73 sub-regions (Table S1 in Supporting Information S1). We therefore consider our "sampling" to be representative of Andes glaciers and for individual sub-regions (Figure

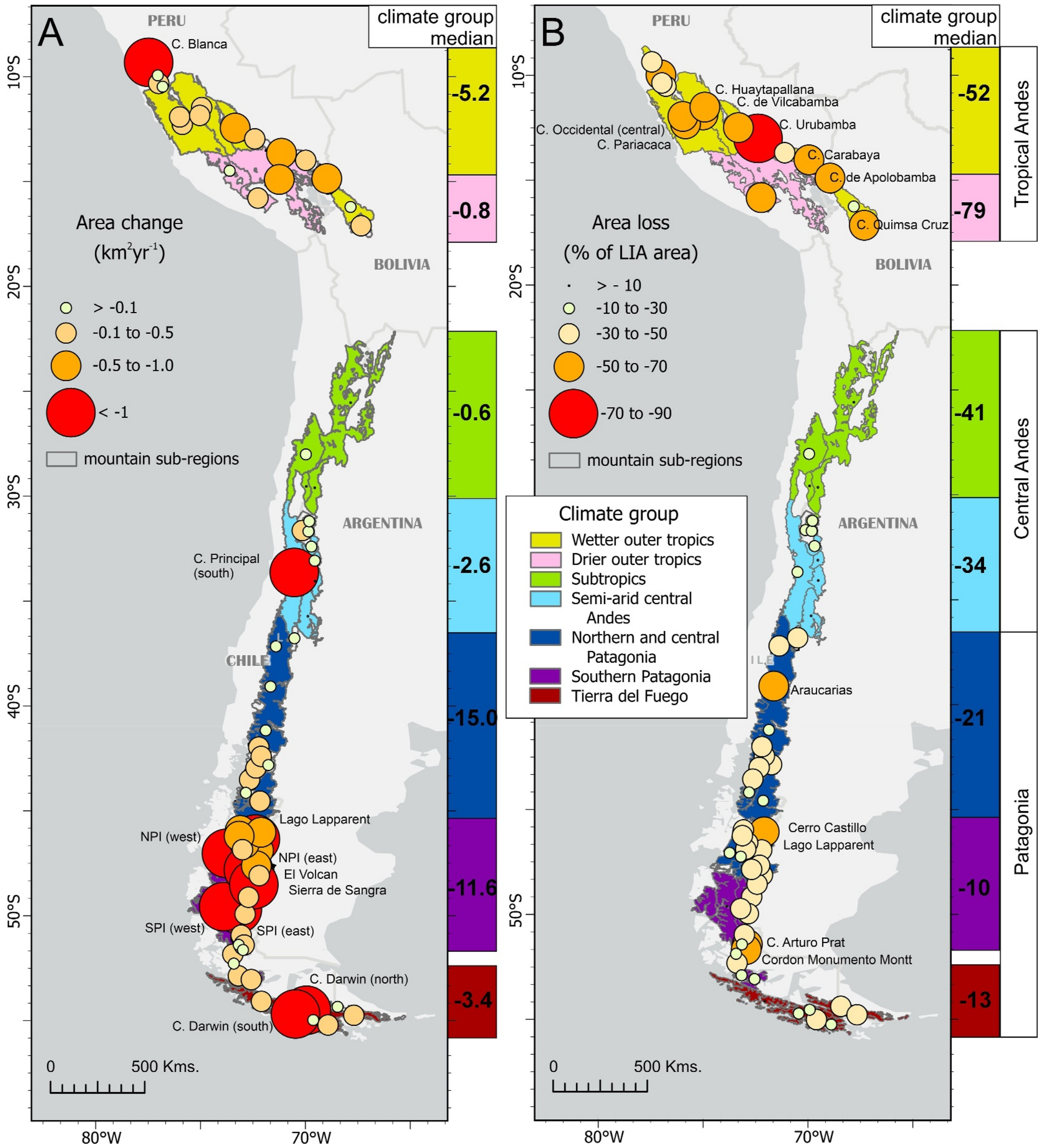

Figure 1. Change in glacier area since the Little Ice Age (LIA) across the Andes per climatically distinct region and mountain sub-region, expressed as an absolute rate $km^2\ yr^{-1}$ (a) and as a percentage of the mapped LIA area (b). Both panels display the median of all individual glacier area changes. Only sub-regions with the greatest changes ($>-1\ km^2\ yr^{-1}$; $< -50\%$) are labeled for clarity. Mountain sub-regions are named and sourced as depicted in Figure S6 in Supporting Information S1 and climatically-distinct regions are as identified by Sagredo and Lowell (2012).

S6 in Supporting Information S1), but nonetheless we focus our results reporting on changes to glaciers, which are calculated only for glaciers that have both a year 2000 and a LIA extent, rather than absolute areas per se. Due to a paucity of glacier mass balance data or other knowledge of equilibrium-line altitudes (ELAs) for contemporary Andean glaciers, we have not sought to reconstruct LIA ELAs, but rather we have analyzed the change in minimum elevation and in the median elevation of GICs between the LIA and 2,000 (Figures S7 and S8 in Supporting Information S1, respectively) for inferring climate forcings.

In order to convert our area changes to rates and to enable comparisons between Andes mountain regions and with other world regions, we had to select a date for the timing of glacier advance during the LIA. In this study, we estimated the ages of moraines in the Tropical Andes (Peru, Bolivia) and Central Andes (Chile, Argentina) using published local lichen growth curves (Supplementary Information, SI) and the probability density analysis of

Rowan (2017) that we applied to (a) the dimensions of hundreds of samples of lichens growing on boulders on the moraines of Tropical glaciers and (b) dates obtained from lichenometry, dendrochronology, radiocarbon, surface exposure (cosmogenic isotope) and historical documents Figure S2 and Table S2 in Supporting Information S1. Overall, we used a date of 1,660 for the Tropical Andes, 1,790 for the Central Andes and 1,870 for Patagonia (Table S4 in Supporting Information S1), whilst accepting the wide intra-region variability of dates (supplementary.xlsx files in Supporting Information S2). Our rates of change are sensitive to the choice of LIA date; for example, if the timing of the LIA occurred 20 years later then our calculated area loss rates (km^2 yr^{-1}) is more negative by 4% for the Tropical Andes, by 5% for the Central Andes, and by 15% for Patagonia. This variability and sensitivity mean that we do not make glacier-specific analyses, rather we analyze the medians of large groups of glaciers to reveal spatial patterns and temporal trends.

3. Results

Overall, we mapped a total area of LIA GICs of 31,938 km^2, compared to 23,917 km^2 of those same glaciers in year 2000. We therefore suggest that there has been a −25% change (i.e., a reduction) in glacier area across the Andes between the LIA and 2,000. The mean rate of GIC area change (area loss) across the Andes between the LIA and 2,000 has been −36.5 km^2 yr^{-1} or −0.11% yr^{-1} overall. Those rates are composed of −0.18 km^2 yr^{-1} or −0.16% yr^{-1} for the Tropical Andes, −0.1 km^2 yr^{-1} or −0.12% yr^{-1} for the Central Andes, and −0.47 km^2 yr^{-1} or −0.28% yr^{-1} for Patagonia.

At a sub-regional level, glacier area changes display considerable variability. Cordillera Blanca (Peru) and Cordillera Principal (Chile) are the two sub-regions outside of Patagonia with the largest rates of glacier area loss and more than −1 km^2 yr^{-1} (Figure 1a; Table S4 in Supporting Information S1). The west and the east sides of the Northern Patagonian Icefield (NPI) lost −2.7 km^2 yr^{-1} and −3.1 km^2 yr^{-1}, respectively. The west and east sides of the Southern Patagonian Icefield (SPI) lost −4.4 km^2 yr^{-1} and −15.3 km^2 yr^{-1}, respectively. Other sub-regions experiencing glacier area loss more than −1 km^2 yr^{-1} are Lago Lapparent, El Volcan and Sierra de Sangra. Several other Peruvian sub-regions; Cordillera de Vilcabamba, Cordillera de Vilcanota, Cordillera de Apolobamba and Cordillera Central (sur) have glacier area loss more than −0.5 km^2 yr^{-1} as are several sub-regions situated close to the NPI; Mount Hudson, Cerro Castillo National Reserve, Cerro Erasmo, Cordon La Parva, Parque Nacional Patagonia, and Monte San Lorenzo (Figure 1a; Table S4 in Supporting Information S1).

Considering the calculated glacier area loss as a proportion of the LIA area, then Cordillera Urubamba (−74%) is the only sub-region to exceed −70% of LIA glacier area change (loss) to 2,000 (Figure 1b; Table S4 in Supporting Information S1). The majority of the Peru and Bolivia sub-regions have exceeded −50% glacier area change since the LIA, as have several regions that are situated on the eastern side of the Patagonian Andes, namely; Cerro Castillo, Lago Lapparent, Cordillera Arturo Prat and Cordón Monumento Montt (Figure 1b; Table S4 in Supporting Information S1). The median glacier area change of all sub-regions is −41%, or −42% if the NPI and SPI are excluded.

Comparing to glacier area measurements for recent decades (and only considering those reported for large groups of glaciers) we find accelerated area change rates compared to the longer-term centennial-scale rate since the LIA (Figure 2). The magnitude of the acceleration is generally double on the east side of the Andes compared to on the west, and five to 10 times higher in the Tropical Andes (Peru, Bolivia) compared to Patagonia (Figure 2). We were unable to consider whether rates of glacier area loss have changed in the Central Andes due to a paucity of studies there on glacier changes in recent decades.

4. Discussion

The inter-regional pattern of glacierized area changes allows interpretation of climatic controls on GIC evolution. The large absolute rates of glacier area loss from the NPI, SPI and Cordillera Darwin and also from Cordillera Principal (Chile), Cordillera Blanca (Peru) and El Volcan (Argentina) (Figure 1a) are not surprising since those sub-regions have amongst the largest total glacierized areas, and it is well known that glacier area loss is a function of the initial area (e.g., Paul and Bolch, 2019; Paul et al., 2004). The latitudinal pattern is primarily dictated by climate; precipitation dominates glacier changes across the Outer Tropics and the semi-arid Central Andes, whereas air temperature exerts the greatest control across Patagonia (Caro et al., 2021; Villalba et al., 2003). The highest proportional rates of glacier area loss occur in the wetter tropical Andes (median −56% LIA area loss, median −0.16% yr^{-1}). These high rates of area loss likely reflect the strong sensitivity of glaciers in

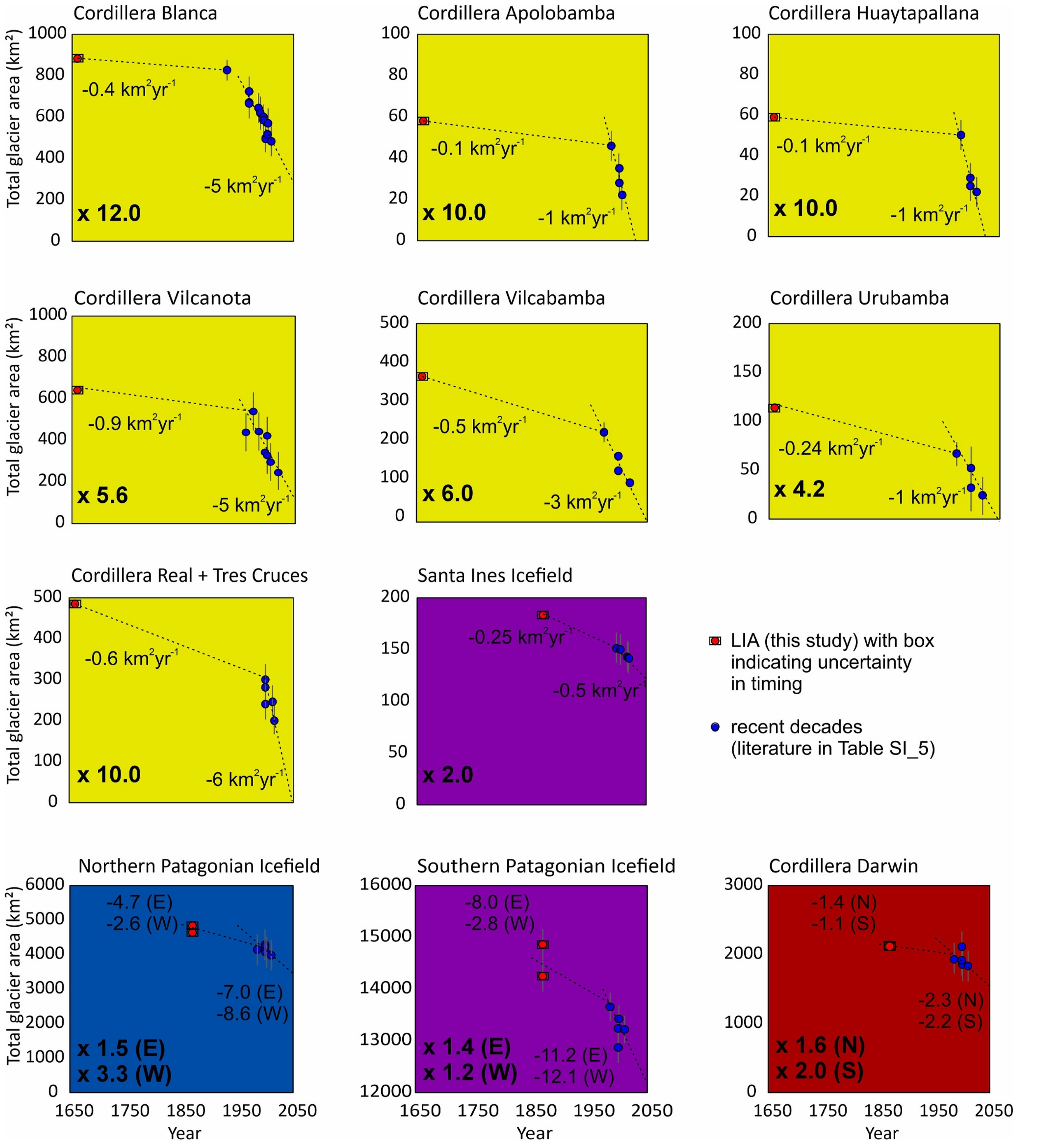

Figure 2. Rates of change and acceleration factor (bold number in lower left of each panel) of glacier area loss for selected sub-regions across the Andes. Selection of sub-regions was restricted by the coverage of our Little Ice Age mapping as well as by a paucity of studies concerning glacier area changes in recent decades in the Central Andes. Note varying y-scale. Background color for each panel corresponds to the climatically-distinct regions as mapped in Figure 1. Note that we sub-sampled within these sub-regions where necessary to maintain comparable sampling and coverage with the literature on post-2000 glacier areas (Table S5 in Supporting Information S1).

the wet Tropics to increases in air temperature which across the 0°C isotherm affect the phase of precipitation and increases melt rates through the albedo effect (Rabatel et al., 2013).

High intra-regional variability in GIC area change (Table S4 in Supporting Information S1) suggest local morpho-topographic factors are important. Relative rates of GIC area loss have been proportionally much lower for the outlet glaciers of the NPI and SPI compared to the rest of the Andes glaciers (Figure 1b, Table S4 in Supporting Information S1). This low proportional area loss could reflect that these icefields have an ice surface hypsometry and ice thickness distribution (Fürst et al., 2024) that encourages high velocity, but they also tend to have very high accumulation and high ablation rates, meaning steep mass balance gradients (e.g., Schaefer et al., 2015). Additionally, the low proportional area loss rates could also reflect a longer response time of icefield outlet glacier terminus position to climate forcing than for small mountain GICs (Jóhannesson et al., 1989; Raper and Braithwaite, 2009).

Relative glacier area loss comprises three spatial groups: Tropical with the highest relative loss, Patagonia with intermediate, and semi-arid Central Andes glaciers with the least relative change (Figure 1b). These groups, together with our acceleration factors (Figure 2), suggest that across the Andes the most pronounced glacier changes since the LIA have occurred in the Tropical Andes. However, it is more cautionary to say that Tropical glaciers are the most sensitive to climate change (cf. Vuille et al., 2008) and have responded the fastest and the greatest proportionally (Figure 1b).

The west–east pattern to our mountain sub-region median area changes (Figure 1b) and in our acceleration factors (Figure 2) also evidences a strong climatic control on glacier area changes. Vuille et al. (2008) and Espinoza et al. (2020) discuss the east-west differences in climate for the Tropics and for the whole Andes, respectively, which informs our interpretations of why glaciers in the dry east of the Central Andes have enhanced area loss rates compared to those in the wetter west, and the same in southern Patagonia (Figures 1a and 1b). Whereas temperature variations in northern Patagonia since the 1850s are dependent on sea surface temperature anomalies in the Pacific, temperature variations in southern Patagonia are controlled by sea surface temperatures over the South Atlantic (Villalba et al., 2003). The far lower rates of the west NPI and west SPI ($-0.09\%\ yr^{-1}$ and $-0.07\%\ yr^{-1}$, respectively) compared to the east probably reflect (i) Southern Annular Mode climate that causes the west to receive more snow and for snow to persist later in a season Garreaud et al., 2009, 2013).

In addition to regional climate forcing of glacier area loss, local factors including glacier elevation (Figures S7 and S8 in Supporting Information S1) cannot be ignored for some sub-regions. Indeed, elevation-dependent warming has occurred across most of the Andes (between 2000 and 2,017) but that warming (and even some sub-regional seasonal cooling) is spatio-temporally variable largely due to landcover albedo (Aguilar-Lome et al., 2019; Chimborazo et al., 2022). The compounding influences of climate and glacier system response time are manifest in (a) rising (>100 m) minimum elevation of GICs across the Andes (Figure S7 in Supporting Information S1) and (b) rising median elevation of GICs within all climatically-distinct regions and reduced elevation range of the median elevation of Tropical glaciers comparing during the LIA to 2,000 (Figure S8 in Supporting Information S1). The minimum elevation of GICs has risen the most (>250 m) for small GICs situated in the Central Andes and those surrounding and separate from the icefields in the east of southern Patagonia (Figure S7 in Supporting Information S1) and given that these two regions encompass relatively dry climates, an interpretation is that rising air temperature effects out-weigh the importance of (seasonal) precipitation for these small GICs (e.g., Fujita, 2008). However, GICs of these regions include a variety of types, including small cold-based glaciers (MacDonell et al., 2013; Rabatel et al., 2011) and small ice cap outlet glaciers such as those of Monte Burney, which is an active volcano that through enhanced geothermal heat flux affects the evolution of glacier thermal regime and dynamics. Both aspects are important to consider when understanding the sensitivity of GICs (e.g., Carrivick et al., 2023) to both past and present climate change across the Andes.

Terminus environment effects have likely also been important for controlling glacier area loss, particularly for the eastern side of Patagonia where very large ice-marginal lakes have developed within LIA glacier extents. Whereas the west NPI and west SPI have mass balance dominated by surface ablation (Fürst et al., 2024; Weidemann et al., 2018) albeit with tidewater effects on major outlet glaciers, the east NPI and east SPI rates ($-0.19\%\ yr^{-1}$ and $-0.24\%\ yr^{-1}$, respectively) reflect additional thermo-mechanical effects of ice-marginal lakes on glacier mass loss, such as at Upsala and Viedma (Malz et al., 2018; Minowa et al., 2021; Schaefer et al., 2015). The contrasting and relatively stable condition over the last century of Perito Moreno on the east of the SPI and the

Table 1
Comparison of Glacier Area Changes Since the LIA for Major World Regions Where Inventory-Style Mapping of Geomorphological Evidence has Been Completed for Hundreds to Thousands of Glaciers Per Region

N/S hemisphere	Region	Area change (% of LIA total)	Reference	Rate (% yr^{-1})
N	Western Italy	−78	Lucchesi et al., 2014	−0.5
N	Austria	−56	Fischer et al., 2015	−0.3
N	Switzerland	−50	Maisch, 2000	−0.4
			Zemp et al., 2008	
N	Altai	−48	Ganyushkin et al., 2022	−0.31
N	Himalaya	−40	Lee et al., 2021	−0.06 to −0.1
N	southern Norway	−35	Jotunheiman (Baumann et al., 2009)	−0.1
		−19	Jostedalsbreen (Carrivick et al., 2022)	−0.08
		−37	Hardangerjøkulen (Weber et al., 2019)	−0.2
N	NE Greenland	−22	Carrivick et al., 2019a, 2019b	−0.2
N	Iceland	−10 to −30	Hannesdóttir et al., 2000	−0.08 to −0.25
N	Svalbard	−13	Martín-Moreno et al., 2017	−0.12
N	Greenland	−5 overall	Carrivick et al., 2023	−0.05 overall
		−18 for CW sub-region		−0.18 CW sub-region
S	Drier outer tropics	−79	This study	−0.23
S	Wetter outer tropics	−52	This study	−0.15
S	Subtropics	−41	This study	−0.19
S	Semi-arid central Andes	−34	This study	−0.16
S	Northern and central Patagonia	−21	This study	−0.16
S	Tierra del Fuego	−13	This study	−0.10
S	Southern Patagonia	−10	This study	−0.08
S	Southern Alps, New Zealand	−24	Carrivick et al., 2020	−0.06

Note. Rate (column) is calculated in this study using date of LIA glacier advance as in Table S4 in Supporting Information S1.

presently-advancing state of Pío XI on the west of the SPI are both likely due to those glaciers having broad and high accumulation areas and relatively thin frontal tongues (Fürst et al., 2024).

Our geochronology and mapping address the data and knowledge gap of LIA glacier extent timing and mapping in the southern hemisphere (Table 1). Comparing our inventory-style mapping/reconstruction to other similar studies accomplished for entire mountain ranges or large regions, we find that the Andes are not unusual with an overall rate of ice loss of −0.11% yr^{-1} (Table 1). However, since the Andes encompasses such a large geographical extent and several major climatically-distinct regions as well as highly varied glacier types (so with varying hypsometry and volume; e.g. Carrivick et al., 2016), then it should be realized that the overall rate is rather skewed by the influence of a few mountain sub-regions; that is, the NPI, SPI and Cordillera Darwin (south Chile). Thus, perhaps the median rate, that is, the middle value of ranked sub-region rates, of −0.18% yr^{-1} is more representative of the Andes. The sub-region with the maximum rate of change is Lago Lapparent (−0.51% yr^{-1}), which is a rate amongst the highest anywhere worldwide and comparable to that calculated for parts of Italy in the eastern European Alps (Table 1).

The exceptionally rapid rate of glacier area loss shown here for some sub-regions of the Andes has profound implications for water resources, riverine habitats and downstream water quality so discriminating glacier changes by drainage basin (Figure 3a) is instructive for studies of those concerns. For example, the headwaters of the east-flowing Madre de Dios and Beni in the Tropics, and the headwaters of the east-flowing Desaguadero, have had the largest (>100 km^2 for each sub-basin) expansions of proglacial landscapes (Figure 3a). These proglacial landscapes contain a record of centennial-scale response to deglaciation and as such offer an insight into the likely future beyond 2,100. They perturb microclimate, possibly exacerbating glacier area loss via the albedo effect as they contain bedrock, soil, vegetation and lakes that are all substantially darker than glacier ice

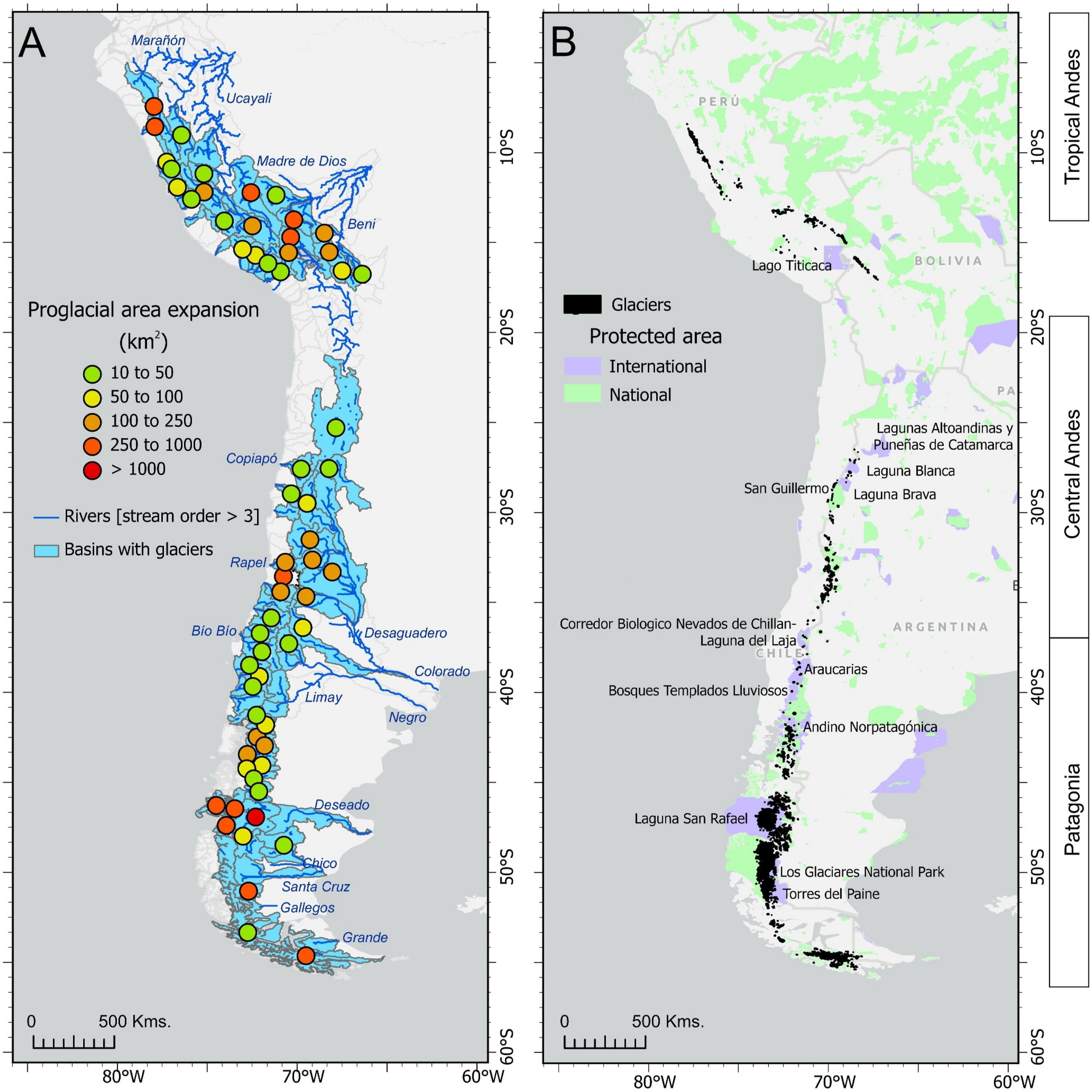

Figure 3. Proglacial area expansion as a function of glacier area loss per river catchment Little Ice Age to 2,000 (a) and per protected area (b). Only basins with the greatest changes (>60%) are labeled for clarity in A, and only protected areas with international designation and with glaciers within them are labeled for clarity in (b).

and snow (e.g., Carrivick et al., 2018; Carrivick & Heckmann et al., 2019, Carrivick & Boston et al., 2019; Grimes et al., 2024).

Proglacial landscapes can be expected to be exceptionally dynamic hydrologically and geomorphologically (cf. Carrivick and Heckmann, 2017; Lane et al., 2017; Carrivick et al., 2018; Carrivick & Heckmann et al., 2019; Carrivick & Boston et al., 2019). In particular, glacier moraine ridges, hillslopes that were abutting the glaciers until recently, and proglacial lakes can all be expected to be unstable, perhaps hazardous, and valley floor sedimentation will be dynamically adjusting to runoff regimes and base levels (Carrivick and Tweed, 2021; Lane et al., 2017). Therefore, Figure 3a highlights those river catchments where not only meltwater runoff but also sediment transport regimes have changed the most since the LIA. Regarding water quality (de)glaciation changes river runoff and river thermal regimes (e.g., Carrivick et al., 2012) and those physico-chemical properties define terrestrial and aquatic habitats. Indeed, fauna within these catchments must adapt quickly to survive within ecological niches that can be expected to shift (e.g., Brown et al., 2015, 2018; Milner et al., 2017) as recently modeled across the European Alps by Wilkes et al. (2023) and globally by Bosson et al. (2023). The influence on water quality of these rapidly deglaciating headwaters diminishes with distance downstream or at the scale of major drainage basins both in the tropical Andes (e.g., Buytaert et al., 2017) and across Patagonia (e.g., de Vries et al., 2023). However, as the majority of (year 2000) Andes glaciers are located within protected areas (Figure 3b) then as deglaciation proceeds and proglacial landscapes expand environmental management strategies for those areas should perhaps urgently consider revising policies for geodiversity and geosystems services conservation (Bollati et al., 2023), as well as for water resources.

5. Summary and Conclusions

We have mapped the extent of >5,500 glaciers and ice caps (GICs) during the LIA chronozone by improving the chronology and interpreting geomorphological evidence. We used a date for the LIA of 1,660 for the Tropical Andes, 1,790 for the Central Andes and 1,870 for Patagonia. Analyzing the areas and changes since, we find that the Andes have deglaciated by −25% in total and by −41% median of all sub-regions. Some Andes sub-regions have lost GIC area since the LIA at rates that are amongst the fastest of any world regions; $> -0.4\%\ yr^{-1}$. The rapid rates of glacier area loss across the Andes and inter-region variability can be attributed to climate and its spatial pattern, most notably air temperature. However, intra-region variability in glacier area change is high, and we contend that is due to the compounding local influences of glacier elevation and terminus environment on response time.

Overall our data sets provide a centennial-scale quantification of glacier changes. They are a crucial base line data set with which to hindcast and to spin-up numerical model simulations from. Model calibration can increase confidence in glacier evolution models, which if over a centennial-scale and with glacier responses to air temperature changes of ~2°C, then become very relevant for, and representative of, projections past 2,100. Our mapping of proglacial landscape expansion has identified river catchments where hydrology and geomorphology has changed the most extensively since the LIA and protected areas that are most rapidly adjusting to deglaciation.

Data Availability Statement

Our LIA glacier outlines (Carrivick, 2024) are available as shapefile polygons openly available from the CEDA Data Repository at https://dx.doi.org/10.5285/7545a606606c4e9bb6139dfc21a95264.

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References

Aguilar-Lome, J., Espinoza-Villar, R., Espinoza, J. C., Rojas-Acuña, J., Willems, B. L., & Leyva-Molina, W. M. (2019). Elevation-dependent warming of land surface temperatures in the Andes assessed using MODIS LST time series (2000–2017). *International Journal of Applied Earth Observation and Geoinformation*, *77*, 119–128. https://doi.org/10.1016/j.jag.2018.12.013

Aniya, M., Sato, H., Naruse, R., Skvarca, P., & Casassa, G. (1997). Recent glacier variations in the southern patagonia icefield, south America. *Arctic and Alpine Research*, *29*(1), 1–12. https://doi.org/10.2307/1551831

Baumann, S., Winkler, S., & Andreassen, L. M. (2009). Mapping glaciers in Jotunheimen, south-Norway, during the "Little Ice Age" maximum. *The Cryosphere*, *3*(2), 231–243. https://doi.org/10.5194/tc-3-231-2009

Bollati, I. M., Viani, C., Masseroli, A., Mortara, G., Testa, B., Tronti, G., et al. (2023). Geodiversity of proglacial areas and implications for geosystem services: A review. *Geomorphology*, *421*, 108517. https://doi.org/10.1016/j.geomorph.2022.108517

Bosson, J. B., Huss, M., Cauvy-Fraunié, S., Clément, J. C., Costes, G., Fischer, M., et al. (2023). Future emergence of new ecosystems caused by glacial retreat. *Nature*, *620*(7974), 562–569. https://doi.org/10.1038/s41586-023-06302-2

Bradley, R. S., Vuille, M., Diaz, H. F., & Vergara, W. (2006). Threats to water supplies in the tropical Andes. *Science*, *312*(5781), 1755–1756. https://doi.org/10.1126/science.1128087

Braun, C., & Bezada, M. (2013). The history and disappearance of glaciers in Venezuela. *Journal of Latin American Geography*, *12*(2), 85–124. https://doi.org/10.1353/lag.2013.0016

Braun, M. H., Malz, P., Sommer, C., Farías-Barahona, D., Sauter, T., Casassa, G., et al. (2019). Constraining glacier elevation and mass changes in South America. *Nature Climate Change*, *9*(2), 130–136. https://doi.org/10.1038/s41558-018-0375-7

Brown, L. E., Dickson, N. E., Carrivick, J. L., & Fuereder, L. (2015). Alpine river ecosystem response to glacial and anthropogenic flow pulses. *Freshwater Science*, *34*(4), 1201–1215. https://doi.org/10.1086/683062

Brown, L. E., Khamis, K., Wilkes, M., Blaen, P., Brittain, J. E., Carrivick, J. L., et al. (2018). Functional diversity and community assembly of river invertebrates show globally consistent responses to decreasing glacier cover. *Nature Ecology & Evolution*, *2*(2), 325–333. https://doi.org/10.1038/s41559-017-0426-x

Buytaert, W., Moulds, S., Acosta, L., De Bièvre, B., Olmos, C., Villacis, M., et al. (2017). Glacial melt content of water use in the tropical Andes. *Environmental Research Letters*, *12*(11), 114014. https://doi.org/10.1088/1748-9326/aa926c

Cai, W., McPhaden, M. J., Grimm, A. M., Rodrigues, R. R., Taschetto, A. S., Garreaud, R. D., et al. (2020). Climate impacts of the El niño–southern oscillation on south America. *Nature Reviews Earth and Environment*, *1*(4), 215–231. https://doi.org/10.1038/s43017-020-0040-3

Caro, A., Condom, T., & Rabatel, A. (2021). Climatic and morphometric explanatory variables of glacier changes in the Andes (8–55° S): New insights from machine learning approaches. *Frontiers in Earth Science*, *9*, 713011. https://doi.org/10.3389/feart.2021.713011

Carrivick, J. (2024). Andes glaciers and ice caps outlines during the Little Ice Age (LIA). *NERC EDS Centre for Environmental Data Analysis*. https://doi.org/10.5285/7545a606606c4e9bb6139dfc21a95264

Carrivick, J., Heckmann, T., Fischer, M., & Davies, B. (2019a). An inventory of proglacial systems in Austria, Switzerland and across Patagonia. In *Geomorphology of proglacial systems: Landform and sediment dynamics in recently deglaciated alpine landscapes* (pp. 43–57).

Carrivick, J. L., Andreassen, L. M., Nesje, A., & Yde, J. C. (2022). A reconstruction of Jostedalsbreen during the Little Ice Age and geometric changes to outlet glaciers since then. *Quaternary Science Reviews*, *284*, 107501. https://doi.org/10.1016/j.quascirev.2022.107501

Carrivick, J. L., Boston, C. M., King, O., James, W. H., Quincey, D. J., Smith, M. W., et al. (2019b). Accelerated volume loss in glacier ablation zones of NE Greenland, Little Ice Age to present. *Geophysical Research Letters*, *46*(3), 1476–1484. https://doi.org/10.1029/2018gl081383

Carrivick, J. L., Boston, C. M., Sutherland, J. L., Pearce, D., Armstrong, H., Bjørk, A., et al. (2023). Mass loss of glaciers and ice caps across Greenland since the Little Ice Age. *Geophysical Research Letters*, *50*(10), e2023GL103950. https://doi.org/10.1029/2023gl103950

Carrivick, J. L., Brown, L. E., Hannah, D. M., & Turner, A. G. (2012). Numerical modelling of spatio-temporal thermal heterogeneity in a complex river system. *Journal of Hydrology*, *414*, 491–502. https://doi.org/10.1016/j.jhydrol.2011.11.026

Carrivick, J. L., Davies, B. J., James, W. H., Quincey, D. J., & Glasser, N. F. (2016). Distributed ice thickness and glacier volume in southern South America. *Global and Planetary Change*, *146*, 122–132. https://doi.org/10.1016/j.gloplacha.2016.09.010

Carrivick, J. L., & Heckmann, T. (2017). Short-term geomorphological evolution of proglacial systems. *Geomorphology*, *287*, 3–28. https://doi.org/10.1016/j.geomorph.2017.01.037

Carrivick, J. L., Heckmann, T., Turner, A., & Fischer, M. (2018). An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps. *Geomorphology*, *321*, 117–128. https://doi.org/10.1016/j.geomorph.2018.08.030

Carrivick, J. L., James, W. H., Grimes, M., Sutherland, J. L., & Lorrey, A. M. (2020). Ice thickness and volume changes across the southern Alps, New Zealand, from the little ice age to present. *Scientific Reports*, *10*(1), 13392. https://doi.org/10.1038/s41598-020-70276-8

Carrivick, J. L., & Tweed, F. S. (2021). Deglaciation controls on sediment yield: Towards capturing spatio-temporal variability. *Earth-Science Reviews*, *221*, 103809. https://doi.org/10.1016/j.earscirev.2021.103809

Chimborazo, O., Minder, J. R., & Vuille, M. (2022). Observations and simulated mechanisms of elevation-dependent warming over the Tropical Andes. *Journal of Climate*, *35*(3), 1021–1044. https://doi.org/10.1175/jcli-d-21-0379.1

Davies, B. J., Darvill, C. M., Lovell, H., Bendle, J. M., Dowdeswell, J. A., Fabel, D., et al. (2020). The evolution of the Patagonian Ice Sheet from 35 ka to the present day (PATICE). *Earth-Science Reviews*, *204*, 103152. https://doi.org/10.1016/j.earscirev.2020.103152

Davies, B. J., & Glasser, N. F. (2012). Accelerating shrinkage of patagonian glaciers from the little ice age (∼ AD 1870) to 2011. *Journal of Glaciology*, *58*(212), 1063–1084. https://doi.org/10.3189/2012jog12j026

De Vries, M. V. W., Romero, M., Penprase, S. B., Ng, G. H. C., & Wickert, A. D. (2023). Increasing rate of 21st century volume loss of the Patagonian Icefields measured from proglacial river discharge. *Journal of Glaciology*, 1–16.

Drenkhan, F., Carey, M., Huggel, C., Seidel, J., & Oré, M. T. (2015). The changing water cycle: Climatic and socioeconomic drivers of water-related changes in the Andes of Peru. *Wiley Interdisciplinary Reviews: Water*, *2*(6), 715–733. https://doi.org/10.1002/wat2.1105

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., et al. (2019). Two decades of glacier mass loss along the Andes. *Nature Geoscience*, *12*(10), 802–808. https://doi.org/10.1038/s41561-019-0432-5

Espinoza, J. C., Garreaud, R., Poveda, G., Arias, P. A., Molina-Carpio, J., Masiokas, M., et al. (2020). Hydroclimate of the Andes part I: Main climatic features. *Frontiers in Earth Science*, *8*, 64. https://doi.org/10.3389/feart.2020.00064

Espizua, L. E., & Pitte, P. (2009). The little ice age glacier advance in the Central Andes (35 S), Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *281*(3–4), 345–350. https://doi.org/10.1016/j.palaeo.2008.10.032

Fernández-Navarro, H., García, J. L., Nussbaumer, S. U., Tikhomirov, D., Pérez, F., Gärtner-Roer, I., et al. (2023). Fluctuations of the universidad glacier in the Andes of central Chile (34° S) during the latest Holocene derived from a 10Be moraine chronology. *Quaternary Science Reviews*, *300*, 107884. https://doi.org/10.1016/j.quascirev.2022.107884

Fischer, A., Seiser, B., Stocker Waldhuber, M., Mitterer, C., & Abermann, J. (2015). Tracing glacier changes in Austria from the Little Ice Age to the present using a lidar-based high-resolution glacier inventory in Austria. *The Cryosphere*, *9*(2), 753–766. https://doi.org/10.5194/tc-9-753-2015

Fujita, K. (2008). Effect of precipitation seasonality on climatic sensitivity of glacier mass balance. *Earth and Planetary Science Letters*, *276*(1–2), 14–19. https://doi.org/10.1016/j.epsl.2008.08.028

Fürst, J. J., Farías-Barahona, D., Blindow, N., Casassa, G., Gacitúa, G., Koppes, M., et al. (2024). The foundations of the Patagonian icefields. *Communications Earth & Environment*, *5*(1), 142. https://doi.org/10.1038/s43247-023-01193-7

Ganyushkin, D., Chistyakov, K., Derkach, E., Bantcev, D., Kunaeva, E., Terekhov, A., & Rasputina, V. (2022). Glacier recession in the altai mountains after the LIA maximum. *Remote Sensing*, *14*(6), 1508. https://doi.org/10.3390/rs14061508

García, J. L., Hall, B. L., Kaplan, M. R., Gomez, G. A., De Pol-Holz, R., García, V. J., et al. (2020). 14C and 10Be dated Late Holocene fluctuations of Patagonian glaciers in Torres del Paine (Chile, 51 S) and connections to Antarctic climate change. *Quaternary Science Reviews*, *246*, 106541. https://doi.org/10.1016/j.quascirev.2020.106541

Garreaud, R., Lopez, P., Minvielle, M., & Rojas, M. (2013). Large-scale control on the Patagonian climate. *Journal of Climate*, *26*(1), 215–230. https://doi.org/10.1175/jcli-d-12-00001.1

Garreaud, R. D., Vuille, M., Compagnucci, R., & Marengo, J. (2009). Present-day south american climate. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *281*(3–4), 180–195. https://doi.org/10.1016/j.palaeo.2007.10.032

Grimes, M., Carrivick, J. L., Smith, M. W., & Comber, A. J. (2024). Land cover changes across Greenland dominated by a doubling of vegetation in three decades. *Scientific Reports*, *14*(1), 3120. https://doi.org/10.1038/s41598-024-52124-1

Grimm, A. M. (2011). Interannual climate variability in South America: Impacts on seasonal precipitation, extreme events, and possible effects of climate change. *Stochastic Environmental Research and Risk Assessment*, *25*(4), 537–554. https://doi.org/10.1007/s00477-010-0420-1

Hannesdóttir, H., Sigurðsson, O., Þrastarson, R. H., Guðmundsson, S., Belart, J. M., Palsson, F., et al. (2000). A national glacier inventory and variations in glacier extent in Iceland from the Little Ice Age maximum to 2019. *Jökull Journal*, *12*, 1–34. https://doi.org/10.33799/jokull.70.001

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Jóhannesson, T., Raymond, C. F., & Waddington, E. D. (1989). A simple method for determining the response time of glaciers. In *Glacier fluctuations and climatic change: Proceedings of the symposium on Glacier fluctuations and climatic change, held in Amsterdam, 1–5 June 1987* (pp. 343–352). Springer.

Jomelli, V., Favier, V., Rabatel, A., Brunstein, D., Hoffmann, G., & Francou, B. (2009). Fluctuations of glaciers in the tropical Andes over the last millennium and palaeoclimatic implications: A review. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *281*(3–4), 269–282. https://doi.org/10.1016/j.palaeo.2008.10.033

Koch, J., & Kilian, R. (2005). 'Little Ice Age' glacier fluctuations, gran campo Nevado, southernmost Chile. *The Holocene*, *15*(1), 20–28. https://doi.org/10.1191/0959683605hl780rp

Lane, S. N., Bakker, M., Gabbud, C., Micheletti, N., & Saugy, J. N. (2017). Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology*, *277*, 210–227. https://doi.org/10.1016/j.geomorph.2016.02.015

Lee, E., Carrivick, J. L., Quincey, D. J., Cook, S. J., James, W. H., & Brown, L. E. (2021). Accelerated mass loss of himalayan glaciers since the little ice age. *Scientific Reports*, *11*(1), 24284. https://doi.org/10.1038/s41598-021-03805-8

Licciardi, J. M., Schaefer, J. M., Taggart, J. R., & Lund, D. C. (2009). Holocene glacier fluctuations in the Peruvian Andes indicate northern climate linkages. *Science*, *325*(5948), 1677–1679. https://doi.org/10.1126/science.1175010

Lucchesi, S., Fioraso, G., Bertotto, S., & Chiarle, M. (2014). Little Ice Age and contemporary glacier extent in the western and south-western Piedmont Alps (north-western Italy). *Journal of Maps*, *10*(3), 409–423. https://doi.org/10.1080/17445647.2014.880226

MacDonell, S., Kinnard, C., Mölg, T., Nicholson, L., & Abermann, J. (2013). Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile. *The Cryosphere*, *7*(5), 1513–1526. https://doi.org/10.5194/tc-7-1513-2013

Maisch, M. (2000). The long-term signal of climate change in the Swiss Alps: Glacier retreat since the end of the Little Ice Age and future ice decay scenarios. *Geografia Fisica e Dinamica Quaternaria*, *23*(2), 139–151.

Malmros, J. K., Mernild, S. H., Wilson, R., Yde, J. C., & Fensholt, R. (2016). Glacier area changes in the central Chilean and Argentinean Andes 1955–2013/14. *Journal of Glaciology*, *62*(232), 391–401. https://doi.org/10.1017/jog.2016.43

Malz, P., Meier, W., Casassa, G., Jaña, R., Skvarca, P., & Braun, M. H. (2018). Elevation and mass changes of the southern patagonia icefield derived from TanDEM-X and SRTM data. *Remote Sensing*, *10*(2), 188. https://doi.org/10.3390/rs10020188

Martín-Moreno, R., Allende Alvarez, F., & Hagen, J. O. (2017). Little Ice Age' glacier extent and subsequent retreat in Svalbard archipelago. *The Holocene*, *27*(9), 1379–1390. https://doi.org/10.1177/0959683617693904

Masiokas, M. H., Luckman, B. H., Villalba, R., Delgado, S., Skvarca, P., & Ripalta, A. (2009). Little ice age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas, South Patagonian Andes, Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *281*(3–4), 351–362. https://doi.org/10.1016/j.palaeo.2007.10.031

Masiokas, M. H., Luckman, B. H., Villalba, R., Ripalta, A., & Rabassa, J. (2010). Little ice age fluctuations of glaciar río manso in the north patagonian Andes of Argentina. *Quaternary Research*, *73*(1), 96–106. https://doi.org/10.1016/j.yqres.2009.08.004

Meier, W. J. H., Grießinger, J., Hochreuther, P., & Braun, M. H. (2018). An updated multi-temporal glacier inventory for the Patagonian Andes with changes between the Little Ice Age and 2016. *Frontiers in Earth Science*, *6*, 62. https://doi.org/10.3389/feart.2018.00062

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., et al. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, *114*(37), 9770–9778. https://doi.org/10.1073/pnas.1619807114

Minowa, M., Schaefer, M., Sugiyama, S., Sakakibara, D., & Skvarca, P. (2021). Frontal ablation and mass loss of the Patagonian icefields. *Earth and Planetary Science Letters*, *561*, 116811. https://doi.org/10.1016/j.epsl.2021.116811

Nunez, M. N., Solman, S. A., & Cabré, M. F. (2009). Regional climate change experiments over southern South America. II: Climate change scenarios in the late twenty-first century. *Climate Dynamics*, *32*(7–8), 1081–1095. https://doi.org/10.1007/s00382-008-0449-8

Paul, F., & Bolch, T. (2019). Glacier changes since the little ice age. In *Geomorphology of proglacial systems: Landform and sediment dynamics in recently deglaciated alpine landscapes* (pp. 23–42).

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., & Haeberli, W. (2004). Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters*, *31*(21). https://doi.org/10.1029/2004gl020816

Poveda, G., & Pineda, K. (2009). Reassessment of Colombia's tropical glaciers retreat rates: Are they bound to disappear during the 2010–2020 decade? *Advances in Geosciences*, *22*, 107–116. https://doi.org/10.5194/adgeo-22-107-2009

Rabatel, A., Castebrunet, H., Favier, V., Nicholson, L., & Kinnard, C. (2011). Glacier changes in the Pascua-Lama region, Chilean Andes (29 S): Recent mass balance and 50 yr surface area variations. *The Cryosphere*, *5*(4), 1029–1041. https://doi.org/10.5194/tc-5-1029-2011

Rabatel, A., Ceballos, J. L., Micheletti, N., Jordan, E., Braitmeier, M., González, J., et al. (2018). Toward an imminent extinction of Colombian glaciers? *Geografiska Annaler - Series A: Physical Geography*, *100*(1), 75–95. https://doi.org/10.1080/04353676.2017.1383015

Rabatel, A., Francou, B., Jomelli, V., Naveau, P., & Grancher, D. (2008). A chronology of the Little Ice Age in the tropical Andes of Bolivia (16 S) and its implications for climate reconstruction. *Quaternary Research*, *70*(2), 198–212. https://doi.org/10.1016/j.yqres.2008.02.012

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., et al. (2013). Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *The Cryosphere*, *7*(1), 81–102. https://doi.org/10.5194/tc-7-81-2013

Rabatel, A., Jomelli, V., Naveau, P., Francou, B., & Grancher, D. (2005). Dating of little ice age glacier fluctuations in the tropical Andes: Charquini glaciers, Bolivia, 16 S. *Comptes Rendus Geoscience*, *337*(15), 1311–1322. https://doi.org/10.1016/j.crte.2005.07.009

Raper, S. C., & Braithwaite, R. J. (2009). Glacier volume response time and its links to climate and topography based on a conceptual model of glacier hypsometry. *The Cryosphere*, *3*(2), 183–194. https://doi.org/10.5194/tc-3-183-2009

RGI Consortium. (2017). Randolph glacier inventory–a dataset of global glacier outlines: Version 6.0: Technical report, global land ice measurements from space [Dataset]. *Digital Media*. https://nsidc.org/data/nsidc-0770/versions/6

Rignot, E., Rivera, A., & Casassa, G. (2003). Contribution of the patagonia icefields of south America to sea level rise. *Science*, *302*(5644), 434–437. https://doi.org/10.1126/science.1087393

Rowan, A. V. (2017). The 'Little Ice Age' in the Himalaya: A review of glacier advance driven by northern hemisphere temperature change. *The Holocene*, *27*(2), 292–308. https://doi.org/10.1177/0959683616658530

Sagredo, E. A., & Lowell, T. V. (2012). Climatology of Andean glaciers: A framework to understand glacier response to climate change. *Global and Planetary Change*, *86*, 101–109. https://doi.org/10.1016/j.gloplacha.2012.02.010

Sagredo, E. A., Reynhout, S. A., Kaplan, M. R., Aravena, J. C., Araya, P. S., Luckman, B. H., et al. (2021). Holocene history of río tranquilo glacier, monte San Lorenzo (47° S), Central Patagonia. *Frontiers in Earth Science*, *9*, 813433. https://doi.org/10.3389/feart.2021.813433

Schaefer, M., Machguth, H., Falvey, M., Casassa, G., & Rignot, E. (2015). Quantifying mass balance processes on the southern patagonia icefield. *The Cryosphere*, *9*(1), 25–35. https://doi.org/10.5194/tc-9-25-2015

Schneider, C., Schnirch, M., Acuña, C., Casassa, G., & Kilian, R. (2007). Glacier inventory of the gran Campo Nevado ice cap in the southern Andes and glacier changes observed during recent decades. *Global and Planetary Change*, *59*(1–4), 87–100. https://doi.org/10.1016/j.gloplacha.2006.11.023

Van Wyk de Vries, M., Carchipulla-Morales, D., Wickert, A. D., & Minaya, V. G. (2022). Glacier thickness and ice volume of the Northern Andes. *Scientific Data*, *9*(1), 342. https://doi.org/10.1038/s41597-022-01446-8

Vera, C., Silvestri, G., Liebmann, B., & González, P. (2006). Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. *Geophysical Research Letters*, *33*(13). https://doi.org/10.1029/2006gl025759

Villalba, R., Lara, A., Boninsegna, J. A., Masiokas, M., Delgado, S., Aravena, J. C., et al. (2003). Large-scale temperature changes across the southern Andes: 20th-century variations in the context of the past 400 years. *Climatic Change*, *59*(1), 177–232. https://doi.org/10.1007/978-94-015-1252-7_10

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., & Bradley, R. S. (2008). Climate change and tropical Andean glaciers: Past, present and future. *Earth-Science Reviews*, *89*(3–4), 79–96. https://doi.org/10.1016/j.earscirev.2008.04.002

Weber, P., Boston, C. M., Lovell, H., & Andreassen, L. M. (2019). Evolution of the Norwegian plateau icefield Hardangerjøkulen since the 'Little Ice Age'. *The Holocene*, *29*(12), 1885–1905. https://doi.org/10.1177/0959683619865601

Weber, P., Lovell, H., Andreassen, L. M., & Boston, C. M. (2020). Reconstructing the Little Ice Age extent of Langfjordjøkelen, Arctic mainland Norway, as a baseline for assessing centennial-scale icefield recession. *Polar Research*, *39*(0). https://doi.org/10.33265/polar.v39.4304

Weidemann, S. S., Sauter, T., Malz, P., Jaña, R., Arigony-Neto, J., Casassa, G., & Schneider, C. (2018). Glacier mass changes of lake-terminating grey and Tyndall glaciers at the southern patagonia icefield derived from geodetic observations and energy and mass balance modeling. *Frontiers in Earth Science*, *6*, 81. https://doi.org/10.3389/feart.2018.00081

Wilkes, M. A., Carrivick, J. L., Castella, E., Ilg, C., Cauvy-Fraunié, S., Fell, S. C., et al. (2023). Glacier retreat reorganizes river habitats leaving refugia for Alpine invertebrate biodiversity poorly protected. *Nature Ecology & Evolution*, *7*(6), 1–11. https://doi.org/10.1038/s41559-023-02061-5

Willis, M. J., Melkonian, A. K., Pritchard, M. E., & Rivera, A. (2012). Ice loss from the southern Patagonian ice field, south America, between 2000 and 2012. *Geophysical Research Letters*, *39*(17). https://doi.org/10.1029/2012gl053136

Zemp, M., Paul, F., Hoelzle, M., & Haeberli, W. (2008). *Glacier fluctuations in the European Alps, 1850–2000*. Darkening Peaks Glacier Retreat Sci. Soc.

References From the Supporting Information

Barcaza, G., Nussbaumer, S. U., Tapia, G., Valdés, J., García, J. L., Videla, Y., et al. (2017). Glacier inventory and recent glacier variations in the Andes of Chile, South America. *Annals of Glaciology*, *58*(75pt2), 166–180. https://doi.org/10.1017/aog.2017.28

Ferri, L., Dussaillant, I., Zalazar, L., Masiokas, M. H., Ruiz, L., Pitte, P., et al. (2020). Ice mass loss in the Central Andes of Argentina between 2000 and 2018 derived from a new glacier inventory and satellite stereo-imagery. *Frontiers in Earth Science*, *8*, 530997. https://doi.org/10.3389/feart.2020.530997

García, J. L., Hall, B. L., Kaplan, M. R., Vega, R. M., & Strelin, J. A. (2014). Glacial geomorphology of the Torres del Paine region (southern Patagonia): Implications for glaciation, deglaciation and paleolake history. *Geomorphology*, *204*, 599–616. https://doi.org/10.1016/j.geomorph.2013.08.036

Raup, B. H., Racoviteanu, A., Khalsa, S. J. S., Helm, C., Armstrong, R., & Arnaud, Y. (2007). The GLIMS Geospatial glacier database: A new tool for studying glacier change. *Global and Planetary Change*, *56*(1–2), 101–110. https://doi.org/10.1016/j.gloplacha.2006.07.018

Snethlage, M. A., Geschke, J., Spehn, E. M., Ranipeta, A., Yoccoz, N. G., Körner, C. H., et al. (2022). A hierarchical inventory of the world's mountains for global comparative mountain science. *Nature Scientific Data*, *9*(1), 149. https://doi.org/10.1038/s41597-022-01256-y

RGI 7.0 Consortium. (2023). *Randolph Glacier inventory - a dataset of global glacier outlines, Version 7.0*. NSIDC: National Snow and Ice Data Center. https://doi.org/10.5067/f6jmovy5navz