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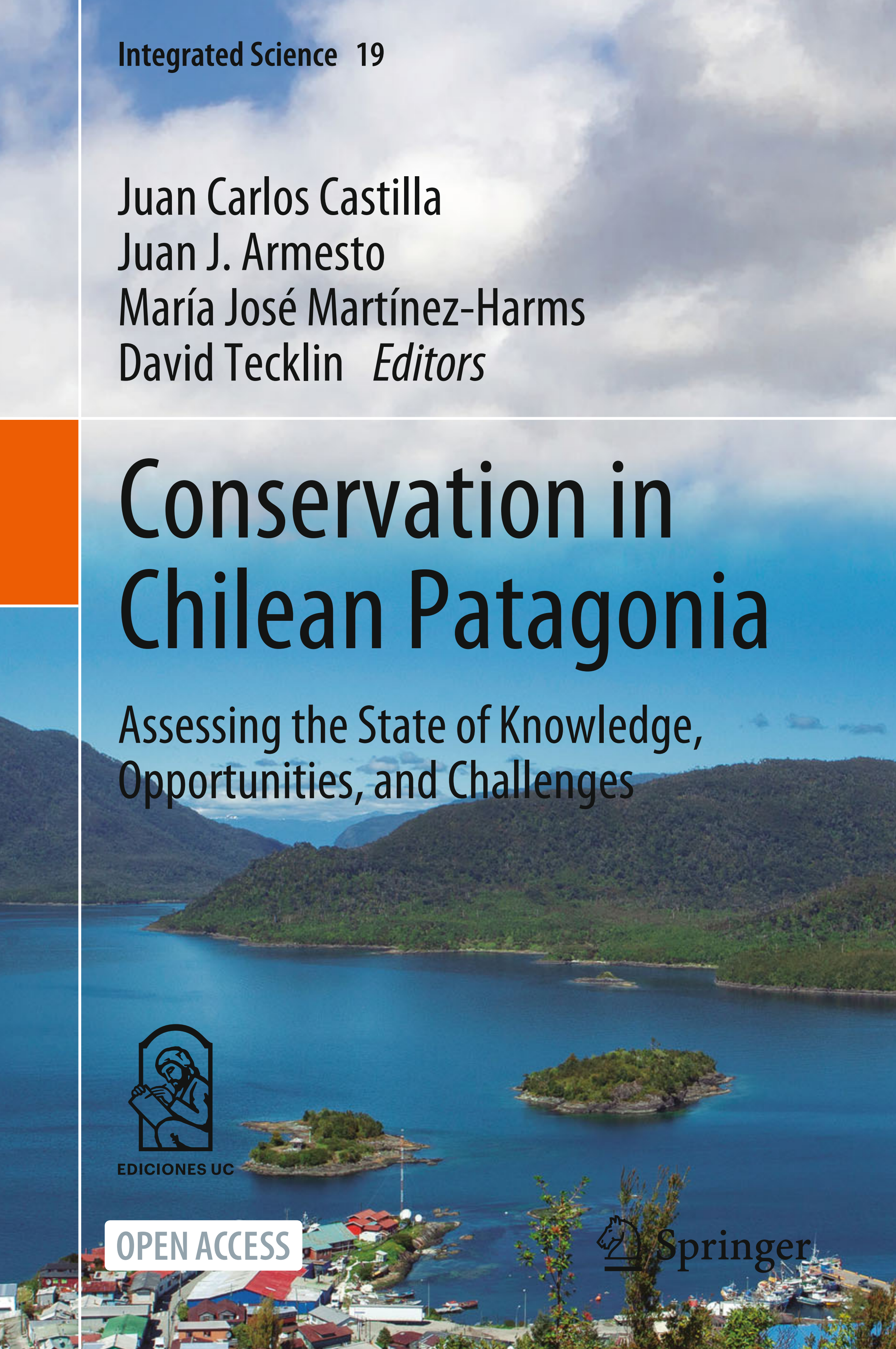
Conservation in Chilean Patagonia

Assessing the State of Knowledge, Opportunities, and Challenges



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Chilean Patagonian Glaciers and Environmental Change

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Andrés Rivera, Juan Carlos Aravena, Alejandra Urra, and Brian Reid

Abstract

Patagonian glaciers (41°–56°S) have experienced strong volume losses and retreats during recent decades in response to the climatic changes affecting this part of Chile, contributing significantly to global sea level rise. These changes have had an impact on the region's ecosystems, due to processes such as the expansion of fjords and lakes, altered hydrology and geology risks, higher sediment loads contributed to rivers, and changes in the altitude and composition of nearby vegetation. These factors affecting the ecosystem services provided by glaciers, such as runoff and flood regulation, slope stability, biodiversity, and cultural services they generate as one of the few remaining pristine components of the Earth. The recent changes in glacier volume make them highly vulnerable to the adverse effects of ongoing climate change, a condition that affects other Subantarctic natural systems of Chile. We emphasize the need to enhance the systematic monitoring of glacier volume and surface extent in Patagonia.

Keywords

Patagonia • Chile • Glaciers • Geological risks • Ecosystem services

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1 Introduction

Glaciers are perennial ice masses with firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation, and showing evidence of present or past flows. This definition includes four elementary characteristics of a glacier: (i) composition (water in a solid state, mainly ice); (ii) origin (solid precipitation on land that recrystallizes to form ice); (iii) temporality (long-lived); (iv) dynamics (flow). This implies that glaciers are climatically open systems, and therefore their volumetric and dynamic changes are susceptible to modification. Each of these characteristics has increasing levels of complexity, for example, in terms of what makes up a glacier, as it may contain water in a liquid state, especially in summer when melting can be very high; it may also contain a large amount and diversity of supra-, intra- and sub-glacial rock material, including cryoconites, coarse sediments, detritus and large (erratic) clasts. In many cases glaciers have their own ecosystem, so they can be considered as biomes [1], containing different types of extremophile organisms including microalgae and insects, such as the “Patagonian dragon” stonefly (*Andiperla winklii*), of which very little is known [2].

Therefore, a glacier is not only the ice that exists in the mountain range; it is a complex natural ecosystem that is associated with a contributing basin that generates rivers with meltwater (surface and/or underground), and also produces icebergs when it terminates in a lake or fjord. The environmental importance and effects of glaciers and their changes are not restricted to their basins, but cascade downstream, even impacting coastal marine environments where the water from melting snow and ice flow into them [3].

These multiple spatial and temporal cascading relationships mean that glaciers provide a range of ecosystem services relevant to human well-being [4], including: (i) water provision (e.g. drinking water, irrigation, power generation); (ii) sediment and nutrient inputs (e.g. fertilization of rivers, lakes, and coastal areas associated with aquaculture resources); (iii) flow regulation (*hydrological regime in dry periods); (iv) flood mitigation* (regulation of flash floods, glacial lake outburst floods or GLOFs); (v) slope conservation (e.g. slope stability and its geological hazards); (vi) biodiversity conservation (e.g. maintenance of wildlife corridors and glacier lake outburst floods, high Andean vegetation, microbial components of glacial surfaces); and (vii) cultural services (e.g. tourism, sports, national identity, sense of belonging). These ecosystem services [5] have decreased over time due to deglaciation, which has affected most of the planet’s mountain glaciers since the mid-nineteenth century, a period that has been called the Anthropocene [6].

This chapter will analyze the glaciers located in Chilean Patagonia, understood as the region of the southern Andes located from 41°S to the southern tip of the continent, which historically has also been called western Patagonia. In this region there are glaciers on the western slope of the Andes and some on the eastern slope, especially in the Southern Patagonia Icefield (SPI), the largest ice mass in South America [7].

Fig. 1 Location and identification of the main glaciers in Patagonia, together with the great Patagonian ice fields

2 Scope and Objectives

This chapter describes the current state of glaciers in Chilean Patagonia (Fig. 1), their ecosystem services, and the possible environmental consequences of the current process of glacial retreat affecting this territory of Chile.

3 Materials and Methods

To conduct this analysis, published scientific literature and grey literature in the ISI Web of Knowledge core collection database (http://apps.webofknowledge.com) were reviewed. Publications with a focus on glaciers in western Patagonia were selected. Google Scholar and sources available in regional institutions were also reviewed.

4 Results

4.1 The Glaciers of Chilean Patagonia

Glacier fluctuations during the Quaternary were the main agent shaping the present landscape of the entire Patagonia region. During the last glaciations, the glaciers formed a large ice cap that covered practically the entire western slope of the continent south of the Island of Chiloé, reaching the oceanic shelf (except for some possible local ecological refuges, as will be seen later). On the eastern slope the glaciers extended towards the Patagonian plains with different magnitudes, forming large lobes that contributed meltwater to the Atlantic Ocean. The onset of deglaciation about 19,000 years before present (BP) [8] transformed the western slope of Patagonia into the Aysén and Magallanes archipelagos, divided by hundreds of fjords and channels, while on the eastern slope the main ice lobes transformed into the large piedmont lakes, General Carrera/Buenos Aires or O'Higgins/San Martín, whose waters began to drain into the Pacific Ocean along deep valleys that dissected the remnants of the mountain range. South of the SPIF, the depth of Quaternary erosion was so significant that the Pacific fjords joined the basins abandoned by the glacial lobes, forming the Otway and Skyring sounds, or joined the Atlantic Ocean, forming the Strait of Magellan.

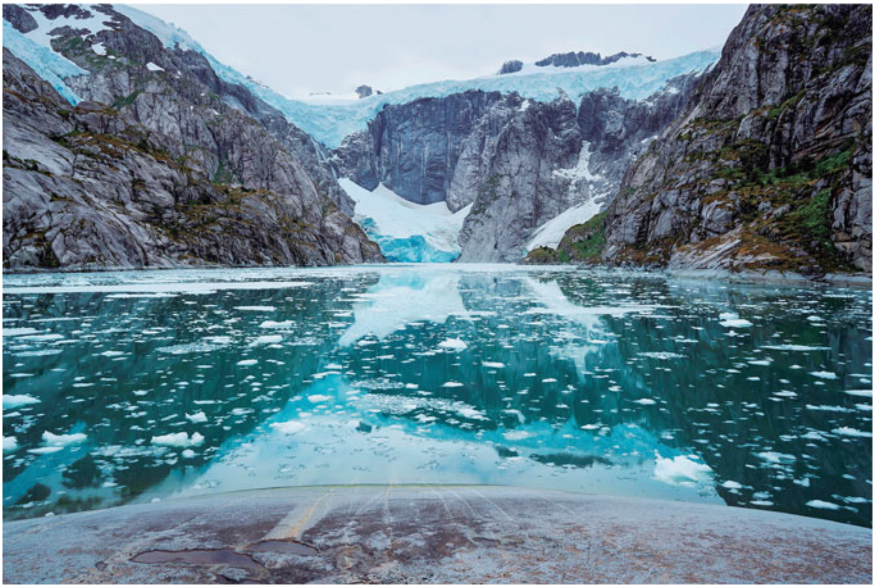
The current remnants of this great glaciation are thousands of glaciers located in the upper parts of the mountains, many of which are volcanoes associated with the Liquiñe Ofqui mega fault [9]. However, the main glacier masses are concentrated in the North and South Patagonian ice fields, which are semi-continuous masses of about 4,000 and 12,300 km^2 area, respectively (Dusaillant et al. 2019). The present long-term deglaciation, with numerous Holocene fluctuations [10], has been accentuated since the Little Ice Age, the last period that showed advances in the vast majority of the planet's glaciers, and which ended in Patagonia approximately 150 years BP [11].

Many glaciers have experienced retreat and thinning in recent decades in Chile, synchronously with volume losses throughout the Andes [12]. These changes relate importantly to increasing atmospheric temperatures, especially the warming experienced by the high Andes in Chile south to 46 °S [13], and by the precipitation decrease observed in several regions of the country, including eastern Patagonia, to about 49°S [14]. However, from the SPIF to the Darwin Range precipitation trends appear to reverse [15] and no definite tendencies are detected in atmospheric temperatures at higher altitudes (no data, only models), although an increase of 0.73 °C was recorded in the city of Punta Arenas between 1960 and 2010 [16].

The combined effect of both processes is that the elevation of the snow line has risen, especially in those glaciers outside the ice fields, negatively impacting snow accumulation and also causing a phase change in precipitation, shifting from solid to liquid in the lower areas of the glaciers, even in winter [17]. Detected a contrasting picture between 2000 and 2015 in the Northern Patagonia Icefield (NPI) and SPI (Fig. 1), with positive trends in snow accumulation on the western slopes and negative trends on the eastern slope. This would imply that the increased snow accumulation is partly offsetting the effects of regional atmospheric warming on glacial retreat, which could even lead to stability or even re-advancement of some glacier tongues, as in the few exceptions observed in the Andes [11].

There are 18,954 glaciers in Chilean Patagonia, with a total area of 22,463 km^2, equivalent to almost 95% of Chile's ice area [18]. It has been estimated that a specific rate of 0.78 ± 0.25 m of water equivalent were lost per year between 2000 and 2018 in this southern region [12], a figure only surpassed by Alaska and other Arctic regions. This amount has been increasing for several decades, contributing significantly to global sea level rise [19].

Due to the large number and diversity of glaciers in Patagonia, an important part of the country's glaciological research is concentrated in this southern area, particularly in the Northern and Southern Ice Fields, where the number and size of proglacial lakes has also expanded due to the retreat and thinning of the ice, many of which have experienced (or could suffer) sudden emptying [20]. Important lahars or rapid debris flows have been generated in this region as a consequence of ice melting due to volcanic activity, such as that detected in the Hudson volcano [9].



Clove Peninsula, Alberto de Agostini National Park, Magallanes and Chilean Antarctica Region. Photograph by Nicolás Piwonka

Very diverse glacier behavior has been detected in the NPI, the largest temperate ice mass in the Southern Hemisphere outside Antarctica; some have experienced strong retreat, while acceleration of ice flow has been observed in several cases in recent decades [21]. These retreats have been accompanied by significant volume loss [12], although there are few exceptions to this trend, the most important being the Pío XI glacier (also called Brüggen), which has been in a maximum neoglacial position since the early 1990s, when it began to overtake centennial trees present on its margins [22].

These different behaviors are attributed to the fact that most NPI glaciers produce icebergs in fjords or lakes, where glacial behavior is correlated with the depth of these bodies of water. When a glacier ends in a fjord or deep lake, its front can be unstable and respond dynamically with strong retreat once it loses its equilibrium with medium-term climatic conditions [23].

The strong losses in area in recent decades also appear to be accelerating in the vast majority of NPI and SPI glaciers. This implies that glaciers remain significantly out of balance with respect to current climate conditions. Recent modelling indicates that there are positive mass balances in the last decades, so that the dynamic responses of the ice (thinning and acceleration of ice flow) are in equilibrium with the current climate conditions. Thinning and acceleration of ice flow by longitudinal extension due to the higher rate of iceberg production at the terminal front are the main factors explaining mass loss in the area, followed by strong melting in the lower parts or ablation zones [21]. South of the Strait of Magellan there has also been contrasting behavior in recent decades, with strong retreats in some glaciers, (e.g. Marinelli Glacier) and advances in others, such as the Garibaldi Glacier [24]. Patagonian glaciers located outside the ice fields have also shown strong retreats and mass losses, such as in Mount San Lorenzo [25] and continental Chiloé [26].

Despite the important advances in glaciological knowledge in Chile, we are just discovering some of the basic characteristics of glaciers, such in ice thicknesses. [27] determined that the existing ice of the NPI and SPI together has a total volume of 4,756 km^3, almost 40 times more than the glacier volume in the Alps. There is also insufficient knowledge about the ecosystem impacts of the deglaciation process, potential effects are addressed in the following sections.

4.2 Environmental Effects of Glacial Changes in Patagonia

Areas freed from ice since the Little Ice Age have given way to hundreds of proglacial lakes, many of which have been dammed by thrust moraines formed when glaciers over-excavated pre-existing valleys. In other cases, these lakes have formed on the margins of glaciers, being dammed by ice (Fig. 2). It can be argued that not all meltwater has been lost to the sea, since an important part has been stored in lakes and wetlands, which have subsoil with unconsolidated Quaternary material. Since proglacial lakes are not stable in many cases, the risk of sudden

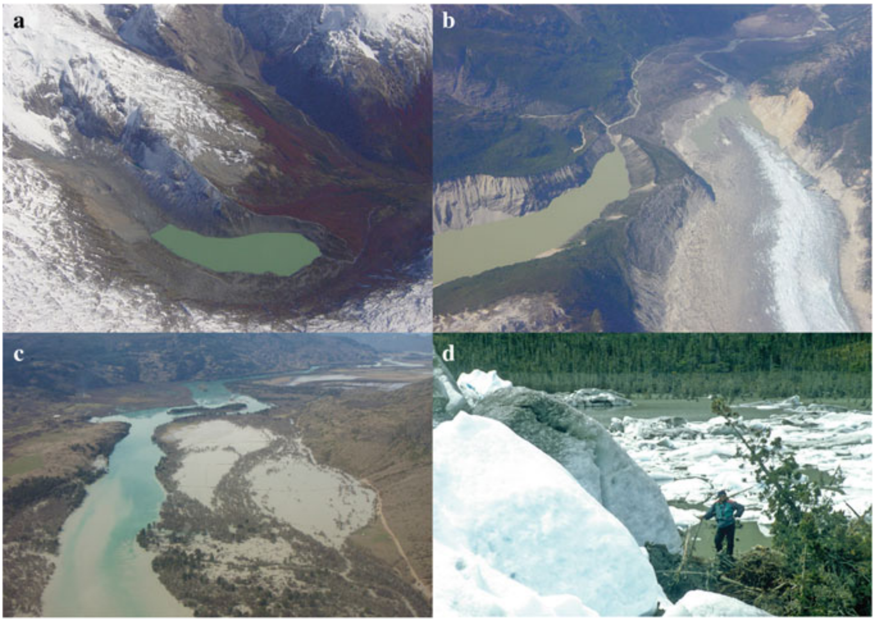


Fig. 2 Chilean Patagonia: examples of proglacial lakes and environmental effects of their changes. **a** Lake dammed by thrust moraines that are uncovered/covered by vegetation on its inner/outer margins. **b** On the left a lake formed by the retreat of the Hyades Glacier and on the right another lake in formation by the retreat of the Soler glacier of the NPI. **c** Flooding of the Baker River valley due to the emptying of Lake Cachet 2 in 2008. **d** Proglacial lake dammed by the advance of the Pío XI Glacier of the SPI in 1993. Photos: Andrés Rivera

emptying is high, as has occurred repeatedly in Lake Cachet 2, dammed by the NPI Colonia Glacier [20].

Another consequence of glacial retreat is that the areas abandoned by the ice have significant geological instability. The glaciers carry and push moraine material that accumulates on the margins and fronts, being partly retained by the ice. These areas may collapse as the buried ice disappears, covering the glaciers or generating rock avalanches such as the one that occurred. on the margin of the Chico Glacier of the SPI (Fig. 3a). In other cases, lateral terraces are formed while buttressed by ice, which can later crack and are susceptible to landslides when they lose support. Cracks may also form in valley walls indicating the position which a glacier reached in the past (trimline), often without vegetation following retreat and thinning, such as those that occur in the terrain that was occupied by the Upsala glacier until about 1945 (Fig. 3b).

An increase in hydrogeological risks has also been observed due to the instability of the fluvioglacial plains formed downstream of the thrust moraines, which are eroded by glacial streams (Fig. 3c), especially during periods of flooding and/or high flows produced by rapid melting of ice during heat waves or heavy rainfall. These phenomena have become more recurrent in recent years [28]. Another

Fig. 3 Examples of hydrological and geological risks associated with glaciers in Patagonia. *Photos* Andrés Rivera (**a**, **c** and **d**), Esteban Lannutti **b**

example are mudflows resulting from heavy rainfall events, such as those that saturated the slopes of the Burritos River valley, causing a process of slope failure that fell partly on a mountain lake and partly on a glacier in 2017 (Fig. 3d) leading to the devastation Villa Santa Lucía.

One of the most prominent effects of glacial changes is geomorphological, particularly in lakes and fjords, many of which have expanded (Fig. 4a and b), generating significant hydrographic and lacustrine changes (Fig. 4c). In some exceptional cases the opposite has occurred, as in the Pío XI of the SPI, which has advanced and formed a thrust moraine due to the high rate of accumulated sedimentation at the head of Eyre Fjord (Fig. 4c).

Finally, there is the glacio-volcanic interaction in Patagonia, where volcanic activity is frequent near glaciers, causing landslides, mudflows, deformations and sudden melting of ice and formation of lahars. Deglaciation has generally been associated with increased volcanic activity due to the effect of ice discharge on volcanic edifices [29], and it cannot be ruled out that this is happening today at Reclus Volcano (Fig. 4a).

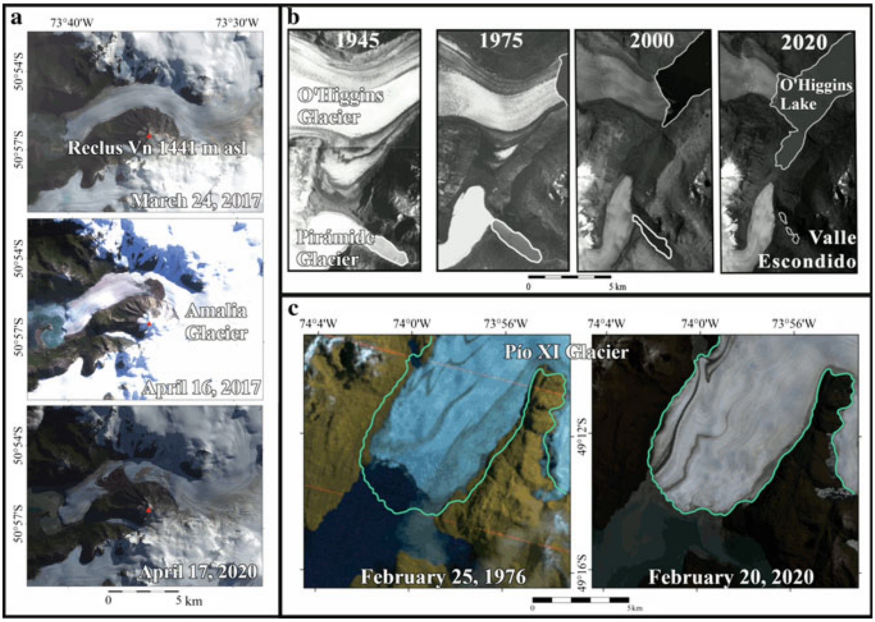


Fig. 4 Chilean Patagonia: examples of glacial changes in the SPI and their effects on the environments. **a** North slope landslide of Reclus Volcano in April, 2017 when part of the tongue of Amalia Glacier was covered. **b** Changes in flow direction of Pirámide Glacier in response to the retreat of O'Higgins Glacier. **c** Generation of a frontal moraine on the Pío XI Glacier in response to its almost uninterrupted advance since 1976. The green line in the 1976 image indicates the extension of the glacier in 2020

4.3 Effects of Glacial Fluctuations on Vegetation and Wildlife

The long-term fluctuations of Patagonian glaciers described in the previous sections of this chapter have generated important environmental modifications in periglacial ecosystems. For example, some effects on vegetation have produced changes in the altitude of high Andean plant community formations, in the underlying forest formations and wetlands, as well as variation in their floristic composition [3, 30], along with changes in the dynamics of natural and anthropogenic disturbances, such as variations in the recurrence of fires and insect attacks.

These types of environmental variation generated by glacial fluctuations also determine the increase or decrease in the surface areas covered by high Andean and forest vegetation formations that share a common limit in the altitudinal gradient. Sustained periods of decrease in the altitude of the zero-isotherm due to lower temperatures and increased ice masses have led to an expansion of the area of high Andean vegetation and a consequent compression of the area occupied by forest formations, with decreases in the altitude of the upper tree line [31].

Glacial advances have conditioned the upper limit of the forests, further compressing the area available for vegetation. The opposite has occurred in warm periods, where the area that expands is that occupied by forests, with an increase in the altitude of tree line and the zero isotherm, compressing the area covered by high Andean vegetation [32]. Changes such as these have repercussions at various levels. The floristic composition of the aforementioned communities can vary from changes in the abundance of taxa to modifications due to the exit/entry of species, which can be expressed in modifications in the diversity of the communities [33]. More extreme changes may involve complete replacement of plant formations with variation in the proportion of arboreal versus non-arboreal vegetation, or of species assemblages with an affinity to grow in conditions of higher or lower humidity [34]. Environmental variations also have an impact on the natural disturbance regime to which plant formations are subjected. For example, the occurrence of fires decreases in cold and humid phases and increases in dry and warm phases. A record that provides evidence of this effect for the last 3,000 years in Chilean Patagonia [34] shows a very good fit of dry and warm phases with the increase in charcoal particle counts associated with the increase in natural and/or anthropogenic fires. All these aspects demonstrate the importance of these periglacial ecosystems subject to glacial fluctuations and their importance in the study of macroecological patterns [28] and evolutionary and successional processes of plant communities.

Environmental fluctuations associated with glacial advance or retreat have determined the formation or interruption of biological corridors associated with periglacial environments of great importance in the connectivity of animal populations, with a significant effect on their conservation, evolution, and genetic diversity, for example the populations of huemul (*Hippocamelus bisulcus*) that inhabit the periglacial areas of the SPI [35]. These populations are relicts of the last ice age, this species is endemic to the southern Andes of South America, adapted to cold conditions and high slopes and irregular terrain, including rocky terraces and cliff edges. The species forms small, isolated groups, which scientists have interpreted as an adaptation to periglacial mountain environments subjected to recurrent and extensive glaciations and the subsequent fragmentation of their habitat, and the restriction and reduction of available resources. These conditions of climate and vegetation oscillation, and recurrence of glacial periods during the Pleistocene meant the creation of geographic barriers that currently result in disjunct animal populations, with refuges of high genetic diversity such as Wellington Island (49°S), west of the SPI. Glaciers and their long-term fluctuations have also determined environmental refuges in semi-permanent water bodies for fish such as catfish (*Hatcheria*), and macroinvertebrates such as *Plecoptera* and *Aeglidae* [36].

4.4 Biogeochemical Effects of Patagonian Glaciers

The fjord systems of Chilean Patagonia are fed by freshwater discharges from continental runoff, rivers, and glacier tributaries. These systems have low salinity, low density, strong stratification and are low in nitrate (NO_3^-) and orthophosphate ($PO_4$3-), but high in silicic acid derived from the erosion of rocky substrates [37]. The fjords are also fed by Subantarctic oceanic waters which have high nutrient concentration ($NO_3^- > 12$ μM and $PO_{43}^- > 1$ μM) but a low concentration of silicic acid [38].

These sub-Antarctic waters interact strongly with freshwater input from large river discharge and glacier melt, causing marked horizontal and vertical salinity gradients in the coastal marine environments of the Chilean Patagonian region. The horizontal input of freshwater runoff in these cases has an important effect on the spatio-temporal patterns of phytoplankton, including biomass distribution, mainly because freshwater has effects on phytoplankton productivity in both surface ocean waters and fjords [39].

The impact that increased freshwater input generated by glacial melt due to climate change could have on Chilean Patagonia is important for the following reasons: (i) this water creates a stratification in the water column that favors phytoplankton growth, but at the same time can reduce the supply of nutrients in the vertical mixing of the water column [38], (ii) glacial runoff and ice floes detached from glacial fronts that end in fjords are likely to act as fertilizers, as they are rich in organic matter in solution derived from terrestrial ecosystems, and have other nutrients that come from substrates such as iron, phosphorus, nitrogen, and silica [3, 40], (iii the high concentration of suspended particles in glacial runoff can have a double effect, adding more nutrients downstream [41], but they can also create light-limiting conditions for plankton within the fjords [37]. These impacts are likely to intensify in the Patagonian fjords as freshwater flows increase in the face of higher increased temperature scenarios.

In any case, the effects of glacial melt on ecosystems (positive such as fertilization or negative such as low transparency/salinity) may undergo profound changes over time depending on the characteristics (e.g. geological conditions) of each large watershed.

5 Conclusions and Recommendations

Since the end of the period known as the Little Ice Age, which began about 150 years BP, most of the glaciers in Chilean Patagonia have been losing mass at an accelerated rate, affecting the regional environment with increased geological, hydrogeological, and glacio-volcanic risks. The ongoing deglaciation is also affecting the vegetation surrounding the glaciers, modifying their altitudinal zoning and floristic composition. The flow and chemical composition of rivers have also been modified [42]. The lakes and fjords that receive glacial meltwater flows have also experienced variations in their nutrient concentrations and productivity [43]. All these changes are a warning that cannot be ignored, especially when all scenarios of future climate change indicate that impacts could be exacerbated, possibly crossing important ecological thresholds [28].

These impacts are much more marked in smaller glaciers and those located at lower altitudes, which are more vulnerable to disappear, affecting the surrounding natural and human communities. Numerous proposals have emerged to address these impacts, which aim to overcome the gaps and deficiencies in the existing information in Patagonia [11]. These include the need to determine more precisely the total volume of glacier ice, to validate future change models with more and better data, and to determine more precisely the associated natural risks. A multidisciplinary approach is required to carry out these tasks, which promotes cooperation for the establishment of systematic long-term glacier monitoring programs, and to this end we recommend:

- The installation of networks of measuring instruments close to glaciers (especially at their source and terminus), spatially arranged in high altitude areas and on rocky outcrops surrounded by ice (nunataks). These networks of monitoring stations should record multiple parameters, including oceanographic, limnological, hydrological, and climatological variables. It would be desirable for the instruments to have the capability to transmit data in real time, and their sensors should meet international standards to ensure quality data capture. These networks should be subject to periodic maintenance and their data should be available for unrestricted public access and use.
- The intensification and extension of campaigns to measure glaciers and surrounding areas with geophysical prospecting methods such as radar, sonar, gravimeters, and LiDAR (Laser Imaging Detection and Ranging), all of which would allow a more precise characterization of glaciers. The main unknowns of Patagonian glaciers are ice thicknesses, mass balances, flow, and sediment input.

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