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Historical records of Cipreses glacier (34°S): combining documentary-inferred 'Little Ice Age' evidence from Southern and Central Chile

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Abstract: The historical behaviour of Cipreses glacier from the nineteenth through the early twentieth century is described based on written records, cartography, iconography and photographs. These data allow us to infer that the last maximum advance of Cipreses glacier attributable to the 'Little Ice Age' occurred around AD 1842. The first historical retreat was recorded in 1858 and, since then, the glacier has shown a clear retreating trend with no new advances. All this information was compared with the historical data gathered for San Rafael glacier, which shows the occurrence of a cold period contemporary with the European LIA. Whereas Cipreses glacier was retreating by 1858, San Rafael glacier was advancing, reaching its last maximum between 1857 and 1875. The dates for the advances and retreats reveal a time-lag of approximately 30 years in the responses of these glaciers. The comparison of timing in glacier advances suggests that this time-lag is due to changes in precipitation and temperature associated mainly with fluctuations of the Westerlies.

Key words: Historical records, glaciers, 'Little Ice Age' (LIA), Central and Southern Chile, combining information.

Introduction

Worldwide, the 'Little Ice Age' (LIA) is one of the most recognized and studied climatic events of the late Holocene (Bradley and Jones, 1993; Bradley, 1994; Pollisar *et al*., 2006). This period (generally AD 1550–1850) was characterised by decreasing temperatures and glacier expansion (Jones and Bradley, 1992; Bradley, 2000). However, in comparison with the Northern Hemisphere, few studies have looked at the LIA in the Southern Hemisphere and even fewer consider the relevant evidence compiled in Chile. This lack of information hampers our ability to understand and predict future global climate changes (Villalba, 1990; Bradley and Jones, 1993; Nesje and Dahl, 2003). Although the LIA has been broadly recognized, its timing and synchronicity as a global phenomenon are still the subject of considerable discussion (Bradley and Jones, 1993; Mann *et al*., 1998; Goosse *et al*., 2005).

Pollisar *et al*. (2006) used a proxy of glacial activity in Venezuela to identify four peaks of glacier advances: 1180–1350, 1450–1590, 1640–1730 and 1800–1820, with the Andean expression of the LIA occurring from 1180 to 1820. In the Southern Hemisphere, the classic paper of Thompson *et al*. (1986) on ice cores from Quelccaya (Southern Peru) reports the LIA between 1530 and 1900, with a predominance of wetter conditions between AD 1500 and 1720, followed by a dry period between AD 1720 and 1860 and an intensification of cold conditions between 1800 and 1820. Recently, Solomina *et al*. (2007) found evidence of glacier advances in Cordillera Blanca (Peru) between 1520 and 1720 and between 1780 and 1880. Villalba (1990) used tree ring records from South-Central Argentina (41°10′S; 71°46′W) to identify a cold-moist period between 1270 and 1670, peaking around 1340

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and 1640; this falls within the temporal frame of the Northern Hemisphere LIA (Lamb, 1977; Jones *et al*., 1998). Later, Cioccale (1999) recognised the occurrence of two cold pulses of LIA in Central Argentina, the first from the fifteenth to sixteenth centuries, and the second and most important from the early eighteenth until the beginning of the nineteenth century. In another location of the Southern Hemisphere, Williams *et al*. (2004) studied speleotherms in New Zealand, finding evidence of a warm period coincident with the 'Medieval Warm Period' of Europe, followed by a temperature decrease 325 years ago, during the LIA. Also in New Zealand, McKinzey *et al*. (2004) found evidence, based on tree ring counts and tree diameters (DBH, Diameter Breast Height), of three possible advances of the Franz Josef glacier during the LIA: 'LIA 1' before 1600, 'LIA 2' *c*. 1600 and 'LIA 3' by 1800. In the southernmost Andes, specifically at Gran Campo Nevado glacier (53°S), Kilian *et al*. (2007) identified moraine formation from 1220 to 1460, then again *c*. 1620 and 1910, associated with the manifestation of the LIA in the area.

Several approaches are used to reconstruct the past climate in recent centuries. Of these, glacier fluctuations in mountainous and maritime areas are recognized as useful tools (Rignot *et al*., 2003; Winkler, 2004; Glasser *et al*., 2005) because of their sensitivity to changes in precipitation and/or temperature. Besides, a comprehensive understanding of glacier fluctuations is very important, among other reasons, because (1) predictions of climate change should be based on better estimates of recent climate variability, for which glacier fluctuations are highly relevant, and (2) people profit from the presence of glaciers, which provide meltwater for hydropower reservoirs and irrigation systems (Oerlemans *et al*., 1998; Le Quesne *et al*., 2008).

Most information regarding glacial behaviour is based on lichenometry studies, radiocarbon chronology, vegetational aspects and geomorphological studies (Winchester *et al*., 2001; McKinzey *et al*., 2004; Glasser *et al*., 2005). Only a few studies have considered the use of historical information on glacier fluctuations (Gellatly, 1985; Araneda *et al*., 2007). Although this proxy has one of the highest temporal resolutions for studying climate change in the last centuries (Bradley and Jones, 1993), and according to Brimblecombe (2005) its specificity in time or place is not equalled by other climate proxies. In the Northern Hemisphere, especially in Europe, there is an extensive source of historical data, which, in some cases, comprises detailed descriptions that allow good reconstructions of glacier behaviour (Holzhauser and Zumbühl, 2002; Brázdil *et al*., 2005). In Chile, the use of historical records to infer past climate has been underestimated, although, since the nineteenth century, the government of the nascent Chilean republic, in an attempt to improve knowledge of the country's nature, hired important European naturalists and scientists who summarized their research in several highly detailed documents.

In the Southern Hemisphere, the use of historical data for inferring glacier fluctuations is even less developed. This is sometimes due to the fact that series of documentary data are not as extensive or regular as elsewhere, and because the available sources (or their depository) are unknown or have restricted access (Prieto and García Herrera, 2008). Furthermore, there are few sites (the Southern Alps of New Zealand, Patagonia and the Southern Andes) at which to study extratropical glacier fluctuations (Winkler, 2004).

Gellatly (1985) used only historical documents to reconstruct glacier behaviour in the New Zealand Alps (Hooker, Mueller, Tasman, Godley and Classen glaciers at Mt Cook National Park) between the second half of the nineteenth century and the first half of the twentieth century, indicating the culmination of glacier expansion around 1860. Elsewhere in the Southern Hemisphere, Araneda *et al*. (2007) reconstructed the glacier front fluctuations of San Rafael glacier in Northern Patagonia, using only historical data and validating the use of this proxy for studying recent climate change in Chile. Hence, the aim of this research is to perform a new analysis and interpretation of the known historical sources that describe the behaviour of Cipreses glacier during the nineteenth century. We compare this information with that gathered for San Rafael glacier in an attempt to evaluate whether the cold conditions inferred for the LIA in Northern Patagonia were already occurring in Central Chile. This information is also contrasted with data from New Zealand, the other area in the Southern Hemisphere with extratropical glaciers. New evidence of a cold period similar to the Northern Hemisphere LIA coming from observations of the glaciers of Patagonia, Central Chile and New Zealand would strengthen the assumption that the LIA was a regional rather than a local event.

Study area

The Cipreses glacier is located in the Cachapoal river watershed between approximately 34°33′S, 70°22′W and 34°37′S, 70°21′W, in the administrative region 'Región del Libertador General Bernardo O'Higgins' and around 56 km northeast of San Fernando city (Figure 1). The glacier itself is confined within a sierra called 'Sierra del Brujo' (Lliboutry, 1956) and the main tongue is currently at 2640 m a.s.l. However, during the nineteenth century, the glacier descended from a breach in the sierra to 1785 m a.s.l. (Barros Arana, 1886). This glacier was chosen for study because it has – probably after San Rafael glacier – one of the longest historical records of front variations; the first such description was made shortly before the mid-nineteenth century. Since then, the glacier has shown a constant retreating trend that has been more dramatic in recent decades (Rivera *et al*., 2006).

According to Montecinos and Aceituno (2003), Central Chile (30°–41°S) is located between two regions with very different climates: the Atacama Desert in the north and one of the wettest regions of the Southern Hemisphere in the south. In the latter, precipitation ranges from 100 to 2000 mm and is explained by cold fronts associated with the migrations of low pressure systems. Furthermore, cutoff lows contribute 5–10% of the annual rainfall between 26° and 36°S.

Other information states that Westerlies are increasingly important south of 31°S and rarely reach as far north as 27°S (Miller, 1976). Also, this circulation belt can generate frontal and orographic precipitation; above altitudes of 2500 m a.s.l., this ranges from < 500 mm/yr in the northern part of the country to 2500 mm/yr around 36°S (Bown *et al*., 2008). This generates an important altitudinal gradient in precipitation, which is four times higher at the ridge line than in the Central Valley at the same latitude (Miller, 1976). The altitude of the 0°C isotherm shows the same decreasing southward trend, going from around 4000 m a.s.l. at 32°S to < 3000 m a.s.l. at 36°S (Carrasco *et al*., 2005). With respect to temperatures, data gathered by Rosenblüth *et al*. (1997) from the nearest meteorological station suggest an increase of 1.8°C from 1933 to 1992, as compared with the average temperatures between 1940 and 1988.

Methodology

Historical sources

The use of historical data in Chile required the selection and exhaustive analysis of nineteenth-century bibliographic sources. These are 'first-hand' sources, including geographical records made by explorers visiting Cipreses glacier. Once the sources were located and their origin, textual form and descriptive quality

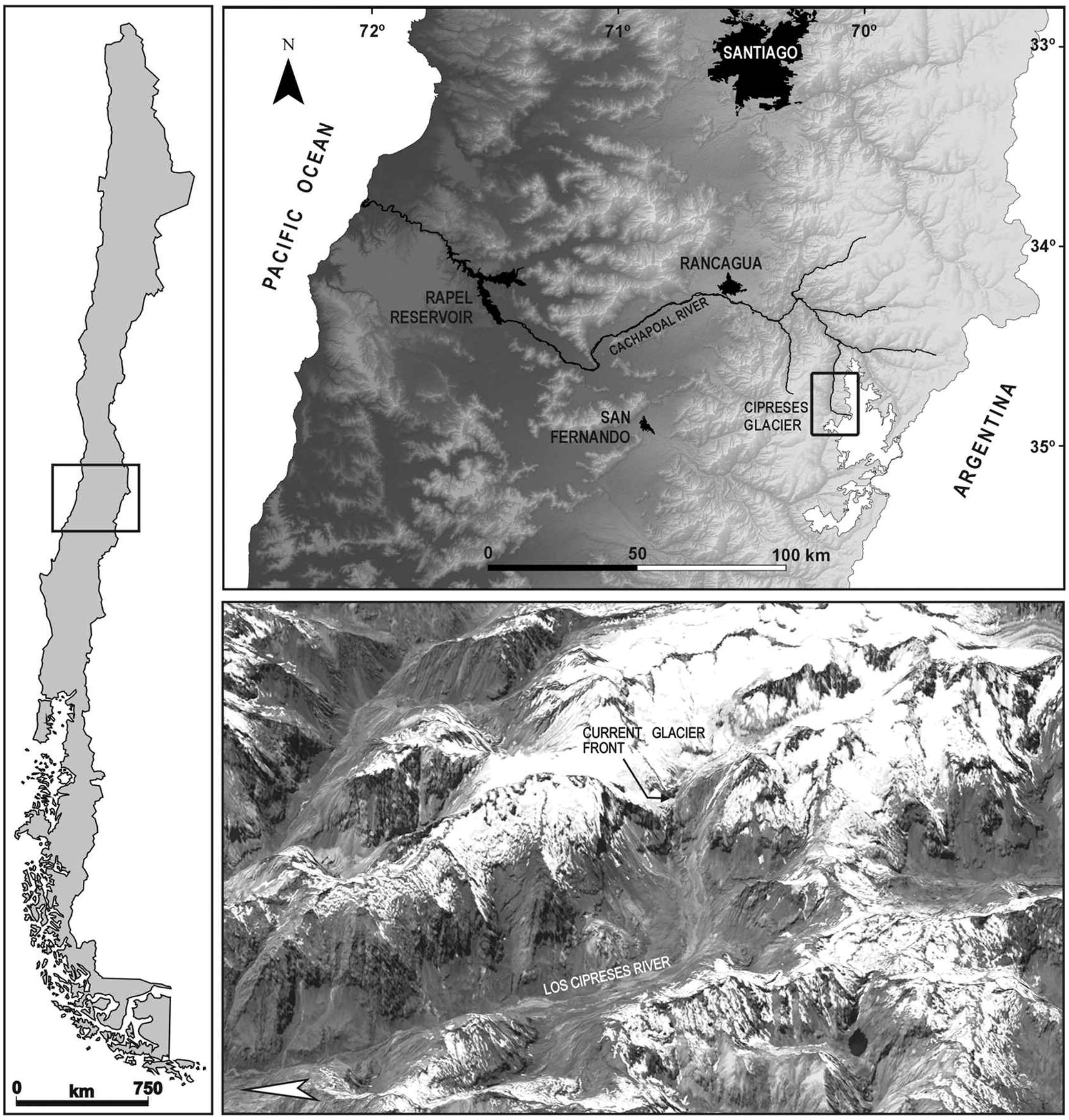

Figure 1 Central Chile and the location of Cipreses glacier

analysed, we extracted all the historical information that directly described Cipreses glacier. These data – written descriptions, iconography, cartography, and ancient photography – were complemented with reserved aerial photography from 1943 taken during the Trimetrogon flight, the first aerophotogrametry flight to cover most of the Chilean territory. Specialized dictionaries (Real Academia Española, 1852, 1933; Novo and Chicarro, 1957; Corominas, 1976) were used to determine the 'epoch-specific' meanings of key concepts used by the explorers. Later, we used the selected data to identify the historical behaviour of Cipreses glacier between 1842 and 1943 following the 'historical progression' method outlined by Bolós (1992). Finally, this historical behaviour was compared with the information generated, for the same period, on San Rafael glacier, Northern Patagonia (Araneda *et al*., 2007) in order to analyse the geographical distribution of the LIA in Chile.

Temporal landscape reconstruction

The temporal reconstruction was based on panchromatic aerial photographs from 'Vuelo Chile 60' of the Servicio Aereo Fotogramétrico (SAF), scale 1:60 000, year 1998. The physiographic elements described in the historical records (eg, rivers, streams, hills, moraines, gorges) were identified with a Wild ST4 stereoscope. In order to validate the historical geographical description, the toponomies were analysed and compared with the current official cartography of the Instituto Geográfico Militar (IGM). All this information allowed us to reconstruct the glacier-front positions in different temporal periods; these were later represented on the aerial photographs. These photographs were georeferenced under the Universal Transversal Mercator projection (UTM), datum WGS 84, to obtain a distance estimation of the glacier front at each moment. This was then used as the base for generating a thematic chart of the historical glacier positions.

Results and discussion

Explorations of Cipreses glacier in the nineteenth century

Although specific historical descriptions for Cipreses glacier are only available since the nineteenth century, this glacier boasts one of the longest and most continuous series of historical data for Central Chile. Although this information has been used partially in other glaciological and dendrochronological studies (Villalba, 1994; Rivera *et al*., 2000, 2006; Le Quesne *et al*., 2006, 2008), the earlier analyses seem to have been superficial and somewhat imprecise regarding the historical glacier behaviour.

Domeyko's trip of 1842

One of the most complete and detailed description of Cipreses glacier was made in January 1842 by the explorer Ignacio Domeyko, a naturalist and geologist hired by the Chilean government to reinforce mining development in the country. During one of those mining prospections in the Central Andes, near the Cipreses River, Domeyko described a huge mass of ice that reached around 120 m high in its terminal part. The glacier lay above a high valley (1600 m a.s.l) where the Cipreses River was generated, according to Domeyko, coming from an ice cavern (Table 1, record 1a, record 2).

In order to reach the so-called 'Rincon de Los Mineros', where Domeyko expected to find rich veins of gold and silver, the geologist had to climb a huge accumulation of rocks, which, he inferred, were transported by the glacier itself. Once beyond the rock pile, he was able to access the ice and walk towards the upper part of it, not an easy task (Table 1, record 1b). Domeyko remarked that the slippery ice surface had plenty of cracks around a half metre wide (~ one 'codo'), which were, according to him, of a considerable depth. At the same time, he indicated that many streams and ponds flowed very noisily

Table 1 Historical written records of Cipreses glacier explorations during the nineteenth century

Record 1	**Ignacio Domeyko, 1842**[a]
1a)	*'Iniciamos el acenso más allá del río de los Cipreses y en un par de horas llegamos a sus fuentes […]. Las rocas se alzan a ambos lados a más de mil metros y encajonan el valle, se interponen en el camino del viajero, el río se transforma en un ruidoso torrente, tuerce hacia sus fuentes, en dirección norte y desaparece en una gruta de hielos.* *Una masa inmensa de hielo eterno, de hasta 400 pies de altura, se concentró aquí, tapada por tres lados, por el oeste, el norte y el este de altas montañas con angosto acceso únicamente por el lado suroeste. Es una especie de heladera natural, donde el hielo se conserva, desde tiempos inmemoriales, de invierno a invierno, pese a que la altura en que se halla no pasa de 1.600 metros sobre el nivel del mar,*
1b)	*Ordené seguir escalando hacia ese glaciar, para llegar al Rincón de los Mineros, el cual domina sobre toda la masa de hielo, pues esperábamos descubrir en él ricas vetas de plata y oro […]. Sin perdida de tiempo pasamos vadeando a la otra orilla del río y antes de que el sol llegara al meridiano, llegamos al borde septentrional del glaciar después de escalar inmensas rumas de piedras. Eran en gran parte, bloques de granito que parecían destrozados allí mismo, y compuestos de rocas diferentes de las cercanas. Pensé que debieron haber sido traídas sobre los hielos, análogamente como – según suponen los geólogos – habían llegado y quedado en nuestras llanuras polacas y prusianas los bloques erráticos (blocs erratiques). Y en efecto, así los califica mi excelente amigo Gay […]. Por estos inmensos derrumbes y rumas de piedras ascendimos más allá del borde septentrional del glaciar, a su cúspide, con dificultad pero sanos y salvos, y fue preciso atravesar a pie, durante media hora, su superficie y su loma, para llegar a ese Rincón de los Mineros.*
1c)	*Fue necesario dejar los caballos en un lugar seco, porque la superficie del hielo, semiderretida por el calor solar, estaba tan resbaladiza que el caballo no podía sostenerse, resbalaba y se caía. Peor todavía era que esa masa de hielo transparente, de color gris verdoso, y de un espesor de más de mil codos, está de arriba abajo partida por grandes grietas de más o menos un codo de anchura. Entre grieta y grieta el hielo está convexo y tan resbaladizo que si uno no afirma bien los pies y pierde el equilibrio, es fácil que caiga por la derecha o por la izquierda al precipicio. Desde el fondo de cada grieta se oye el susurro de los torrentes, y el lomo del hielo es a trechos tan angosto que es preciso encaminar por él con tal cuidado y arte como los volantineros. Por toda la superficie del glaciar que, desde lejos me parecía casi una planicie lisa y pareja, fluyen pequeños arroyos y napas de agua que, al precipitarse en esas grietas producen un estrépito subterráneo y a trechos un ruido atronador. Para colmo, el sol era a esa hora tan violento, cegador y caluroso, reflejándose y atravesando esas masas, que resultaba difícil orientarse en el camino y apreciar por dónde era más seguro caminar o saltar a través de las grietas […]. En cuanto a mí, sentí ciertas dificultades respiratorias y, no obstante hallarme sobre el hielo, el aire recalentado del ardiente sol me quitaba fuerzas y hube de detenerme y jadear a cada paso. Sentí sed y la garganta seca […]. Una vez atravesado ese glaciar, llegamos finalmente a ese Rincón de los Mineros'.*
Source: Domeyko (1978: 588–90)	
Record 2:	**Ignacio Domeyko, 1842**[a]
	'el lugar mas bajo en que he encontrado las nieves a un grado de latitud mas al Norte, en los mismos declives occidentales de los Andes, se halla en el nacimiento del rio de los Cipreses (Cordillera de Cauquenes), donde un banco de hielo de mas de cien varas de grueso ocupa el fondo de una quebrada situada a unas 3000 varas sobre el nivel del mar.'
Source: Domeyko (1850: 9–29; 16)	
Record 3:	**Pedro Amado Pissis, 1858**[a]
	– 'rio de los Cipreses, corriente mui caudalosa que viene del sur i nace en un poderoso banco de hielo, situado al pié del Alto de los Mineros, a una altitud de 1785 metros'. *– 'en el valle de los Cipreses, a una altitud de 1680 metros i a inmediaciones de un banco de hielo, el termómetro indicaba el 12 de febrero de 1858, 31° 9' […]. 'Es tambien en los Andes de Colchagua donde aparecen los primeros bancos de hielo (glaciers). Estos bancos se hallan siempre situados en los nacimientos de los rios, i mas particularmente en la vertiente sur de los cordones de los Andes. Son formados de hielo trasparente, dividido en una infinidad de pequeños fragmentos prismáticos, lo que los diferencia de los nevados, compuestos solo de nieve o de granizo lijeramente conglutinados; ocupan una altitud mui inferior al límite de las nieves eternas, i el mas notable de todos, el que forma el rio de los Cipreses, principia a 1785 metros'.*
Source: Pissis (1860: 685, 703)	
Record 4	**Pedro Amado Pissis, 1858**[a]
	'Tambien es desde el grado 34 cuando se encuentran los primeros ventisqueros de los Andes: allí donde hay altas montañas que forman crestas dirijidas del este al oeste, el vertiente sur no recibe mas que una débil parte de los rayos solares, el agua procedente de las nieves

Table 1 *(Continued)*

Record 4	**Pedro Amado Pissis, 1858**[a]
	superiores se congela y transforma la que ocupa un nivel mas bajo ó una masa de hielo. El primer ventisquero que se encuentra es el del valle de los Cipreses que ocupa una profunda cortadura situada en el lado sur de las montañas que forman el Alto de los Mineros y baja desde allí hasta 1785 metros donde dá orígen al rio de los Cipreses. Cuando le visitámos á principios del año 1858, habia habido un gran hundimiento cerca de su extremidad inferior; y el hielo cortado á pico formaba en su base una magnifica gruta de donde brotaba el rio; el canchal estaba separado por un intervalo de mas de cien metros en el cual se hallaban dispersos enormes trozos de hielo que resistian todavia á la accion del sol. Encima del hielo se notaba una capa terrea de muchos metros de espesor, compuestas de peñascos desprendidos de las montañas vecinas y que habian rodado por la superficie del ventisquero; esta capa se extendia, al sur, sobre un espacio de un kilómetro; luego venian la agujas de hielo, y por último la nieve que cubre siempre los ventisqueros á una cierta altura.
Source:	Pissis (1875: 200–201)
Record 5	**Rodolfo Philippi, 1875**[a]
	'Resolvimos, pues, contentarnos con ir con el guia hasta cerca del ventisquero o banco de hielo, como lo llaman, mientras nuestro fiel Pablo preparaba el almuerzo. Apenas aclaró el día, nos levantamos i tomamos té para desayunarnos. Mientras se ensillaban los caballos, me fui adelante para herborizar, i me reuní con los compañeros en el manantial [...]. *Apenas habíamos marchado media hora, cuando se nos presentó delante, a la izquierda, el ventisquero, a una distancia de unas cuatro o cinco cuadras. Viene de un valle lateral que corre de sur-este a nor-este, i forma por consiguiente un ángulo casi recto con el valle principal, que está cortado en este lugar perpendicularmente por un ramal de la alta cordillera. Delante del ventisquero hai una moraina enorme, que llena todo el valle, que es mui ancho de unas tres cuadras. El agua sale de dos galerias del hielo, cuyas aberturas se ven claramente. Visto del fondo del valle, el ventisquero no parece tener estension; pero cuando se sube a bastante altura, en los cerros que están enfrente, se conoce, según dicen las personas que han sido bastante afortunadas para poder verlo, que se estiende por algunas leguas'.*
Source: Philippi (1875: 666)	
Record 6	**Alberto Plagemann, 1886**[a]
	'Was nun den Gletscher selbst anbetrifft, den Herr Dr. Güssfeldt – man weifs hier nicht, aus welchem Grunde – Ada-Gletscher mennt, so wissen wir, dafs derselbe vor Jahren auch oberhald der Eiskaskade verfolgt worden ist. Es ist richtig, dafs viele Reisende bis zum Fufs des Cypressen-gletscher gelangt sind, und dafs den meisten derselben der Wunsch fehlte, ihre Eindrücke mitzuteilen; indes besitzen wir docheinige Notizen, nicht nur über das Gletscherende, sondern auch über den vom Thales aus absolut unsichtbaren ca '15' langen Lauf im Cajon de los Mineros. *Wie z. B. der vielgeschmäte Pissis zur Einsischt gelangen konnte, dafs der Gletscher, welchem der Rio de los Cipreses Seine Entstehung verdankt, vom Alto de los Mineros komme, und dafs derselbe eine 'profunda cortadura', d. i. eine tiefen Einschnitt, eine tiefe Spalte – also einen Cajon – ausfüle in Süden der Berge, welche das Alto de los Mineros bilden, das ist nich ersichtlich, da die Geografia fisica von Pissis keine Reiseschilderungen enthält. Hingegen weifs man durch die Mitteilungen des Herrn Münnich aus Valparaiso und des Lorenzo Zamorano, Führers der Herren Münnich, v. Dessauer, v. Schroeder, Güssfeldt und u. a. auch von meiner Wenigkeit, die ganz genau, wie der leider über der Aussarbeitung eines Reisewerks plötzlig hingestorbene Arzt, Herr Dr. v. Dessauer, dazu gekommen ist, in sein Kärtchen oberhald der Eiskaskade (wo sich die beiden Gletcher – vom Cerro Colorado und aus dem Cajon de los Mineros – treffen) des 'Ventisquerio del Cipres einen längern, direct aus Süden fliefsenden 'Ventisquero des Alto de los Mineros' einzuzeichnen. Herr Dr. v. Dessauer hat ganz einfach die Beobachtungen seines Reisegefährten Münnich, der am Nordende des Gletchers auf beschwerlicher Wanderung so weit vorgedrungen war, bis er den Cajon de los Mineros überschauen konnte, in seine Karte aufgenommen'.* *Herr Prof Philippi, der auf der Pflanzensuche nach dem Cajon de los Cipreses gepilgert war, wunderte sich nicht wenig, al ser auf der Pississchen Karte an Stelle des Gletscher vier allerliebste Flufsläufe entdeckte' (p. 70).*
Source: Plagemann (1887)	

[a]Dates correspond to the years in which the explorers visited the Cipreses glacier.

all over the glacier surface towards the ice cracks (Table 1, record 1c). After crossing the glacier, he reached 'Rincon de Los Mineros'.

It can be inferred from Domeyko's report that the glacier front ended in an evident moraine, which could reflect the last maximum advance during the late Holocene, probably associated with the manifestation of the last pulse of the LIA. However, these descriptions do not allow us to determine if the glacier was advancing or retreating at that moment. Although Domeyko indicated evident melting, this corresponded to a seasonal process (he was there in summertime). Nevertheless, the glacier was, by then, a huge mass of ice that occupied most of the gorge (Table 1, record 2) from whence the Cipreses River currently originates (Figure 2).

Pissis' description of 1858

Sixteen years after Domeyko's trip, the French geologist Pedro Pissis, also hired by the Chilean government to study and describe the country's geology, added new information about the glacier's behaviour. This explorer visited the Cipreses glacier in February 1858. He indicated that the Cipreses River came from a 'big bank of ice' (Table 1, record 3).

Pissis also reported the occurrence of a big sink in the terminal part of the glacier which generated a huge cave from whence the Cipreses River flowed. Besides, he emphasized the presence of a 'canchal' separated from the glacier front by more than 100 m; some enormous ice chunks in this gap even resisted summer melting. In some parts (towards the south), the glacier was covered by a debris and clastic layer that came from the adjacent mountains.

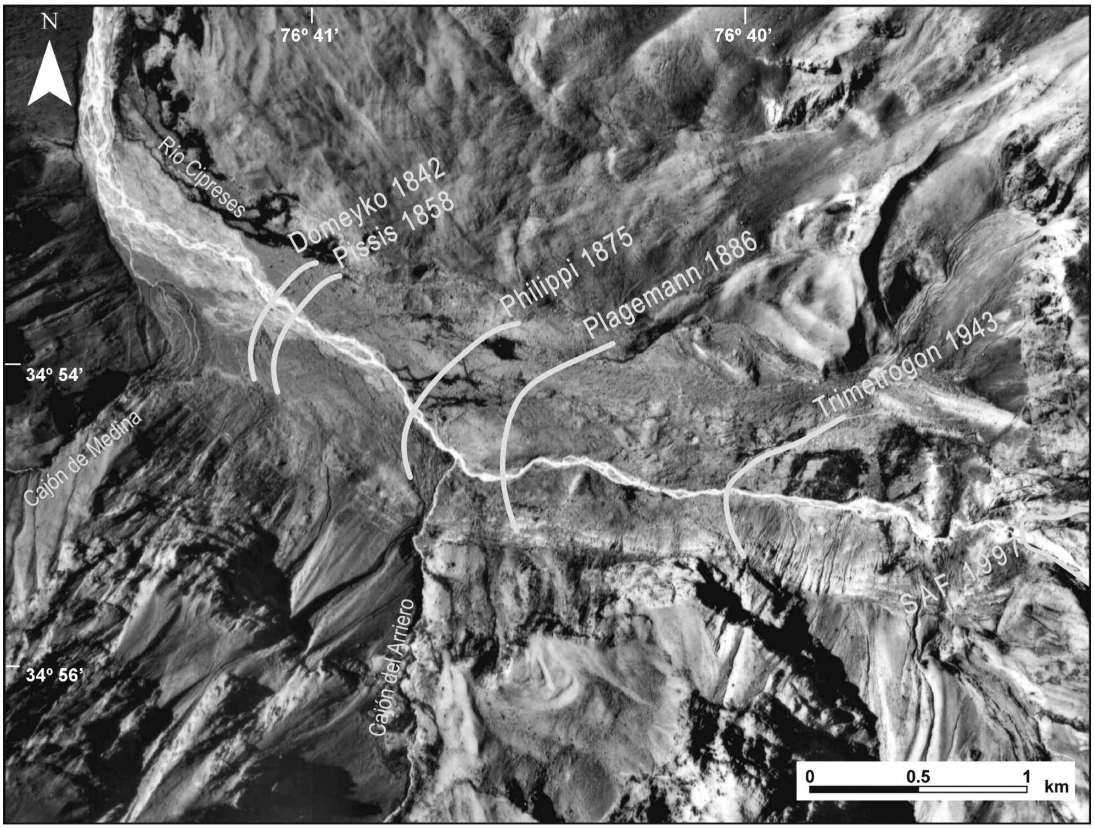

Figure 2 Historical comportment of Cipreses glacier inferred from documentary data

In the upper part of the glacier, 'ice needles' were followed by séracs and finally the firm field (Table 1, record 4).

The most important inference that can be made from the historical data gathered by Pissis is that the Cipreses glacier was clearly retreating by 1858: (1) the glacier front was separated more than 100 m from the frontal moraine; note that Pissis did not use the term 'moraine', but referred to a 'canchal', an old-fashioned synonym of moraine according to the Real Academia Española (1933) and Novo and Chicarro (1957); (2) the gap between the moraine and the glacier front, which did not exist in Domeyko's 1842 description, was partially occupied by huge ice chunks, remains that had fallen off the glacier and partially melted under the summer sun; and finally, (3) an important sink was recorded in the terminal part of the glacier, possibly reflecting a destabilization process due to melting (Figure 2).

Pissis also delivered the first graphical representation of the Cipreses glacier by 1858. His lithography represents a portion of the glacier and was drawn from the southwest and at such an elevation that the Cipreses River, the ice cave where it was born, and the ice chunks did not appear in the drawing. However, the lithography coincides with the rest of the description by the author (a huge mass of ice that occupied most of the gorge) (Figure 3).

Philippi's description of 1875

In 1875, the German naturalist Rodolfo Philippi, was carrying out scientific fieldwork in the Cipreses River valley, near Cipreses glacier. In his narration of this expedition, he commented on the local geography. His descriptions about the frontal moraine, a huge one that occupied the entire width of the valley (~ 400 m or three 'cuadras'), are especially important. Regarding the glacier, he described two ice caves from whence water flowed, forming the Cipreses River. Finally, Philippi mentioned that the glacier extension seemed small if seen from the valley bottom, but reached some kilometres (some 'leguas'; Table 1, record 5) if observed from the higher mountains facing it.

Based on this description, it is possible to state that Cipreses glacier had continued the retreating trend observed 17 years before by Pissis. Philippi estimated a distance of around 600 m (four to five 'cuadras') between the bottom valley and the glacier front, an observation made by the explorer probably from or next to the frontal moraine, as opposed to the ~100 m that Pissis reported between the moraine and the glacier front. Furthermore, Philippi noted two ice caves from which the river emanated, unlike the single cave that Pissis described, reinforcing the assumption of continuous melting. It is important to emphasize that Philippi was the first explorer to provide an approximate measurement of the moraine (400 m), thereby allowing us to estimate that the historical front of the glacier was similar in extension (Figure 2).

Plagemann's exploration of 1886

This German scientist arrived in the Cipreses glacier area by the summer of 1886, searching for geological evidence of past glaciations. He mentioned Cipreses glacier as an ice fall ('Eiskaskade') over which the glacier extended some 15 km towards the heights of the Andes within the 'Cajón de los Mineros' gorge; it was not visible from the bottom valley. He also mentioned that the previous expedition of Dr Güssfeldt named this glacier 'Ada' glacier ('Ada-Gletscher'). Plagemann also made some inferences about Cipreses glacier based on information gathered by other German explorers during the same decade, indicating that at the location where Pissis recorded the glacier front in 1858 (Table 1, record 6), Philippi would have found just four river branches in 1875.

Most importantly, the data generated by Plagemann indicated that the glacier was still retreating. In fact, Plagemann referred to the glacier as an ice fall, a term that nobody used before, indicating that the glacier could have been lying down on the rocky mountain

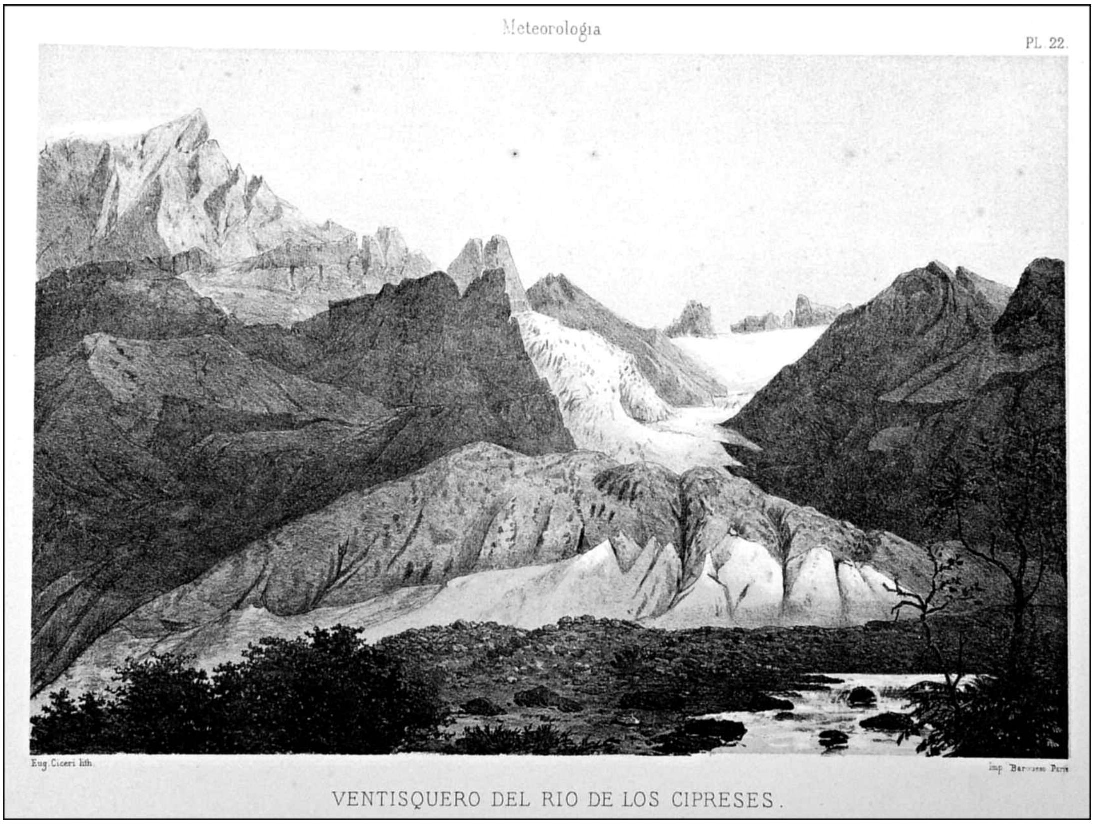

Figure 3 Lithography of Cipreses glacier in 1858, published in Pissis (1875)

slope, even further back than when Philippi saw it in 1875. The latter idea is supported by a photograph taken by Plagemann at a certain altitude from the northwest (published later by Martin, 1909), showing a remnant ice tongue of Cipreses glacier (Figure 4A). Finally, it is important to mention that Plagemann also drew a map of the area, revealing the relative position of the glacier (Figure 4B). Based on this map's scale and Plagemann's photograph, we estimated that the glacier had retreated around 500 m from the position indicated by Philippi 12 years before (Figure 2).

Relating historical data on the LIA for Cipreses and San Rafael glaciers (nineteenth century)

The historical data on Cipreses glacier dates back to 1842 and comprises the period of the last LIA peak in Central Chile. Hence, we were able to compare Cipreses' fluctuations with those of San Rafael (Northern Patagonia); the latter has one of the longest historical records, beginning in the mid-seventeenth century (Araneda *et al.*, 2007). Following is a chronological comparison of the changes in both glaciers during the nineteenth century.

The historical data show the last pulse of the LIA near the San Rafael glacier could have begun around 1766, as seen in an incipient advance of the ice front. This process was evident in 1857, when the glacier already extended some distance into the Laguna (Araneda *et al.*, 2007). The only record of Cipreses glacier known for this period is the detailed description made by Domeyko in 1842, when the glacier front was probably stationary next to the moraine. However, we cannot reject the possibility that the glacier was still forming the moraine; this suggests that, around that time (the last phase of the LIA), Cipreses glacier could have reached its maximum advance. According to Le Quesne *et al.* (2006), at that time, the glacier extended some 4.5 km into the valley from it present position; this distance coincides with our estimation based on aerial photography (Figure 2).

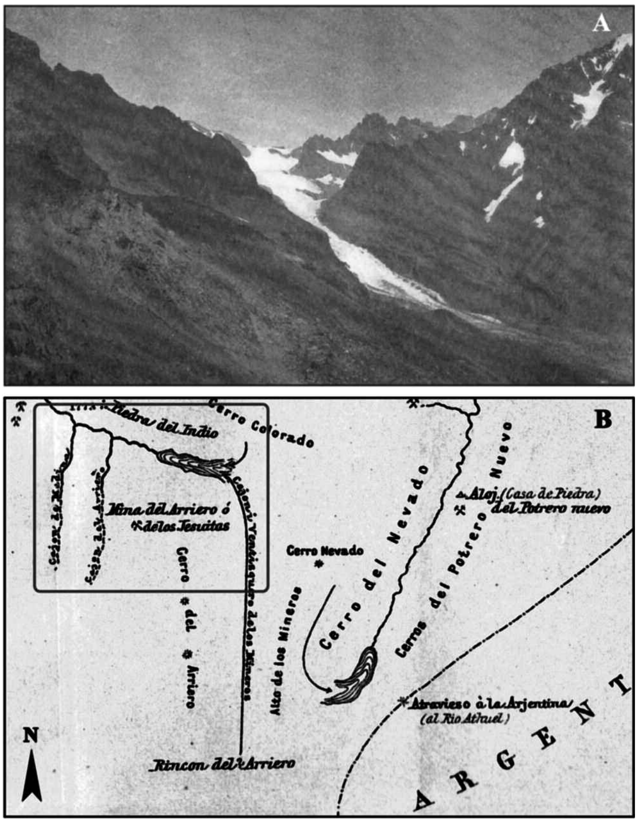

Figure 4 Cipreses glacier during Plagemann's exploration. (A) First photograph known so far of the glacier in 1886 and published by Martin (1909); (B) section of the map 'Originalskizze des Nord-Östlichen Teiles der Hacienda de Cauquenes', made by Plagemann (1887)

The timing of this cold period agrees with a previous study of the eastern Andes in Central Argentina (28°–36°S, 61°–67°W) that proposes a two-pulse LIA; the last pulse started in the eighteenth century and ended at the beginning of the nineteenth century (Cioccale, 1999). When comparing this information with that on the Southern Alps of New Zealand, where three pulses of LIA are recognized (McKinzey *et al*., 2004), we see that the behaviour of the New Zealand glacier falls between that of Cipreses and San Rafael glacier. Gellatly (1985) used historical data to indicate the culmination of glacier expansion at Mt Cook National Park (NZ Southern Alps) around 1860. At that time, the Cipreses glacier was already showing an evident retreat, whereas the San Rafael glacier was still advancing into the Laguna.

Historical climatological data for Central Chile suggests, for the Cipreses glacier zone, the prevalence of colder and more humid conditions from 1841 through 1847. According to Vicuña Mackenna (1877), 1845 was an 'excessively cold year'. These cold conditions probably continued until 1850 because, in the winter of 1848, a very important snowstorm was recorded in all 'Santiago's shire' turning the entire 'Maipo plain into a small Siberia'; 'great cold, storms and alluviums' were also recorded in 1850 (Vicuña Mackenna, 1877).

Even though some researchers have indicated that glacier advances are determined by precipitation rather than by temperature (Winchester and Harrison, 1996; Luckman and Villalba, 2001), recent studies on glacier fluctuations in New Zealand found temperature to be the most important driving force. In their modelling, Anderson and Mackintosh (2006) stated that a cooling of ~1°C is required for the LIA advance, whereas an increment of 37% in precipitation is necessary to simulate the same ice boundaries. Hence, the colder, more humid conditions mentioned above suggest that Cipreses glacier was likely advancing in that epoch.

By 1858, Cipreses glacier showed a clear retreating trend (Pissis, 1860) as compared with the position observed by Domeyko in 1842. In fact, the glacier front was more than 100 m from the moraine, which could indicate a retreat rate of roughly 6.25 m/yr. Meanwhile, during the same epoch, San Rafael glacier was still advancing into the Laguna, as inferred from Hudson's 1857 description (Hudson, 1859). This advance continued until Simpson's expedition (1871–1873), probably the last maximum cooling peak of the LIA in Northern Patagonia (Araneda *et al*., 2007). The evident retreat of Cipreses glacier by 1858 is concurrent with the slow retreating trend of other Andean glaciers that could have begun between 1855 and 1910 (Cioccale, 1999). The retreat of Cipreses glacier began slightly before that of some glaciers in Mt Cook National Park (Southern Alps), which Gellatly (1985) reported to have started around 1862.

The Cipreses glacier retreat of 1858 contrasts with the advance described for the same glacier around 1860 by Villalba (1994). This author made his estimate based mainly on Rothlisberger's (1986) radiocarbon results, which gave two dates for Cipreses glacier: '625 ± 155 yr BP' and another 'modern' date, probably < 200 yr (Villalba, 1994). Certainly, the radiocarbon dates are not accurate enough to account for these short-term fluctuations. The historical data gathered for this glacier, however, provide the more detailed, specific chronology necessary for recording such short-term climate variations. Le Quesne *et al*. (2008) used Pissis's data to indicate an advance of Cipreses glacier by 1858. However, the analysis of Pissis's historical information presented herein does not support this interpretation.

The climatological data registered in the same epoch by Vicuña Mackenna (1877) showed an 'exceptionally humid period' between 1851 and 1860, with average annual rainfall of 419 mm. Furthermore, this author emphasized that, in 1856 and 1860, great alluvions and floods occurred at the end of the summer in rivers descending from the Andes, which could imply higher summer melting. Regarding temperatures, Vicuña Mackenna (1877) did not mention particularly cold years during this period, unlike his description for the 1841–1847 period, as indicated above. These data are congruent with Pissis's observation that the glacier was retreating by 1858, evidencing warmer conditions and, therefore, higher melting than in previous decades. Again, the historical data suggest that temperature should be a dominant factor in determining glacier fluctuations, as stated by Anderson and Mackintosh (2006).

This retreating trend apparently continued during the nineteenth century, as recorded by Philippi (1875). At that time, the glacier could have retreated around 500 m from the position registered by Pissis (1860), although it is important to consider that both explorers made merely rough calculations of the distance, hampering accurate estimations of retreat rates. The trend of the Cipreses glacier contrasted with the previously documented behaviour of San Rafael glacier, which showed a noticeable advance, penetrating up to 8 km into the Laguna (Simpson, 1875). According to Araneda *et al*. (2007), this advance corresponded to the LIA manifestation in Northern Patagonia, with a peak cold pulse between 1857 and 1871.

A decade after Philippi's exploration, data from Plagemann (1887) confirmed the retreating trend of Cipreses glacier, whereas San Rafael glacier would have been stable (Steffen, 1909) or just beginning to retreat. The retreating trend of the latter was evident by 1904, as San Rafael glacier withdrew 1 km (García-Huidobro, 1905). Consequently, we determined a delay in the response of both glaciers when facing climate forcings; the Cipreses glacier seemed to be more sensitive to current global warming, responding more quickly than San Rafael glacier.

Reconstructing the historical behaviour of both glaciers, the last LIA cooling peak for Cipreses glacier would have occurred around 1842 whereas, for San Rafael glacier, the cooling range took place between 1857 and 1875; it was possible to estimate an average date for this cooling in 1864. Hence, the cooling peak of San Rafael glacier lagged 22 years behind that of Cipreses glacier. In terms of retreat, Cipreses glacier withdrew slightly by 1858, whereas San Rafael could have begun to retreat around 1898, 40 years later. Consequently, by averaging the difference of years between the cooling peak and the beginning of the retreat, we found a 31-year delay between these two glaciers. In others words, the response of San Rafael glacier to climate forcing began 30 years after that of Cipreses glacier. Both the retreating trend and the difference in the response for the two glaciers continued during the twentieth century, as seen in aerial photographs from 1943 (Figure 5).

However, despite this approximately 30-year delay, the historical information analysed herein for Cipreses glacier, along with the behaviour of San Rafael glacier (inferred using the same proxy), allows us to state that the LIA was manifested both in Northern Patagonia and Central Chile. By comparing this information with glacier behaviour in New Zealand, we were able to outline a hemispheric culmination of LIA, which was first expressed in the central Andes, then in the Southern Alps of New Zealand and finally in Northern Patagonia. This assumption is reinforced by Fitzharris *et al*. (2007), who found 'teleconnections' between glacier responses in the Andes and New Zealand during the twentieth century, specifically arguing that the 'glacier behaviour must be driven by atmospheric and SST [sea surface temperature] changes that occurred about the mid-1970s'. If this was true in the twentieth century, then it is to be expected that the same teleconnection would have acted in previous centuries.

The differential manifestation of LIA at the aforementioned sites could be associated principally with the Westerlies migration. In Chile's Norte Chico (27°–33°S), Veit (1996) indicated a period of increased humidity due to the Westerlies around 1300 to 1800. Jenny *et al*. (2002), working at Aculeo Lake (33°S), found the local signature of LIA from 1300 to 1700, with a second phase peaking around 1850. These authors infer that this signature was

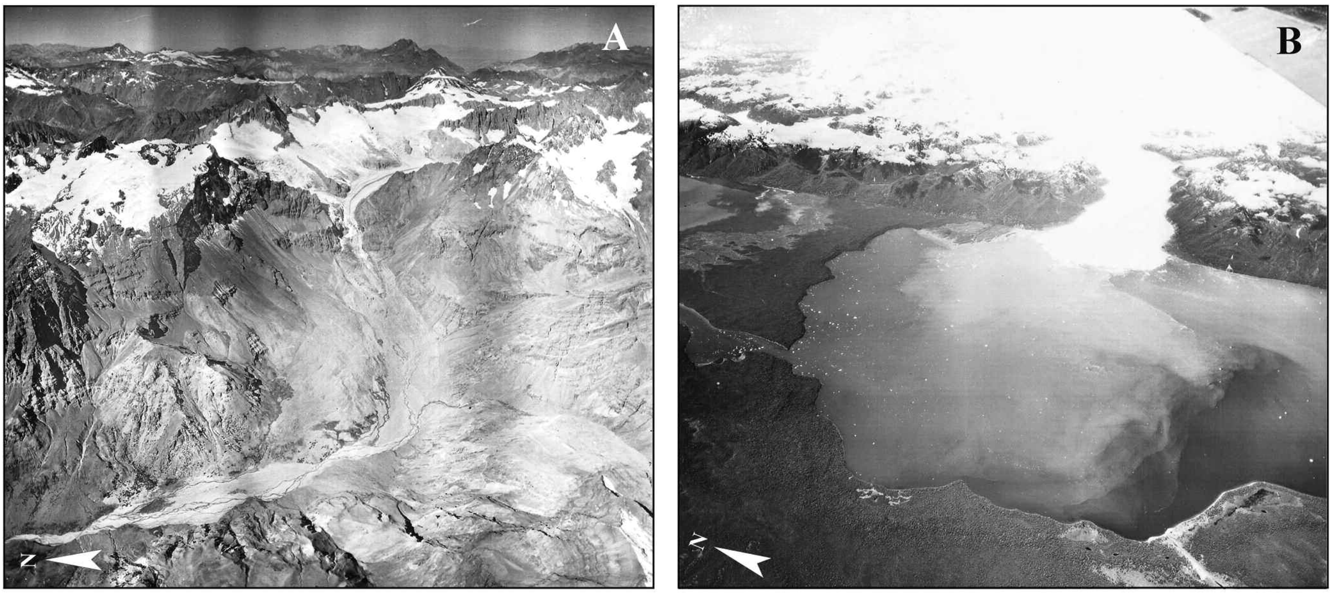

Figure 5 Relative position of Cipreses (A) and San Rafael (B) glaciers in 1943, during the first set of aerial photographs of Chile (Trimetrogon flight, 1943)

caused by a weakened southeast Pacific high-pressure cell and enhanced Westerlies and frontal system activity. Lamy *et al.* (2001) evidenced the occurrence of LIA at 41°S, as manifested by higher rainfall due to an equatorward shift of the Southern Westerlies, explaining this through the 'synchronous enhancement of atmospheric circulation on both hemispheres during the LIA, causing a mean equatorward shift of the Westerlies'.

Currently, ENSO variability constitutes an important driver of changes in precipitation in Central Chile on interannual timescales. It is possible to relate increased ENSO intensity as another factor responsible for glacier advances during the LIA. However, Valero-Garcés *et al.* (2003) found no conclusive evidence of more frequent and intense ENSO during the LIA around 27°S.

Hence, by integrating the above statements with our results, we can infer an extension of the northern boundary of the Westerlies during the last phase of the LIA, followed by a gradual relocation to its current position. This, in turn, offers a preliminary explanation of the glacial delay reported in this work. Another explanation for the delay in the response of the two glaciers studied could be their relative altitudes; Cipreses glacier is currently located at 2640 m a.s.l. During the LIA, however, it experienced more humid conditions because of a Westerlies enhancement, so that the precipitation should have been mainly solid (snow). Thus, this glacier should advance faster than San Rafael, which is located at sea level.

However, the role of the Westerlies as a climate driver in the last millennium is still unclear. Moy *et al.* (2008), working at Lake Guanaco (51°S) in Torres del Paine National Park, indicated a southward extension of the southern boundary of the Westerlies during the LIA, although they did not offer a detailed chronology of the LIA evolution, as found in the historical data. According to these and other authors (Veit, 1996; Lamy *et al.*, 2001; Jenny *et al.*, 2002, 2003), more studies are required to elucidate the role of the Westerlies during the late Holocene (as asked by Veit: do the Westerlies migrate as a whole, was it just a meridional expansion, or just experience changes in intensity of atmospheric dynamics?) and to prove whether such humid conditions in Central Chile during the LIA were accompanied by cold conditions. Then is still necessary to use proxies that generate quantitative temperature reconstructions (eg, TEX, chironomids).

Conclusions

The documentary evidence gathered for Cipreses glacier indicates that the position of the glacier front around 1842 corresponded to its last LIA maximum advance during the late Holocene, associated with the manifestation of the LIA in Central Chile. The same evidence clearly shows that, by 1858, Cipreses glacier was retreating as a result of the prevalence of warmer conditions; this retreat continued uninterrupted until the end of the present record (1943). Despite some degree of uncertainty in the distance estimation based on the historical records, after 1858, the retreating trend of Cipreses glacier seems to have accelerated.

By considering both the behaviour of Cipreses and San Rafael glaciers, it was possible to determine a delay of approximately 30 years in the expression of the LIA between Central Chile and Northern Patagonia. According to the data, the LIA conditions were first expressed in the advance of Cipreses glacier and later in that of San Rafael glacier. This deviation was probably associated with an enhancement of the Westerlies, generating more precipitation over Cipreses glacier. Its relative high altitude (as compared with San Rafael glacier) would have determined this faster response to the LIA.

Compared with San Rafael, Cipreses glacier has a shorter but more temporally complete historical series, allowing higher resolution for the timing of the glacier response. More than just recognizing and temporally bounding the LIA in Central Chile through documentary sources, this study strengthens the high resolution of this proxy for studying climate fluctuations over recent centuries. The resolution of this proxy is even higher than that of the radiocarbon dating of moraines and probably of tree rings as well.

Finally, a preliminary comparison of LIA evidence in the Central Andes, Northern Patagonia, and Southern Alps of New Zealand allow us to report a hemispheric expression of the LIA, although with some local deviations in timing, probably associated with an equatorward migration of the Westerlies and different local geomorphological settings. However, more quantitative reconstructions are needed for a better understanding of the role played by this circulation belt in the climate events of the late Holocene in Central Chile.

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