The Holocene 17,7 (2007) pp. 989–1000

Historical records of San Rafael glacier advances (North Patagonian Icefield): another clue to 'Little Ice Age' timing in southern Chile?

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Received 2 January 2007; revised manuscript accepted 16 May 2007

A HOLOCENE RESEARCH PAPER

Abstract: Past ice lobe behaviour at Laguna San Rafael is described in documents provided by Spanish and then Chilean explorers from the late seventeenth to the early twentieth centuries. These records begin in AD 1675, when temperate conditions, probably similar to those at present, prevailed. At that point, the glacier was confined within its valley, not penetrating the Laguna. The glacier advanced noticeably during the nineteenth century and probably reached a maximum position for the 'Little Ice Age' around AD 1875. The historical sources suggest a slight retreat in AD 1904 in relation to the conditions prevailing 29 years earlier. The historical data show that the eighteenth to nineteenth century cooling period at San Rafael glacier was within the temporal window of the European 'Little Ice Age'. This work provides independent, direct historical evidence for the occurrence of this event in southern Chile.

Key words: Historical records, glacier advances, 'Little Ice Age' (LIA), southern Chile, North Patagonia Icefield.

Introduction

Palaeoclimatic studies in the Southern Hemisphere, and particularly Holocene reconstructions in South America, are less developed than in the Northern Hemisphere (Villalba, 1994; Koch and Kilian, 2005). This limitation reduces our ability to understand and predict future global climate changes (Villalba, 1990; Bradley and Jones, 1993; Nesje and Dahl, 2003). Of all the climatic changes during the Holocene, the recent cooling period, the 'Little Ice Age' (LIA), is one of the most broadly recognized events in the Northern Hemisphere (Bradley and Jones, 1993; Bradley, 1994, 2000; McDermott *et al*., 2001; Esper *et al*., 2002; Soon *et al*., 2003; Rabatel *et al*., 2005; Polissar *et al*., 2006). However, the duration and timing of the event has been disputed.

Mann (2001) stated that Matthes initially proposed the term LIA in 1939, and that it included all the marked glacier advances and retreats over the last 4000 years. Nowadays, the term is conventionally defined as the period between the sixteenth and nineteenth centuries, when Europe and the North Atlantic regions underwent climatic alterations implying, among other processes, cooling and glacier expansion (Mann, 2001). Recently, some researchers have used the term LIATES ('Little Ice Age' Type Events) to refer to previous cooling events similar to the LIA that occurred during the Holocene (Matthews and Briffa, 2005).

A problem for the definition of the LIA is its variable timing and duration in different regions; thus, its synchronicity as a global phenomenon is still a matter of debate (Lamb, 1977; Bradley and Jones, 1993; Mann *et al*., 1999; Grove, 2001; Ogilvie and Jonsson, 2001; Soon and Baliunas, 2003; Goosse *et al*., 2005). In general terms, the Northern Hemisphere experienced particularly cold conditions

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 10.1177/0959683607082414

during the seventeenth and early nineteenth centuries, interrupted by relatively short warm intervals (Villalba, 1990; Jones and Bradley, 1992), including one in the mid-eighteenth century (Goosse *et al*., 2005). Other studies have traditionally recognized the LIA between AD 1550 and 1850 (Jones and Bradley, 1992; Bradley, 2000).

Several different approaches have been used to try to identify the LIA in the Southern Hemisphere. Thompson *et al*. (1986) used stable isotopes ($\delta^{18}O$) and dust contents from the Quelccaya ice core (Southern Peru) to place the LIA between *c*. AD 1530 and 1900, showing a peak in cooling around AD 1800–1820. Villalba (1990) used tree ring records from southern-central Argentina (41°10′S; 71°46′W) to identify a cold-moist period between AD 1270 and 1670, which, the author states, is 'contemporaneous with two principal Little Ice Age events registered in the Northern Hemisphere' and should be indicative of a two-phase LIA, as recorded by other researchers in the Northern Hemisphere (Lamb, 1977; Dahl *et al*., 1998; Jones *et al*., 1998). Cioccale (1999) used historical sources, meteorological records and aerial photographs to determine that the LIA in central Argentina consisted of two cold pulses interrupted by an intermediate period. The first pulse lasted from the beginning of the fifteenth to the end of the sixteenth century and the second and most important from the early eighteenth until the beginning of the nineteenth century. Finally, Kreutz *et al*. (1997) found evidence of a synchronous onset of the LIA when comparing their results from studies of West Antarctic ice cores with the Greenland Ice Sheet Project Two (GISP2).

In Chile, historical records of the LIA are scarce. Luckman and Villalba (2001) indicated that, although LIA glacial deposits can be identified throughout the mountain ranges, detailed chronological control is lacking and little historical data is available. Most evidence of the LIA comes from studies using proxy indicators. For example, Lamy *et al*. (2001) used humidity proxies in marine sediments to show the existence of the 'Mediaeval Warm Period' and the LIA in southern Chile (41°S). Bertrand *et al*. (2005) used sedimentological parameters in a sediment core from Lake Puyehue (40°S) to reveal a predominantly wet climate between AD 1490 and 1700, which they associated with the onset of the European LIA. On the other hand, glaciological studies of the South Patagonian Icefield (SPI) – which, according to Glasser *et al*. (2005), is extremely sensitive to climatic change – showed the formation of a moraine at Glaciar Lengua (53°S) between AD 1280 and 1460, corresponding to a LIA glacier advance (Koch and Kilian, 2005). Later, Glasser *et al*. (2006) used sedimentary and geomorphological studies to show a LIA advance of the San Rafael glacier prior to the mid-1800s, whereas Winchester *et al*. (2001), on the east side of the North Patagonian Icefield, dated the retreat of the Nef glacier from moraines formed during the LIA maximum in the mid-nineteenth century, using both lichenometry and tree-ring dating.

However, with the exception of a few studies (Heusser, 1960; Warren, 1993; Winchester and Harrison, 1996; Harrison *et al*., 2007), most research does not include historical data as a source of information in spite of Bradley and Jones' (1993) remark that historical records over the last centuries are among the most important high-resolution proxies for studying climate change. Chile has many historical records dating from Spanish colonial rule in the sixteenth century and it has been confirmed that these documents reliably date a succession of catastrophic events and provide a basis for reconstructing contemporary environmental conditions (Torrejón *et al*., 2004; Cisternas *et al*., 2005).

To date, no detailed analysis of either written or cartographic sources (seventeenth to nineteenth centuries) relating to Laguna San Rafael has been attempted although, as noted above, historical information regarding the behaviour of the glacier over the last four centuries has been cited in previous research. However, because previous authors had no access to the original documents, occasional historical errors have occurred. Thus, the aims of this paper are: (i) to rectify this situation by providing an accurate account drawn from the original source material and (ii) to review all the historical documents, known to date, mentioning the position of the San Rafael glacier. Hence, the main contribution of this research is the use of original Spanish colonial and republican written records and maps describing advances and retreats of the San Rafael glacier in an area that Koch and Kilian (2005) and Luckman and Villalba (2001) described as lacking detail on glacier fluctuations.

Study area

The North Patagonian Icefield (NPI), approximately 100 km long by 42 km wide, caps the Andes between altitudes of 700 and 2500 m a.s.l. (Figure 1). It lies at the southern end of 'Patagonia Septentrional', a term used by Niemeyer (2000) to define the area from the Seno de Reloncaví (41°30′S, 72°55′W) to the 'Península de Taitao' (46°50′S, 75°27′W). Annual precipitation on the western side of the ice field is approximately 3700 mm at sea level and around 6700 mm on the ice field (Escobar *et al*., 1992). According to Rivera *et al*. (2007), the ice field has *c*. 70 outlet glaciers and, by 1995, 13 of these glaciers were recorded as calving into proglacial lakes or lagoons (Aniya *et al*., 1999). Of these, the San Rafael and San Quintin glaciers are the two largest, each covering around 760 km^2.

San Rafael is a calving glacier (46°40′S; 74°56′W) that descends from the NPI and discharges into Laguna San Rafael, a fan-shaped body of water covering a surface area of 76 km^2 and having a maximum depth of 140 m, with water temperatures ranging from 5.5 to 6.5°C (Ahumada and Rudolph, 2003). The Laguna is connected to the Pacific Ocean through 'Río Témpanos' and the 'Golfo Elefantes', making the San Rafael glacier the lowest latitude tidewater glacier in the world. It is also one of the fastest-flowing glaciers on Earth, with the lower tongue moving, on average, at 17 m/day (Winchester and Harrison, 1996). Despite important seasonal variations in glacier movement in other regions, in Patagonia such fluctuations are less pronounced or event absent, as indicated in previous research that suggests limited seasonal variability for the San Rafael glacier (Kondo and Yamada, 1988; Warren and Aniya, 1999). Moreover, Glasser *et al*. (2006) pointed out that this glacier has the most extensively documented historical record of ice fluctuations in all the NPI.

Methodology

Historical sources

The use of historical data in Chile required the collection, selection and analysis of both colonial and republican (seventeenth, eighteenth and nineteenth centuries) bibliographic sources. These are reserved, 'first-hand', original documents, including geographical and hydrographical records made by explorers visiting Laguna San Rafael. Once the sources were located and their origin, textual form and descriptive quality analysed, all the historical information that directly or indirectly mentioned the Laguna and the glacier morphometry was extracted. In addition, specialized dictionaries (Pagés, undated; Corominas, 1976) were used to determine the 'epoch-specific' meanings of key concepts used by the explorers. Finally, the selected documents were used to identify the historical movements of San Rafael glacier from the first Spanish exploration until the early twentieth century following the methods outlined by Bolós (1992).

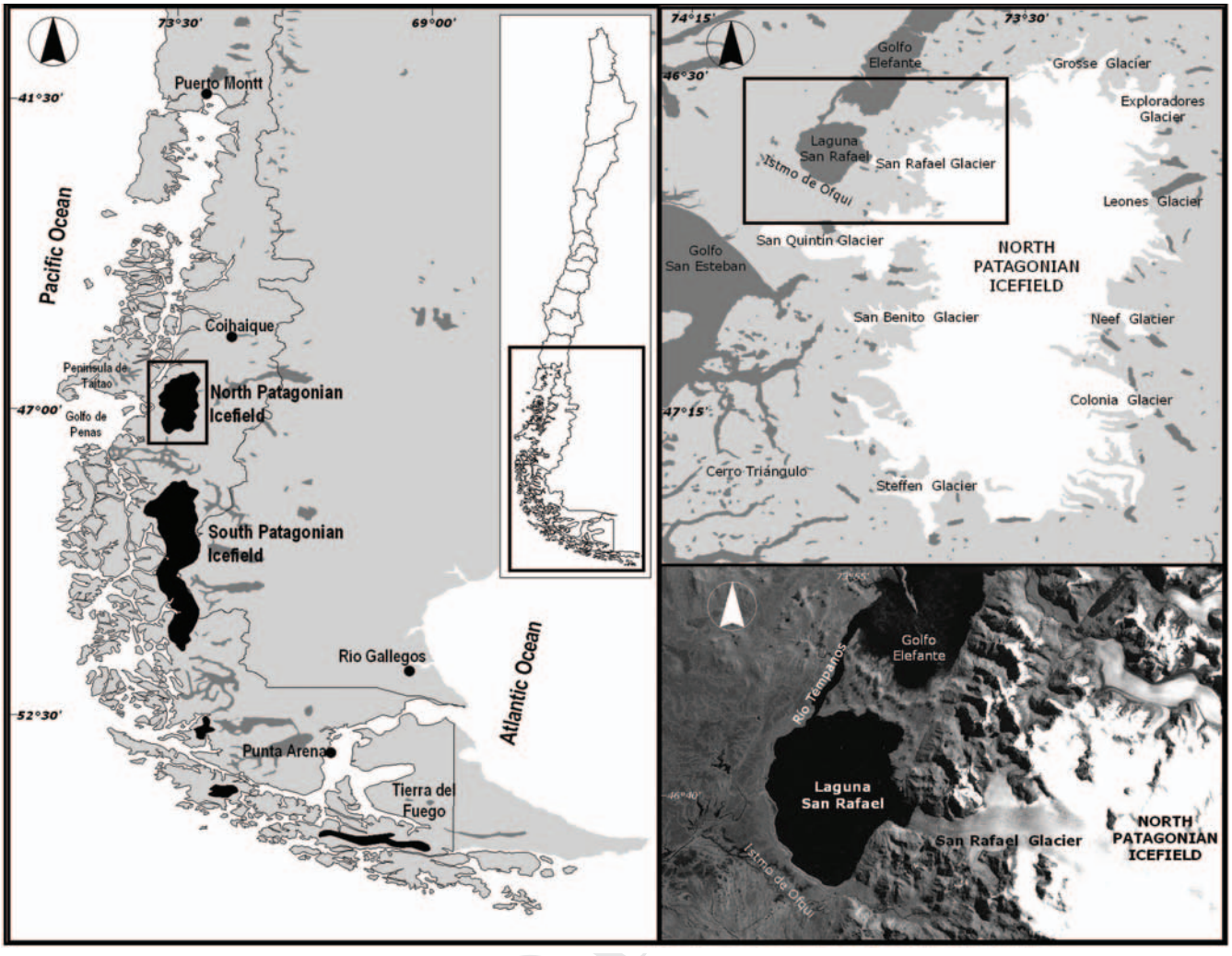

Figure 1 Patagonian icefields of southern South America and the location of the San Rafael glacier

Temporal landscape reconstruction

The documented positions of the San Rafael glacier were superimposed over a Landsat ETM, 2001 image. The image was orthorectified applying the Datum WGS84, Ellipsoid WGS84, Universal Transversal Mercator (UTM) projection and, to aid interpretation, a false colour composite was created using green, red and near-infrared bands to enhance the contrast between ice, water, soil and vegetation (Figure 2).

In order to locate the glacier advance mapped by Simpson in 1875, the glacier's position in the Laguna at that time was georeferenced. At the same time, earlier explorers' descriptions, some including measurements of the San Rafael glacier's ice front positions between the mid-seventeenth and early twentieth centuries, were superimposed over a digital base map to enable reconstruction, in a GIS environment, of the behaviour of the San Rafael glacier advances for the above-mentioned period.

Results and discussion

San Rafael glacier during the seventeenth and eighteenth centuries

The first known historical record that mentions the San Rafael glacier is from AD 1675, when the Spanish pilot Antonio de Vea explored the Patagonian channels, commissioned by the viceroy of Peru. In this exploration, de Vea arrived at the mouth of Laguna San Rafael on Sunday, 15 December 1675, having sailed from the north via Río Témpanos. Upon entering Laguna San Rafael (which he called 'Laguna de la Candelaria'), he discovered a glacier that extended from the eastern shoreline toward the interior; according to his description, water running off the glacier gave rise to the Laguna (Table 1, record 1).

It can be inferred from de Vea's description that the glacier could have been in a position close to that of the present day, that is, near the end of the fjord (Figure 2). This interpretation is supported by de Vea's map, which shows a nearly circular Laguna and no glacier (Figure 3A). His lack of any mention of icebergs suggests either the absence of glacier calving or that icebergs were small and difficult to see, perhaps driven by the wind or tide close to the ice front.

John Byron was shipwrecked 67 years later (AD 1742) on the south side of Golfo de Penas, near Wager Island (as it was later named after Byron's ship). Byron crossed the Laguna San Rafael in the company of canoe-dwelling Indians, who took him towards Chiloé. He provided data that seem to indicate that the landscape of the Laguna had not changed substantially at this time. Byron (1768:147) only indicated that he returned to a meeting point just 'before my companions embarked with the Indians upon a great lake, the opposite part of which seemed to wash the foot of the Cordilleras'. From this brief description, the following aspects can be deduced: (i) that the glacier was not found in the lake, but rather on its opposite side, and (ii) that icebergs were absent. This information would give more credibility to the description provide by de Vea.

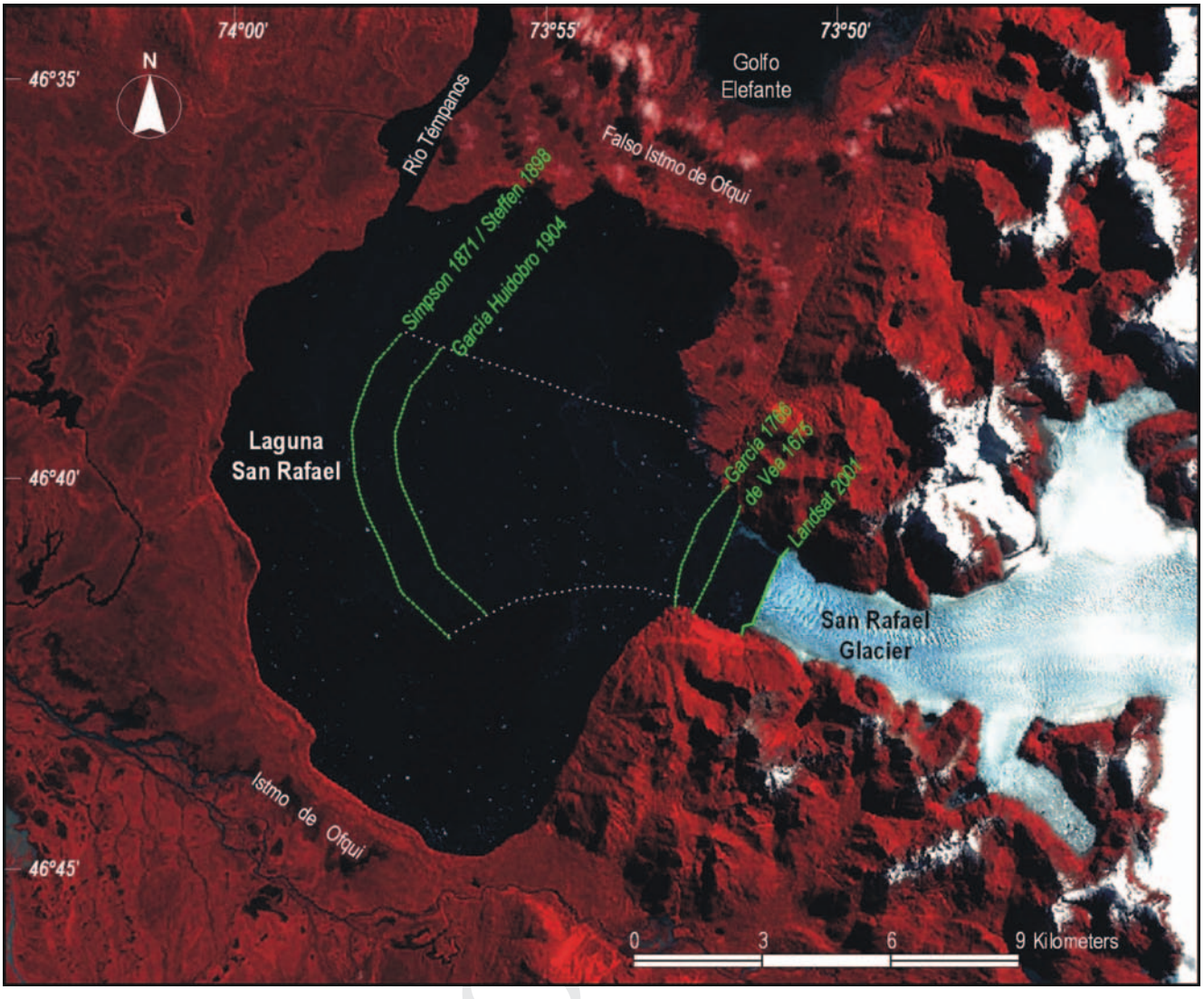

Figure 2 Historical fluctuations of the San Rafael glacier inferred from documentary data

Twenty-four years later, in 1766, a Jesuit priest, José García Alsué, visited the Laguna San Rafael, which he called Laguna de Ofqui, during a missionary campaign. This priest arrived at the Laguna by the Río Témpanos, as is extracted from his trip diary and map (Table 1, record 2 and Figure 3B). In his report, he said that large drifting icebergs, up to approximately 130 m long by 100 m wide and 7 m high, could be seen in the Laguna. On the eastern side of the Laguna, he described two tall, snow-covered hills with a glacier sliding between them to the edge of the water. The author indicated that the large chunks of ice that calved from the glacier sounded like the firing of artillery. According to García's trip diary, some of these icebergs even exited through Rio Témpanos (Table 1, record 2).

This information, the first to record iceberg calving, strongly suggests that, by AD 1766, the above-described lacustrine landscape was different; the glacier had advanced since de Vea's visit in 1675 (Figure 2), although García's information and map suggest that the advance had not gone much beyond the edge of the Laguna's eastern shoreline (Figure 3B). Nevertheless, the inference is that sometime in the preceding 91 years, temperatures would have decreased.

The assumption of an advance is also supported by a note in the diary of the Spanish pilot Francisco Machado. During April 1769, Machado recorded the presence of abundant snow on the Istmo de Ofqui, which made passage difficult[1] and he described the Laguna as a small, nearly circular gulf (making no mention of icebergs), supporting the hypothesis that the glacier was still near the eastern shoreline. The snow at sea-level in April suggests a colder climate than found today (2006), which is also confirmed in García's diary, where he mentioned snow at sea level in November 1766.

The last recorded visitors at Laguna San Rafael in the Spanish colonial period were the Franciscan priests Benito Marin and Julian Real who came, respectively, in 1778 and 1779 to preach to the indigenous canoe-dwelling peoples in the area. However, these priests made no mention of the landscape or climate at Laguna San Rafael (Hudson, 1859; Steffen, 1910, 1947).

San Rafael glacier during the nineteenth and early twentieth centuries

In AD 1857, Francisco Hudson, commander of the Chilean Navy, carried out a survey of the area during the first expedition to be ordered by the government of the new Republic of Chile. On 23 January, Hudson anchored his vessel near the southern shore of Golfo Elefantes, believing it to be Laguna San Rafael, as stated in his report and on his map (Hudson, 1859; Steffen, 1910, 1947). Persisting in his error, Hudson confused the San Rafael glacier, lying before him, with the San Quintín glacier (southeast of the Istmo de Ofqui). To inspect the ice mass more closely, Hudson attempted to cross the peninsula separating the southern coast of Golfo Elefantes from the northern shore of Laguna San Rafael on

Table 1 Historical written records of the Laguna San Rafael explorations from the seventeenth to the twentieth centuries

Record 1	**Antonio de Vea, 1675**[a]
	'anduve dos leguas y media hasta la boca de la laguna, donde observé el sol en 47½º escasos y al promedio de ella descubrí un abra al L.4ª del NE. que todo cuanto se estendía a la vista se veia un ventisquero de nieve que corre desde la playa la tierra adentro. De esta abra y destiladero de la nieve se forma esta laguna cuyos contornos son de tierra baja y cualquier movimiento del viento la encrespa, como la mar'.
Source:	'Espedición de Antonio de Vea (1675–1676). Relación diaria del viaje que se ha hecho a las costas del estrecho de Magallanes con recelo de enemigos de Europa por don Antonio de Vea'. Anuario Hidrográfico de la Marina de Chile No 11, Santiago de Chile, 1886, pp. 539–96; p. 568.
Record 2	**José García, 1766**[a]
	'Dio lugar el tiempo para dejar el puerto Mecas después del mediodía [...]; pasadas seis cuadras fuimos enderezando al sur, dejando al poniente un río cenagoso; a média legua empezó a verse la arboleda mas frondosa, i el canal parecia un rio con sus costas bajas y anegadizas. A las cuatro de la tarde pasó por nuestro lado un pedazo de nieve sobre el agua hasta de ocho varas de largo, y dos por lo mas alto de la flor del agua; poco mas tarde pasó otro tan grande [...], i a media legua de navegación llegamos a la boca de la laguna de San Rafael de Ofqui tendrá de ancho la boca media cuadra estrecha; por el poniente tiene unos bajos que pueden servir de impedimento en baja mar; al entrar en la laguna vi varios isletoncillos que iban errantes por la laguna, i uno ví de cerca que tendria cuadra de largo, i poco menos de ancho i por partes ocho a nueve varas de alto; hermosa era la vista con la variedad que formaban al paso que se deshacian. Al lado del este hai una ancha quebrada entre dos altos cerros, cubierta de muchas varas de nieve que besa la orilla del agua; de esta nieve se desmoronan los grandes pedazos que van errantes por la laguna; i algunos salen por la boca, i al desmoronarse da un estallido, como de tiro de artillería, o como trueno de tempestad; i de éstos oimos muchos. [...] La laguna tendrá de norte a sur dos leguas i poco menos de este a oeste. El agua es bastante dulce i mui clara'.
Source:	'Diario del viaje i navegacion hechos por el padre José García, de la compañía de Jesus, desde su mision de Caylin, en Chiloé hácia el sur, en los años 1766 i 1767'. Anales de la Universidad de Chile, tomo XXXIX, 20 semestre , Santiago de Chile, 1871, pp. 351–79; pp. 358–59.
Record 3	**Enrique Simpson, 1871–1873**[a]
	'Conociendo que estos témpanos solo podian provenir del ventisquero que teniamos a la vista, resolví seguir su curso y penetrar en el rio hasta donde fuera posible, fiado en que por donde pasaban masas de hielo de mas de tres metros de calado, podia pasar el vaporcito [...], i siguiendo el derrotero de los témpanos, entramos en procesion con ellos, a un rio de mas de cien metros de ancho i de siete a quince brazas de fondo [...]. Esta laguna, sin duda alguna, es la verdadera de San Rafael de los jesuitas del siglo pasado; pero se habia perdido tanto de vista que ni el práctico don Juan Yates, que es el ser viviente mas antiguo de estas rejiones, ni siquiera tenia idea de su existencia [...]. La laguna es de forma casi circular, de ocho a nueve millas de diámetro i, como he dicho ántes, dentro de ella se proyecta el gran ventisquero de San Rafael, el cual se desprende de una gran sábana de hielo en la cordillera, que a una altura de mas de mil metros se estiende muchas millas de Norte a Sur por detras de las montañas del litoral, i bajando por una garganta de mas de una milla de ancho entre picos escarpados, se lanza cuatro millas i media dentro de la laguna, ensanchándose hasta mas de cuatro millas en su terminacion. De suerte que forma una especie de trapecio de no menos de seis millas i media de altura, i cuyo perímetro se compone de precipicios que pasan de cien metros de elevacion, siendo su superficie un mar de grietas i picos. El resto de la laguna se encontraba sembrado de numerosos témpanos sueltos, algunos de ellos mui grandes, llegando hasta mas de treinta metros de altura con cien de base, de los tintes mas variados, blanco, azul, rosado, etc., i de las formas mas fantásticas i caprichosas, figurando todos los objetos de la creacion [...]. estos témpanos no son sino masas desprendidas del ventisquero por el derretimiento de las partes sumerjidas en el agua, la cual, por supuesto, tiene una temperatura superior [...]. Mientras nos encontrábamos en tierra observando la latitud, sentimos un gran ruido prolongado, que provenia del volteo i consiguiente desmembracion de un enorme témpano, como sucede siempre que por la disolucion de su base sube demasiado el centro de gravedad. Calculando que esto produciria grandes olas, corrimos inmediatamente al bote, justamente a tiempo para asegurarlo, pues en ese instante ya se retiraba de la orilla por efecto del mismo retroceso de las aguas que se nota en los terremotos, llegando en seguida a estrellarse contra la playa varias olas. Del mismo modo, mas tarde, a nuestra vuelta, habiéndonos acercado hasta media milla del ventisquero para observar mejor la altura del precipicio; oimos repetidamente por detrás de nosotros un terrible estruendo parecido a la descarga de una batería entera de artillería, causado por el desprendimiento de un nuevo témpano, i en seguida notamos una ola encrespada que avanzaba hácia nosotros amenazando sumerjirnos. Felizmente dejó de reventar antes de alcanzarnos. El efecto de estas olas se nota en todo el perímetro de la laguna, donde causan derrumbes que serian mayores si la espesa vejetacion no defendiese el terreno'.
Source:	'Esploraciones hechas por la corbeta Chacabuco, al mando del Capitán de Fragata D. Enrique M. Simpson, en los archipiélagos de Guaitecas, Chonos i Taitao'. Anuario Hidrográfico de la Marina de Chile, No 1, Santiago de Chile, 1875, pp. 3–147; pp. 30–33.
Record 4	**Hans Steffen 1898**[a]
	'Despues de dos horas i media de navegacion entramos en el lago de San Rafael, dirijiéndonos hacia su orilla occidental, formada por la continuacion de las barrancas que ya observamos en el rio Témpanos i que alcanzan aquí una altura de 10 a 15 metros sobre el nivel del lago. El paisaje que tuvimos a la vista tiene casi los caracteres de una rejion polar. La ancha cuenca del lago está cubierta por un sinnúmero de trozos de hielo de las dimensiones i formas mas variadas, moviéndose despacio segun los caprichos del viento, i en su parte media desciende, desde un abra de las cordilleras la lengua del ventisquero de San Rafael, avanzando en forma de un enorme abanico, hasta el centro del lago, donde termina en una muralla de hielo rajada por innumerables grietas verticales. Estudiando la situacion i las dimensiones actuales de este grandioso ventisquero, no encontramos casi ninguna diferencia con la descripción que dió de él el comandante Simpson en la relacion de sus viajes, así que se puede presumir que la lengua de hielo haya quedado casi estacionaria en los últimos 30 años'.
Source:	Steffen, Hans (1910). 'Viajes de exploracion i estudio en la Patagonia Occidental 1892–1902'. Imprenta Cervantes, Santiago de Chile, vol. II , 549 pp.; p. 303.
Record 5	**Guillermo García Huidobro, 1904**[a]
	p.3 'El falso istmo se encuentra separado de la Península de Taitao por el rio de los Témpanos que es el desague de la Laguna San Rafael i corre de Norte á Sur magnético hácia la baia del mismo nombre. La distancia menor entre el Golfo i la Laguna, a travéz de este istmo, es solo de 3500 metros en terrenos bajos i pantanosos existiendo solo una angosta faja de terreno firme . 'La laguna está limitada en sus contornos por terrenos bajos i pequeños escarpes ó barrancos, no teniendo el mas alto de ellos, una altura superior a 12 ó 15 metros.- Los del Sur i SO son los de menor altura i guardan mui poca diferencia de nivel con la laguna; son casi llanos, i por tal motivo exesivamente pantanosos, siendo molesta i difícil su travesia [...].- El contorno de la laguna es casi circular, midiendo de Norte á Sur aproximadamente 15 kilómetros, i 11 de Este á Oeste. A su costado Este, hai una ancha i profunda quebrada formada por dos altos cerros del continente i por donde se precipita hácia la laguna el gran ventisquero que lleva su nombre i se interna en ella 7 kilómetros, ensanchándose hasta 9 en su terminacion.- La curva que forma contorno al nivel de la laguna, es tambien circular i aproximadamente concéntrica con aquella.

(continued)

Table 1 (continued)

	El ventisquero arranca del elevado monte San Valentin, de 3987 metros de altura i situado mas al interior en latitud 46 grados 35 minutos 29 segundos Sur por 73 grados 22 minutos 27 segundos de lonjitud Oeste'.
	p.4 "El ventisquero San Rafael descansa gran parte en el fondo de la laguna, dragada por el mismo, pero no así su perímetro que permanece suspendido i esperimenta frecuentes derrumbes que cambian la configuración de sus contornos.- Estos son, en parte, cortados a pique con 40 i más metros de elevacion i en otras casi al nivel del agua. Sin embargo, como hemos dicho, esta forma se modifica por el avance del hielo i los derrumbes citados. Su superficie es formada por un mar de grietas i picos, separados por profundos precipicios. De los contornos es de donde se desprenden los témpanos que vagan en la laguna, algunos de grandes proporciones i alcanzando un volúmen quizás superior a 1000 toneladas. Estos grandes témpanos i miles pequeños que adoptan la forma mas caprichosa i variadas dan a la laguna un hermoso aspecto realzado grandemente por la presencia de aquella montaña de hielo que se proyecta i destaca sobre los bosques verdes, tupidos ó impenetrables, que la rodean'.
	p.5 'En los dias de fuertes lluvias tiene lugar el mayor desprendimiento de témpanos i debido probablemente a la acción del agua que cae en las grietas i obra a manera de cuña cuando se solidifica.- Tambien ejerce gran accion la marea á caúsa del desnivel que produce . Ella i los vientos dirijen la marcha de ellos, llevándoselos a vararse en las riveras o conduciéndolos a la boca del rio Témpanos por donde siguen al Norte dragando su fondo i demoliendo sus orillas con el roce o los golpes'. pp. 16–17 'El fondo de la Laguna [San Rafael] en la parte que rodea el ventisquero es variable entre 35 i 75 metros; aumenta despues en la mediania del espacio entre este i la rivera alcanzando hasta 118 para disminuir enseguida rapidamente hacia la costa. La calidad del fondo es fango e igual al de la bahia San Rafael i rio Témpanos i que bien podria llamarse tierra sumergida. La cubre una pequeña capa de arena fina arrastrada por el ventisquero en su descenso. La ocsilacion de las mareas, en la Laguna, no sobrepasan de 1 metro 50 i no existe otra corriente que la producida por el rio Témpanos, hacia dentro ó fuera según sea la marea llenante ó vaciante'.
Source:	'Memoria presentada por el comandante de la cañonera Pilcomayo, Capitán de Fragata señor Guillermo García Huidobro, sobre los trabajos hidrográficos que comprenden el Plano General a la escala de 1:50 000 y que encierran desde la Punta Quesahuen al norte del Golfo de los Elefantes, dicho golfo, la bahia y laguna San Rafael, Istmo de Ofqui y rios Lucac, Negro, San Tadeo hasta su desembocadura en el Golfo San Esteban'. Año 1905. Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA). Informe de Comisión 8660-1905. No 8, 25 pp. (Documento original mecanografiado).

[a]These dates correspond to the years in which the explorers already visited the Laguna San Rafael.

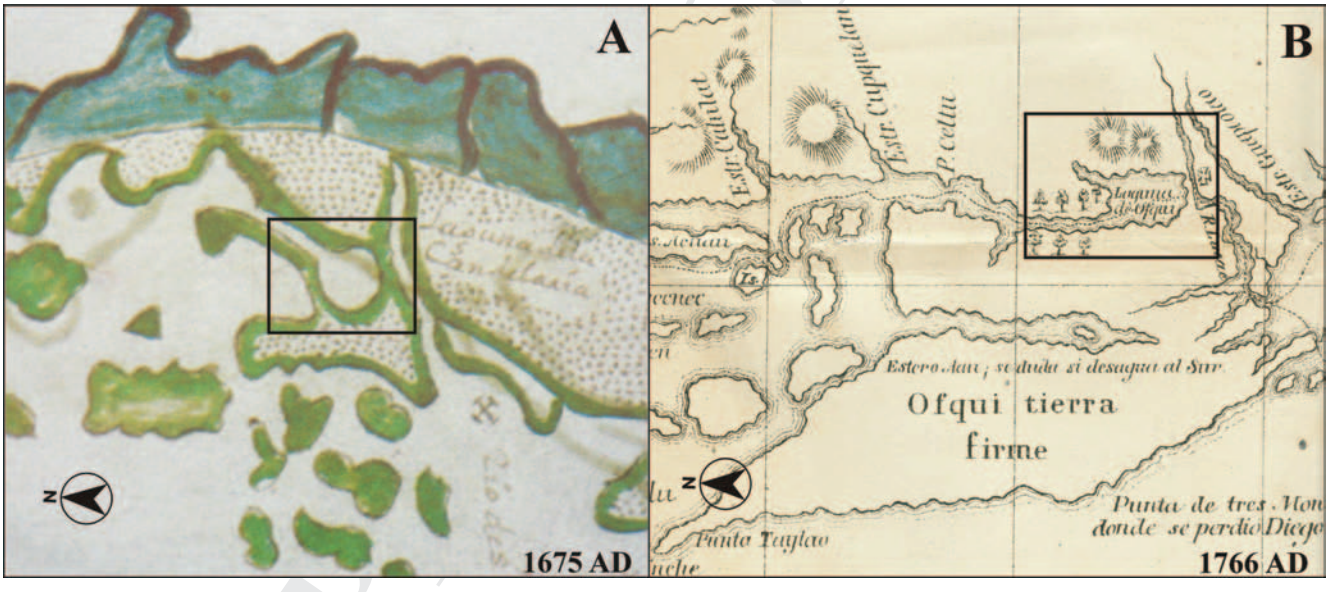

Figure 3 Rudimentary early cartography of Laguna San Rafael (squares). (A) Small section of the map made by de Vea in 1675, which he called 'Laguna de la Candelaria' (source: Atlas Cartográfico del Reino de Chile, siglos XVII, XVIII y XIX, Instituto Geográfico Militar, Santiago de Chile, 1981, Lámina No. 12). (B) Map section of the same area made by García in 1766; he called the area 'Laguna de Ofqui' (source: Anuario Hidrográfico de la Marina de Chile, No. 14, Santiago de Chile, 1889)

foot; this peninsula would later be known as the Falso Istmo de Ofqui (see Figure 6B). Unfortunately, because of the swampy and dense vegetation, the expedition failed.

Although he did not actually reach the Laguna, the information provided by Hudson allows us to deduce that the San Rafael glacier already extended some distance into the Laguna, possibly reaching a position similar to that described by Simpson (1875) 14 years later. This deduction is based on the local topography and landscape; the sight point from which Hudson made his descriptions (the lowland of Falso Istmo de Ofqui) only allowed him to see a huge ice mass that appeared over the forest canopy. Given that, what he saw was the San Rafael glacier, which hid the San Quintin glacier, then located approximately 26 km southward (see Figure 6B). It should be noted that Hudson only mentioned one single glacier in his observations, reinforcing the previous deduction.

Commander Enrique Simpson, an officer of the Chilean Navy, re-discovered Laguna San Rafael in 1871 and returned there in 1873. He explored the Laguna on the orders of the government, providing a detailed map and a lengthy report in which he described the Laguna as nearly circular in shape, with the San Rafael glacier protruding some 4.5 miles (~8 km) into the water. He also noted that the glacier was fan-shaped, with a 4 mile (~7 km) wide ice front reaching heights of up to 100 m (Simpson, 1875; Table 1, records 3 and Figure 4).

Figure 4 Cartographic section of Laguna San Rafael, made by Simpson in 1875 (source: Anuario Hidrográfico de la Marina de Chile, No. 1, Santiago de Chile, 1875)

Simpson also noted an abundance of calved icebergs floating in the Laguna. Some of these were quite large (100 m wide by 30 m high), with many still of sizeable proportions, exiting through Río Témpanos into Golfo Elefantes, a situation that Simpson described as he navigated through Río Témpanos (Table 1, record 3). Simpson's observations show that the glacier had advanced considerably westward across the Laguna since the time of García and Machado, nearly 100 years before, reflecting an intensification of climate cooling in the region (Figure 5).

In 1898, in the last expedition of the nineteenth century to reach Laguna San Rafael, the geographer Hans Steffen was commissioned by the Chilean government to survey both the coastal area and the interior territory of Northern Patagonia. The data provided by Steffen (1910) indicate that the shape and dimensions of the glacier then protruding into the Laguna were practically identical to those given by Simpson. Steffen described a fan-shaped ice tongue of the San Rafael glacier descending from a mountain gorge, reaching the middle of the lake, and ending in an ice wall full of cracks and fissures (Figure 6). Steffen also mentioned that the Laguna basin was full of floating icebergs of different sizes (Table 1, record 4). The similarity of the lacustrine landscapes observed by Steffen and Simpson suggest that the glacier had remained more or less at a standstill during the intervening 27 years.

As there is no historical information between the expeditions of García, Machado and Simpson (between 1770 and 1870) except for the vague indications taken from the Hudson report, an important cold pulse in Northern Patagonia could be inferred. This was clearly manifested in the advance of the San Rafael glacier toward the interior of the lake. This advance probably began toward the end of the eighteenth century and peaked in the nineteenth century.

Figure 5 Historical comparison of the San Rafael glacier position. Simpson's iconography representing the glacier advance in 1875 (top). Glacier photography of 1994 (F. Torrejón), probably depicting conditions similar to those observed by García in 1766 (bottom)

Detailed measurements showing that the glacier was retreating in 1904 were provided by Guillermo García Huidobro,[2] commander of the Chilean gunboat *Pilcomayo.* By that date, the glacier extended 7 km into the Laguna, with an ice front over 9 km long paralleling the western shore of the Laguna, and ice-surface heights varying from 40 m to water level. García Huidobro also noted sustained ice calving and mentioned that the icebergs floating in the Laguna numbered in the thousands, some of which reached a volume of nearly 1000 tons. He reported water depths of 35 to 75 m around the glacier margin, reaching down to a maximum depth of 118 m elsewhere (Table 1, record 5).

A detailed comparison of the information provided by García Huidobro and that of Steffen six years earlier shows that the glacier was in an evident retreat, having lost 1 km of its extension. This decrease was also manifested in the noticeable loss of glacier volume; Simpson's report indicated a maximum perimetral height of 100 m, whereas García Huidobro, 33 years later in 1904, indicated this height to be only 40 m.

The above allowed the inference that, at the beginning of the twentieth century, the climatic conditions in Northern Patagonia were warmer than those previously inferred for the second half of the nineteenth century. This general tendency continued to be seen during the rest of the twentieth (Winchester and Harrison, 1996) and the present century (Rignot *et al*., 2003; Glasser *et al*., 2005), in spite of some minor advances of the glacier front such as that identified in the middle of the twentieth century (Heusser, 1960; Warren, 1993).

Relationship of the historical analysis with other studies in the area

Errors in the interpretation of the historical data

Although some works have used historical data to reconstruct the behaviour of the glacier in past times, errors of historical appreciation have been perpetuated, because the sources – mostly written in old-style Spanish – have not been duly interpreted. Concrete cases, such as the work of Warren (1993), suggest explicitly that, in 1675, the glacier occupied the eastern shoreline of the Laguna. Our historical analysis indicates that, at that time, the glacier was located a little bit toward the interior of the fjord. It was then indicated that the glacier had advanced toward the interior of the Laguna between 1742 and 1766, based on a supposed description of John Byron. Upon reviewing Byron's original text, no allusions were made to a glacier advance; Byron only indicated that he 'embarked, with the Indians, upon a great lake, the opposite part of which seemed to wash the foot of the Cordilleras'. Furthermore, a comparison with the data from García and Machado established that, although the conditions in the area appeared to be colder between 1766 and 1769, the glacier was on the east shore and did not penetrate the water body (Fig. 2 and 3b). Nonetheless, our analysis coincided with the date indicated by Warren (1993) and Harrison *et al*. (2007), which indicated that the peak of the LIA occurred during the second half of the nineteenth century.

Climatic interpretation of the historical data

Previous research around the NPI has shown that many glaciers are currently retreating from maximum positions reached during the LIA (Warren and Aniya, 1999; Harrison and Winchester, 2000; Glasser *et al*., 2002, 2006; Koch and Kilian, 2005). This is probably related to the climatic change recorded in southern South America, which, at the same time, contribute to rising sea levels (Rignot *et al*., 2003; Rivera, 2005). However, there have been fluctuations in the trend, and calving glaciers are particularly affected – in a non-linear way – by changes in precipitation rather than temperature (Luckman and Villalba, 2001). Winchester and Harrison (1996) indicated that precipitation was the dominant factor controlling the fluctuations of the San Rafael glacier, with a timelag of 20 years between precipitation input and glacier fluctuation. Then they estimate – according to the nearest precipitation records – that the glacier should have experienced a new advance between 1991 and 2006. However, this situation was not recorded; rather, a retreat was observed. This indicates that temperature also does play an important role in glacier fluctuations. Unfortunately, there is no precipitation record for Northern Patagonia until late in the Republican period; hence, it is impossible to associate winter precipitation with historical glacier front fluctuations.

Consequently, caution is required when making climatic inferences from the behaviour of calving glaciers. Despite this caveat, the San Rafael glacier may be an exception. Both tree-ring and lichenometric evidence indicate that the glacier reached its maximum position sometime before 1876, probably early in the second half of the nineteenth century (Winchester and Harrison, 1996; Winchester *et al*., 2001; Harrison *et al*., 2007) and later behaved in a similar manner to most land-terminating glaciers in the region; the

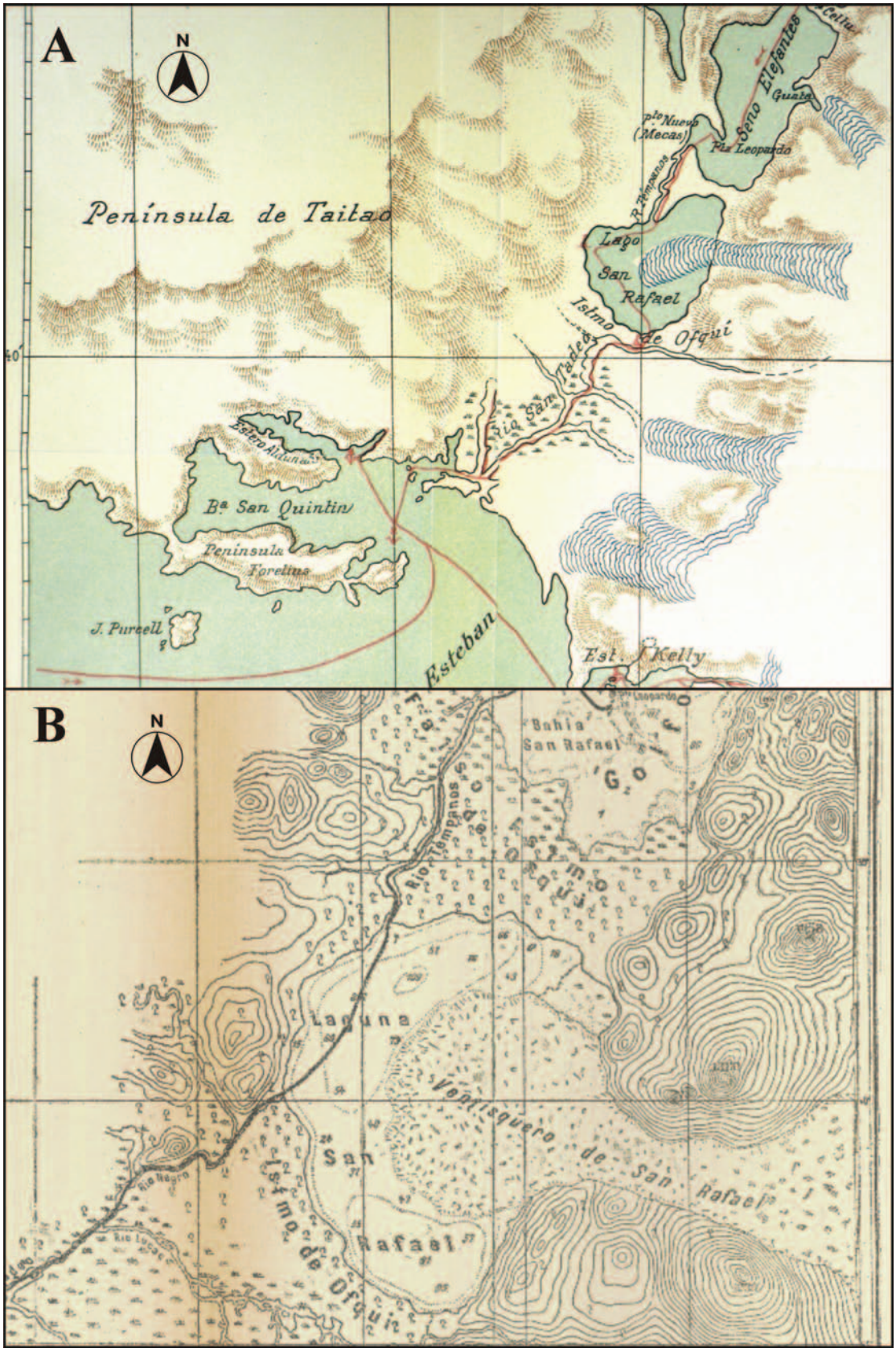

Figure 6 Steffen's maps of Laguna San Rafael. (A) Section of 'Mapa de la Rejion Andina estudiada por la Comision Esploradora del Estero i Rio Baker', representing conditions in 1898 (source: Steffen, 1910). (B) Section of the map 'El Istmo de Ofqui, diseñado por el Dr. H. Steffen', based mainly on the data from the García Huidobro exploration of 1904 and first published in Berlin in 1919 (source: Steffen, 1947)

latter show a consistent and accelerating tendency to retreat despite occasional variations (Luckman and Villalba, 2001).

The historical evidence presented suggests that the San Rafael glacier, in spite of being a calving glacier, presents a retreating tendency since 1898 to the present, interrupted by a slight advance between 1935 and 1959 (Warren, 1993). This trend coincides with the behaviour described by Luckman and Villalba (2001) for the continental glaciers of Northern and Southern Patagonia, indicating

that it is possible to make some preliminary climatic inferences based on historical fluctuations. Rignot *et al*. (2003) confirmed this by establishing that calving glaciers are more sensitive to climate changes than non-calving glaciers.

Comparison with previous results obtained for the NPI

Glasser *et al*. (2006) used geomorphological evidence from the San Rafael glacier to propose a four-stage model of formation of the 'Témpanos' moraine. In Stage 3, these authors state that the glacier had advanced again as far as the moraine 'Témpanos', which was built in Stage 1, during a LIA event prior to mid-1800. In Stage 4, the glacier retreated to the level observed by Simpson in 1871, although he indicated that this retreat was produced prior to this date. The historical evidence contributed greater detail to the Glasser *et al*. (2006) dates given for Stages 3 and 4, which are imprecise concerning the Stage 3 advance, dating it as 'prior to the mid-1800s?'. The historical records, on the other hand, are more precise, suggesting that this advance occurred prior to AD 1675 when the glacier remained confined to its valley until probably a relatively short time before Garcia's 1766 date for icebergs in the Laguna (Figure 2 and 3A). This situation should have remained largely unchanged until approximately 1769, when the glacier had already reached the shore of the Laguna. The slight advance probably reflected an incipient cooling process that began around 1766.

Glasser *et al*. (2006) also stated that, in Stage 4, the Témpanos channel opened, establishing a connection (Río Témpanos) between the Laguna and the sea. However, the historical data presented herein showed that de Vea (1675), Byron (1742), García (1766) and Machado (1769) had already navigated this channel before the date indicated by Glasser *et al*. (2006) for its opening. Thus, we infer that the Río Témpanos was an early natural connection between the Laguna San Rafael and Golfo Elefantes.

On the other hand, Heusser (1960), during a scientific expedition to Laguna San Rafael, indicated that winter snowfalls are important in the mountains but are light and short-lived at sea level. These climatic conditions contrast with those indicated by Machado who, in April 1769, highlighted the presence of abundant snow in the Istmo de Ofqui. Colonial reports[3] from 1773, 1783 and 1784–1788 recorded the routine presence of winter snow in the near sea-level city of Castro, Isla de Chiloé (42°29′S, 73°46′W), where no snowfall is presently recorded, with the likelihood of a similar situation throughout the Septentrional Patagonia. Hence, the notorious cold conditions detected for the end of the eighteenth century probably corresponded to the manifestation of the LIA in the Septentrional Patagonia. According to the analysis and reinterpretation of the historical sources, this period extended from approximately 1766 to 1898, and peaked between 1857 and 1871.

These dates do not coincide completely with other LIA research carried out by Villalba (1990) in Septentrional Patagonia. Using tree ring records from the Río Alerce sector (Argentina), this author found cold episodes between 1270 and 1380 and from 1520 to 1670; both periods are contemporary with the two main LIA events in the Northern Hemisphere (Lamb, 1977; Jones *et al*., 1998; Dahl-Jensen *et al*., 1998) and the latter period contrasted with the warm conditions that probably occurred in the San Rafael area, as inferred from the historical data.

Comparison with other climate records in South America

Villalba (1994) used a record of radiocarbon dating from Röthlisberger (1986) to survey large advances of the glacier Los Cipreses in 1640 and from 1800 to 1850. Although no historical data are available for contrasting the information of this glacier's 1640 advance with that of the Laguna San Rafael glacier, the Los Cipreses 1800–1850 advance would be synchronous with that of the San Rafael glacier.

In the zone located to the south of the Septentrional Patagonia, Koch and Kilian (2005) mentioned that the culmination of the LIA in the Patagonian Andes occurred between AD 1600 and 1700. These authors also indicated that several glaciers at NPI and SPI formed prominent moraines around 1870 and 1880, a situation that is reflected in the results for the advance of the Lengua glacier, in Gran Campo Nevado. This glacial advance coincided, approximately, with the peak of cooling identified in San Rafael between 1857 and 1871.

The time difference presented above also agrees, with a slight lapse, with the temporal window described for the LIA in Central Argentina by Cioccale (1999) and is supported by historical information as well as other proxies. Cioccale (1999) proposed two cooling pulses that peaked in the middle of the fifteenth century and towards the end of the eighteenth century. Both pulses were interrupted by a warm period that coincided perfectly with the position of the San Rafael glacier described by de Vea in 1675. Although Cioccale's study area does not correspond to the same geographic zone, the comparison is not invalid, since hemispheric comparisons of LIA events have been made between farther areas (eg, Villalba, 1990, 1994; Bertrand *et al*., 2005).

With respect to the end of the LIA in Septentrional Patagonia, Winchester and Harrison (1996) used the estimate of the age of the oldest trimline trees for 1882 (Lawrence and Lawrence, 1959) and the six-year time gap calculated for the ecesis, to establish 1876 as the date when the glacial retreat began. This tendency is also reflected in other glaciers located in the NPI (Harrison and Winchester, 1998). Nonetheless, given the historical evidence provided by Simpson in 1871, Steffen in 1898 and García Huidobro in 1904, we estimate that the retreat of the San Rafael glacier began after 1898; the retreat of only 1 km in 1904 would have marked the end of the LIA in the Septentrional Patagonia. However, it should be noted that calving glaciers may not retreat linearly, but can exhibit many fluctuations (Winchester and Harrison, 1996; Luckman and Villalba, 2001).

The results of the present study are based on the analysis of historical data and the relationship with tree-rings, glaciologic, stratigraphic and radiocarbon studies, allowing us to validate the great usefulness of these traditionally underestimated documentary proxies in the reconstruction of past climate events in the Chilean Septentrional Patagonia. Given this, we find that the integration of documentary and natural proxies would be valuable, and plan to develop such an approach in future palaeoclimate research in the area.

Conclusions

In general, documentary sources show that the behaviour of the San Rafael glacier agrees with the findings of other indicators suggesting that, despite its being a calving glacier, it has reacted to climatic changes similarly to land-terminating glaciers in the area. The major contribution provided by the documentary evidence has been to confirm the occurrence of a cold period in the Laguna San Rafael area, which would be within the temporal window defined for the European LIA.

Although the changes in the glacier front could be related to precipitation rather than temperature fluctuations, and considering the lack of long precipitation records in the area, the sole historical evidence suggests that warm conditions prevailed around 1675, a date in which the front of the San Rafael glacier did not extend beyond the eastern shoreline of the lake. Later, a cooling period occurred from 1766 to 1898, with a peak between 1857 and 1871, during which the glacier advanced up to 8 km into the interior of the Laguna San Rafael. This cooling period declined after 1898, as evidenced by the decrease of the San Rafael glacier, which had retreated 1 km by 1904.

The recognition of the LIA in Northern Patagonia, through the use of documentary sources, provides important, independent evidence for the occurrence of this phenomenon in the region. Our results highlight and emphasize the usefulness of often ignored or poorly quoted historical documents for reconstructing past climates in the Chilean Patagonia.

These conclusions seem to oversimplify glacier fluctuations with regards to climate variations and are based solely on historical testimonial evidence, which herein is presented to be contrasted with other natural proxies.

Acknowledgements

Funding for this research was supported by Fondecyt projects 1070508 and 1060227, and DIUC 205.310.044 sp and 204.310.039–1. This research is also an associated contribution of the Patagonian Ecosystem Research Centre (CIEP). We give special thanks to Professor Rick Battarbee of UCL for his encouragement and general comments and to Professor Vanessa Winchester for her observations and suggestions. Finally, the authors would like to thank Øyvind Nordli and Sébastien Bertrand for their suggestions, which most certainly improved the quality of this work.

Notes

1 'Diario de la espedición que el piloto don Francisco Machado hizo desde el puerto de San Antonio de Chacao, en la provincia de Chiloé, para reconocer los archipiélagos de Guaitecas i Guayaneco, por órden del gobernador, que entonces era de aquella provincia, don Carlos de Beranger. 11 de junio de 1769'. Anuario Hidrográfico de la Marina de Chile, No. 14, Santiago de Chile, 1889, pp. 143–49.

2 'Memoria presentada por el comandante de la cañonera Pilcomayo, Capitán de Fragata señor Guillermo García Huidobro, sobre los trabajos hidrográficos que comprenden el Plano General a la escala de 1:50.000 y que encierran desde la Punta Quesahuen al norte del Golfo de los Elefantes, dicho golfo, la bahia y laguna San Rafael, Istmo de Ofqui y rios Lucac, Negro, San Tadeo hasta su desembocadura en el Golfo San Esteban'. 1905. Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA). Commission report 8660–1905. No. 8, 25 pp. (Original typed document).

3 Beranger, Carlos de. 'Relación jeográfica de la isla de Chiloé'. Anales de la Universidad de Chile, Santiago, 1893, tome LXXXIV, pp. 181–243. 'Copia de un cuestionario sobre costumbres, producción, etc.'. Archivo Nacional, Fondo Archivo Hidrográfico 'Vidal Gormaz', Vol. 18, Pieza 1, fojas 1–6. 'Descripcion y noticia de las dos naciones Patagónica y Guaigüene, Isla de Chiloe'. Biblioteca Americana José Toribio Medina, Fondo Manuscritos, Tome 257, Manuscript 7454 (Microfilm Ms. M59), fojas 59–81.

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