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*INVITED REVIEW*

# Holocene glaciations of Hielo Patagónico (Patagonia Icefield), South America: A brief review

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The Hielo Patagónico (Patagonia Icefield), South America, is the largest temperate ice body in the Southern Hemisphere with more than 70 major outlet glaciers and a total area of *ca*. 17,200 km$^2$. For the Hielo Patagónico, two major schemes for the Holocene glaciations (Neoglaciations) have been proposed. Mercer first proposed three Neoglaciations, I at 4500–4000 years before the present (yr BP), II at 2700–2000 yr BP and III at the 17–19th centuries. Aniya later postulated a scheme of four Neoglaciations, I at *ca*. 3600 yr BP, II at 2400–2200 yr BP, III at 1600–900 yr BP, and IV at the 17–19th centuries, which is congruent with other regions of the Andes. The main differences are the age of Neoglaciation I and the existence of a Neoglaciation at 1600–900 yr BP. After examining the dates given by other studies, although scanty, I propose a new scheme of five Neoglaciations, I at 4500–4000 yr BP, II at 3600–3300 yr BP, III at 2700–2000 yr BP, IV at 1600–900 yr BP and V at 17–19th centuries, that is, the Little Ice Ace (LIA). In addition, there were two earlier Holocene glaciations, probably at 5700–5000 yr BP and 8100–6800 (or 7500) yr BP. Two older ages, 8800–8500 yr BP and 9700–9100 yr BP, are uncertain.

Keywords: Patagonia Icefield, Holocene, glaciations

## INTRODUCTION

In view of the current global warming and its effect on glaciers all over the world, it is important to know the past state of glaciers, from which we may be able to infer the future of glaciers. The Hielo Patagónico (Patagonia Icefield) is located at the southern end of South America and is the largest temperate ice body in the Southern Hemisphere. Therefore, it is very important and critical to study glaciations at the Hielo Patagónico in order to understand the behavior of glaciers at the global scale. Because we live in the age of the Holocene, I briefly review the Holocene glaciations at the Hielo Patagónico, based on which I propose a new scheme. In this paper, dates indicate more or less when a glacier advance reached the maximum extent (culmination), unless otherwise indicated, which I call "glaciation."

## HIELO PATAGÓNICO

The Hielo Patagónico, with a total area of about 17,200 km$^2$, stretches from Lat. 46°25′ S to 51°30′ S along Long. 73°30′ W for a total of more than 540 km long with the width ranging from 8 km to about 60 km. Presently it is divided into two separate icefields, Hielo Patagónico Norte (HPN, or Northern Patagonia Icefield) and Hielo Patagónico Sur (HPS, or Southern Patagonia Icefield) by a fjord at about 47°40′ S (Fig. 1). The area of the HPN is about 4200 km$^2$ (Aniya, 1988) while that of the HPS is about 13,000 km$^2$ (Aniya *et al*., 1992). The HPN has 28 major outlet glaciers (Aniya, 1988) and the HPS has 48 major outlet glaciers (Aniya *et al*., 1996). Recently, Rivera *et al*. (2007) updated the inventory of the HPN using satellite images, including small ice masses which Aniya (1988) omitted, thereby obtaining an ice area (excluding nunataks within the icefield) of about 3950 km$^2$. During the last Pleistocene glaciation, it was much larger than today, with an area of 480,000 km$^2$, stretching over 1800 km long and 300 km wide at the widest (Hollin and Schilling, 1981).

Presently the elevation of the icefield ranges from 0 m on the west side to 3910 m at Monte San Valentin located near the northeast corner of the HPN (Fig. 2); however, much of the icefield lies at elevations between 1000–1500 m. Major high mountains include Cerro (Co.) Arenales (3365 m) of the HPN and Volcán Lautaro (3380 m), Co. Fitz Roy (3405 m) and Co. Paine Grande (3248 m) of the HPS (Fig. 3).

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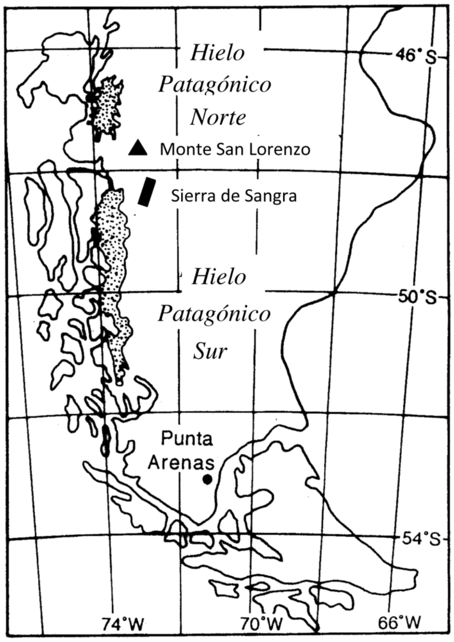


*Fig. 1. Location of Hielo Patagónico (Patagonia Icefield), South America. Locations of Monte San Lorenzo (3704 m) and Sierra de Sangra that are mentioned in the text are indicated.*

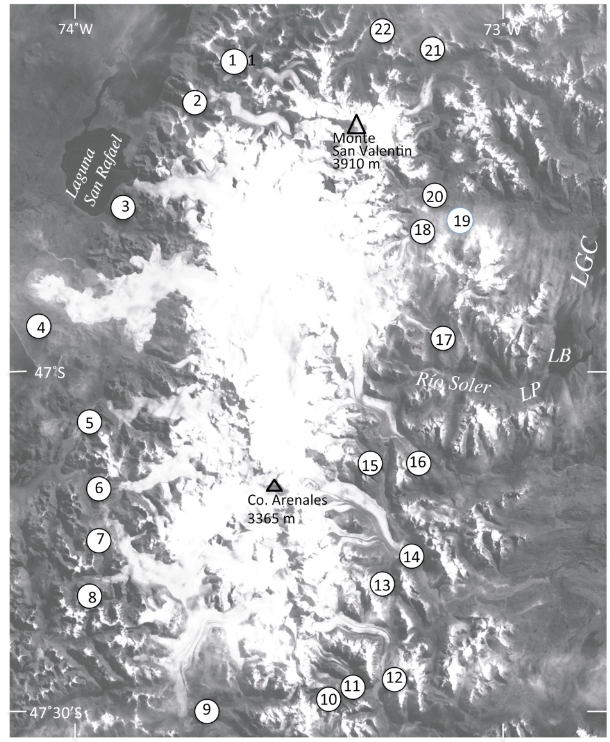


*Fig. 2. Landsat ETM+ mosaic of the HPN (Hielo Patagónico Norte, April 2, 2003), showing major outlet glaciers and others. 1, Reicher; 2, Gualas; 3, San Rafael; 4, San Quintin; 5, Benito; 6, HPN1; 7, HPN2; 8, HPN3; 9, Steffen; 10, Piscis; 11, Pared Sur; 12, Pared Norte; 13, Arco; 14, Colonia (branch is Arenales); 15, Cachet; 16, Nef; 17, Soler; 18, León; 19, Calafate; 20, Fiero; 21, Exploradores (location of meteorological station); 22, Grosse. LP, Lago Plomo; LB, Lago Bertrand; LGC, Lago General Carrera (in Argentina, Lago Buenos Aires). Laguna San Rafael connects to the Pacific Ocean.*

Of the 21 outlet glaciers of the HPN that have been monitored for variations since 1945 (Aniya *et al.*, 2011), 17 are calving glaciers including Glaciar (Glacier) San Rafael, a tidewater glacier located closest to the equator at 46°41′ S. The largest glacier of the HPN is Glaciar San Quintin with an area of 765 km$^2$ (Aniya, 1988: cf., Rivera *et al.*, 2007, listed as 795 km$^2$), and the next largest is Glaciar San Rafael with an area of about 760 km$^2$, which correspond to the 5th and 6th largest glaciers, respectively, in the Hielo Patagónico.

In the HPS, 46 out of 48 major outlet glaciers are calving glaciers; those on the west side mostly draining into fjord, while many of those on the east side terminating in proglacial lakes that are dammed by terminal moraines. In the HPS there are many large outlet glaciers including the largest in South America, Glaciar Pio XI with an area of 1265 km$^2$ (Aniya *et al.*, 1996), followed by glaciares Viedma (945 km$^2$), Upsala (902 km$^2$), and O'Higgins (819 km$^2$).

Since the Hielo Patagónico is located in the latitude south of 46°S, the climate is characterized by the strong Southern Westerlies, which bring plenty of precipitation on the Chilean side resulting in snowfalls over the icefields, thereby nourishing many glaciers despite the moderate temperatures. There is no meteorological station on or even near the icefield. Only recently, annual measurements of air temperatures and precipitation have been successfully obtained at the snout of Glaciar Exploradores (elev., *ca.* 182 m), which is located on the northeast side of the HPN (Aniya *et al.*, 2007b; Aniya *et al.*, 2011, see Fig. 2 for location). According to Aniya *et al.* (2011), from 2005 to 2009, the mean annual air temperature varied between 6.8 and 7.3°C. During this period, the highest air temperature was 17.4°C in January and the lowest air temperature was –10.5°C in July. The precipitation was about 3000 mm. The temperature records indicate a temperate climate, and the precipitation was distributed pretty evenly throughout year. Moderate air temperatures in winter implies some snow melting in the accumulation area even in winter and low air temperatures in summer implies snow fall in the accumulation area even in summer; therefore, accumulation and ablation occur almost year round (Barcaza *et al.*, 2009).

In the HPS, air temperatures were measured intermittently from 1996 to 2003 near the snout of Glaciar Perito

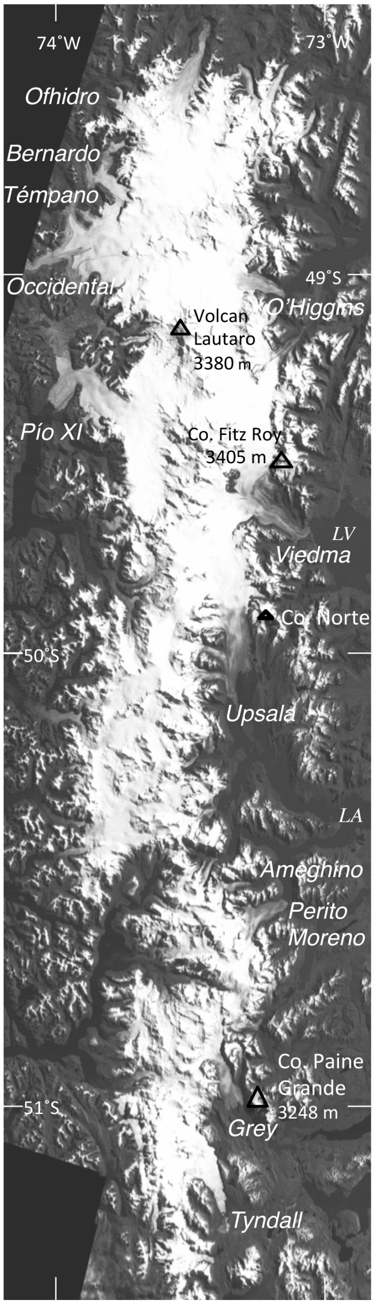


*Fig. 3. Landsat TM mosaic of the HPS (Hielo Patagónico Sur, March 12, 2001), showing place names referred to in the text. Glaciar Occidental is referred to as Glaciar Hammick by Mercer (1970). Co. Norte Cañon and Glaciar Dos Lagos are located near Co. Norte in this figure. LV, Lago Viedma; LA, Lago Argentino.*

Moreno (see Fig. 3 for location). The mean daily air temperatures in summer to early fall were 5.6–9.6°C and those in winter were 4.2–5.6°C (Stuefer *et al.*, 2007), also indicating moderate climate on the east side.

Mass balance measurements in the field at the accumulation area have not yet been carried out in the Hielo Patagónico. The mass balance was estimated at 6000–8000 mm from drillings (Yamada, 1987; Matsuoka and Naruse, 1999; Shiraiwa *et al.*, 2002) and satellite image analysis (Rott *et al.*, 1998), while from hydrological balance it was estimated at 6000–7400 mm (Escobar *et al.*, 1992).

## HOLOCENE GLACIATIONS OF HIELO PATAGÓNICO

### *Early works*

Nichols and Miller (1951), who visited Glaciar Ameghino in the HPS (Fig. 3), reported for the first time in Patagonia a Little Ice Age (LIA) advance at around AD 1870–1880 from dendrochronology. Next, a member of the American Geographical Society's expedition to Laguna San Rafael of the HPN (Fig. 2), Muller (1959) recognized three rows of terminal moraines surrounding the Laguna and named them, from the oldest to the youngest, Témpanos I, II, and III. Heusser (1960) dated sediments in a pond developed on the Témpanos I moraine to be 3610 ± 400 year before present (yr BP) and inferred the advance of Glaciar San Rafael at around 5000–4000 yr BP by considering the time required for sediment accumulation. However, although Muller (1959) provided no date, he considered the Témpanos I moraine to be of Lateglacial in age, a view of which was supported by Clapperton and Sugden (1988). In his book, Heusser (2003) argued for the Holocene, though, saying that their reasons to dismiss the possibility of the late Holocene in age are not compelling (p. 36). Heusser's argument appears to be supported by a recent study by Harrison *et al.* (2012), who dated the Témpanos moraines I and II with optically stimulated luminescence (OSL) and obtained three early to mid-Holocene glaciations at 9700–9300 yr BP, 7700 yr BP and 5700 yr BP. Heusser (1960) also dated peat located on the north fringe of the Laguna to be 6850 ± 200 yr BP and concluded that about 7000 yr BP, Glaciar San Rafael was more receded than 1959. Lawrence and Lawrence (1959), after examining the historical records of navigators who visited Laguna San Rafael, interpreted that Glaciar San Rafael advanced between AD 1675 and 1766, which was supported by a recent study (Araneda *et al.*, 2007), although the advance was small.

### *Mercer's scheme*

It was Mercer (1965, 1968, 1970, 1976, 1982) who first studied systematically the Holocene glaciations in Patagonia by dating moraines at several outlet glaciers of the HPS with $^{14}C$ and dendrochronology, and proposed a scheme for the Holocene glaciations. By reviewing each article by Mercer, we see how he developed the idea of Neoglaciations in Patagonia.

Mercer (1965) visited the Río Fitz Roy area, the area around Glaciar Upsala and Co. Norte Cañon in the HPS. In the head area of Río Fitz Roy where a small valley glacier, Glaciar Adela is located, he identified four rows of terminal moraines, thereby denoting Fitz Roy I, II, III and IV, from the oldest to the youngest. He obtained a date of 800 ± 85 yr BP from peat developed in a depression between Fitz Roy II and III. From tree ring analysis he inferred Fitz Roy III to be *ca*. AD 1690. Around Glaciar Upsala, he recognized two rows of terminal moraines, which he called the Pearson I and II. He obtained $^{14}$C dates of 3600 yr BP, 2000 yr BP and 2300 yr BP for them and assigned 2300–2000 yr BP to the Pearson I moraine. For the Pearson II moraine, he assigned dates of AD 1600–1760 from dendrochronology. He also obtained a $^{14}$C date of 1600 yr BP for an advance of Glaciar Dos Lagos, which is located near Glaciar Upsala. From these data he concluded that there might have been the maximum extent of the glaciers at *ca*. 3600 yr BP, followed by an advance at 2300–2000 yr BP. He thought an advance of Glaciar Dos Lagos at *ca*. 1600 yr BP may have been very short and the climate change was too short for a large glacier such as Glaciar Upsala to respond.

Mercer (1968) obtained a $^{14}$C date of 4600 yr BP from peat in a pond on the outermost moraine at Monte San Lorenzo (3704 m) located between the HPN and HPS (see Fig. 1 for location), and 4320 ± 110 yr BP for the outermost moraine of Glaciar Narvaez of Sierra de Sangra (Fig. 1). Since there was an advance at *ca*. 4300 yr BP in the Northern Hemisphere (Switzerland and North America), Mercer called this advance Post-glacial advance I in Patagonia. For Post-glacial advance II, he quoted his previous results (Mercer, 1965) from Glaciar Upsala (2000 yr BP) and Glaciar Dos Lagos (1600 yr BP). Post-glacial advance III is younger than 300 yr BP (*ca*. AD 1650) from tree ring analyses.

During the austral summer of 1967–1968, Mercer visited five glaciers located on the northwestern part of the HPS, glaciares Ofhidro Norte (North), Ofhidro Sur (South), Bernardo, Témpano and Hammick (on the Chilean topographic map published by Instituto Geográfico Militar, listed as Occidental) (Fig. 3). From several fieldworks during 1967–1968, Mercer (1970) obtained the following results. At Glaciar Ofhidro Norte, he recognized three rows of moraines, for which he inferred dates of AD 1790–1850 from dendrochronology. For nine rows of moraines at Glaciar Ofhidro Sur, he obtained dates of 4060 ± 110 yr BP and 3740 ± 110 yr BP from peat in a depression developed on the second and sixth moraine from the seaside, respectively. At Glaciar Bernardo, there are five rows of moraines (heights, 1–4 m within a distance of *ca*. 100 m) at about 500 m from the present glacier snout, which were dated to be AD 1775 from trees growing (the number of rings plus ecesis time of 70 years) on outwash plain between these moraines. Resurrected tree remains that used to be buried with till deposited by the advancing glacier yielded a $^{14}$C year of 270 ± 90 yr BP, which can be translated to calendar years of AD 1430–1740. At Glaciar Témpano, tree ring analyses of shoved trees at the vegetation trimline gave a date of *ca*. AD 1760. A peat sample collected from a pond formed by a lateral moraine yielded a date of 4120 ± 105 yr BP. At Glaciar Hammick (Occidental), large moraines located 50–200 m below the present snout were formed around AD 1750 and AD 1840 from tree ring analyses. Peat in bogs located in front of each of three rows of moraines yielded dates of 3110 ± 130 yr BP, 2300 ± 110 yr BP and 2070 ± 95 yr BP. Based on these results and other data, he postulated three Neoglaciations for the Hielo Patagónico: Neoglaciation I, roughly *ca*. 4000 yr BP; Neoglaciation II, about 2700–2300 yr BP; and Neoglaciation III, about AD 1750–1800.

Mercer (1976), with additional data, postulated a series of glaciations as follows: Neoglaciation I, 4600–4200 yr BP; Neoglaciation II, 2700–2300 yr BP, and Neoglaciation III, past few centuries. After considering the results from the Chilean Lake District, further north of the Hielo Patagónico, Mercer (1982) proposed the following three Holocene glaciations for the Hielo Patagónico, which had become the standard for Patagonia.

Neoglaciation I: 4500–4000 yr BP;

Neoglaciation II: 2700–2000 yr BP (Pearson I advance); and

Neoglaciation III: Past several centuries (mainly 17–19th centuries, Pearson II advance), that corresponds to the LIA.

Clapperton and Sugden (1988) raised a question about this scheme of the three Holocene glaciations, after studying recent glaciations at the northern Andes (Peru, Bolivia, Columbia), Antarctic Peninsula and South Georgia (Island), where they recognized four instead of three Holocene glaciations including one at 1300–1100 yr BP (Neoglaciation III at the northern Andes). However, at that time, there was no data from the Hielo Patagónico corresponding to 1300–1100 yr BP.

*Aniya's scheme*

Aniya (1995, 1996), taking up the study of the Holocene glaciations after Mercer, identified and dated moraines at glaciares Tyndall, Upsala and Ameghino with $^{14}$C, thereby obtaining dates including ones which are equivalent to the Neoglaciation III of Clapperton and Sugden (1988). At Glaciar Tyndall, Aniya (1995) identified four Neoglacial advances for the first time in Patagonia at *ca*. 3600 yr BP, *ca*. 2300 yr BP, *ca*. 1400 yr BP and *ca*. AD 1700. At Glaciar Upsala where Mercer had established the scheme of three Neoglacial advances, Aniya (1995) obtained new dates for a new scheme.

Malagnino and Strelin (1992) found a new terminal moraine, Herminita moraine, at Glaciar Upsala in 1990 and Aniya (1995) dated it with $^{14}C$ to be *ca*. 2400–2200 yr BP, indicating that it corresponds to the second Neoglaciation. Aniya (1995) also dated the Pearson I moraine with $^{14}C$ to be 1600–900 yr BP, which corresponds to the third Neoglaciation that was supposed by Clapperton and Sugden (1988), instead of long-believed *ca*. 2300 yr BP proposed by Mercer (1965). At Glaciar Ameghino where Nichols and Miller (1951) reported a LIA at AD 1870–80, Aniya (1996) recognized four sets of terminal moraines. The youngest terminal moraine that is damming the proglacial lake consists of two closely spaced rows, and for the outer row another LIA date, 320 ± 80 yr BP, was obtained. Based on these results, Aniya (1995, 1996) proposed a scheme of the Neoglaciations in Patagonia as follows:

Neoglaciation I: *ca*. 3600 yr BP;
Neoglaciation II: *ca*. 2400–2200 yr BP;
Neoglaciation III: *ca*. 1600–900 yr BP; and
Neoglaciation IV: 17–19th centuries.

*Other works at HPS*

At Glaciar Grey, which is located just north of Glaciar Tyndall, Marden and Clapperton (1995) obtained three LIA dates for three inner moraines of four LIA moraines, *ca*. AD 1805, AD 1845 and after AD 1890. Wenzens *et al*. (1997) recognized five Neoglacial advances in the valley of Río Fitz Roy of the HPS. At Glaciar Viedma located next to the valley of Río Fitz Roy, Wenzens and Wenzens (1998) identified four Neoglaciations, the oldest of which they reported was 7500 yr BP. Wenzens (1999), also working in a small valley that is not connected to the icefield and located between Lago Viedma and Lago Argentino, concluded that there were eight Holocene glacial advances at: *ca*. 8500 yr BP, 8000–7500 yr BP, 5800–5500 yr BP, 4500–4200 yr BP, 3600–3300 yr BP, 2300–2000 yr BP, 1300–1000 yr BP and AD 1600–1850. Of these, the date 4500–4200 yr BP corresponds to the Neoglaciation I of the Mercer's scheme, while the date 3600–3300 yr BP corresponds to the Neoglaciation I of the Aniya's scheme. The date 2300–2000 yr BP agrees with the Neoglaciation II of both the Mercer's and Aniya's schemes. The date 1300–1000 yr BP corresponds to the Neoglaciation III of the Aniya's scheme, which the Mercer's scheme did not recognize.

*Works at HPN*

Thus, the early studies of the Neoglaciations in Patagonia were mostly carried out at the HPS and two general schemes were presented; one with three Neoglaciations and the other with four Neoglaciations. Although at the HPN, a pilot study was carried out at Laguna San Rafael in 1958, it was not until 1996 when the next study on glaciation in the HPN was reported. At Glaciar San Quintin, the largest glacier in the HPN, Winchester and Harrison (1996) examined a terminal moraine that is almost completely surrounding a large proglacial lake, concluding that a LIA maximum occurred at *ca*. mid-19th century. Harrison and Winchester (1998) studied advances at glaciares Gualas and Reicher located on the northwest side of the HPN with dendrochronology and lichenometry, thereby obtaining dates, AD 1876 and 1909. They interpreted that these variations were caused by the change in precipitations rather than the change in temperatures. Using the same dating techniques at glaciares Colonia and Arco located on the east side of the HPN, Harrison and Winchester (2000) recognized an advance during the late 19th century. At Glaciar Nef that is located immediately north of Glaciar Colonia, Winchester *et al*. (2001) reported that the glacier attained a LIA maximum at AD 1863.

Aniya and Naruse (1999) studied moraines at Glaciar Soler of the HPN, that is located on the east side just north of Glaciar Nef, thereby obtaining two dates, 1300 ± 50 yr BP and AD 1650. The latter date is very similar to that at Glaciar Ameghino of the HPS (Aniya, 1996). The date of *ca*. 1300 yr BP was obtained from a piece of wood buried in a depression on a lateral moraine, but the provenance of the sample was not certain. Since its date corresponds to that of the Neoglaciation III in the HPS, they interpreted that the lateral moraine was formed during this period. Subsequently, Aniya and Shibata (2001) undertook extensive investigations in the valley of Río Soler (Fig. 2) and obtained six Neoglaciation dates at; 6800 yr BP, 5300 yr BP, 3300 yr BP, 1300 yr BP, AD 1300, and AD 1657–1700. Of these dates, 3300 yr BP, which was obtained at a terminal moraine separating Lago Plomo from Lago Bertrand, the southern extension of Lago General Carrera (or Buenos Aires, in Argentina), is roughly contemporaneous with the Neoglaciation I of the HPS proposed by Aniya (1995). The date of 1300 yr BP supports the tentative conclusion for the Neoglaciation III at Glaciar Soler (Aniya and Naruse, 1999). An advance at AD 1657–1700 agrees very well with an advance of Glaciar Soler at AD 1650. In the valley of Río Soler, there is a lake located at the head of a branch valley, which is dammed by two closely spaced rows of terminal moraines. The older one of these two moraines yielded a date of *ca*. AD 1700, which is roughly contemporaneous with those at Glaciar Soler and Río Soler, indicating that there were two LIA advances in this valley. Glasser *et al*. (2002), after extensive sampling from the terminal moraine located in front of the present Glaciar Soler, inferred a glacier advance around 10–13th centuries, which corresponds to AD 1300 obtained in the valley of Río Soler (Aniya and Shibata, 2001). Thus, in the HPN, advances during the later half of the 17th century as well as 19th century were also recognized, and during the LIA from the 17th to 19th centuries, two or three advances may have occurred (Koch and Kilian, 2005).

Glasser *et al*. (2005), using Landsat and ASTER satellite images of the HPN, recognized in general three rows of terminal moraines in front of the present glacier snout and identified the closest to snout as of the LIA. However, they did not present any concrete dates. Aniya *et al*. (2007a) studied moraines at Glaciar Exploradores of the HPN. They recognized three groups of terminal moraines (I, II, and III), concluding that the date unknown for I, the 12–17th century for II (largest) and the late 19th century for III.

*Patagonia in general and LIA*

Glasser *et al*. (2004) made a review of paleoclimate of Patagonia including the Holocene, in which they called "Mercer type" for the scheme of three Neoglaciations, and "Aniya type" for the scheme of four Neoglaciations. The differences in these two types are the date of the Neoglaciation I (Mercer, 4500–4000 yr BP vs. Aniya, *ca*. 3600 yr BP) and the existence of the Neoglaciation III at *ca*. 1400 yr BP. Although Mercer (1965) obtained an advance date, 1600 yr BP, at a small valley glacier, Glaciar Dos Lagos near Glaciar Upsala, he dismissed this advance as it was too short for a large glacier such as Glaciar Upsala to respond.

Douglass *et al*. (2005), working in the valley of Río Avilés (46°35′ S) that is located about 25 km east of the HPN and drains into Lago General Carrera from the south, obtained two advance dates, *ca*. 8500 yr BP and 6200 yr BP by dating glacial boulders with cosmogenic surface-exposure dating technique. The mountains of Río Avilés are about 2000–2200 m high, a part of Cordon Gloria that is a small mountain range. Since this mountain range is located east of the HPN, climate is considerably drier, with the current snow line altitudes of *ca*. 1250–1750 m.

Araneda *et al*. (2007), analyzing historical records written by explorers of Laguna San Rafael, deduced a date of AD 1875 for a maximum position for the LIA advance of Glaciar San Rafael. Harrison *et al*. (2007) reviewed LIA studies at eleven outlet glaciers (Reicher, Gualas, San Rafael, San Quintin, Arco, Colonia, Arenales—a branch of Colonia, Nef, Soler, León, Calafate, and Exploradores) of the HPN, concluding that glacier recession from maximal positions began in the early 1860s to the 1870s. Harrison *et al*. (2008) used four complementary dating techniques, including cosmogenic isotopes, OSL, dendrochronology and lichenometry at Glaciar León of the HPN. They obtained a date of 2500 yr BP with OSL for a terminal moraine damming Lago Leones, and AD 1867 (LIA) with lichenometry for a moraine closest to the present glacier. The date 2500 yr BP fits into the Neoglaciation II of the Mercer's scheme and is also very close to the Aniya's Neoglaciation II.

Masiokas *et al*. (2009) made a comprehensive, thorough review of glaciations of the Andes during the past 1000 years, in which the Hielo Patagónico was included. As the conclusion for the Hielo Patagónico, they pointed out a regional contrast between the HPN and HPS: in the HPN the LIA maximum mostly occurred during the 19th century whereas in the HPS it occurred one to three centuries earlier. Some glaciers made two or more LIA advances before the 21st century. Since Masiokas *et al*. (2009) mentioned and listed individual studies and their results in detail (p. 258), I do not repeat them here. Recently, Aniya and Skvarca (2012) made a LIA study at Glaciar Perito Moreno of the HPS, one of the most well known glaciers in Patagonia. They dated with $^{14}$C the prominent vegetation trimline of the glacier and still-standing trees killed by lake inundation caused by glacier damming of Brazo Rico, thereby obtaining two LIA dates: one at AD 1650 and the other at AD 1820–1850. These dates fit very well into the general conclusion for the LIA of Patagonia that Masiokas *et al*. (2009) summarized.

## Discussion and Conclusions

So far, two schemes of the Neoglaciation have been proposed: one with three Neoglaciations by Mercer and the other with four Neoglaciations by Aniya. The main differences are the date of the Neoglaciation I and the existence of the Neoglaciation at *ca*. 1400 yr BP (Neoglaciation III by Aniya). Although at Glaciar Upsala Mercer (1965) obtained a date, 3600 yr BP, for an advance, he proposed the date of 4500–4000 yr BP for the Neoglaciation I, after working at several other glaciers of the HPS and the nearby areas. Aniya obtained a date, *ca*. 3600 yr BP, from glaciares Tyndall and Upsala. We have two interpretations for these two dates. One would be that the Neoglaciation I lasted for a long time, that is, 4500–3600 yr BP. The other is that they represent two different Neoglaciations; the date of 4500–4000 yr BP as the Neoglaciation I, and the date of *ca*. 3600 yr BP as the Neoglaciation II, making a total of Neoglaciations four for the Mercer's scheme and five for the Aniya's scheme. From the dates Wenzens (1999) obtained in a small valley of the HPS, i.e., 4500–4200 yr BP and 3600–3300 yr BP, the interpretation of two separate Neoglaciations appears more reasonable. The existence of a Neoglaciation around 1400 yr BP is not yet firmly confirmed; however, since we have this date from a few areas, i.e., Glaciar Dos Lagos, Glaciar Tyndall and the valley of Río Fitz Roy of the HPS, and Glaciar Soler and the valley of Río Soler of the HPN, it seems very probable that there was a Neoglaciation at this time. Based on these data and interpretations, I propose a following scheme of the

Neoglaciations for the Hielo Patagónico.

Neoglaciation I: 4500–4000 yr BP;
Neoglaciation II: 3600–3300 yr BP;
Neoglaciation III: 2700–2000 yr BP;
Neoglaciation IV: 1600–900 yr BP; and
Neoglaciation V: 17–19th centuries (LIA).

Wenzens (1999) obtained dates for earlier glaciations than those proposed either by Mercer or Aniya for the scheme, namely, *ca*. 8500 yr BP, 8000–7500 yr BP and 5500–5000 yr BP in a small valley near Lago Viedma in the HPS. Aniya and Shibata (2001) also obtained earlier dates, *ca*. 6800 yr BP and *ca*. 5300 yr BP in the valley of Río Soler of the HPN. In addition, at Glaciar San Rafael of the HPN, Harrison *et al*. (2012) obtained advance dates at 9700–9300 yr BP, 7700 yr BP and 5700 yr BP. Since the date ca 7700 yr BP was in a period of "drier than today" (Massaferro and Brooks, 2002), they attributed the advance to glacier dynamics such as calving. However, the date 7700 yr BP is within the period 8000–7500 yr BP of the HPS, and as we reviewed, since there was some time lag in glaciations between the HPS and HPN, the date *ca*. 6800 yr BP of Río Soler (HPN) may correspond to this period. The period 5500–5000 yr BP of the HPS includes the date *ca*. 5300 yr BP of Río Soler, while the date of 5700 yr BP from Glaciar San Rafael is very close to this period. At Glaciar Grey of the HPS, Clapperton (1993) obtained two dates, 8750 ± 170 yr BP and 8150 ± 45 yr BP, for the inner two of three sets of moraines, which are close to the first two of the Wenzens' (1999) dates for the earlier Holocene glaciations. Clapperton (1993) cited also a date *ca*. 9180 yr BP for the outer moraine of Glaciar Grey, which is close to the date 9700–9300 yr BP of Glaciar San Rafael. Douglass *et al*. (2005) obtained two early to mid-Holocene advance dates, *ca*. 8500 yr BP and 6200 yr BP, for a small valley glacier located about 25 km east from the HPN. The date, *ca*. 8500 yr BP, is exactly synchronous with the Wenzens' date from the HPS, and the date, *ca*. 6200 yr BP, is somewhat close to *ca*. 6800 yr BP of Río Soler. However, the interpretation of these dates in relation to the icefields is difficult, because the climate setting of the valley of Río Avilés is quite different from that of the icefields.

From these dates, it appears probable that there were at least two more Holocene glaciations at 5700–5000 yr BP and 8100–6800 (or 7500) yr BP. The additional ages of 8800–8500 yr BP and 9700–9100 yr BP are, however, still tentative, needing more data to confirm.

Warren (1993) concluded that winter precipitation was a driving factor for the variation of Glaciar San Rafael after examining the meteorological records (1914–1989) at Cabo Raper located *ca*. 50 km west of the HPN. Because of their proximity and similarity in variations to glaciares San Rafael and San Quintin, Harrison and Winchester (1998) interpreted that precipitation was also a dominant factor for the LIA variations of glaciares Gualas and Reicher of the HPN. These glaciers are located in the zone of latitudes across where the seasonal precipitation patterns changes: to the north, (austral) winter precipitation; and to the south, summer precipitation (Endlicher and Santana, 1988; Winchester and Harrison, 1996). Since the large amount of precipitation, which nourishes the extensive icefields in the otherwise mild climate zone, is brought by the strong Southern Westerlies, the north-south shift and oscillation of the Westerlies may explain the general time lag in the LIA between the HPN and HPS, as well as multiple (two or three) advances during the LIA.

In Patagonia, as we have seen, studies on the Holocene Neoglaciations have been carried out at a very limited number of glaciers and areas. Studies focusing on the LIA have been increasing; however, still only 25 of more than 70 major Hielo Patagónico glaciers have been studied for the LIA (Masiokas *et al*., 2009). Many outlet glaciers are calving in proglacial lakes, which are dammed by terminal moraines. It is very important and interesting to date these damming moraines, because dates may vary widely, some maybe of the LIA and others before the LIA such as the one at Lago Leones that was *ca*. 2500 yr BP. In the HPN, there are many damming moraines, which have not yet been studied, including at proglacial lakes of glaciares Fiero, Grosse, Steffen, Pared Norte, Piscis, Colonia, and Cachet. It is important to employ and combine many different dating techniques such as the one done by Harrison *et al*. (2008) in areas such as the Hielo Patagónico where accessibility is very restricted under the year-around inclement weather conditions and sampling with a single technique is often severely limited.

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