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The timing and nature of recession of outlet glaciers of Hielo Patagónico Norte, Chile, from their Neoglacial IV (Little Ice Age) maximum positions

Stephan Harrison, Vanessa Winchester, Neil Glasser

Abstract

The dates of recession of eleven outlet glaciers of the Hielo Patagónico Norte (Northern Patagonian Icefield) from their recent maximum positions have been inferred from dendrochronology, lichenometry, radiocarbon dating and historical sources. We have refined the dating for part of the Little Ice Age period in this area placing a glacial advance to between AD 1650 and 1766 with the latter date favoured as conformable with historical records and an uncalibrated radiocarbon determination. Glacier recession from maximal positions began in the early 1860s–1870s. Recession was largely synchronous on the western and eastern sides of the Icefield. This synchronicity suggests that climate forcing over-rides second-order controls on glacier behaviour such as the nature of the terminal environment (e.g. calving/non-calving) or differences in glacier drainage basin area. We argue that this icefield-wide glacier recession represents a response to post-Little Ice Age warming, and provides further evidence for the global extent and near synchronous termination of the Little Ice Age.

1. Introduction

There are few detailed mass-balance studies from the Southern and Northern Patagonian Icefields (Hielo Patagónico Sur and Hielo Patagónico Norte), but the available evidence suggests that their outlet glaciers are extremely sensitive to climatic change (Rignot et al., 2003). We argue that historical variations in the extent of their glaciers, and those of other smaller icefields including the Cordillera Darwin further south, reflect changes in mass balance.

Porter and Denton (1967) defined the period of Neoglaciation as a geological time unit reflecting glacial advances following the Hypsithermal interval. The Holocene chronology of Neoglaciation in Patagonia owes much to the pioneering work of Mercer (1970, 1976, 1983). He constructed a scheme based on radiocarbon determinations showing three Neoglacial Advances in the region during the Holocene dated at 4700–4200; 2700–2000 and 300 years ^{14}C yr BP, with a date of 3060 years ^{14}C yr BP for the first Neoglacial Advance in the Cordillera Darwin by Kuylenstierna et al. (1996). This scheme was expanded by Aniya (1995), following work on the Upsala and Tyndall glaciers, to four Neoglacial Advances,

dated to c. 3600 BP, c. 2300 BP, c. 1400 ^{14}C yr BP and during the seventeenth and eighteenth centuries. The present paper focuses on glacier fluctuations during Neoglacial IV (the Little Ice Age), the term conventionally used to describe the period of glacial advances between the Middle Ages and the warming of the first half of the twentieth century (Bradley and Jones, 1995; Grove, 2004) when glacier expansion was accompanied by increasing storminess and lowered temperatures. Neoglacial IV is suggested to have begun in South America sometime between AD 1450 and AD 1650 (Röthlisberger, 1987).

2. The importance of Patagonia for palaeoclimatic studies

The scarcity of data concerning the timing and nature of climatic shifts from the Southern Hemisphere is a major problem in palaeoclimatology over Pleistocene and Holocene timescales (Lowell et al. 1995; Denton et al., 1999a, b; Glasser et al. 2004). The problem centres on a number of important unresolved issues: these include a full understanding of the timing and effects of climatic changes; whether changes were synchronous between the hemispheres and the nature of the forcing factors involved. Information on these issues would enable inter-hemispheric comparisons to be made on the timing of glacial events and, further, would help to test some of the hypotheses concerning the role of the Southern Westerlies during glacial–interglacial transitions (Denton et al., 1999a). Testing these hypotheses requires the construction of an accurate account of glacier fluctuations in southern South America focusing on the region exposed to the Southern Westerlies and, in particular, on the Hielo Patagónico Norte whose present northern margin defines an area of transition between north and south Patagonian weather patterns (Winchester and Harrison, 1996; Heusser, 2003).

The location and dynamics of the Patagonian Icefields are controlled by variations in the Southern Westerlies and associated ocean currents and there is considerable evidence that the icefields have expanded and contracted in the past in response to variations in these important mid-latitude climate systems (Harrison, 2004). Together with sharp local topographic and climatological contrasts, these circumstances create a dynamic and temperate glacier system, with outlet glaciers draining the icefields to sea level at lower latitudes than those of any other substantial ice masses in the world. The icefields are characterised by abundant precipitation, high ablation rates, steep mass-balance gradients, high ice velocities, and a steep west–east precipitation gradient (Warren and Sugden, 1993).

Three large ice masses exist in southern South America: Hielo Patagónico Norte, Hielo Patagónico Sur and Cordillera Darwin, and there is a rapidly expanding scientific literature on the recent and historic fluctuations of their glaciers (e.g. Marden and Clapperton, 1995; Rivera et al., 1997; Heusser, 2002; Koch and Kilian, 2005). Aniya and co-authors have reviewed the fluctuations of the outlet glaciers of both icefields from the first aerial photograph coverage in 1944 to the present (e.g. Aniya and Enomoto, 1986; Aniya, 1988;

Aniya et al., 1997; Aniya 1999), and Warren and Sugden (1993) reviewed the glaciological information from the icefields using data sets dating mainly from the middle of the twentieth century. The evidence for glacier fluctuations during the Little Ice Age is still incomplete and comes from a relatively small number of the area's glaciers (cf. Luckman and Villalba, 2001). However, if we are to assess the global synchronicity of late-Holocene climatic events the evidence for Little Ice Age glacier fluctuations from this region needs to be established.

Whilst much of the recent glaciological work in the region has concentrated on the Hielo Patagónico Sur, the study of Little Ice Age fluctuation histories of the outlet glaciers of these icefields has largely concentrated on the Hielo Patagónico Norte but of its 30 or so outlet glaciers only a few have been studied in detail. Because of this, there have been no attempts at reviewing this data set, nor at assessing the evidence for a Little Ice Age glacial signal from the region. The aim of this paper is to address these issues.

3. Study area

The Hielo Patagónico Norte (47° 00'S, 73° 39'W) is 120 km long and 30–60 km wide and caps the Andean Cordillera between altitudes of 700–2500 m a.s.l. (Fig. 1). Annual precipitation on the western side of the Icefield increases from 3700 mm at sea level to an estimated maximum of 6700mm at 700m a.s.l. (Escobar et al., 1992). Precipitation decreases sharply on the eastern side of the Icefield. Although precise data are sparse, the evidence for decreased precipitation is inferred from the increasingly xeric nature of the vegetation to the east of the Icefield.

There are a number of reasons why this area provides opportunities for elucidating the fluctuation behaviour of its outlet glaciers. First, the dynamic nature of the glaciers and their topographic settings means that many moraine systems exist throughout the region and most remain undated (e.g. Glasser et al., 2005). Second, the glacier snouts during the 18th and 19th centuries extended into forested zones and this means that there are abundant opportunities to establish these variations via dendrochronological methods. Third, recent work has demonstrated the success of optical dating techniques (Winchester et al., 2005) and dates derived from analysis of cosmogenic isotopes (Glasser et al., 2006) for the determination of mid-Holocene and Pleistocene moraine chronologies and these can be used to constrain the dating of later fluctuations.

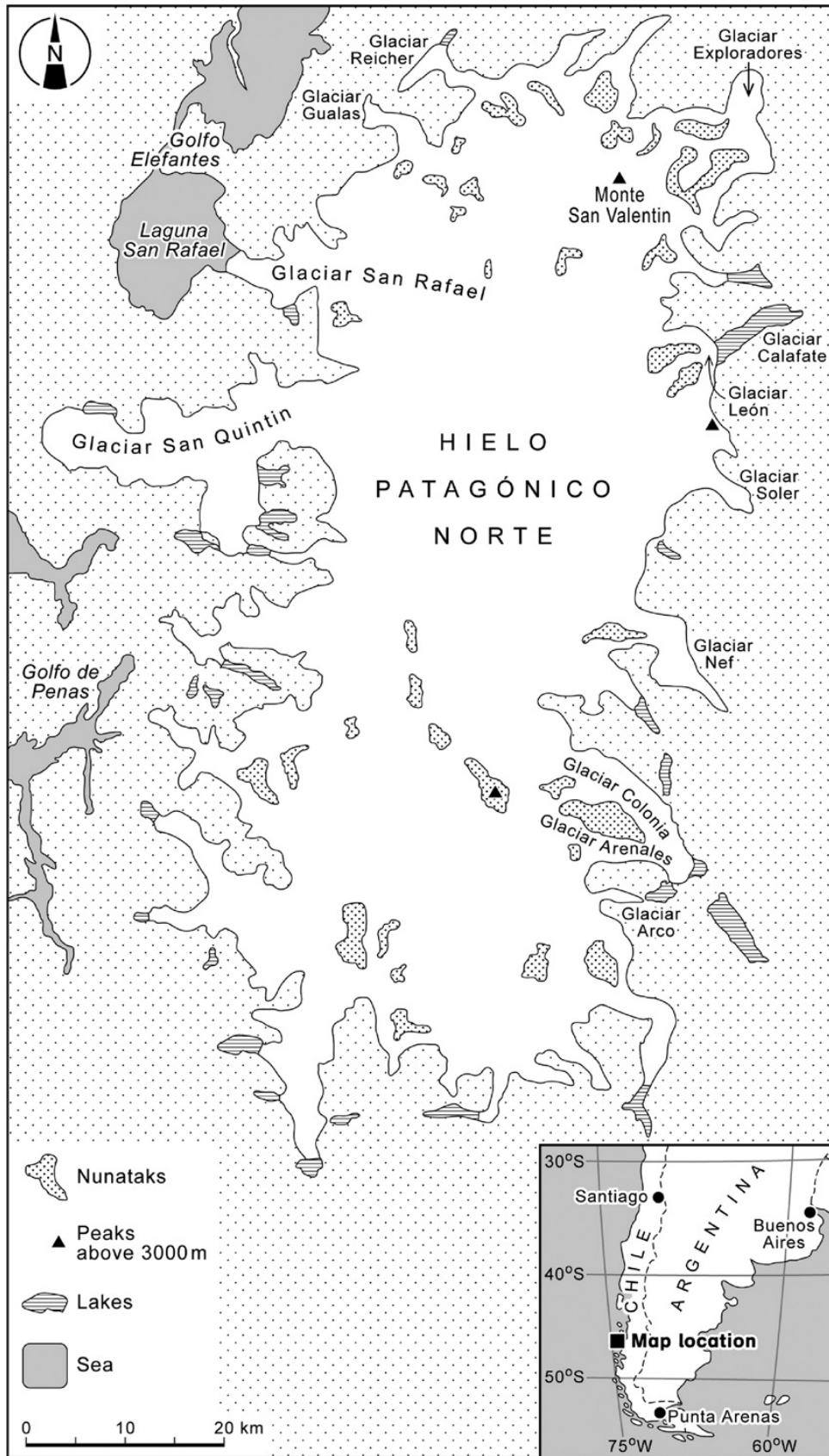


Fig. 1. The Hielo Patagónico Norte showing the outlet glaciers mentioned in the text.

4. Methods

The recent fluctuation histories of eleven glaciers of the Hielo Patagónico Norte have been reconstructed using the following information.

4.1. Historical sources

Historical sources include scientific reports from previous expeditions to the glaciers and Icefield (e.g. Steffen, 1947; Lawrence and Lawrence, 1959) and accounts from early travellers to the region (e.g. Darwin, 1839). The region, including its glacier positions, was first mapped in detail by Chile's Instituto Geográfico Militar at a scale of 1:50,000 in 1981 based on 1975 aerial photographs.

More recently, on the northern side of the San Rafael glacier, paint markings on valley side rockwalls have been made by scientists and climbers and these mark the former positions of the ice front.

4.2. Aerial photographs

In the absence of large-scale accurate maps prior to and after 1975, aerial photographs of the glaciers have proved invaluable in defining their former limits. The United States Air Force in 1944/45 took Trimetrogon oblique and vertical photographs of the region using three cameras to give a 180° field of vision (1944: 391PC 4M-4028 406.6.118). In 1975 vertical aerial photographs were acquired which provided the base for the subsequent 1:50,000 scale maps, the largest scale currently available, although some of the ground is obscured by cloud (a perennial problem in this region). Later high-level aerial surveys were carried out by Chile's Servicio Aerofotogramétrico (SAF) in 1979, 1981 and 1983 (SAF79, CH616 No. 0045; SAF83, CH60 No. 021163) and the Japanese took lower oblique photographs at a smaller format in 1986, 1990 and 1993 (Aniya, 1992; Wada and Aniya, 1995). These allowed Aniya (1988) to compare glacier frontal positions between 1944 and 1986, and Winchester and Harrison (2000) to construct recent fluctuation histories of glaciers on the eastern margin of the Icefield based on lichenometric and dendrochronological dating schemes.

4.3. Geomorphological mapping, lichenometry and dendrochronology

The present authors have mapped moraines and associated glacial sediments, meltwater channels, exposed bedrock and other landforms associated with fluctuations of a number of the outlet glaciers (Winchester and Harrison, 1994, 1996; Harrison and Winchester, 1998, 2000; Winchester et al., 2001; Glasser and Hambrey, 2002; Glasser et al., 2002).

Lichenometry and dendrochronology were used to date constructional landforms, boulders, and bedrock surfaces exposed by the receding glaciers. Dates are given in calendar years. Largest lichen diameters were measured and cores were taken from the oldest trees to provide minimum absolute dating estimates on and around the features. The growth rate

determined for the lichen species *Placopsis perrugosa* and *Placopsis patagonica* was 4.7 mm yr^{-1} based on correlation of largest diameter lichen with bedrock-surface-exposure age defined, firstly, by the paint marks showing changes in Glaciar San Rafael's ice thickness on the west side of the Icefield over decadal timescales and, secondly, on the much drier east side of the Icefield, by tree ages in the Colonia and Arco valleys (Winchester and Harrison, 1994, 1996, 2000; Winchester et al., 2001).

The minimum lichenometric age of a surface is derived from the diameter measurement divided by growth rate plus a colonization (establishment) delay. At Laguna San Rafael near sea level *P. patagonica* establishment was found to occur within the same growing season (Winchester and Harrison, 1994) while for *P. perrugosa* on the eastern side of the Icefield a minimum delay of 2.5 years in the Colonia and Arco valleys and a maximum delay of 13 years on an exposed mountainside were deduced (Winchester and Harrison, 2000). The common growth rate found for both sides of the Icefield and other possible sources of dating error for both lichens and trees are commented on below in the Discussion Section.

Cores were taken from the oldest trees growing on critical surfaces to provide minimum absolute dating estimates within glacial forefields and on moraines. The tree species used for dating were *Nothofagus nitida*, *Nothofagus betuloides*, *Nothofagus pumilio*, and *Nothofagus antarctica*. Surface exposure dates were estimated from ring counts plus an estimate for the number of years taken to grow to the coring height together with a delay period before seedling establishment. Estimation of the time taken to grow to coring height was based on ring counts of small trees (up to 222 cm tall) sectioned near ground level, with an average growth rate supplied by tree height divided by ring count (Table 1). A regional average of approximately 11.75 cm yr^{-1} was established for the Colonia, Arco and Nef valleys. The main area of uncertainty for surface dating, with trees as for lichens, is the estimation of establishment delay following glacier recession. Depending on position and degree of exposure, maximum delay periods for establishment of *Nothofagus* seedlings in the Colonia valley may vary from 22, 26, to over 93 years. The 22-year delay was determined for trees near Lago Arco, deduced from a 1958 flood date (Tanaka, 1980); the 26-year delay is relevant to trees growing on valley sides and terraces in the Arco valley, based on a high-lake level shown covering these features in an oblique 1944 aerial photograph and the 93-year delay was extrapolated from a lichen date on an ice-formed trimline compared with maximum tree age on an exposed mountainside nearby (Winchester and Harrison, 2000).

Table 1

Varying height–age relationships and average growth rates in the Colonia, Arco and Nef valleys of *Nothofagus* species (including *N. Antarctica*, *N. betuloides*, *N. nitida*, and *N. pumilio*) based on ring counts from small trees sectioned at ground level. Average growth rates are included to show growth range and provide a measure of comparability between trees of different heights (adapted from Winchester et al., 2001)

Tree height (cm)	Ring count (age)	Growth rate (cm/yr ⁻¹)
<i>Colonia and Arco</i>		
40	14	2.9
58	14	4.1
85	15	5.7
18	3	6
45	5	9
51	5	10.2
58	5	11.6
170	12	14.2
177	10	17.7
126	7	18
130	7	18.6
112	5	22.4
Average		11.7
<i>Nef</i>		
75	16	4.7
125	24	5.2
125	18	6.9
200	19	10.5
140	11	12.7
95	7	13.6
120	8	15.0
159	10	15.9
222	13	17.0
120	7	17.1
Average		11.86
<i>San Rafael</i>		
100	6	16.7

4.4. Radiocarbon dating

Radiocarbon (¹⁴C) dating has also been used to date wood and tree remains preserved in lateral and frontal moraines of the Soler Glacier, one of the eastern outlet glaciers of the Hielo Patagónico Norte (Aniya and Naruse, 1999; Glasser and Hambrey, 2002; Glasser et al., 2002).

5. Results

Evidence for the cooling corresponding to the inception of the Little Ice Age in the region is conflicting and it is not clear at present why this is the case. Pollen from lake cores and tree-ring evidence from Andean sites close to Puerto Montt, 650 km to the north of the Hielo Patagónico Norte, suggest that there was cooling between AD 1490–1700 (Lara and Villalba, 1993) or, alternatively, between AD 1520–1670 (Villalba, 1990). Röthlisberger (1987) employs radiocarbon dating on moraines to suggest a warm period between 1435 and 1650 and a cool period around 1600 (Heusser and Streeter, 1980).

Historical evidence from early travellers in the Laguna San Rafael implies that it was warm in AD 1675 when de Vea reported the San Rafael Glacier as being more recessed than at present and as “running from the beach inland” with warmth possibly continuing until after 1741 when Byron failed to notice any icebergs (Brüggen, 1950). Icebergs were, however, reported by Garcia in 1766 (Casassa and Marangunic, 1987) so a glacier advance may have taken place between 1741 and 1766.

Further evidence supporting Byron and Garcia's 1741 and 1766 reports is provided by a, previously unpublished, uncalibrated radiocarbon age of 180 ± 45 years (BFM/465.0891) for the outer 6 cm of a *N. pumilio* trunk lying uprooted but largely *in situ* among other similar broken trunks at an altitude of 800 m a.s.l. The trunk is lying among erratics and moraine fragments on the southwest side of a former nunatak that partially restricts the outflow of the San Rafael Glacier from the Icefield (sample collected by V.W, 1992). Because of fluctuations in atmospheric radiocarbon over the period, when calibrated its calendar equivalent time span provides only a 2 sigma analytical probability of tree growth between 1650 to the present (1950).

However, this period can be narrowed considerably. The Icefield is rimmed by a bare-rock/vegetation trimline c. 100-m above the 1992 ice surface. The trimline was dated by regrowth of *N. antarctica* scrub on the nunatak to the last quarter of the nineteenth century (in 1992 there was no *N. pumilio* growing on the slope or locally at this altitude). The tree at its death could have been 139-year old, based on its 238 mm radius divided by the average 1.7-mm ring width of its outer 35 sapwood rings. This age precludes its growth between 1875 to the present. Although there were glacier fluctuations between 1766 when it was calving into the Laguna and 1875, conditions are unlikely to have been suitable for *N. pumilio* growth on the nunataks since this is a species that requires a more moderate microclimate than *N. antarctica* (Weinberger, 1973).

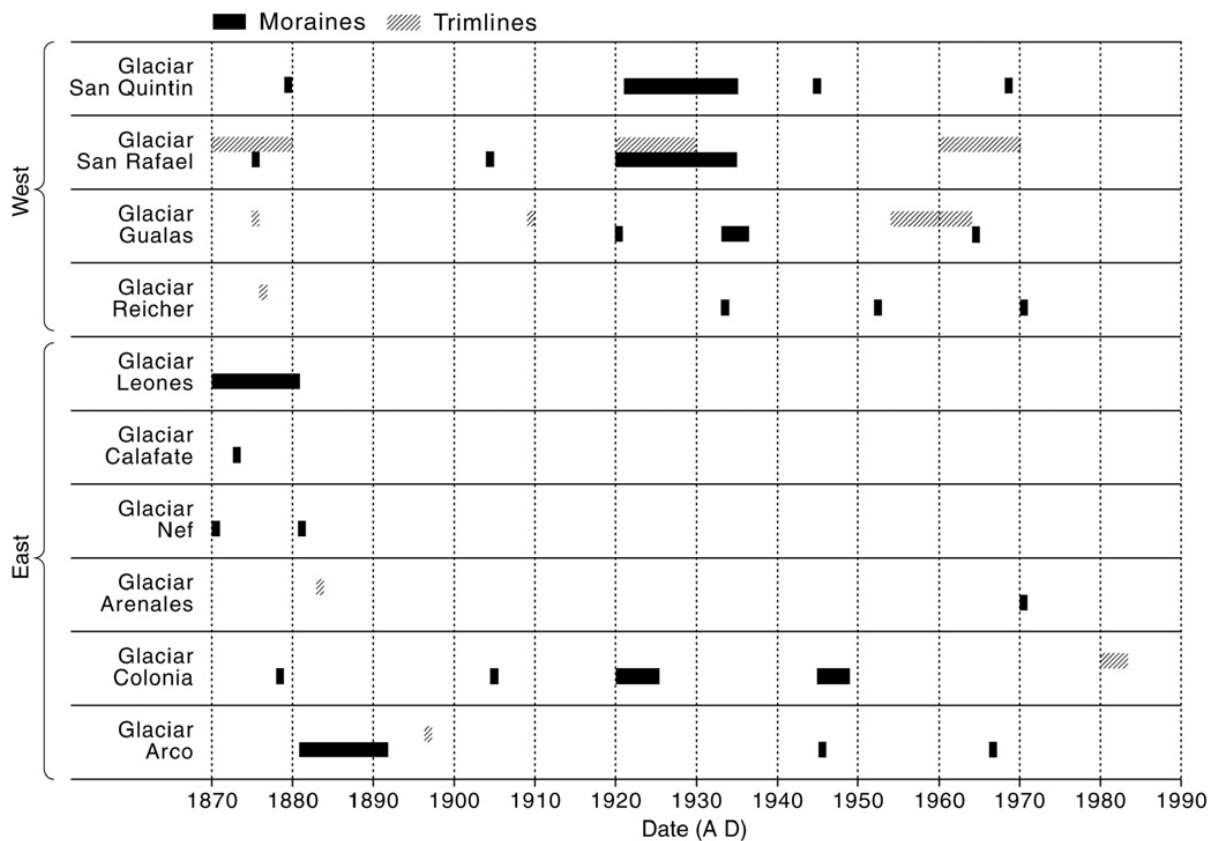


Fig. 2. Dates of glacier recession from their Little Ice Age maximum positions. Glaciar Soler is not included as its recent terminal moraines have not been dated.

Thus, a minimum date for the 139-year old tree on the nunatak is 1766, established by the historical record, and a maximum date is 1650 set by the radiocarbon evidence. A nearby, *in situ*, larger tree (420-mm radius) but with a broken trunk, based on the same ring width, could have lived for 245 years. Hence, a warm period lasting for at least this time span is required for tree growth prior to the Little Ice Age. Röthlisberger's (1987) identification of a warm period beginning in AD 1435 would provide the necessary time period for growth.

Whenever cooling began, the change must have been dramatic. The climate deteriorated sufficiently for the San Rafael Glacier to advance during the Little Ice Age to within 2.5 km of its mid-Holocene limit last attained perhaps some 7000 years earlier (Clapperton and Sugden, 1988).

5.1. Frontal variations

Lichenometry, dendrochronology and in one case radiocarbon dating have provided dating determinations for fluctuations of eleven of the outlet glaciers of the Hielo Patagónico Norte during the Little Ice Age (ten of these are shown in Fig. 2). Selected characteristics of these glaciers are shown in Table 2.

Data on maximum Little Ice Age positions comes from four glaciers draining the western flanks of the Icefield (Glaciares San Rafael, Gualas, Reicher, and San Quintín). At Laguna San Rafael the Laguna rim, over 11 km distant from the Andean wall, is defined by a pre-Little Ice Age 15-m high moraine,

termed the Témpanos I and II moraines by Muller (1960). Simpson (1875) may have observed the maximum Little Ice Age extension of the ice front in the Laguna in 1873 when he said it projected about 8.33 km from the mountain wall into the centre of the Laguna. Residual moraine fragments defining the Little Ice Age maximum are restricted to the northern shore of the Laguna some 4 km from the present ice front, with these dated by dendrochronology to 1876 (Winchester and Harrison, 1996). Moraine ridges relating to early expansion of the Gualas and Reicher glaciers form low-lying drift islands within Golfo Elefantes, but maximum glacier thickness during the Little Ice Age, as at Laguna San Rafael, is also dated to 1876 by tree cores taken from trimlines around the present proglacial lakes 10 km inland from Golfo Elefantes. An accumulation of large boulders, probably representing the maximum extent of the Little Ice Age moraine, partially blocks the outflow from the combined Gualas and Reicher systems (Harrison and Winchester, 1998). Glaciar San Quintín receded from its large Little Ice Age terminal moraine much later than the other glaciers on the western flanks of the Icefield, with ice-front recession between 1879 and 1993 limited to less than 1.5 km due to the quite different dynamics of this the largest glacier of the Hielo Patagónico Norte (Winchester and Harrison, 1996). However, there were considerable fluctuations between these dates and by 2000 large-scale recession and calving into proglacial lakes was underway (Harrison et al., 2001).

Table 2

Selected characteristics of the eleven outlet glaciers of the Hielo Patagónico Norte investigated in this study. Recession of Soler glacier from its Neoglacial IV limit occurred earlier than the other glaciers described in the text. AAR: accumulation area ratio. *Surface area and AAR are based on Aniya (1988)

Glacier	Surface area (km ²)	AAR	% of snout which is calving	Calving type	Date of recession from maximum 19 th century moraine (distance from present terminus to moraine in km)
San Quintín	765	0.9:1	100	Freshwater	1863-1879 (1.4)
San Rafael	760	3.3:1	100	Tidal	1873-76 (4.6)
Gualas	167	2.3:1	50	Freshwater	1876 (0.6)
Reicher	92	2.9:1	100	Freshwater	1876 (1.1)
León	62	2.1:1	50	Freshwater	1867-1877 (3.1)
Calafate	Not known	Not known	0	Not calving	1874-1876 (0.7)
Nef	164	1.5:1	100	Freshwater	1863-1878 (4.5)
Soler	51	2.5:1	0	Not calving	Na (1730) (na)
Colonia	437	2.7:1	50	Freshwater	c. 1881 (0.9)
Arenales	Na	Na	0	Not calving	c. 1883 (na)
Arco	41	6.8:1	0	Not calving	c. 1881 (3.3)

The maximum Little Ice Age positions of six outlet glaciers on the eastern side of the Icefield have also been dated. The northernmost of these, Glaciar León, calves into 12-kmlong Lago Leones and glacier recession from a rock-cored moraine 3 km from the present ice front at the foot of the mountain wall has been dated by both lichenometry and dendrochronology to 1867 (Haresign, pers. comm). Four and a half kilometres southeast of Lago Leones' ancient terminal moraine at the end of the proglacial lake (Winchester et al., 2005), the Little Ice Age limit for a small tributary glacier, locally called Glaciar Calafate, was formerly marked by a terminal moraine at 500ma.s.l. Glacier recession from this moraine was dated to 1874 and 1876, based on lichen and tree evidence respectively (Harrison et al., 2006). At the time of the initial fieldwork in 2000 the moraine was approximately 700 m from the glacier snout and dammed a small lake. However, at the end of February 2001 when the valley was revisited, it was found that a glacial-lake outburst flood had occurred, destroying the moraine.

Glaciar Soler lies 21 km to the south of Glaciar Calafate. Until recently Soler was one of the last remaining land-terminating eastern outlet glaciers of the Hielo Patagónico Norte, although the front of the glacier is now collapsing into an expanding proglacial lake (Glasser and Hambrey, 2002). Radiocarbon dating of tree remains in front of the glacier demonstrated that the glacier began to advance towards its Little Ice Age maximum position sometime between AD 1222 and 1342 (Glasser et al., 2002). The Little Ice Age maximum position was attained ca. AD 1730 (Aniya and Naruse, 1999).

Twenty kilometre south of Glaciar Soler, Glaciar Nef terminated in a 4.5 km long proglacial lake in 1998. Lichenometric dates suggest that the terminus began to recede from its nineteenth century limit in 1863 now marked by the outermost terminal ridge standing 0.5 km from the lakeshore, (Winchester et al., 2001). An 1878 date, based on the largest lichen beside Río Nef where it cuts through the terminal moraine system, indicates that the river has flowed in its present channel since at least that date. A further lichen measurement on the distal side of the terminal-ridge top also dates to 1878. Lichen dating of intermediate moraine ridges suggests that glacier recession after 1884 seems to have slowed with the ice front, based on lichen and tree evidence, lying in the vicinity of the present lakeshore by 1938. Dendrochronological investigations in the primary forest growing on the shoulder of the lowest of a series of ancient lateral moraines lining the southern-valley side and some 500 m downvalley southeast of the Little Ice Age terminal moraine indicate that 600 years may be a maximum age for *Nothofagus*. This suggests that Glaciar Nef's maximum nineteenth century position has not been exceeded since at least AD 1370.

South of Glaciar Nef the Icefield is drained by Glaciares Arco, Colonia and Arenales whose glacier systems are bounded by a c. 100-m high bare-rock trimline dated to the Little Ice Age maximum by dating trees above the trimline at the junction of the Arenales and Colonia glaciers and just below a vegetation trimline in the Arco valley. The dates are, respectively 1883 and 1881, with the latter date marking an outburst flood possibly occurring a short

time before the Little Ice Age maximum when the Arco glacier rested against its 90-m high terminal moraine (Winchester and Harrison 2000).

The moraines that have been dated from the western and eastern flanks of the Icefield thus form the late-Holocene glacier limits. Many of them may have been in contact with glacier ice on a number of occasions, but it is not possible to determine the timings of these previous glacial fluctuations. No other moraine systems of similar age exist downvalley of these moraine limits. Indeed, the limited information that is available from OSL and cosmogenic dating shows that the downvalley moraine systems closest to those described in this paper (forming the eastern rim of Lago Leones for instance) are more than 2500 years old (Winchester et al. 2005).

5.2. Rates of downwasting

Vegetation and ice-scoured trimlines marking the former surfaces of the outlet glaciers along their valley sides are characteristic features around the Icefield, reflecting glacier downwasting in association with frontal recession from maximum Little Ice Age positions. Dates for these trimlines have enabled us to supply some estimates for rates of glacier surface downwasting since the Little Ice Age (Table 3).

On the northern flank of Glaciar San Quintín on a prominent ice-scoured bedrock knoll dendrochronology shows that the glacier downwasted about 184 m between 1907 and 1980 (Winchester and Harrison, 1996), with a mean surface loss of 2.52 m a^{-1} . On the eastern flanks of the Icefield, lichenometric investigations on the southern side of the Nef valley date exposure of the highest lateral moraine, some 40 m above lake level to 1863, with the glacier surface thinning ca. 20 m above lake level by 1881 according to tree age (Winchester et al., 2001). Thus, between 1863–1881, thinning of Glaciar Nef averaged approximately 1.11 m yr^{-1} , and then slowed to average 0.09 m yr^{-1} over the next 56 years, 1881–1937.

Above Glaciar Colonia lichen and tree-ring dating of the youngest trimline suggests that in 1883 maximum ice thickness was around 100 m above that of today (Winchester and Harrison, 2000). This implies downwasting between 1883 and 1996 at a rate of 0.88 m yr^{-1} . However, the rate is likely to have been variable, since Aniya (1988) found a rate of 1.7 to 2.7 m yr^{-1} between 1944 and 1974 based on aerial photographs of Glaciar Colonia's snout.

6. Discussion

6.1. Quality of the dating evidence

In any assessment of Little Ice Age glacier fluctuations, the accuracy of dating evidence is a primary concern. However, dating estimates based on lichen or tree ages can only be supported by empirical evidence and tests of significance cannot be applied due to the approach to data collection and uncertainty caused by the large number of variables

affecting establishment and growth. In this regard, the identical linear 4.7 mm yr^{-1} cumulative growth of *P. patagonica* and *P. perrugosa* on the Icefield's west and east sides is surprising, but the close agreement of trees and lichens on surface age in different microhabitats and across the dating range is reassuring and strongly suggests that growth here remains constant across the areal range.

The commonly accepted internal lichen measurement error is $\pm 1 \text{ mm}$ (Innes, 1985). This error, applied to a *Placopsis* growth rate of 4.7 mm yr^{-1} , is equivalent to ± 11 -week growth. However, repeat measurement trials during work carried out by VW on *Rhizocarpon alpicola* in Sweden (Winchester and Sjöberg, 2003) suggest that errors introduced by irregularities in rock surfaces and habitat variations for larger specimens, could amount to $\pm 2 \text{ mm}$. In the present study, this represents an error term of 5.5 months with little impact on dating. We have confidence that our sampling strategy enabled us to measure the largest lichens, since it was based largely on the size/frequency approach which employs measurement of large numbers of lichens (see Winchester and Harrison, 1994 for more details).

Estimates of the time it takes for a lichen propagule to become established after ice recession are more problematic unless supported by historical evidence. For example flooding records and dated aerial photographs of ice fronts at Glaciar Nef, and at Laguna San Rafael supply direct evidence provided by a cliff fall near sea level where regrowth took place within a year. Generally, a 2.5-year delay was established for lichen growth on the glacier margin at Laguna San Rafael (VW unpublished data), with this delay confirmed in the Arco valley. The minimum 13-year delay estimated for lichen establishment at the junction of the Colonia and Arenales Glaciers remains unconfirmed with the delay possibly of much longer duration. The associated 93-year estimate for tree establishment here is also a minimum, as is the 92-year value in the Nef valley. In the Arco valley, maxima for tree germination of 22 and 26 years are reasonably securely based on known flood dates in a system prone, prior to 1963, to violent outburst floods.

Ring counts from tree cores, as long as there are no missing or false (extra, non-annual) rings, provide a minimum age for trees. The time taken for the tree to grow to core ring height must be estimated and added to the core ring count to find true tree age. If the estimate is based only on average growth to core height (11.75 cm/year on the east side of the Icefield) then there could be, according to the data in Table 1, approximately a 10-year error. The error could be as much as 5–40 years and it is likely that the first colonised trees would grow more slowly than subsequent colonisers. This error could be reduced if attention is paid to the local growing conditions, with these matched to the growth rates of small trees sampled in similar microhabitats.

At Lago Leones a different and more approximate approach was taken. Estimates for the number of year's growth below core height were derived by dividing the estimated height of the tree above the core by its age from the ring count. However, this assumes that tree growth rate below a core is the same as that above it: plainly a questionable assumption,

especially when tree height is an estimate in the first place. Thus, the fairly close approximation of the 1867 Leones date to the regional norm (between 1876 and 1881) for maximal glacier positions at the end of the Little Ice Age is reassuring, especially if the possibility of a 10-year error is considered. At Glaciar Calafate the 1874/1876 lichen and tree dates were obtained based on the assumptions used for dating at the Nef and Colonia glaciers (Harrison et al., 2006).

6.2. Synthesis of the data

It is clear that the outlet glaciers of the Hielo Patagónico Norte receded from their Little Ice Age moraine limits in the last quarter of the 19th century. Similar timing can be observed in other parts of Southern Chile. For instance, Koch and Kilian (2001, 2005) showed that the significant advance of the Gran Campo Nevado glaciers at 53°S terminated in the late 19th century. Whether such glacier recession is synchronous globally is more difficult to assess but the evidence for a climatic deterioration during the Little Ice Age is currently highly contentious (see discussion by Mann et al., 1999; Soon and Baliunas, 2003; Jones and Mann, 2004; Schmidt et al., 2004). In areas peripheral to the North Atlantic and in Central Asia, the available evidence shows that glaciers underwent considerable recession at this time (cf. Savoskul, 1997; Grove, 2004; Solomina et al., 2004), but in North America many glaciers receded from their Little Ice Age limits slightly earlier than those of the Hielo Patagónico Norte. For example, on Mount Rainier, the Nisqually glacier receded from its Little Ice Age limit by about 1825 (Porter, 1981a) and in the Canadian Rockies the oldest moraines of historic age show a wide range of ages from the 17th to the 19th centuries (Luckman, 2000). However, during this time there was probably a considerable decadal variability of climate which the glacial record is not able to resolve.

The reconstruction of former glacier positions carries with it the assumption that dated moraine sequences reflect a linear response of the glaciers to climate forcing. However, this assumption is called into question by the behaviour of certain glaciers whose characteristics mean that their response to first-order climate forcing is partly obscured by second-order controls (Benn and Evans, 1998). For instance, there are difficulties in identifying the glacier/climate signal from calving glaciers. The proximity of the Pacific Ocean to the Andes in much of western Patagonia means that during periods of glacier expansion, many of the glaciers terminated in the sea and therefore experienced tidewater calving (Harrison, 2004). It is well known that calving processes induce second-order controls on glacier behaviour and therefore partly decouple and obscure the glacier/climate signal (e.g. Reeh, 1968; Van der Veen, 1996). The picture is further complicated by the different calving responses in freshwater and tidewater. Since much of the geomorphological evidence that has been used to infer climate change in Patagonia comes from the position and ages of moraines associated with glaciers which are calving or have calved in the past, it has been suggested that the problem of assigning climatic inference to oscillations of calving fronts is a serious one (e.g. Warren and Sugden, 1993; Porter, 2000).

On the eastern side of the Icefield a number of large valley glaciers drain narrow, steep-sided valleys and terminate with calving fronts into deep freshwater lakes. For instance, at Glaciar Nef, Warren et al. (2001) showed that lake depths in places exceed 200 m and this contributed significantly to large-scale breakup of the glacier terminus following recession from its Little Ice Age moraines, some 4 km from the present front. Similarly, Glaciar Arco receded from its Little Ice Age moraine into a 104 m deep lake towards the end of the 19th century and Lago Leones (into which Glaciar Leon now calves) is also 200–300 m deep in the vicinity of the present calving front (Haresign, pers. comm.).

Other topographic factors can also produce asynchronous glacier responses to climate (cf. Hubbard, 1997). For instance, many of the climatic reconstructions from the Chilean Lake District and the Magellan Straits area are partly based upon dates of the fluctuations of piedmont lobes with low ice gradients (see Porter, 1981b; Denton et al., 1999b). It has been suggested that the termini of such ice masses may oscillate in response to variations in bed conditions rather than climatic inputs. These factors mean that considerable caution should therefore be exercised when reconstructing palaeoclimates from the positions of moraines.

7. Conclusions

We have presented here data concerning the Little Ice Age fluctuations of eleven of the twenty four major outlet glaciers of the Hielo Patagónico Norte. We argue that these glaciers responded to a Little Ice Age climatic deterioration and this further highlights the likely global extent of this climate event. Glacier fluctuation data were compiled from field investigations, dendrochronology, lichenometry and radiocarbon dating. Although many moraine systems remain undated, the data collected from these eleven glaciers indicate that they reached their recent maxima in the late 19th Century. Indeed, ten of the eleven glaciers studied reached their maximum position between AD 1863 and 1880. Calculated rates of downwasting since the Little Ice Age maximum vary widely, from 0.09 to 2.52 ma^{-1} . The glaciers of the Icefield started receding from these 19th century positions at a similar time and continue to retreat at present, although synchronicity during the intervening period cannot be assured due to lack of data. These frontal variations reflect mass-balance changes during this period, presumably in response to increasing annual average air temperatures (see Rosenblüth et al., 1997), although precipitation might also have played an important role. Most of the glaciers of the Hielo Patagónico Norte now have freshwater or marine calving termini, which may serve to decouple their contemporary behaviour from mass-balance changes.

The data presented in this paper demonstrate that glacier recession at the end of the 19th century occurred synchronously on both sides of the Icefield, and at glaciers in different topographic settings. This suggests that calving played a relatively unimportant role in determining the approximate date of the maximum advance at this time. We can conclude,

therefore, that there has been a significant shift in the mass balance of the Icefield over the 20th century. Sometime before 1870 or so, mass balance of the outlet glaciers was strongly positive and this allowed glacier termini to advance (often along deep troughs) and produce extensive terminal moraines. After the end of the 19th century, mass balance appears to have been generally negative, and it is clear that this trend continues strongly at the present time (Rignot et al., 2003).

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