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'Little Ice Age' glacier fluctuations, Gran Campo Nevado, southernmost Chile

Johannes Koch[1]* and Rolf Kilian[2]

([1]Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada;[2]Lehrstuhl für Geologie, FB VI, Universität Trier, 54286 Trier, Germany)

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Abstract: Moraine systems of Glaciar Lengua (unofficial name) and neighbouring glaciers of Gran Campo Nevado (53°S) in the southernmost Andes were mapped and dated by dendrochronological means. They were formed around AD 1628, 1872/1875, 1886, 1902, 1912 and 1941 with the advance in the 1870s being calendar dated. Recessional moraines within each moraine system correspond to brief standstills or minor readvances. A significantly older moraine could not be directly dated by dendrochronological methods as the forest on it was assumed to be second-generation or older. From soil-formation rates, it is assumed that this moraine was formed at some time between AD 1280 and 1460, a time in which many other glaciers in Patagonia formed moraines. Overall, fluctuations of Glaciar Lengua show a strong synchronicity to other glaciers in the Patagonian Andes between 41°S and 55°S. This study suggests that Glaciar Lengua and possibly all glaciers of Gran Campo Nevado reached their Holocene maximum during the 'Little Ice Age.'

Key words: 'Little Ice Age', glacier variations, dendrochronology, southernmost Andes, late Holocene.

Introduction

The 'Little Ice Age', a period during the last millennium in which glacier cover was generally more extensive (Grove, 1988), is a phenomenon recorded in all mountainous areas of the world (e.g., Luckman, 2000; Holzhauser, 1985; Wiles *et al.*, 1999; Villalba, 1994). These glacier fluctuations seem to be synchronous on a centennial scale along the pole-equator-pole I transect (along the Americas). However, long stretches along the Cordillera remain uninvestigated. Therefore, Luckman and Villalba (2001: 136) pointed out that 'there remains a significant need for detailed, well-dated records of ['Little Ice Age'] glacier fluctuations'.

Gran Campo Nevado is a small ice cap (approximately 200 km^2) in the southernmost Andes (53°S; Figure 1). It is located between the Hielo Patagónico Sur (48°20′ to 51°30'S) and the Cordillera Darwin (54–55°S), both of which have been the focus of glaciological studies (e.g., Warren and Sugden, 1993; Casassa, 1995; Holmlund and Fuenzalida, 1995). However, due to relatively difficult access only a few studies on Holocene glacier activity have been carried out (e.g., Mercer, 1968; 1970; 1982; Clapperton and Sugden, 1988; Aniya, 1995; 1996; Kuylenstierna *et al.*, 1996). As recent variations of Patagonian glaciers are highly localized, probably due to topographic-climatic effects and glacier dynamics (Warren and Sugden, 1993; Holmlund and Fuenzalida, 1995), further studies are needed to establish a complete picture of the Holocene glacial chronology in Patagonia. In all previous studies, glacial advances were dated to the 'Little Ice Age' (LIA). However, studies concerning specifically the LIA are very few (Villalba *et al.*, 1990; Harrison and Winchester, 1998; 2000; Winchester and Harrison, 2000; Winchester *et al.*, 2001; Strelin and Casassa, unpublished data) and therefore more detailed LIA chronologies would be welcome (Luckman and Villalba, 2001).

Study area

The investigated Andean area at 53°S is characterized by deeply incised fiords and islands with their highest elevations around 2000 m (Figure 1). The north–south trending Andes form an orographic barrier to the very strong and prevailing westerlies, leading to annual precipitation in excess of 6000 mm (Schneider *et al.*, 2003). Precipitation is evenly distributed throughout the year and the area is characterized by cool summers and mild winters.

Glaciar Lengua, as well as approximately 25 other unnamed outlet glaciers of Gran Campo Nevado, has not been subject to any study known to the authors. Glaciar Lengua is located west of Bahia Bahamondes on Canal Gajardo, a fiord connect-

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*Author for correspondence: (e-mail: jkoch@sfu.ca)

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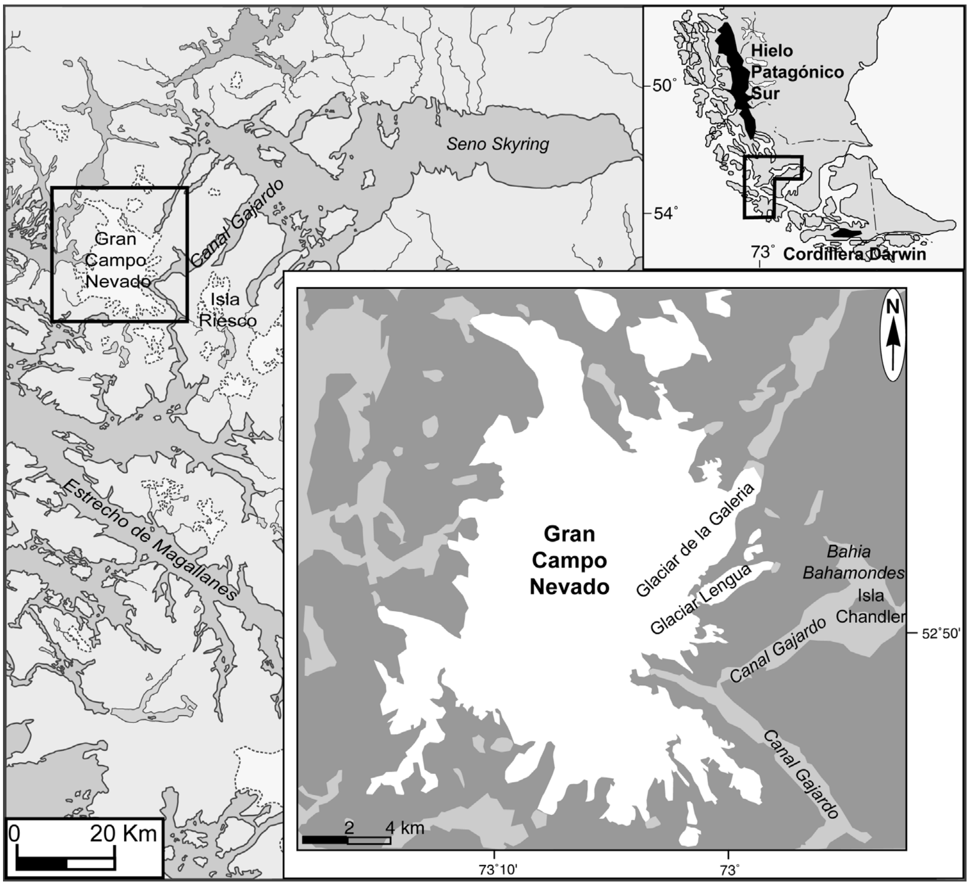

Figure 1 Location of Glaciar Lengua. The small map in the top right shows the location of the study site with the Hielo Patagónico Sur to the north, and Cordillera Darwin in the south. The main map shows the location of Gran Campo Nevado in relation to Estrecho de Magallanes and Seno Skyring and the map of Gran Campo Nevado ice cap (lower right) includes the names mentioned in the text.

ing Seno Skyring in the northeast with the Estrecho de Magallanes to the southwest (Figure 1). The valley between the glacier front and Bahia Bahamondes is mainly occupied by a bar of Holocene sediments. The well-drained parts of the bar are forested by Magellanic Rainforest, with the remaining area covered by Magellanic Moorland. Forests are dominated by *Nothofagus betuloides* (Mirb.) Blume with *Nothofagus antarctica* (Forst) Oerst, *Pilgerodendron uviferum* (D. Don) Florin and *Drimys winteri* J.R. & G. Forst being minor components.

The moraine systems in the glacier foreland of Glaciar Lengua were mapped during the austral summer of 2000. The outermost moraine lies approximately 900 m in front of the present glacier snout. The geomorphic and vegetational evidence show four distinct moraine complexes lying within 300 m of each other (moraines B–E; Figure 2). A fifth moraine system (moraine A) was found only on the north side of Rio Lengua. The moraine systems dam Lago Lengua, a small lake drained by Rio Lengua. Rio Lengua has breached all the moraine systems and its course has changed since the last glacier advance. Each moraine complex is better defined north of Rio Lengua, whereas the south side has been modified by fluvial activity. All moraine systems comprise complex multiple moraines and push moraines; for example, moraine C has four distinct ridges within the main moraine complex (Figure 3). It is therefore assumed that during the general recession of Glaciar Lengua there were various standstills and minor readvances.

All moraine systems are extensively covered by dense forest (Figure 4). However, each system shows a different succession stage (Figure 3), ranging from pioneer *Nothofagus antarctica* forest on the innermost moraines (moraine E) to primary Magellanic Rainforest dominated by *Nothofagus betuloides* on moraine A, with forest on moraine B appearing to be slightly younger, lacking the fallen trunks and stumps of moraine A. The forest cover on intervening moraine systems (moraines C and D) represents intermediate succession stages with *Nothofagus antarctica* and *N. betuloides* codominating.

Methods

The formation of the moraines was dated by dendrochronological means. The age of the oldest tree on a moraine provides a minimum estimate for moraine formation and stabilization (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993). On the foreland, tree invasion appears to be uniform and at an early stage in succession. One problem is that, due to the very dense forest cover on all moraines, it is possible that the oldest trees were not always sampled and dated. Two increment cores were extracted from several trees on each moraine using a 4.3 mm diameter increment borer. By removing two cores, data are replicated and the possibility of missing rings or 'false' rings is reduced (Stokes and Smiley, 1968). Cores were mounted and prepared for analysis by sanding with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Rings were measured with a precision of ± 0.01 mm. Trees damaged or tilted by a glacier advance provide additional age controls on moraines and trees killed by a glacier advance can be used to develop floating chronologies that can be crossdated with living chronologies, with the year of death providing a minimum age for the moraine. Discs were cut from any damaged or killed trees found on the moraines and analysed

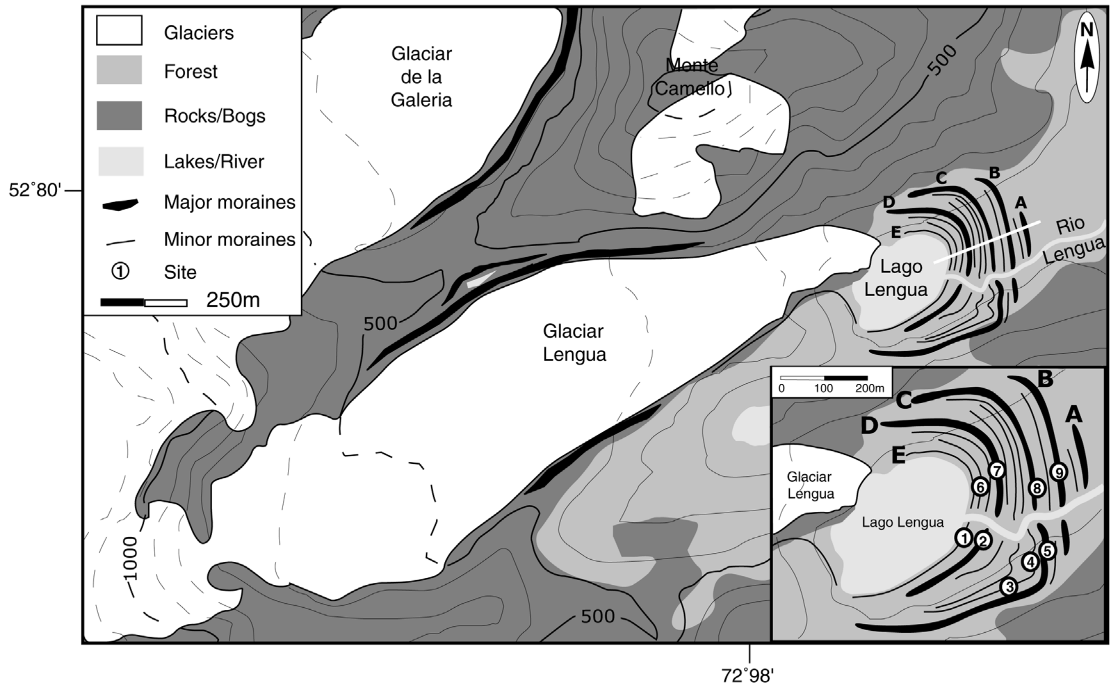

Figure 2 Geomorphic map of Glaciar Lengua and its surroundings. Shown are the mapped and dated moraine systems A–E with the transect across the moraines in white (Figure 3). The insert map shows the mapped moraines A–E and the location of sampling sites numbered 1–9. The bold lines indicate the major moraines, while the lighter lines indicate minor moraines formed by standstills and/or readvances. Contour intervals are 100 m.

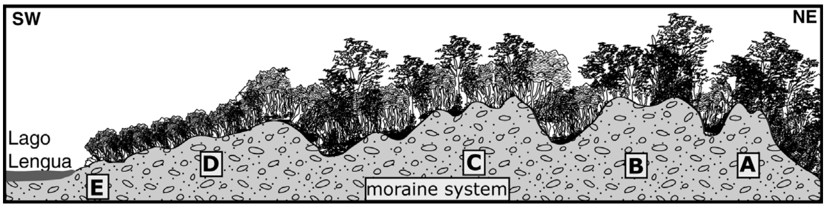

Figure 3 Cross-section of the moraine systems of Glaciar Lengua. The sketch is approximately to scale with a slight vertical exaggeration. The length of the transect is approximately 300 m and the height of the biggest moraine is approximately 25 m.The location of the transect is shown in Figure 2. The different succession stages are indicated by different heights of vegetation cover.

in the same way as the cores. However, four radii were measured on the discs to improve the certainty of the crossdating.

A living tree-ring chronology was formed from all trees growing on the various moraines. The series was checked and verified by the International Tree-Ring Data Bank (ITRDB) software program COFECHA and crossdated (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32), thus creating a master ring-width chronology (Holmes, 1983). A floating chronology was developed from a killed tree including the bark. The floating series was crossdated against the living chronology using COFECHA (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32) to determine the year of death.

When trees are used to date a moraine, a more accurate estimate of the surface age is obtained by adding the ecesis interval (time from surface stabilization to seedling germination) to the age of the oldest tree (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993; Matthews, 1992). Ecesis in this study was estimated by two independent methods. The first approach to determine ecesis was by air-photo examination. The second was by taking the time difference between kill and/or tilt dates by glacier advances and the date of germination of the oldest trees on the same moraine. Furthermore, the time trees need to grow to sampling height must be corrected for (McCarthy *et al.*, 1991; Winchester and Harrison, 2000). We used the method proposed by Winchester and Harrison (2000). To establish age/growth relationships below coring heights, 15 small trees were cut at ground level. Each tree's local environment, its height and basal ring count were recorded. Furthermore, where applicable, trees with sections suggesting stressful growth conditions (e.g., narrow rings or compression wood) were recorded. Ages of trees below core height were then based on the characteristics of the rings nearest the central pith and the recorded details for each tree. With trees showing multiple stress factors, a maximum number of years were added to the ring count to establish a germination date. If trees were unstressed and there were wide rings at the pith end of a core, rapid growth to core height was assumed and a minimum number of years was added.

Results

Dendrochronology

A living tree-ring chronology of all sampled trees was built which spans the time period from AD 1646 to 2000. From AD 1663 the chronology comprises at least 10 trees (16 cores). Interseries correlation according to the ITRDB COFECHA

Figure 4 Oblique view of Glaciar Lengua from the north. The plateau-like main body of the glacier can be observed below the icefall feeding the glacier from the ice cap. To the left of the glacier tongue is Lago Lengua, dammed by the heavily forested 'Little Ice Age' moraines.

program is significant at 0.497. A floating chronology (four radii) of a tree killed by a boulder on moraine C was crossdated with the living chronology using COFECHA. The highest correlation with the living chronology was achieved for AD 1795–1875 with the correlation significant at 0.59. This indicates that the tree was killed in AD 1875.

Tree age below core height

Table 1 shows variations in growth rates and tree height. The data show that average annual growth rates for young *Nothofagus* spp. vary from 7.1 to 25 cm/year. Therefore these trees can take 2–7 years to grow to the coring height of 50 cm. However, it was found afterwards that highly stressed trees had not been sampled. This was probably because these trees are almost impossible to core, as they almost always develop multiple branches in the lower reaches of the trunk. Therefore, it is assumed that the sampled trees took less than five years to grow to the coring height of 50 cm.

Table 1 Tree height estimates at Gran Campo Nevado. Varying age-height relationships and average growth rates of *Nothofagus* species (*N. betuloides* and *N. antarctica*), based on ring counts from trees cut at ground level. Average growth rates are included to show growth range

Ring count (age)	Tree height (cm)	Growth rate (cm/year)
2	34, 45, 50	17, 22.5, 25
3	23, 44	7.6, 14.7
4	49, 55, 75, 87	12.3, 13.8, 18.8, 21.8
7	50, 98, 157	7.1, 14, 22.4
11	134, 156	12.2, 14.2
15	115, 187	7.7, 12.5

Ecesis

Aerial photographs from 1942, 1984 and 1998 were obtained from SAF (Fuerza aerea de Chile, Servicio Aereofotogrametrico). On the picture taken in 1942 Glaciar Lengua had already receded into the lake with the tongue close to the shore and the innermost moraine. In 2000, trees sampled on moraine E showed a maximum age of 40 years. Therefore ecesis is a maximum of 18 years ± an unknown time interval, as it is unknown if the glacier readvanced to form moraine E after 1942 or when the glacier receded from moraine E to the position of 1942.

Aerial photographs of neighbouring Glaciar de la Galeria (unofficial name; Figure 1) show the recession at a part of the lateral moraine. Between 1942 and 1984 recession was very small and moraines of this time are close to each other. Trees growing in an area still under ice in 1942, but ice-free in 1984, were sampled in 2000 and show maximum ages of around 11 years. Therefore ecesis is a maximum of 47 years and a minimum of five years. If glacier recession between the formation of the two moraines is assumed to be constant, an ecesis interval of 15–20 years seems to be reasonable.

A tree on moraine C, north of Rio Lengua, was killed by a boulder in AD 1875 (site 8 in Figure 2 inset). The oldest age obtained from trees established after glacier recession germinated at around AD 1884. Therefore, ecesis took at least nine years at this site. As the date between glacier advance and tree death could be some years apart this is still a minimum estimate. A tree on moraine C, south of Rio Lengua, was tilted by a glacier advance in AD 1872 (site 5 in Figure 2 inset). The oldest age obtained from trees established after glacier recession started growth around AD 1894. Therefore, ecesis took at most 22 years at this site. Here the date of the glacier advance is known, but not when the glacier started receding. Again the tilting date could be some years apart from the start of recession and therefore it is a maximum estimate. The tilting and killing of trees in the 1870s occurred on the same moraine and therefore another picture could be drawn. Glacier Lengua advanced to the position of moraine C and tilted a tree in AD 1872. Three years later a tree was killed by a boulder rolling off the moraine during stabilization. The oldest tree on moraine C germinated in AD 1884 and thus ecesis took between nine and 12 years. However, it cannot be taken for granted that Glaciar Lengua receded from all of moraine C at the same time and thus a more conservative estimate of nine to 22 years is assumed.

Taking all the above results into account, ecesis at Glaciar Lengua at Gran Campo Nevado takes 9–22 years, with the most likely estimate at around 15 years.

Glacial chronology

Ten to fifteen trees were sampled on each moraine complex to determine a minimum age for each advance (Figure 2; Table 2). However, about 30% of all samples could not be analysed due to little contrast or tree rings being less than 0.01 mm apart and thus below the resolution of the measuring device. On moraine C a tree tilted by the moraine deposition was found and sampled to establish a calendar date for this advance. On the same moraine system north of Rio Lengua a tree was killed by a big boulder (240 m^3) rolling off the moraine crest. It is assumed that this occurred shortly after moraine deposition while the surface was stabilizing. Therefore this moraine system can be precisely dated without taking any ecesis interval into account. Also, these dates enable a better estimate for ecesis (see above).

Our investigations at Glaciar Lengua show that glacier cover was more extensive during the 'Little Ice Age' than it is today (Figure 2). In 2000, trees sampled on moraine E yielded a maximum tree age of 41 years. Tree ages are 70 years for moraine D2, 80 years for moraine D1, 96 years for moraine C2, 116 years for moraine C1 and 354 years for moraine B. Core ring counts, with the addition of 15 years for ecesis and three years for growth to core height, date the formation of moraines B–E (Figure 2 inset) to the years *c.* AD 1628 (B), 1872/75 (C1), *c.* 1886 (C2), *c.* 1902 (D1), *c.* 1912 (D2) and *c.* 1941 (E; Table 2). While the first two dates are interpreted to be glacier advances due to their location and morphology, the later dates may represent standstills and/or minor readvances that occurred since the last major advance in the 1870s.

Between AD 1628 and 1872/75 the glacier receded upvalley before readvancing and forming moraine C, tilting and killing trees that were 127 and 80 years old, respectively. Therefore, we conclude that in the intervening 245 years between the advance that formed moraine B around AD 1628 and the advance that formed moraine C in AD 1872/75 Glaciar Lengua receded behind the position of moraine C around AD 1730 to an unknown position upvalley. The date AD 1730 was obtained by subtracting 127 years (the age of the tree tilted on moraine C) and 15 years for ecesis from AD 1872, the time that tree was tilted by the glacier advance. This also means that our record of glacier advances between 1730 and 1872/75 may be incomplete as the following advance would have overridden and destroyed these moraines. This scenario is further corroborated by dated advances during the late eighteenth century at the Hielo Patagónico Sur (Table 3; Mercer, 1970) and also in northern Patagonia (Table 3; Lawrence and Lawrence, 1959; Röthlisberger, 1986; Villalba *et al.*, 1990).

Along Rio Lengua (Figure 2), approximately 250 m further downstream from the outermost LIA moraine, a peat bog is eroded by the river and approximately 250 cm of peat are overlying fluvial sediments. At the boundary of the peat and fluvial sediments are several well-preserved *in situ* rooted trees, which were radiocarbon dated to 4850 cal. yr BP. This indicates that Glaciar Lengua has not advanced beyond this point since then. Furthermore, at the bottom of a core from a small lake on Isla Chandler (Figure 1 inset) the transition of glacier clay to organic-rich lake sediments was recorded and radiocarbon dated to 12 540 cal. yr BP, thus indicating that this area was ice-free since then. No terrestrial or submarine moraines are recorded between the LIA moraines and Isla Chandler and therefore it is argued that Glaciar Lengua reached a position close to present-day or LIA conditions sometime soon after 12 540 cal. yr BP and has since then not reached a more extensive position than during the LIA. Therefore, the maximum LIA position of Glaciar Lengua marks the most extensive extent during at least the last 5000 years and possibly throughout the Holocene.

Discussion and conclusions

Regional *ecesis* rates

The time interval established for ecesis is of great importance for comparison of dendrochronologically dated glacier fluctuations. The time interval of 15 years for ecesis at our study site is to some degree comparable to ecesis intervals reported from other areas of the Patagonian Andes (Table 4). However, ecesis is significantly influenced by the local climatic conditions which change dramatically from our study site in the south towards the north, and from the west of the Andes to the east. Many of these differences can be ascribed to dramatic changes in the local precipitation regimes.

At Monte Tronador at 41°S ecesis was found to take 5–10 years in sheltered spots and up to 67 years on the exposed valley bottom (Villalba *et al.*, 1990). Veblen *et al.* (1989) estimated ecesis to be 1–3 years in the same area.

Table 2 Location, number and ages of sampled trees on the north and south sides of Rio Lengua. Sampling site numbers are shown in Figure 2 (inset). In the last column, estimated dates of glacier advances are derived from ring counts added to estimates of 15 years for ecesis and three years for growth to sampling height. The most probable date for each moraine is given in bold type.

Moraine	Sampling site number	Sampled tree numbers	Age (N) years	Age (S) years	Date AD
A	n/a	n/a	n/a	n/a	n/a
B	9	12	354	n/a	**1628**
C1	5&8	13	116	109	1865/1872
C1	8	1	n/a	n/a	**1875** (date of death)
C1	5	1	n/a	n/a	**1872** (date of tilt)
C2	3&4	14	n/a	96	**1886**
D1	6	11	80	n/a	**1902**
D2	2&7	14	70	66	**1912**
E	1	15	n/a	41	**1941**

Table 3 Dated LIA glacier advances in Patagonia from previous publications. The table is ordered from north to south and the icefields are separated into east and west of the divide

Location	Ages for dated moraines	Method of dating	Reference
Northern Patagonia: Mt Tronador (41°S)			
Glaciar Frias	> AD 1236, *c*. 1638, ~1722, ~1747, ~1839, *c*. 1881, ~1914, ~1952, 1977	Tree rings	Villalba *et al*., 1990
Glaciar Rio Manso	Early eighteenth century, AD 1795, 1809–21, 1832–34, 1847	Tree rings	Lawrence and Lawrence, 1959
Glaciar Rio Manso	AD 1040, 1330, 1365, 1640, 1800–50	Radiocarbon	Röthlisberger, 1986
HPN (46°30'S–47°30'S) – west side			
Glaciars Gualas, Reicher	AD 1876, 1909, 1954, 1970	Tree rings	Harrison and Winchester, 1998
Glaciar San Rafael	AD 1675, 1675–1766, 1882	Radiocarbon	Heusser, 1960
HPN (46°30'S–47°30'S) – east side			
Glaciar Soler	AD 1850s, 1890s, 1910s, 1940s	Tree rings	Sweda, 1987
Glaciar Soler	*c*. AD 1222–1342	Radiocarbon	Glasser *et al*., 2002
Glaciars Colonia, Arenales, Arco	AD 1870s, 1900s, 1940s	Tree rings	Harrison and Winchester, 2000
Glaciar Nef	AD 1863, 1884, 1935	Tree rings, lichen	Winchester *et al*., 2001
HPS (48°20'S–51°30'S) – west side			
Glaciar Ofhidro Norte	AD 1790, 1850–60, 1940s	Tree rings	Mercer, 1970
Glaciar Bernardo	AD 1775, 1810–20, 1940s	Tree rings	Mercer, 1970
Glaciar Tempano	AD 1760 ± 10, 1940s	Tree rings	Mercer, 1970
Glaciar Hammick	AD 1750, 1840, 1940s	Tree rings	Mercer, 1970
HPS (48°20'S–51°30'S) – east side			
Glaciar Narvaez	Seventeenth century, AD 1880	Estimate, historic	Mercer, 1968
Paine National Park	AD 1660 or 1725, 1805, 1845, post-1890	Tree rings	Marden and Clapperton, 1995
GCN (~53°S)			
Glaciar Lengua	~AD 1628, 1872/75, ~1886, ~1902, ~1912, ~1941	Tree rings	This study
Cordillera Darwin (54°S–55°S)			
Bahia Pia	No evidence for LIA; *c*. 940–675 BP	Radiocarbon	Kuylenstierna *et al*., 1996
Glaciar Ema (Mt Sarmiento)	*c*. 695 BP, *c*. 335 BP, *c*. 315 BP, 140–90, 110–60, 90–60	Radiocarbon, estimates	Strelin and Casassa, unpublished data

At various glaciers on the eastside of Hielo Patagónico Norte (HPN; 46°30' to 47°30'S) ecesis was found to take between 22 and 93 years depending on whether the site was near water or on an exposed mountainside (Winchester and Harrison, 2000; Winchester *et al*., 2001). Sweda (1987) obtained a short ecesis period of 24–30 years for his study site east of the Andes, but his study site was near water and thus compares favourably to other estimates from the same area. On the west side of the icefield, ecesis was determined to be between less than 10 years (Warren, 1993; Winchester and Harrison, 1996) and a maximum of 25 years (Heusser, 1964). This indicates that generally at this latitude ecesis on the west side of the Andes is much shorter than on the leeward side, suggesting that low precipitation east of the Andes hinders tree recruitment to some degree. This is also suggested by the fact that east of the Andes, near water, ecesis is similar to that of the wet west side.

At Hielo Patagónico Sur (HPS; 48°20' to 51°30'S) no difference in ecesis east and west of the Andes is obvious. Nichols and Miller (1951) estimated that ecesis takes more than 70 years at Glaciar Ameghino on the east side. Pisano (1978) found an even longer period of around 100 years for his site, also east of the Andes. Recent studies at various glaciers at the east side of HPS show that ecesis takes less than 50 years (Dollenz, 1991; Armesto *et al*., 1992). It seems that, further east, less time is needed for tree recruitment, as is apparent from the latter two studies. Mercer (1970; 1982), studying sites both east and west of the Andes, estimated ecesis to be similar on both sides and to take up to 70 years or more. If following along a transect from west to east at this latitude one could argue that, in accordance with a very similar vegetation cover directly east and west of the Andes, ecesis is in the same range too (> 70 years). However, further east, as with the vegetation cover, changes in ecesis are apparent (40–50 years versus > 70 years) and are most likely related to changes in the precipitation regime. It is interesting to note that studies finding long ecesis (> 70 years) were mostly done until the 1980s and studies finding shorter ecesis (< 40 years) were done after 1990 (Table 4). Therefore, it could be argued that in recent times, due to the worldwide warming trend, ecesis takes less time than it did in the early and mid-twentieth century and that tree recruitment at this latitude has generally improved in the present-day climate.

South of our study site, in the Cordillera Darwin (54–55°S), a region climatically quite similar to our site, Holmlund and Fuenzalida (1995) obtained an estimate of less than 20 years for ecesis, which is in good accordance with our findings. Why ecesis is so much shorter this far south, where precipitation is very high (> 6000 mm; Schneider *et al*., 2003) and thus similar to conditions at HPS, cannot be easily explained. Both studies were done in recent times and thus could be explained by the aforementioned warming trend that favours tree recruitment this far south. However, our best estimate for ecesis comes from a LIA moraine, formed in the 1870s,

Table 4 Ecesis estimates in Patagonia from previous publications. Again they are ordered from north to south and the icefields are separated into east and west of the divide

Location	Estimate	Method	Reference
Northern Patagonia: Mt Tronador (41°S)			
Glaciar Casa Pangue	1–3 years	Estimate	Veblen *et al.*, 1989
Glaciar Frias	5–10 years	In sheltered spots	Villalba *et al.*, 1990
	67 years	Exposed valley bottom	
HPN (46°30'S–47°30'S) – west side			
Glaciar San Rafael	25 years	Estimate	Heusser, 1964
Glaciar San Rafael	<10 years	50 cm tall *Nothofagus* at spot under ice in early 1980s	Warren, 1993
Glaciar San Rafael	min. 6 years	Estimate	Winchester and Harrison, 1996
HPN (46°30'S-47°30'S) – east side			
E-side HPN	22 years	Near water level	Winchester and Harrison, 2000
	26 years	Valley sides and terraces	
	93 years	Exposed mountainside	
Glaciar Soler	24–30 years	Estimate	Sweda, 1987
Glaciar Nef	35–92 years	See Winchester and Harrison, 2000	Winchester *et al.*, 2001
HPS (48°20'S–51°30'S) – west side			
Glaciar Tempano	70 years	Tree tilt date 1760 ± 10; oldest new tree: 140 years	Mercer, 1970
HPS (48°20'S–51°30'S) – east side			
E-side HPS	>70 years	Older than 1897 moraine in 1966 still tree less	Mercer, 1982
Glaciar Ameghino	>70 years	80-year-old LIA moraines still devoid of vegetation	Nichols and Miller, 1951
Glaciar Dickson	<40 years	Estimate	Dollenz, 1991
Torres del Paine	40–50 years	Estimate	Armesto *et al.*, 1992
Glaciar Serrano	~100 years	Estimate	Pisano, 1978
GCN (~53°S)			
Glaciar Lengua	~15 years	Remote sensing, calendar dated	This study
Cordillera Darwin (54°S–55°S)			
Bahia Pia	<20 years	30-year-old tree on spot still ice covered in 1943	Holmlund and Fuenzalida, 1995

on which germination of new trees occurred at a time when colder conditions still prevailed and tree recruitment was not yet favoured by the warming trend. Both our estimates of ecesis, though from different centuries and climates, indicate a rather constant ecesis period not influenced by minor changes in climate. The difference of ecesis period found in our study and at various glaciers of HPS remains to be explained. The results at Gran Campo Nevado corroborate the remark of Warren and Sugden (1993: 325) that 'such wide divergence casts doubt on the reliability of any regional dendrochronology, and emphasizes the importance of detailed case studies in this region of dramatic local contrasts'.

Regional comparison of glacial chronologies

Reconstruction of Glaciar Lengua's fluctuations shows a great degree of synchronicity with other glacier fluctuations along the Patagonian Andes between 41°S and 55°S (Table 3 and Figure 5). Along this section of the Andes they present one

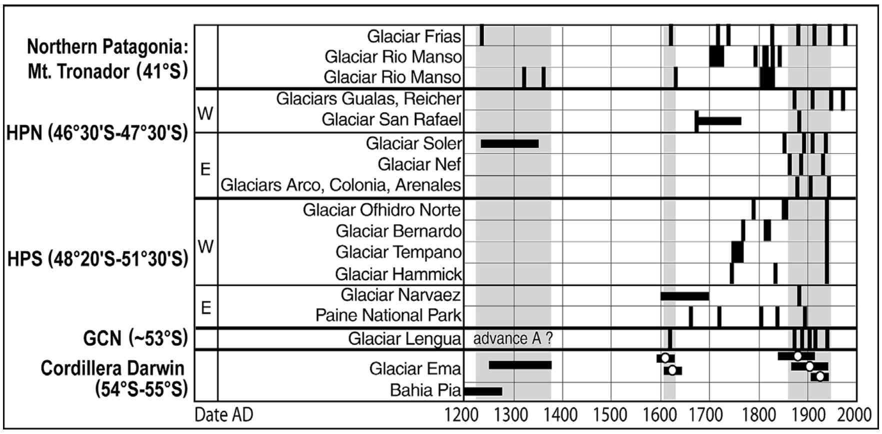

Figure 5 Overview of dated glacier advances in Patagonia as shown in Table 3. Horizontal bars indicate rather precise dates (dendrochronology, lichenometry and some radiocarbon dates), vertical bars indicate uncertain radiocarbon dates or estimates, and vertical bars with a circle indicate dates with questionable methods. For a discussion, see the text. As there is some overall correlation between Glaciar Lengua and other sites in Patagonia, it is proposed that advance A at Glaciar Lengua occurred some time in the thirteenth and/or fourteenth centuries. Also, it should be pointed out that there is an obvious gap in Glaciar Lengua advances between the late seventeenth and early nineteenth centuries.

of the most pronounced climate divides on earth. Glaciers on the western side and the divide zone of the Andes may be strongly influenced by precipitation and by the intensity of the westerlies, while glacier fluctuations on the eastern side of the Andes may more likely be controlled by temperature. It is thus obvious that comparisons along almost 2000 km from north to south and across this very pronounced climate divide bear many complications. However, as they show a strong degree of synchronicity it appears relevant to include a comparison of the results presented here and the wider regional context.

At Monte Tronador, the northernmost location considered here, two major glacial advances of Glaciar Frías have been dated to between AD 1270 and 1380, and 1520 and 1670 (Villalba *et al.*, 1990). The former advance could coincide with the formation of moraine A at Glaciar Lengua (see below), and the latter may be equal to our moraine B. Only the latter advance and recessional moraines of Glaciar Frías could precisely be dated by tree-ring records of damaged trees and dates of 1638, 1722, 1747, 1839, 1881, 1914, 1952 and 1977 were found (Table 3 and Figure 5). Similar results at Glaciar Rio Manso (Lawrence and Lawrence, 1959; Röthlisberger, 1986) show a strong synchronous response to some climate forcing at Monte Tronador.

Around Hielo Patagónico Norte only the culmination of LIA glacier fluctuations, and the subsequent recessional moraines, have been dated. These results suggest that the LIA culminated during the second half of the nineteenth century, with various standstills in the first half of the twentieth century (Table 3 and Figure 5; Sweda, 1987; Harrison and Winchester, 1998; 2000; Winchester and Harrison, 2000; Winchester *et al.*, 2001). Only Glaciar San Rafael shows glacial advances dating to the late seventeenth and early eighteenth centuries (Heusser, 1960), a period of advance found at all other major icefields along the transect. It therefore could be argued that most studied glaciers of HPN have obliterated any previous evidence of this advance by later more extensive advances. Between AD 1222 and 1342 Glaciar Soler was also much more extensive than at present (Glasser *et al.*, 2003), again a phase of glacier activity found at various locations along this transect and therefore most likely a regional event.

Glaciers of Hielo Patagónico Sur formed moraines in the late seventeenth century, in the mid- to late eighteenth century, in the early to mid-nineteenth century and the first half of the twentieth century (Table 3 and Figure 5; Heusser, 1960; Mercer, 1968; 1970; Marden and Clapperton, 1995). All studied glaciers at HPS show a synchronous response most likely due to a regional climate signal rather than to local conditions.

On Isla Riesco (53°22′S; Figure 1), just east of Gran Campo Nevado, Coppinger (1883: 124) observed in 1880 a glacier advancing into the forest and overturning trees, closely corresponding to our advance forming moraine C, with this moraine incorporating 'crushed, torn and distorted out of shape trees'. This observation supports our assumption that Glaciar Lengua receded further upvalley before readvancing into forest and reaching its late-nineteenth century maximum.

In the Cordillera Darwin on Tierra del Fuego varying responses of glaciers during the twentieth century have been noted (Holmlund and Fuenzalida, 1995). Glaciers on the northern and eastern sides of the Cordillera Darwin have been receding since the start of the century. However, those on the southern and western sides only recently reached positions at or close to their Holocene maxima. Kuylenstierna *et al.* (1996) found no evidence for LIA glacier activity at Bahia Pia on the southern side of the Cordillera Darwin and noted that the only advance coming close to the LIA time interval has been radiocarbon dated to between 940 and 675 BP. In contrast to these findings Strelin and Casassa (unpublished data) found 'Little Ice Age' glacier activity at their study site west of the Cordillera Darwin and radiocarbon dated the moraines to *c.* 695 BP, 335 BP and *c.* 315 BP. The sizes of the tree trunks were used to date the innermost moraines to 140–90, 110–60, 90–60 years ago (Table 3 and Figure 5). Even though both methods of dating are questionable in their precision, they indicate LIA advances and are assumed to be important for inclusion in this comparison.

In the Patagonian Andes, the sparse data available show that overall the culmination of LIA glacier advances occurred between AD 1600 and 1700 (e.g., Mercer, 1970; Röthlisberger, 1986; Aniya, 1996). Various glaciers at Hielo Patagónico Norte and Hielo Patagónico Sur also formed prominent moraines around 1870 and 1880 (Warren and Sugden, 1993; Winchester *et al.*, 2001; Luckman and Villalba, 2001). Our data from Gran Campo Nevado further supports this scenario. Most radiocarbon dates in the Patagonian Andes fall in three periods: AD 1280–1460, AD 1560–1690 and around AD 1860 (Villalba, 1994), the latter advance corresponding with our advance C, and the penultimate occurring concurrent with advance B at Glaciar Lengua. We suggest that our undated moraine A was formed during the first period of widespread glacier advances in Patagonia from 1280 to 1460. This hypothesis is supported by the soil on moraine A being only a little more developed than on moraine B, thus excluding an earlier mid-Holocene date for this moraine. Furthermore, our study suggests that at Glaciar Lengua, and from observations of neighbouring glaciers at Gran Campo Nevado, the 'Little Ice Age' advance was possibly the most extensive one during the Holocene for this ice cap.

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