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Little Ice Age fluctuations of Glaciar Río Manso in the north Patagonian Andes of Argentina

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ABSTRACT

Little Ice Age (LIA) fluctuations of Glaciar Río Manso, north Patagonian Andes, Argentina are studied using information from previous work and dendrogeomorphological analyses of living and subfossil wood. The most extensive LIA expansion occurred between the late 1700s and the 1830–1840s. Except for a massive older frontal moraine system apparently predating ca. 2240 ^{14}C yr BP and a small section of a south lateral moraine ridge that is at least 300 yr old, the early nineteenth century advance overrode surficial evidence of any earlier LIA glacier events. Over the past 150 yr the gently sloping, heavily debris-covered lower glacier tongue has thinned significantly, but several short periods of readvance or stasis have been identified and tree-ring dated to the mid-1870s, 1890s, 1900s, 1920s, 1950s, and the mid-1970s. Ice mass loss has increased in recent years due to calving into a rapidly growing proglacial lake. The neighboring debris-free and land-based Glaciar Frías has also retreated markedly in recent years but shows substantial differences in the timing of the peak LIA advance (early 1600s). This indicates that site-specific factors can have a significant impact on the resulting glacier records and should thus be considered carefully in the development and assessment of regional glacier chronologies.

Introduction

The Patagonian Andes in southern South America have an enormous potential for the study of past and present glacier and climate changes in this region. The juxtaposition of a dense forest cover with former glacier termini over a latitudinal range of ca. 1500 km makes this area particularly suitable for studies using several independent techniques to date glacial deposits and develop multi-proxy paleoclimate reconstructions. However, despite this potential, past glacier fluctuations and glacier–climate relationships in the Patagonian Andes are still not well known. Most investigations in this region have concentrated on the larger glaciers south of 45°S and usually focused either on 20th century glacier changes (e.g., Aniya et al., 1997; Rignot et al., 2003), or on glacial variations during the late glacial and Holocene periods (e.g., Mercer, 1982; Rabassa and Clapperton, 1990; Clapperton, 1993; Glasser et al., 2004; Sugden et al., 2005). In the north Patagonian Andes (i.e., between ca. 37° and 45°S) much more information is available about regional glacier fluctuations during the last glacial maximum (see, e.g., Denton et al., 1999, and references therein) than for glacier fluctuations during the past few centuries.

Few studies have focused on the fluctuations of Patagonian glaciers during the last 1000 yr (e.g., Villalba et al., 1990, Koch and Kilian, 2005; Masiokas et al., in press) for which the available glacial evidence is usually relatively abundant, well preserved and most easily dated. Although the number, magnitude and dating precision of glacial events for this time frame differ from site to site, the available information suggests that the most extensive glacier advances in the Patagonian Andes occurred between the 17th and 19th centuries [globally identified as the Little Ice Age (LIA), Grove, 2004]. There is also scattered evidence for glacier advances that occurred in the first half of the past millennium (e.g., Glasser et al., 2002), and during the 20th century (e.g., Masiokas et al., 2008). However, the small number of glaciers studied and the poor dating control for most events suggests that the existing regional glacial chronologies can only be considered provisional until more detailed studies at suitable glaciers are developed. According to Luckman and Villalba (2001, p. 136), “there remains a significant need for detailed, well-dated records of glacier fluctuations, coupled with a better understanding of the factors that control glacier mass balance” during this time frame.

In this paper we present a revised LIA chronology of fluctuations for Glaciar Río Manso (also known as Ventisquero Negro) at Monte Tronador (41°10′S, 71°52′W), north Patagonian Andes, Argentina (Fig. 1). This glacier is one of the most easily accessible glaciers in

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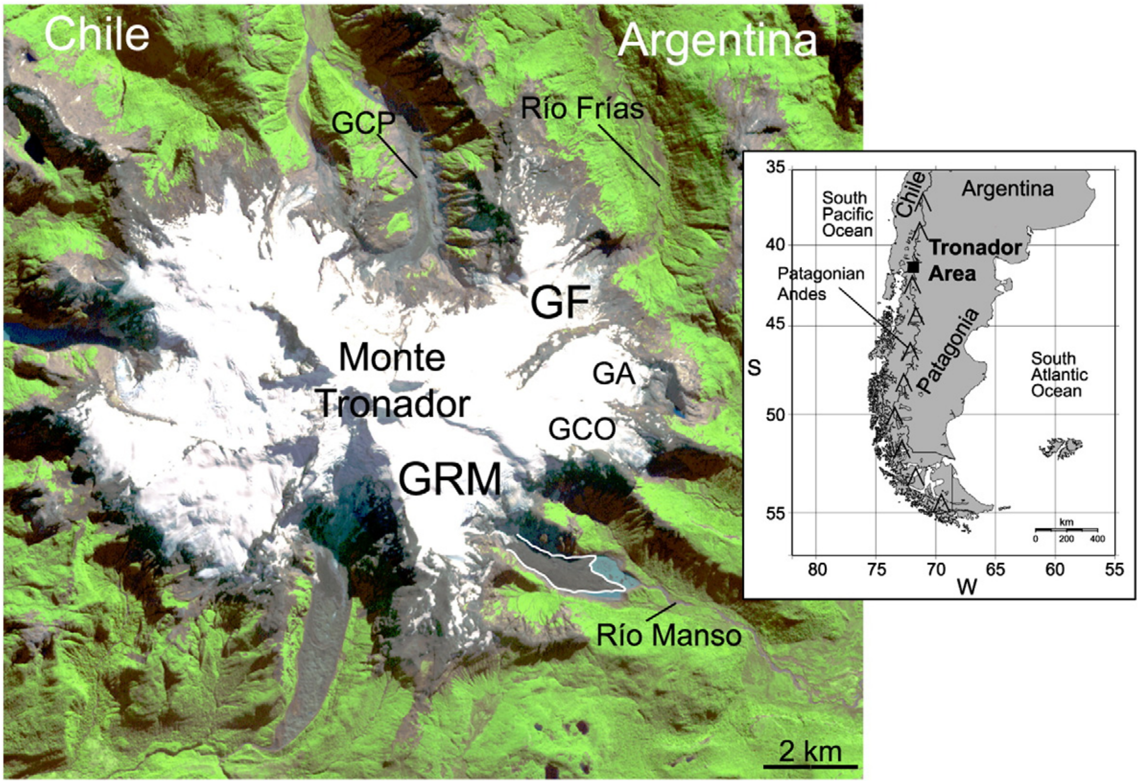

Figure 1. Location of Monte Tronador in the north Patagonian Andes and ASTER image from April 2003 showing the location of Glaciar Río Manso (GRM) and Glaciar Frías (GF) on the eastern side of Monte Tronador. Note the dark, debris-covered surface of the regenerated lower portion of GRM at the head of Río Manso. Río Frías and the neighboring glaciers Alerce (GA), Castaño Overo (GCO) and Casa Pangue (GCP) are also shown.

Patagonia and has been studied by several researchers (e.g., Lawrence and Lawrence, 1959; Rabassa et al., 1978, 1984; Röthlisberger, 1986; Masiokas et al. 2001). Yet, the evidence documenting the late Holocene history of this glacier remains scattered and has not been analyzed comprehensively to provide an integrated picture of recent glacier variations. Here we integrate the information from previous glaciological studies and new results from recent extensive tree-ring investigations. We also discuss some interesting contrasts with the neighboring Glaciar Frías (Fig. 1) in an attempt to place the record of fluctuations at Río Manso in a broader context. Although the evidence available does not allow a detailed discussion of the main causes for differences in the recent history of these two glaciers, the comparison highlights the importance of site-specific factors on the records of glacier fluctuations at adjacent glaciers.

Study area

Monte Tronador (3554 m) straddles the international border of Argentina and Chile in the north Patagonian Andes, and its upper slopes are completely covered by a thick icecap that feeds several glaciers. Frías, Alerce, Castaño Overo, and Río Manso are the main glaciers on the eastern side (Fig. 1). This region is particularly suitable for dendroglaciological investigations because it contains several small glaciers in a small area with forest recolonization of glacial forefields that allows dendrochronological and/or ^{14}C dating of past glacier fluctuations. The most common tree species colonizing the glacier forefields are *Nothofagus dombeyi* (locally known as coihue) and *Nothofagus pumilio* (lenga), but in some humid and protected sites the long-lived *Fitzroya cupressoides* (alerce) is also frequent.

Despite having the same source, the glaciers on the Argentinean side of Monte Tronador are quite varied. For example, Glaciar Frías is largely devoid of debris cover with a steep but continuous profile. On the other hand, the upper and lower portions of Glaciar Río Manso are separated by a steep cliff several hundred meters high and the lower glacier is regenerated from snow, ice and debris avalanching from the steep slopes above (Fig. 2). The sound of these avalanches is the source of the name Tronador ("The Thunderer"). The lower portion of Glaciar Río Manso has a relatively gentle slope and is covered by a thick debris layer, hence the local name, Ventisquero Negro ("Black Glacier"). In front of this glacier a massive (presumably late Holocene), terminal moraine of complex morphology has been partially overridden by subsequent readvances, giving an unusual fork-like shape to the recent terminal moraines (see Fig. 2; Lawrence and Lawrence, 1959). Available documentary evidence and aerial photographs (Table 1) indicate that, despite minor readvances, the position of the glacier margin varied relatively little between AD 1937 and 1991. However, rapid thinning and recession of the lower tongue in subsequent years have resulted in the formation of a large, rapidly growing proglacial lake between the glacier margin and the main moraine ridges (see Fig. 2).

Previous work

Lawrence and Lawrence (1959) carried out the first detailed glaciological study at Glaciar Río Manso and used dendrochronology and tephrochronology to estimate a late Holocene sequence of events at this site. They assumed that a thick tephra layer found on top of the massive frontal moraine corresponded to a tephra recovered from nearby peat samples and dated to 2240 ± 60 ^{14}C yr BP (Auer, 1958), providing a minimum age for this older glacier event. They also reported a drowned forest on the north margin of the glacier that was apparently killed during a glacier advance that dammed Río Blanco forming a temporary lake. The innermost rings of living trees growing on the drained lake bed and inside the moraine formed by this glacier advance were dated to AD 1852 and 1855, respectively. Therefore Lawrence and Lawrence (1959) suggested that the ice was in recession and the lake had probably drained by the early 1850s. They also found several mature trees partially buried by glacial outwash in front of the

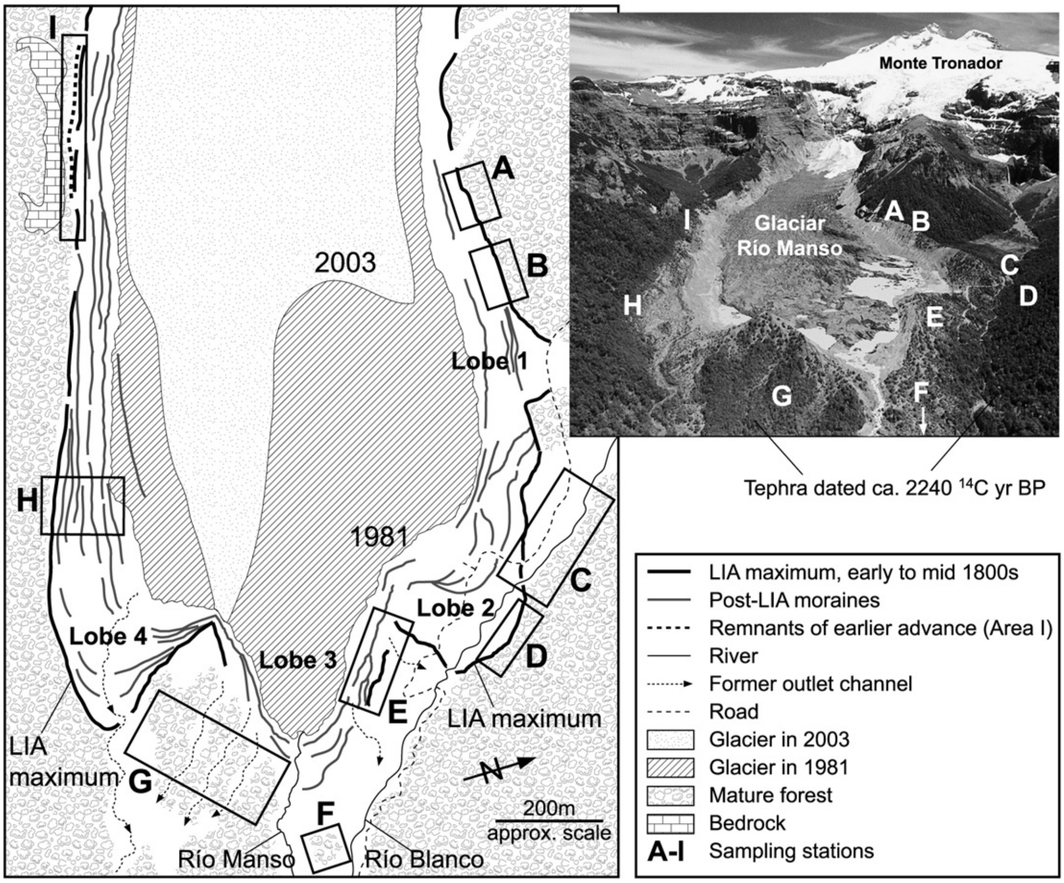

Figure 2. (Left) Map showing the lower portion of Glaciar Río Manso, the location of LIA and post-LIA moraine systems and recent ice margin positions based on field surveys, air photo interpretation, satellite imagery and historical documents (data sources in Table 1). (Upper right) Oblique view of Monte Tronador and Glaciar Río Manso in the late 1990s showing the location of sampling Areas A–I (photo source: http://www.tronador.com). Areas E and G are located on the distal slope of a massive end moraine tentatively dated to ca. 2240 ^{14}C yr BP using a volcanic tephra layer (Lawrence and Lawrence, 1959).

moraine formed by this event. Some of these trees, killed by the glacial outwash, have since decayed, and several empty cylindrical holes or "tree wells" were reported at this site. A more recent readvance was dated to ca. AD 1952 based on the tree-ring patterns of a young (<35 yr) living tree that was being partially buried by fine outwash just 1.5 m in front of the easternmost margin of the ice at the origin of Río Manso.

Rabassa et al. (1978) used extensive field work and measurements of ice margin positions to identify a relatively synchronous glacier readvance of the four Argentinean glaciers at Monte Tronador between the early 1970s and 1976–1977. This is probably the best documented recent glacier advance in the Patagonian Andes north of 45°S and has been linked to a period of cooler and wetter conditions across the region (Rabassa et al. 1979; Villalba et al., 1990; Masiokas et al., 2008). Rabassa et al. (1984) used dendrochronology and lichenometry to estimate the dates of the most important events associated with the LIA at Glaciar Río Manso and Glaciar Castaño Overo (Fig. 1). They identified up to eight moraine ridges on the south margin of Glaciar Rio Manso; based on preliminary tree-ring counts, lichen sizes and a ^{14}C date of a stump associated with the outermost deposit, they suggested that the largest LIA expansion took place at around AD 1772. Tree age estimations based on tree diameters were used to infer the age of the major LIA deposits on the south margin of Glaciar Castaño Overo. According to this preliminary evidence, the

Table 1
Summary of the available sources of information for the Argentinean glaciers on Monte Tronador.

Glaciers	Area in 2003 (km^2)	References	Dates of available pictures	Available air photos (AP) or satellite images (SI)
Río Manso	Upper: 6.57[a] Lower: 1.73[b]	Jakob, 1937; Auer, 1956; Thomasson, 1959; Lawrence and Lawrence, 1959; Rabassa et al., 1978, 1984; Röthlisberger, 1986; Rabassa, 2007; Masiokas et al., 2008	1936, 1937, 1942, 1948, 1954, 1982, 1991, 2000, 2001, 2005, 2007	AP (all glaciers): 1944, 1953, 1961, 1970, 1981, 1998 SI (all glaciers): 1985 and 1987 (Landsat 5), 2000 (Landsat 7), 2003 (ASTER)
Castaño Overo	3.25[a]	Jakob, 1936; Rabassa et al., 1978, 1984; Röthlisberger, 1986; Rabassa, 2007; Masiokas et al., 2008	1936, 1982, 2003, 2005	
Alerce	2.23[a]	Rabassa et al., 1978; Lliboutry, 1998	1977, 2005	
Frías	6.69[a]	Fonck and Hess, 1857; Steffen, 1909; De Agostini, 1945, 1949; Rabassa et al., 1978; Villalba et al., 1990; Masiokas et al., 2008	1856, 1893, late 1930s, 1977, 1985, 1994, 2005, 2007	

The dates of pictures showing partial or complete views of the glaciers were compiled by the authors and include published and unpublished sources. Dates for available air photos and satellite images apply to all glaciers.

[a] Approximate areas based on a semi-automated analysis of a 15-m resolution 2003 ASTER satellite image and a 30-m resolution Digital Elevation Model (Delgado et al., 2006).

[b] The area of the mostly debris-covered lower tongue of Glaciar Río Manso was delineated manually on the same image.

most extensive LIA event at this glacier was dated to ca. AD 1818–1829.

Röthlisberger (1986) visited Glaciar Río Manso in 1982 and discovered several *in situ* stumps on the proximal slope of the main north lateral moraine, west of the drowned forest of Lawrence and Lawrence (1959). Four *in situ* stumps located about 40 m above the glacier surface and 70 m below the moraine crest were dated to 940 ± 110, 620 ± 50, 585 ± 50, and 300 ± 85 ^{14}C yr BP (Table 2). An additional rooted stump was found only 10 m below the moraine crest and dated to "modern" times. Röthlisberger interpreted these results as representing several glacier advances with the latest (assumed to have occurred during the 19th century) being the most extensive of the last centuries. Near the shoreline of Lago Frías (some 11 km north of Glaciar Frías at the end of Frías valley) Röthlisberger found a 0.4–1.4 m thick tephra layer with *in situ* plant remains that were dated to 2435 ± 65 ^{14}C yr BP. He linked this tephra to that described by Lawrence and Lawrence (1959) at Glaciar Río Manso and used this evidence to support the minimum age proposed for that moraine.

Villalba et al. (1990) used dendrogeomorphology and documentary sources to develop a chronology of fluctuations for the past 1000 yr for Glaciar Frías (Fig. 1). They suggested, based on the ages of trees growing on the most extensive LIA moraine deposits and growth suppression in the tree-ring series from a tree just outside this moraine, that the maximum LIA advance occurred ca. AD 1638–1639. Another ice-scarred tree associated with a moraine immediately inside the main LIA advance provided a maximum date of ca. AD 1719–1721 for this event. Five subsequent glacier advances were dated mainly by dendrogeomorphic techniques to ca. AD 1742–1752, 1835–1843, 1878–1884, 1912–1916 and 1941–1943 (Villalba et al., 1990).

On the Chilean side of Monte Tronador, 20th century changes in ice thickness and frontal variations have only been studied at Glaciar Casa Pangue (Bown, 2004; Bown and Rivera, 2007) (Fig. 1). Masiokas et al. (2008) used photographic comparisons of selected glaciers (including Frías, Castaño Overo and Río Manso) and hydro-climatic records from northwestern Patagonia to demonstrate that the drastic ice mass loss observed over the past century is at least partially explained by a highly significant regional trend of reduced winter accumulation and increased summer ablation. They also linked some of the 20th century readvances in the Tronador area to multi-year periods of overall cooler and wetter conditions across this region. Bown (2004) and Bown and Rivera (2007) presented analyses of surface climate records and 1958–2000 upper-air temperatures derived from radiosonde records at Puerto Montt (41°26′S, 73°07′W; ca. 95 km SW of Tronador). They found a significant warming between the 850 and 300 hPa geopotential height levels (i.e., between ca. 1500 and 9000 m in elevation) with the strongest warming located at around 3000 m (700 hPa geopotential height). They proposed that this tropospheric warming, in conjunction with the significant decrease in precipitation observed in this region, had probably contributed to the recent, generalized glacier recession observed at Tronador (see also Rabassa, 2007).

Methodology

Glacial deposits were dated using standard dendrogeomorphic techniques similar to those in Luckman (1988, 1998, 2000). The analysis of historical documents and aerial photographs (Table 1) was used to determine former ice marginal positions. Minimum ages of surfaces and related glacial events for Glaciar Río Manso were usually determined from the age of the oldest trees sampled on these deposits using increment corers. Where the oldest cores lacked the pith, pith offset values were estimated based on ring curvature (Applequist, 1958). In cases where trees had rotten centers and no pith correction could be applied, an arbitrary value of 20 yr was added to the date of the innermost countable ring. Cores were taken as close to the root collar as possible to minimize errors in estimating tree age due to sampling height. However, as it was difficult to core low on the stem except for a few very young trees, most cores were taken 50–100 cm above the tree base. Six young *N. pumilio* trees growing on the drained lake floor at the north margin of this glacier were sampled at the base and at 50 and 100 cm heights to provide estimates of vertical growth rates. Ring counts indicate that the trees took an average of 10.3 yr to reach 100 cm height, and we used a vertical growth rate of 10 cm per year to correct for sampling height. Colonization on a south lateral moraine formed between 1970 and 1981 [based on field observations (Rabassa et al., 1984) and air photo interpretation] was used to estimate the ecesis or time interval between moraine stabilization and tree seedling establishment (Sigafoos and Heindricks, 1969; McCarthy and Luckman, 1993). The innermost basal rings of the two oldest of nine trees sampled on this moraine were dated to AD 1983. As this moraine probably corresponds to the well-documented glacier event that culminated in 1976–1977 at other glaciers in the Tronador area (Rabassa et al. 1978; Villalba et al., 1990), we used a 6-year ecesis throughout this study. This is a relatively conservative measure compared to the findings of Lawrence and Lawrence (1959), who found an almost immediate *Nothofagus* tree seedling establishment based on direct observations of a new push moraine on the eastern

Table 2
Radiocarbon ages of *in situ* stumps from Glaciar Río Manso (Areas A, C, and H; Fig. 2).

Sample code	^{14}C age (yr BP)	2σ age range, yr AD (probability)	Location	Reference
HV-11800[a]	940 ± 110	950–1300 (0.987)	Area A; 40 m above glacier, 70 m below moraine crest	Röthlisberger, 1986
HV-12865[a]	620 ± 50	1300–1430 (1.000)		
HV-12864[a]	585 ± 50	1380–1450 (0.713)		
HV-11799[a]	300 ± 85	1450–1710 (0.705)		
HV-11798[a]	Modern	N/A	Area A; 10 m below moraine crest	
NSRL-12465[b]	285 ± 35	1490–1600 (0.592)	Area A; same site as above 5–15 m below moraine crest	This study
NSRL-12466[c]	280 ± 50	1470–1680 (0.917)		
NSRL-12464[c]	220 ± 55	1720–1890 (0.466)		
HEL-4547[b]	290 ± 70	1450–1680 (0.864)	Area C; bed of former ice-dammed lake	
HEL-4549[b]	200 ± 60	1630–1950 (0.967)		
HEL-4548[b]	160 ± 80	1630–1950 (0.989)		
HEL-4546[b]	110 ± 60	1800–1950 (0.611)		
NSRL-12640[b,d]	90 ± 35	1800–1940 (0.708)		
LP-82[a]	178 ± 56	1650–1890 (0.831)	Area H; within outermost moraine	Rabassa et al., 1984

Calibrated calendar dates and their associated probabilities (only the most probable calendar date range shown) were obtained using the CALIB program (Stuiver and Reimer, 1993) available at http://radiocarbon.pa.qub.ac.uk/calib/ and the Southern Hemisphere calibration dataset of McCormac et al. (2004).

[a] Position of sample within tree was not specified but probably collected from outer rings.

[b] Sample taken from outer rings.

[c] Sample from innermost rings.

[d] Not included in Río Blanco tree-ring chronology.

margin of the glacier. At Glaciar Casa Pangue (Fig. 1), Veblen et al. (1989) also found rapid *Nothofagus* seedling establishment on recently deposited substrates. In contrast, Villalba et al. (1990) estimated variable ecesis values ranging between 8 and 71 yr for the LIA and post-LIA moraines at Glaciar Frías. Overall, the approximations for sampling height and ecesis correction factors used in this study suggest that, when the pith is present, the absolute tree ages obtained at Glaciar Río Manso provide a relatively minor average error (usually $<$10–15 yr) when estimating dates of moraine formation from tree rings. The number of living trees cored at each sampling station, together with the absolute dates of the oldest trees, pith offset, sampling height corrections and estimated minimum ages of surfaces, are listed in Appendix A.

Information about earlier glacier activity at Glaciar Río Manso was obtained from trees killed or tilted by past glacier advances. Several cross-sections were obtained from subfossil stumps below tills in the lateral moraines and along the margins of proglacial Río Manso. Numerous stumps were also sampled in the bed of the former ice-dammed lake on the north margin of the glacier. The cross-sections were processed and analyzed following standard dendrochronological procedures (Stokes and Smiley, 1996). The nearby *N. pumilio* tree-ring width chronology (La Almohadilla chronology, COV6 in Villalba et al., 1997) was used as a reference series to crossdate the “floating” (undated) tree-ring series derived from these stumps. Crossdating trials were carried out using the program COFECHA (Holmes, 1983; Grissino-Mayer, 2001). Radiocarbon dates were also obtained from selected stumps (Table 2). In rare cases, we found mature, living trees that had been tilted by the glacier or partially buried by glacial outwash during past readvances. These trees were cored using increment borers and provided important information on the chronology of the main glacier events. Mature trees growing outside the main LIA deposits and not directly affected by glacier events were also sampled to compare and differentiate minimum ages from this forest with those obtained from trees colonizing the glacier deposits.

Results

Detailed investigations were carried out at nine key areas of the Glaciar Río Manso forefield (Fig. 2). The results will be presented for three major areas: the north lateral moraine (Areas A–D), the terminal zone (Areas E–G), and the south lateral moraine (Areas H and I).

The north lateral moraine (Areas A–D)

At Area A the north lateral moraine has a steep proximal slope in which Röthlisberger (1986) found several *in situ* stumps (Table 2). We revisited this site and found several *in situ* stumps within 5–15 m of the moraine crest and with no apparent spatial or elevation pattern. Eleven cross-sections and three ^{14}C dates were obtained from these snags. The tree-ring width patterns from seven stumps were successfully combined into a floating tree-ring chronology of 111 yr that was crossdated with the 450-yr-long La Almohadilla chronology to provide calendar dates for the floating tree-ring series (VNF chronology, Fig. 3). The outermost ring dates and position of these *in situ* stumps on the steep proximal slope of the north lateral moraine, suggest that they were killed and buried by glacier deposits during the mid to late 18th century as the glacier thickened and advanced. The calibrated ^{14}C determinations obtained from these stumps show a wide range of possible calendar dates (Table 2) and very poor agreement with the tree-ring based results (see Table 3). We were unable to locate additional subfossil material to corroborate Röthlisberger's older dates, obtained in 1982 from a site ca. 70 m below the moraine crest (Table 2). These trees had probably been removed or buried by mass wasting processes in the two decades before our visit. They remain the only evidence of older LIA advances from the north lateral moraine.

Living trees were sampled on the outer moraine at site B, approximately 150 m downvalley from the stumps in Area A (Fig. 2). Tree diameters on the proximal slope of the moraine ranged between 20 and 50 cm and the innermost ring of the oldest tree was dated to AD 1892 (taking into account pith offset and sampling height correction factors; see Appendix A). An older, 1.0-m-diameter *N. pumilio* tree was found near the bottom of the distal slope of this moraine. This tree had an almost horizontal main trunk tilted towards the mature forest and two (one dead and one alive) vertical branches. The pith of the main trunk was rotten with an innermost ring dating to AD 1885. The innermost rings at the base of the two vertical branches dated to AD 1843 (dead) and 1841 (live branch). Other trees cored on the distal slope were clearly smaller (20–60 cm in diameter) with the oldest innermost ring dating to AD 1874 (Appendix A). The old tree at the base of the slope seems to have been knocked over during moraine formation and survived, producing two vertical “leaders” that assumed apical dominance. The basal dates from these branches suggest that the tree was tilted (and the moraine emplaced) shortly before AD 1841–1843.

In 2001 we relocated the site of the former ice-dammed lake on the north margin of Glaciar Río Manso described by Lawrence and Lawrence (1959) (Area C in Fig. 2). During the most extensive historic advance Río Blanco was blocked by Lobe 2 and the marginal lake formed received discharge from Lobe 1 and small hanging glaciers upstream (Fig. 2). Over 20 cross-sections were collected from *in situ* stumps exposed by the incision of the stream into laminated lake sediments. Five ^{14}C dates were obtained from these stumps (Table 2).

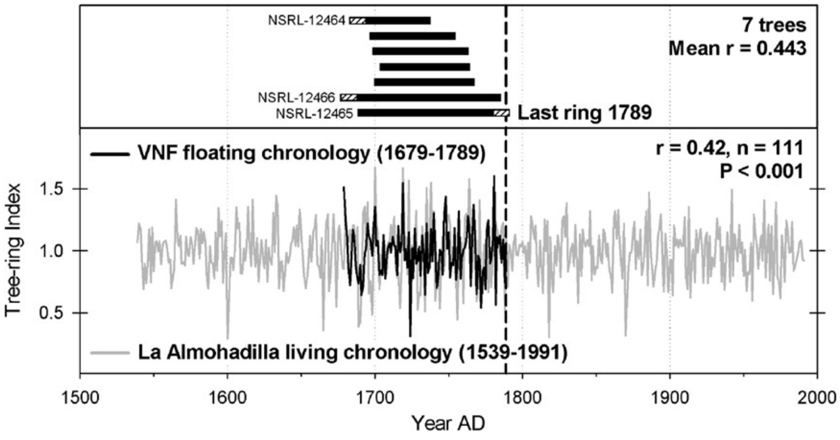

Figure 3. Time span of *in situ* stumps found inside the north lateral moraine of Glaciar Río Manso (Area A in Fig. 2). The location of the samples used for ^{14}C dating (Table 2) is shown as white hatched boxes in the upper diagram. Crossdating the floating VNF chronology derived from these stumps with La Almohadilla ring-width chronology indicates that the last of these trees died ca. AD 1789.

Table 3
Comparison between ^{14}C determinations from *in situ* stumps at Glaciar Río Manso and their absolute, tree-ring based date range determined by crossdating analyses with a nearby living tree-ring chronology (Figs. 3–5).

Area	Sample code	^{14}C age (yr BP)	Most probable calibrated age range (yr AD)[a]	Tree-ring based date range (yr AD)[b]
A	NSRL-12464	220 ± 55	1720–1890	**1685**–1705
	NSRL-12466	280 ± 50	1470–1680	**1679**–1699
	NSRL-12465	285 ± 35	1490–1600	1769–**1789**
C	HEL-4549	200 ± 60	1630–1950	1776–**1796**
	HEL-4548	160 ± 80	1630–1950	1823–**1843**
	HEL-4547	290 ± 70	1450–1680	1828–**1848**
	HEL-4546	110 ± 60	1800–1950	1828–**1848**

The samples for ^{14}C dating included 15–25 rings in each cross-section.

[a] Most probable calibrated calendar date range derived from Table 2.

[b] Tree-ring based, calendar dated range of the ^{14}C dated portion of the stump. The maximum/minimum limiting ring dates are shown in bold.

In 2004 a landslide from the steep southern valley side slope modified the course of Río Blanco exposing many additional *in situ* stumps along the new channel (Figs. 4A–C). Radii from 18 cross-sections were used to build the “floating” RBL tree-ring width chronology that was crossdated against the La Almohadilla chronology (Fig. 5). Although a few peripheral rings may have been eroded from these samples, the calendar dates obtained for the outer rings of these cross-sections indicate that the last two trees were drowned in the former ice-dammed lake and died ca. AD 1848. The wide range of outer ring dates suggests that lake formation may have affected this portion of forest for several decades and some of the trees in close proximity to the lake or the ice survived longer than others. The earliest date from these *in situ* stumps indicate that trees were growing at the lake site between AD 1569 and the early 1800s, and therefore Lobe 2 of Glaciar Río Manso was less extensive between these two dates. Calibrated ^{14}C ages from the outer portion of selected snags provided a wide range of potential death dates between AD 1450 and 1950 and, as at Area A, showed only weak agreement with the absolutely dated dendrochronological determinations (Tables 2 and 3).

Several living trees (Fig. 4A) were sampled at Area C. The estimated germination dates of the oldest living trees cored on the former lake floor and the distal slope of the moraine that formed this marginal lake were AD 1880 and 1875 respectively (Appendix A). This indicates that the lake finally drained prior to ca. AD 1875 and that the outer moraine of Lobe 2 became stabilized and colonized sometime in the late 1860s or early 1870s (Appendix A). A minimum date of AD 1841 was obtained from 10 trees in the dense forest on the valley side north of the creek, just beyond the former lake floor and approximately 3 m above Río Blanco (Figs. 4A and C). The oldest tree found by

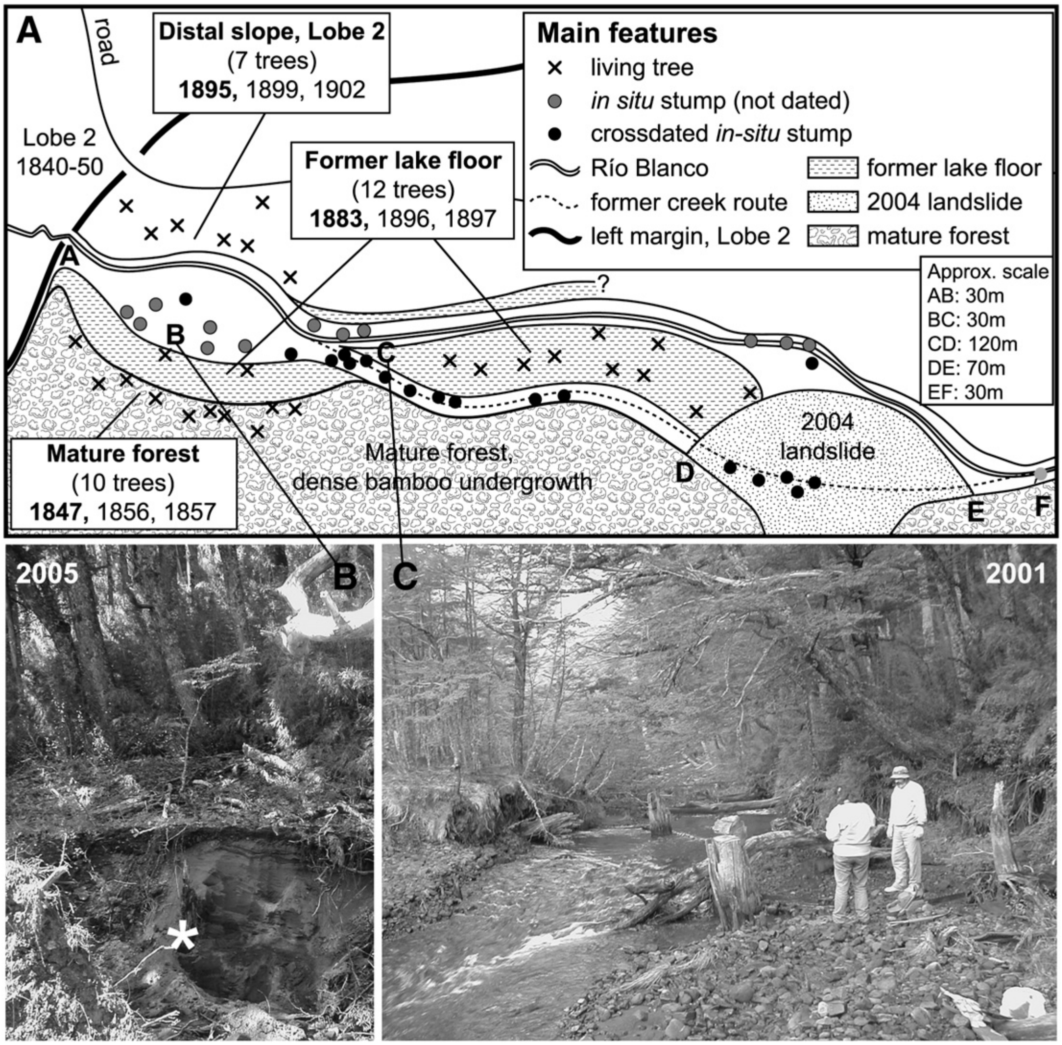

Figure 4. (A) Schematic map showing the location of *in situ* stumps and living trees sampled at Area C on the north margin of Glaciar Río Manso. The number of living trees sampled at the different sites is listed together with the age (uncorrected values, year AD) of the three oldest specimens (oldest in bold). (B) Cross-section of the former lake floor sediments at point B in 2005, with the rotten remnants of an *in situ* stump (*) embedded in the deposits. The limit for dense bamboo undergrowth and mature forest starts ca. 5 m behind this pit. (C) 2001 view of Río Blanco channel (abandoned due to a landslide in 2004) showing some of the *in situ* stumps sampled close to point C.

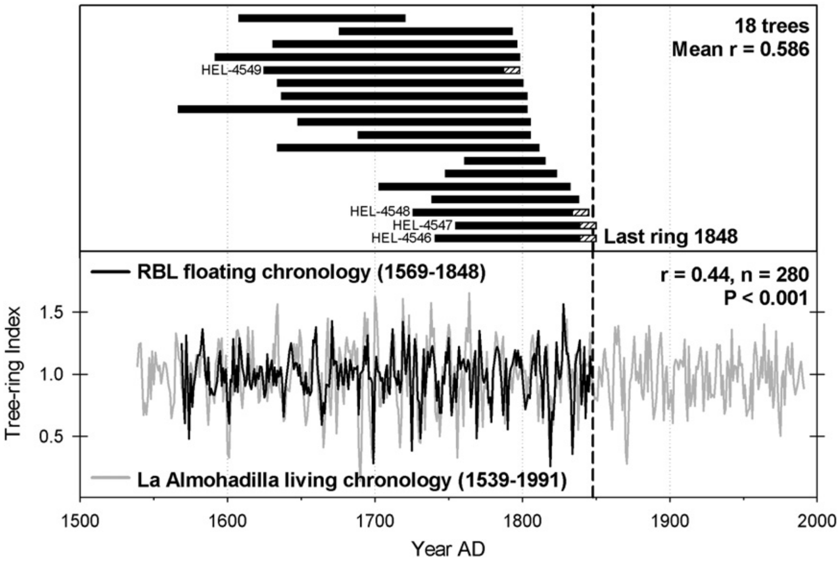

Figure 5. Time span and calendar dating of the floating tree-ring chronology derived from 18 *in situ* stumps found in Area C. The dates obtained for these snags and the setting of the site suggest that the glacier advanced, dammed Río Blanco and created a small lake that killed the last of these trees ca. AD 1848. The range in kill dates also indicates that this glacier advance may have started affecting these trees by the late 1700s. Complementary ^{14}C dates were obtained from selected portions in the cross-sections (white hatched boxes). For calibrated ^{14}C dates see Table 2.

Lawrence and Lawrence (1959) at this site was dated to AD 1732, suggesting that this surface was probably not severely affected by the marginal lake that drowned the adjacent portion of forest a few meters to the south.

Approximately 200–300 m east of Area C, Lobe 2 advanced up the opposite (south) valley side and deposited a symmetrical morainic arc (Area D in Fig. 2). Although at the highest, central point this deposit is only about 1 m high, well-marked differences in tree age and forest characteristics exist on either side of this moraine. Mature trees growing a few meters outside this moraine were up to 387 yr old and 1.7 m in diameter, whereas trees growing on its proximal slope were between 30 and 70 cm diameter and dated to AD 1862 (Appendix A). Lawrence and Lawrence (1959) reported a minimum age of AD 1855 for a tree growing in this area. However, the most striking contrast is between the dense, impenetrable undergrowth of bamboo (*Chusquea culeou*, locally known as caña colihue) in the mature forest beyond the moraine and an almost bamboo-free zone inside the glacial limit (Fig. 6). To our knowledge, this “bamboo line” has not been previously described in the scientific literature. Its presence facilitated the identification of the margin of this glacier advance by simply mapping the density of bamboo colonizing the surface. Similar “bamboo lines” have been seen at other glaciers in the north Patagonian Andes [e.g., Glaciar Torrecillas (42°40′S, 71°54′W) and Glaciar Esperanza Norte (42°09′S, 72°01′W) in Argentina and Glaciar Universo (42°07′S, 72°03′W) in Chile]. Using the limiting dates from the trees and assuming relatively rapid recolonization, these data suggest that the glacier was in recession by the late 1840s or early 1850s when the first trees started colonizing the fresh glacial deposits.

The terminal zone (Areas E–G)

Rabassa et al. (1984) collected tree-ring samples from Area E (Fig. 2) that were re-analyzed in 2005 to obtain approximate minimum ages for the sub-parallel moraine ridges at this site. The oldest tree sampled on the outermost moraine ridge was dated to AD 1867, and tree-ring counts of trees associated with three inner ridges indicate that the ridges were formed in the first half of the 20th century (Appendix A). However, except for the outermost ridge (which seems to be a continuation of the arcuate moraine described in Area D above), significant fluvioglacial activity on the distal slopes and recent mass wasting processes on the proximal slopes combined with the complex geomorphological setting of this particular site complicate the correlation of these moraines with those observed elsewhere along the glacier margin (Fig. 2).

Area F is a valley floor site, immediately outside the main morainic complex (Fig. 2). Lawrence and Lawrence (1959) described an area of old-growth forest floor that had been partially or completely buried by

Figure 6. View towards the south showing the location of the “bamboo line” in Area H (Fig. 2). Clear differences in forest undergrowth are apparent between the almost bare surface on the outermost LIA moraine in the foreground and the dense bamboo cover of the old-growth forest immediately outside this moraine.

fine glacial outwash over 1 m thick associated with the most extensive glacier advance of recent centuries. Although the morphological evidence of the terminal moraines of Lobe 3 has been considerably modified by fluvioglacial activity at this site, it is possible to estimate the date and position of the glacier advance based on evidence from several trees sampled in this sector. Five living trees with their lower trunks buried by fluvioglacial gravels began growth before AD 1680 and two similarly buried dead trees (crossdated with La Almohadilla chronology) had innermost rings dating to AD 1730 and 1761 and died in the early 20th century (Appendix A). Two living trees growing on these fluvioglacial deposits began growth ca. AD 1849 and 1863 (Appendix A). As the trees are highly unlikely to seed successfully in an actively aggrading outwash environment, these dates suggest that the outwash was probably deposited some time after AD 1761 and before the early 1840s. Numerous *in situ* and reworked subfossil snags were found scattered over a ca. 200-m-long stretch of Río Manso adjacent to Area F (Fig. 2). Unfortunately, despite numerous attempts, these stumps have not been crossdated. The short, usually distorted, tree-ring patterns in most of these samples suggest that they are *Nothofagus antarctica* (ñire), a relatively less studied and short-lived tree species generally colonizing lower, flood-prone sites in this region.

On the southern side of Río Manso (Area G in Fig. 2), the recent advance appears to have only partially overtopped the older massive moraine. Boulders up to 4×4×3 m in size occur on the upper third of this slope and appear to delimit the maximum extent of this advance. The forest on the distal, east-facing slope of the massive moraine has been dissected by several former stream channels that begin at the maximum limit of the recent advance at the top of the slope. The oldest of 26 trees sampled in the intervening forest patches downslope of this maximum limit dates to AD 1673 (Appendix A). Scattered bamboo undergrowth also occurs between the former channels, indicating that the forest is older than that developed elsewhere on the 1840s moraine.

The south lateral moraine (Areas H and I)

Multiple moraine ridges within the LIA maximum position along the south lateral margin of Glaciar Río Manso indicate several readvances during the last two centuries (Fig. 2). However, most of the evidence for these events has been destroyed by extensive mass wasting and fluvioglacial processes at the glacier margin. Area H along the south lateral moraine is the only location where a clear sequence of moraine ridges is present and shows an increase in tree age and forest cover between the present proglacial lake and old-growth, mature forest with bamboo outside the LIA limit.

Eight vegetated moraine ridges (M1–8) were sampled on both distal and proximal sides to obtain minimum age estimates. These data have been reworked from the original samples discussed by Rabassa et al. (1984) plus additional samples collected in 2001 and 2006, and a revised chronology is presented here. These samples indicate that M1 was formed prior to AD 1839, whereas trees growing in mature forest with dense bamboo undergrowth on the valley side immediately outside this moraine are over 100 yr older (Appendix A). Trees from Moraines 2–6 indicate minimum ages of AD 1875, 1890, 1899, 1919 and 1949, respectively (Appendix A). Moraine 7 forms a conspicuous trimline on the south margin of the glacier and was visible immediately outside the glacier margin in aerial photographs taken in 1961 (Table 1). The age of the oldest tree on this moraine (1961) indicates that this deposit was probably formed before the mid-1950s (Appendix A). This event may correspond to the advance dated to the early 1950s by Lawrence and Lawrence (1959) on the eastern margin of the glacier (see above). The two oldest trees cored on M8 were dated to AD 1983 (Appendix A). As M8 was likely formed by the mid to late 1970s, these dates suggest that ecesis is less than 10 yr for these moraines. Another minor ridge lacking vegetation was observed between M8 and the southeast margin of the glacier (Fig. 2). Available photographic evidence (Table 1 and Fig. 2) suggests that this innermost ridge was probably formed between the late 1990s and 2001.

Several *in situ* stumps that had been buried by the distal slope of M1 (Fig. 2) were also sampled but most of the cross-sections were rotten and no tree-ring based maximum age estimates were obtained. Rabassa et al. (1984) reported a date of 178 ± 56 ^{14}C yr BP from an *in situ* stump within glacigenic deposits on this outer moraine (Table 2). They also reported that the oldest tree on this moraine (13 were dated) was 184 yr old and suggested that this oldest advance probably occurred ca. AD 1772. Our recent, extensive tree-ring sampling along this same transect did not locate an older moraine of this age and we thus believe that M1 corresponds to the maximum LIA advance of the early to mid-1800s at this glacier.

Approximately 200–300 m upvalley from Area H (Area I, Fig. 2), the outermost moraine is marked by a relatively well-preserved ridge. Old-growth, bamboo-floored forest over 320 yr old (10 trees sampled) occurs on the adjacent slope. The outermost moraine was initially correlated with M1 in Area H, but the 23 trees sampled on this ridge were significantly older than those in M1 farther downglacier, and trees on the distal slope have an innermost ring of AD 1707 (Appendix A). The outermost ridge at Area I may represent deposits of an earlier glacier event that was almost completely overridden by the LIA maximum advance elsewhere along the glacier margin. This event could correspond to the advance identified by Röthlisberger (1986) and dated to ca. 300 ^{14}C yr BP using *in situ* material from Area A (see Table 2). However, more evidence is needed to clarify this issue. There is a partially dissected moraine ridge inside the outermost moraine at station I, but unfortunately no tree-ring dates are available and mass wasting of the steep moraine slopes has removed any evidence for subsequent glacier advances.

Discussion and conclusions

The small glaciers and associated forests of the Patagonian Andes can provide important and complementary information for the study of past and present glacier and climate changes in southern South America. However, to date most glacier studies in Patagonia have concentrated on the larger glaciers south of 45°S, and very little is known about late Holocene glacier behavior in the north Patagonian Andes. Here we present a revised chronology of Little Ice Age fluctuations for Glaciar Río Manso on the Argentinean side of Monte Tronador (ca. 41°S) based on the integration of results from previous studies and extensive new collections of living and subfossil tree-ring material. Although some uncertainties remain, the rich array of complementary evidence available demonstrates the great potential for dendroglaciological investigations in this area and provides one of the most detailed chronologies of LIA and subsequent glacier fluctuations in the north Patagonian Andes.

At Glaciar Río Manso a massive, older, frontal moraine apparently predating 2240 ^{14}C yr BP was partially overridden by four main glacier lobes during the LIA. Evidence from *in situ* subfossil stumps and living tree-ring samples indicates that the most extensive LIA expansion took place between the late AD 1700s and the 1830–1840s as the lower tongue thickened and advanced into adjacent forests. Overridden *in situ* snags on the inner flank of the north lateral moraine were calendar dated to the late 1700s and provide a maximum age for this event. On the distal side of this moraine a tilted tree and stumps drowned by an ice marginal lake indicate that this glacier advance culminated in the 1840s. Living trees on the proximal side of this north lateral moraine indicate that the glacier was already in recession by the mid-1850s, providing closely bracketed dating control for this event. Dates from trees downvalley of the moraine corroborate these results, indicating aggradation of proglacial outwash between the 1760s and the early 1840s. On the south margin of the glacier (Area H), the oldest tree growing on the distal slope of the most extensive LIA moraine indicates that this deposit was formed ca.

AD 1839. In contrast, the mature forests immediately outside this LIA maximum moraine date back to at least the 17th century.

Generally poor agreement was found between the absolute, tree-ring based calendar dates obtained from selected *in situ* stumps and the ^{14}C dates derived from the same samples (Table 3). This disparity is probably related to the non-linearity of the ^{14}C calibration curve during the past few centuries (see Porter, 1981) and highlights some of the difficulties associated with ^{14}C dating of evidence associated with LIA and post-LIA glacier events (e.g., Luckman, 1986). Similar uncertainties remain in relation to the four ^{14}C dates from *in situ* stumps reported from the north lateral moraine and interpreted as evidence for multiple glacier events between 950 and 300 ^{14}C yr BP by Röthlisberger (1986). Unfortunately we could not relocate this material to evaluate this evidence (the stumps were probably buried or eroded by active mass wasting on this slope). However, given the wide range in calibrated calendar dates (Table 2), and the limited documentation available about the geomorphic and stratigraphic relationships of these stumps, it seems prudent to interpret these results with caution. The only morphological evidence for earlier glacier activity at this site during the last millennium comes from an older lateral moraine section on the south glacier margin (Area I on Fig. 2) that is at least 300 yr old, based on the oldest trees growing on its surface.

Thus, the evidence available for Glaciar Río Manso indicates that, with the exception of a few marginal sites, the main LIA advance of the early mid-19th century was probably the most extensive event of the past 1000 yr. It seems probable that earlier advances were confined within the massive older frontal moraine system (predating ca. 2240 ^{14}C yr BP, see above) and any evidence of such events was overridden by the glacier advance culminating ca. AD 1830–1840.

The clearest evidence for subsequent glacier activity at Glaciar Río Manso comes from a sequence of relatively well preserved moraine ridges between the present proglacial lake and old-growth forests on the southern slope of the valley (Area H, Fig. 2). This morphological evidence indicates that over the past 150 yr the lower glacier tongue has experienced several short periods of readvance or stasis while downwasting. Minimum ages obtained from trees growing on these deposits suggest that the moraines were formed around the mid-1870s, 1890s, 1900s, 1920s, 1950s, and during the mid-1970s. Historical documents and photographs (Table 1) indicate that, despite these minor readvances, the lower tongue remained in approximately the same position between AD 1937 and 1991 and that the present proglacial lake started to form on the northeastern margin of the glacier by the early 1990s. Although another recent moraine, tentatively dated to around the late 1990s, is present on the southeast margin of the lake, the overall thinning and retreat of the glacier snout and the concurrent rapid growth of the proglacial lake during the last 10–15 yr are clearly evident at this site.

A novel finding at Glaciar Río Manso was the strong contrast in the density of the bamboo understorey on either side of the LIA maximum limit. This “bamboo line” is clearly apparent at many places and can be used as a quick, apparently reliable tool for mapping the LIA maximum extent at this glacier (Fig. 6). The tree-ring dating of the moraine deposits indicates that, at this site, *Chusquea culeou* needs over 150 yr to recolonize the surfaces abandoned after a glacier advance. We have observed similar “bamboo lines” at other glaciers in the north Patagonian Andes but the phenomenon has not been reported previously. Although this interesting feature is probably related to the particular reproductive strategy of this species[1], specific research is needed before we can provide reasonable ecological and physiological explanations for this phenomenon.

The recent glacier shrinkage and relatively well-documented glacier reactivation during the AD 1970s suggest that the glaciers at Tronador have been responding to a common regional forcing during the last few decades. Recent studies (e.g., Masiokas et al., 2008) suggested that the widespread glacier mass loss in this part of Patagonia was probably the result of the combined effect of decreasing winter accumulation and increased summer ablation across the region. During the past three decades the clean, steep Glaciar Frías has shown dramatic recession of the glacier terminus whereas the gently sloping and heavily debris-mantled Glaciar Río Manso has downwasted and formed a rapidly growing ice-contact lake (that has significantly increased ice mass loss and frontal retreat through calving processes; Kirkbride, 1993; Benn et al., 2004). However, despite this evidence of regional synchroneity and the proximity and common accumulation zones for Glaciar Frías and Glaciar Río Manso, there are intriguing differences in the number and relative magnitude of glacier events identified during the last millennium at these two sites. The most extensive and conspicuous LIA event at Río Manso occurred between the late 1700s and mid-1800s, whereas the most extensive advance at Frías was during the early 17th century. In addition, Glaciar Río Manso has downwasted, remaining relatively close to its LIA maximum position until the 1990s, but Glaciar Frías has receded over 1 km during this period (Villalba et al., 1990).

These differences indicate that each glacier record contains unique elements that may reflect the influence of local topographic controls and other site-specific characteristics in addition to regional climate forcing. Río Manso is a reconstituted glacier at the base of a large cliff, is not physically connected with its accumulation area and the LIA advance terminated against a large topographic obstruction. Glaciar Frías, on the other hand, is a continuous glacier tongue that descends a steep slope onto a broad, relatively gently sloping valley floor. Unlike the lower Río Manso, the lower Glaciar Frías is (and was) largely devoid of supraglacial debris. Thus, while the evidence at these two sites allows detailed reconstruction of part of the late Holocene record of glacier fluctuations, these chronologies give only a partial picture of the regional glacier record.

It is clear that many additional detailed studies are needed before a representative late Holocene regional glacial history can be developed for northern Patagonia. Our results show that differences in moraine records that are likely due to topographical and other site-specific features can occur even in adjacent glaciers with similar climatic settings. The careful selection of suitable glacier sites together with the consideration of site-specific factors appear to be crucial steps for the development of regional glacier records and for minimizing the potentially confounding, non-climatic influence of these factors when drawing paleoclimatic inferences from glacier records. Ongoing research at other glaciers in the Tronador area and along the Patagonian Andes will provide complementary evidence to test the findings presented here and will hopefully strengthen the available glacier record, allowing a more detailed evaluation of past and present glacier and climate variations in this region.

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[1] *C. culeou* bamboos are known to flower, seed and die synchronously after a long vegetative period during which they are non-aggressive invaders of new areas (Pearson et al., 1994; see also Veblen, 1982). Although the regularity and intervals between mast seedings remain uncertain, Pearson et al. (1994) indicated that the flowering cycle may take over five decades in our study area.

Appendix A

Summary of available dendrochronological evidence from selected living and dead trees cored at sampling areas B–I, Glaciar Río Manso (Fig. 2). Number of trees and earliest ring dates (year AD) from the three oldest trees are indicated. Pith offset and sampling height correction factors are shown in brackets. Estimated minimum ages for surfaces are based on a 6-yr ecesis. Notes: (D) distal slope of moraine; (P) proximal slope; (B) dense bamboo undergrowth; (*) an older tilted tree on the same surface suggests the moraine was emplaced ca. 1841–1843 (see text for details); (#) dead trees, minimum ages obtained after crossdating with La Almohadilla living chronology.

Area	Sampling site	Number of trees; innermost ring dates (pith offset and sampling height correction factors)	Minimum age for surface (yr AD)
B	Outer moraine (P)	7 trees; 1905(10,3), 1924(0,2), 1926 (0,2)	1886
	Outer moraine (D)	3 trees*; 1883(5,4), 1904(10,2), 1923(2,4)	1868
	Mature forest (B)	8 trees; 1840(5,8), 1852(10,15), 1853(0,10)	1821
C	Outer moraine (D)	7 trees; 1895(10,8), 1899(20, 4), 1902(20,4)	1869
	Former lake floor	12 trees; 1883(0,3), 1896(0,4), 1897 (10,5)	1874
	Mature forest (B)	10 trees; 1847(0,6), 1856(5,10), 1857(0,9)	1835
D	Outer moraine (P)	8 trees; 1866(0,4), 1866(0,3), 1876 (3,4)	1856
	Mature forest (B)	7 trees; 1650(20,12), 1715(10,12), 1755(20,12)	1612
E	Outer moraine (D)	18 trees; 1896(3,5), 1899(5,5), 1903 (5,5)	1882
	Outer moraine (P)	13 trees; 1894(10,5), 1894(5,5), 1902(10,5)	1873
	Inner moraine 1	25 trees; 1930(10,4), 1931(0,4), 1932(0,4)	1910
	Inner moraine 2	4 trees; 1944(0,4), 1949(0,4), 1956 (0,4)	1936
	Inner moraine 3	2 trees; 1957(0,4), 1960(0,4)	1947
F	Trees with base buried by outwash	6 trees; 1712(20,12), 1760#(20,10), 1791#(20,10)	1674
	Mature trees not affected by outwash	5 trees; 1724(5,11), 1853(0,12), 1857(3,9)	1702
	Trees growing on top of outwash	2 trees; 1859(0,10), 1870(3,4)	1843
G	Mature forest (B)	26 trees; 1706(20,13), 1731(15,12), 1731(15,10)	1667
H	Mature forest (B)	21 trees; 1764(20,12), 1785(20,12), 1806(20,11)	1726
	M1	32 trees; 1854(5,10), 1854(3,10), 1870(15,10)	1833
	M2	24 trees; 1891(0,10), 1898(0,5), 1902(3,8)	1875
	M3	17 trees; 1897(0,1), 1912(3,3), 1912 (0,3)	1890
	M4	21 trees; 1911(5,1), 1920(0,4), 1931 (3,4)	1899
	M5	19 trees; 1943(15,3), 1956(20,3), 1958(20,4)	1919
	M6	9 trees; 1958(0,3), 1960(0,3), 1961 (0,3)	1949
	M7	18 trees; 1963(0,2), 1972(5,1), 1973 (0,3)	1955
	M8	9 trees; 1984(0,1), 1985(0,2), 1988 (1,1)	1977
I	Mature forest (B)	10 trees; 1700(20,8), 1763(0,4), 1790(20,12)	1666
	Channel between outer moraine and mature forest	3 trees; 1748(0,12), 1793(20,10), 1798(20,10)	1730
	Outer moraine (D)	23 trees; 1737(20,10), 1785(20,9), 1817(0,10)	1701
	Outer moraine (P)	14 trees; 1864(20,10), 1881(20,8), 1884(3,8)	1828

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