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Dominant ENSO frequencies during the Little Ice Age in Northern Patagonia: The varved record of proglacial Lago Frías, Argentina

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Abstract

The global character of the time interval known as the Little Ice Age (LIA) is at present relatively well established. However, the forcing mechanisms behind this cooling interval are still elusive. Investigations in annually laminated sediments have shown that varved sediments are among the best climate archives to tackle these questions. Proglacial Lago Frías in northern Patagonia is fed by the Tronador ice cap (3554 m). Previous investigations have shown that this glacier has reacted sensitively to climate change during the LIA, with well-identified major glacial advances between AD 1800–1850. Results of a multiproxy study of Lago Frías sediments reflect variations in the transport of glacially derived clay and silt to the basin that can be directly linked to changes in climate. Sedimentological evidence combined with a chronological model indicate variations in varve thicknesses showing two frequencies centered at 16.4 and 10.5 years that have been previously attributed to the solar cycles and the Tropical Atlantic Sea Surface Dipole (TAD), respectively. The main frequency is, however, located between 2.5 and 3.0 years pointing towards a dominant El Niño/Southern Oscillation (ENSO) signal. Thus, the Lago Frías record provides new insights about the complexity of the various forcing mechanisms behind the cooling during the LIA in an area with a paucity of high-resolution climate records.

1. Introduction

The global character of the time interval known as the Little Ice Age (LIA) is at present relatively well established. Luckman and Villalba (2001) have recently summarized glacial events during this time interval for a transect throughout the Americas. They found a broad synchronicity in the initiation and timing of LIA glacial events, and particularly good evidence of the classic LIA advances during the seventeenth to early twentieth centuries. A detailed analysis of the data at a decadal level, however, shows considerable variability among sites in both the relative magnitude and date of the events as well as the age of the LIA maximum position. Whether these differences are the result of the varying dominance of temperature and/or precipitation controlling glacier mass balance remain an unsolved question. Hence, the forcing mechanisms behind these discrepancies among records are still elusive. Investigations in annually laminated sediments have shown that varved sediments are among the best climate archives to tackle these questions (e.g., Sturm, 1979; Leemann and Niessen, 1994; Trauth et al., 2000; Blass et al., 2003; Zolitschka, 2003; Chondrogianni et al., 2004). Once the mechanism behind their formation is well understood, lacustrine varved sequences provide us with not only an excellent chronology, but also with a unique source of environmental information.

Our results from northern Patagonia lake sediments indicate that fluctuations in El Niño/Southern Oscillation (ENSO) and both the solar cycles and the Tropical Atlantic Sea Surface Dipole (TAD) may have been the main controlling factors on the observed changes in varve formation and consequently in the activity of the Tronador ice cap.

2. Regional geographical setting and climate

The present climate of northeastern Patagonia is mostly controlled by the westerlies. At the latitude of 40°S, the source of moisture is particularly regulated by the persistence of the westerly storm tracks during austral winter (Prohaska, 1976; Barrey and Chorley, 1992). A

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satellite image from July 2005 (Fig. 1) clearly shows this situation and indicates that the main source of atmospheric moisture at this latitude is coming from the Pacific region. A 30-year mean temperature series from a meteorological station located in the city of San Carlos de Bariloche shows a conspicuous seasonality for the Argentinean Lake District (data provided by the Servicio Meteorológico Nacional, Fuerza Aérea Argentina). Fig. 2 indicates that both maximum and minimum mean temperature values also follow this seasonal pattern. Furthermore, this seasonality controls the precipitation centered during austral winter confirming that the instantaneous situation shown in Fig. 1 is consistent through time.

Lago Frías (40 °S, 71 °N, 790 m a.s.l.) is a 4.1-km-long and 1.1-km-wide proglacial lake (Fig. 3). The maximum water depth is 75 m and the lake is located at ca. 7.5 km north of the Frías glacier, which is one of the seven tongues from the Mt. Tronador ice cap (3554 m) flowing towards the Argentinean side of the Andes (Fig. 3a). Previous investigations in the region have shown that the Tronador ice cap has reacted sensitively to climate change during distinct episodes such as the Late Glacial–Holocene transition (Ariztegui et al., 1997; Hajdas et al., 2003) and the Medieval Warm Epoch and the LIA, with well identified major glacial advances at the Frías Glacier between AD 1800–1850 (Rabassa et al., 1979; Villalba et al., 1990).

A meteorological record for the 1969–1985 interval at the Mascardi weather station, located at 20 km from the Frías Glacier, shows identical trends to the one observed in Bariloche (Fig. 2) with a mean annual temperature of 7.6 °C, varying from 12.9 °C in January to 2.4 °C in July (Villalba et al., 1990). Additionally, these data indicate a strong precipitation gradient between Mascardi (1409 mm year^{-1}) and the River Frías valley (4300 mm year^{-1}; Perez Moreau, 1945) as well as 1 °C lower temperatures at the Frías site relative to the Mascardi meteorological station. This difference seems to be independent of the altitude and has been attributed to the combined effect of heavy cloudiness and high precipitation at the Frías Glacier area (Villalba et al., 1990).

During the 20th century, the ENSO and ENSO-like phenomena have dominated climate variations in the Americas on interannual and decadal time scales, respectively (Dettinger et al., 2001). The ENSO impact on local

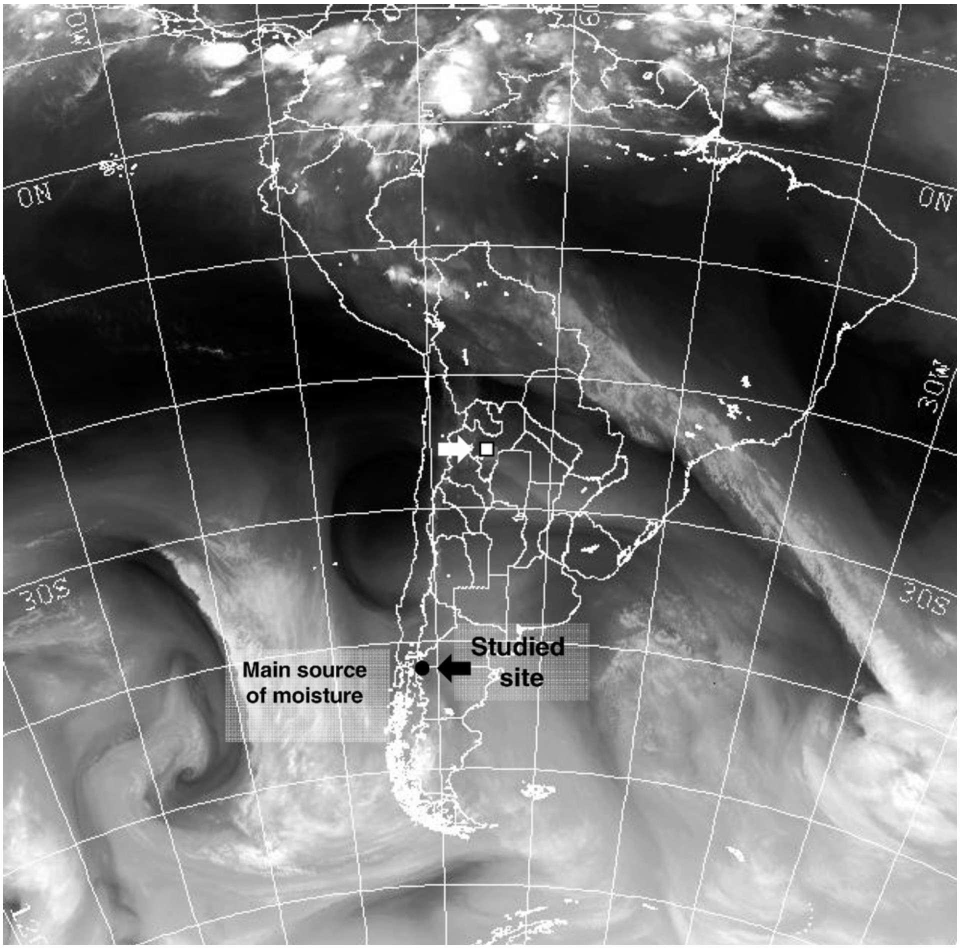

Fig. 1. Satellite image (18 July 2005) showing the distribution of moisture for South America (Servicio Meteorológico Nacional, Fuerza Aérea Argentina). Most of the rainfall during austral winter is associated with a seasonal northward migration of the westerlies system.

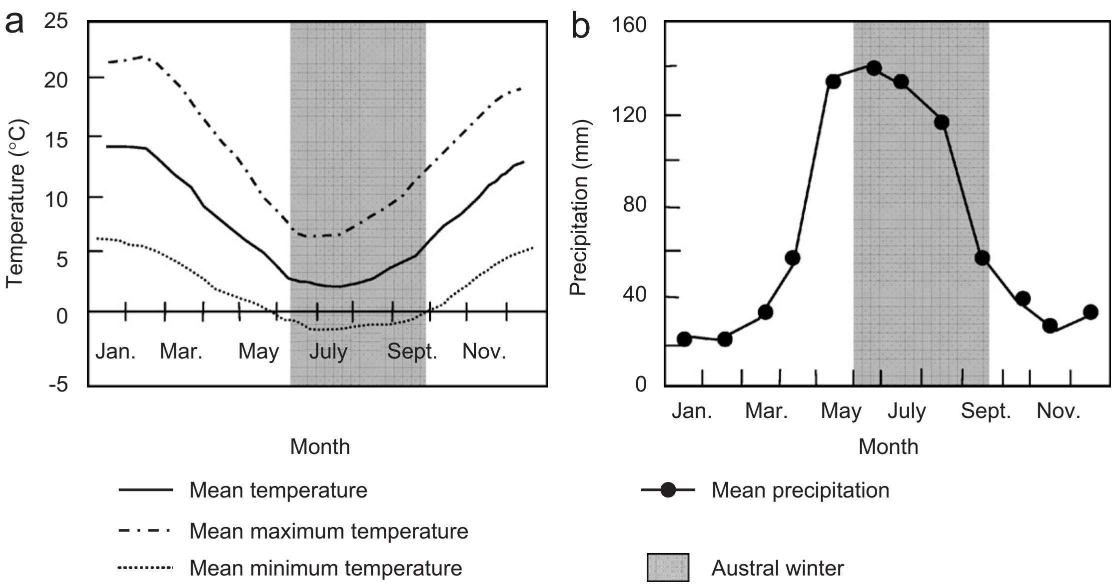

Fig. 2. (a) Mean, maximum and minimum temperature values per month at the Bariloche meteorological station for the 1961–1990 interval; (b) Values of average monthly precipitation for the same time slice and station. Shaded intervals indicate austral winter. All data provided by the Servicio Meteorológico Nacional, Fuerza Aérea Argentina ⟨http://www.meteofa.mil.ar⟩.

climate has been well determined using meteorological, historical, and dendrochronological approaches at the Frías valley (Villalba et al., 1990, 1998).

More recently, a sediment trap study in Lake Mascardi covering the 1992–1998 interval combined with meteorological data have shown changes in sedimentation rates that can be linked to ENSO climatic events (Villarosa et al., 1999). As both proglacial lakes, Frías and Mascardi, are fed by the Tronador ice cap, the laminated sequence of Lago Frías can provide a continuous record of ENSO and ENSO-like variations through time.

3. Material and methods

Seismic profiles were collected in January 1994 by using an Ocean Research Equipment (ORE)-GEOPULSE® 3.5 kHz single-channel pinger system with a vertical resolution of approximately 10–20 cm. A multiset of short sedimentary cores was recovered using a gravity corer during the same field season and storage at 4 °C. Whole-core petrophysical properties (magnetic susceptibility (MS)) were measured using a Multisensor Track Core Logger (GeoTek®) at the ETH-Zürich limnogeology facilities. Sedimentary cores were subsequently opened and photographed at the Institute Forel, Geneva. Lithological features were defined combining a detailed core description with observations in both smear slides and epoxy-impregnated thin-sections. A lamination index (LI) was defined following Ariztegui et al. (2001a) and Piovano et al. (2002) ranging from excellent (4) to lack of noticeable lamination (1). Further analyses of the lamination included SEM backscattered electron micrographs using a Jeol JSM840 SEM.

Total organic and inorganic carbon values (TOC and TIC, respectively) were obtained by Rock-Eval® Pyrolysis at the University of Neuchâtel (Ariztegui et al., 2001a). The chronology of the reference core was achieved using a combination of ^{137}Cs decay for the most recent sediments, and AMS ^{14}C dating and varve counting for the older section. Varve counting was achieved visually and using a computer-assisted method developed at the Department of Geology and Paleontology of the University of Geneva. Statistical (Fourier) analyses were performed using the Statistica® software.

4. Results and discussion

High-resolution seismic profiling in lakes coupled with targeted coring sites provides powerful tools for paleoenvironmental reconstructions (Ariztegui et al., 2001b; Gilli et al., 2001). Fig. 3b displays the bathymetric map of Lago Frías with a relatively large and flat area towards the outflow that would indicate steady sedimentation. A seismic profile throughout this part of the basin (Fig. 3c), however, shows a complex pattern of sediment distribution. Despite the low penetration of the acoustic signal, this profile was used in the field to find the best position for core retrieving in order to avoid mass wasting events. Hence, core F94-2 was recovered in the best location with apparently continuous sedimentation, whereas cores F94-3 and F94-6 display more irregular sedimentation and are not discussed in this article (Bösch, 2004).

MS shows quite uniform values (average 500 × 10−5 SI) throughout core F94-2, except at ca. 84 cm where a peak is associated with a ~3 cm thick layer mostly composed of a reworked tephra (Fig. 4). Thinner tephras at mm scale have been also identified in smear slides at different depths (see

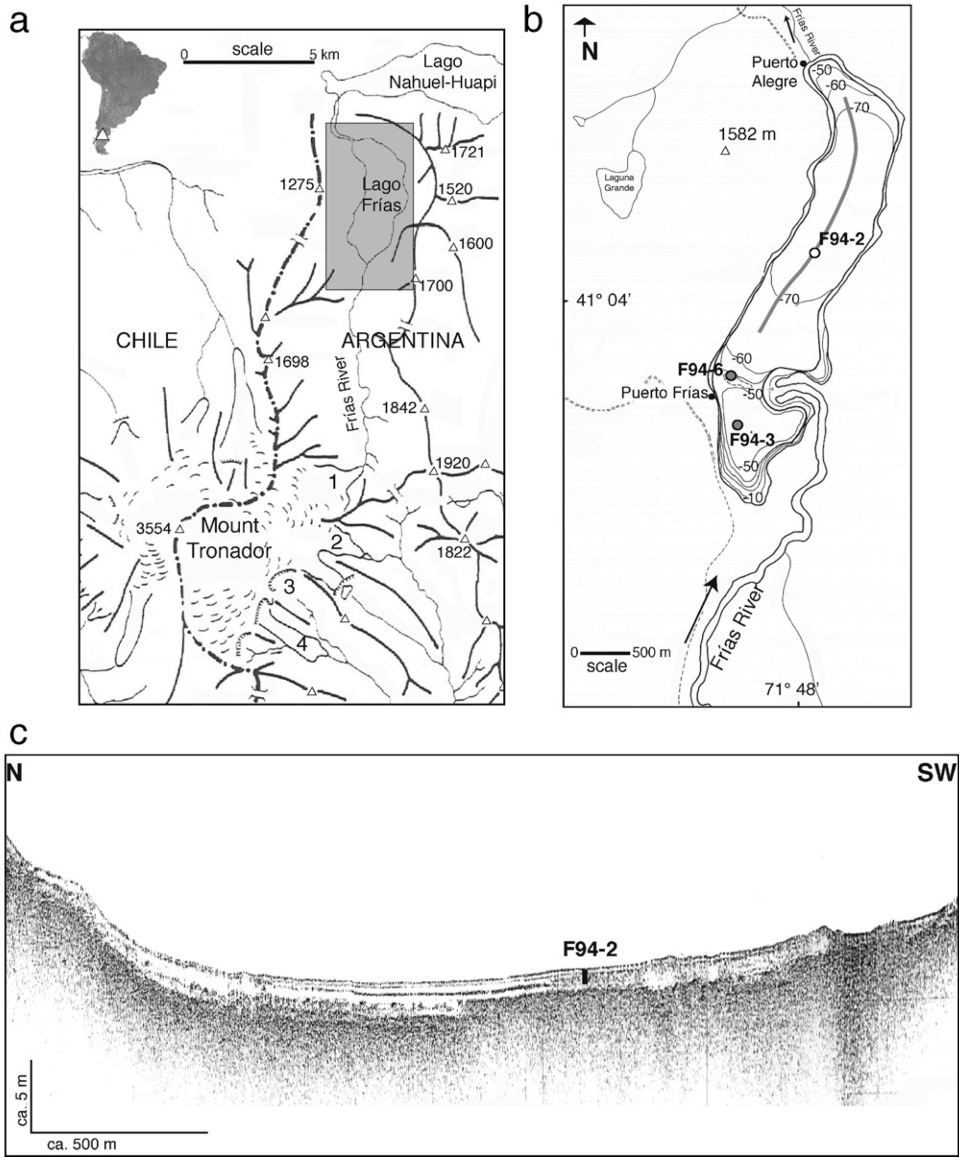

Fig. 3. (a) Map of the Tronador ice cap on the Argentinean/Chilean border (modified from Villalba et al., 1990). The location of the main glacier ice-tongues descending towards Argentinean territory are indicated by numbers, from north to south as follows: Frías Glacier (1); Alerce Glacier (2); Castaño Overo Glacier (3); and Río Manso Glacier (4). The shaded rectangle indicates the location of proglacial Lago Frías zoomed out in (b). The bathymetric data was produced during this survey and further compiled and drawn by C. Bianchi and M. V. Amos, respectively (CONICET, Argentina). The gray line indicates the position of the seismic profile shown in (c). The white dot shows the position of the reference sedimentary core F94-2 (see text). Gray dots show the location of two additional short cores.

white arrows in Fig. 4), although they do not show up in MS. Despite that the entire core is well laminated, there are changes in the development and quality of the lamina. These fluctuations have been semi-quantified using the LI (Fig. 4). An excellent lamination (LI 4) is observed from the bottom of the core up to ca. 40 cm except in the interval between 100 and ca. 85 cm. A similar less developed type of lamina dominates the interval between 40 cm towards the top of the core. A clear improvement of the lamination appears from 10 to 5 cm. The uppermost 5 cm are partly disturbed due to coring operations showing less developed layers. Total organic carbon is relatively low throughout the core (average 1%) and carbonate contents are negligible. An obvious event occurred between ca. 20 and 16 cm, as shown by a decrease in MS and an increase in TOC (Fig. 4). A quick observation of this layer shows that it is mostly composed of allochthonous organic matter such as roots, leaves and other organic remains. The latter was further confirmed in smear slides. It is important to point out that a dense vegetation surrounds the lake due to the extremely high precipitation regime of the area.

4.1. Varves or lamination?

The presence of laminations does not guarantee that they are true varves (e.g., Zillen et al., 2003). One way to verify

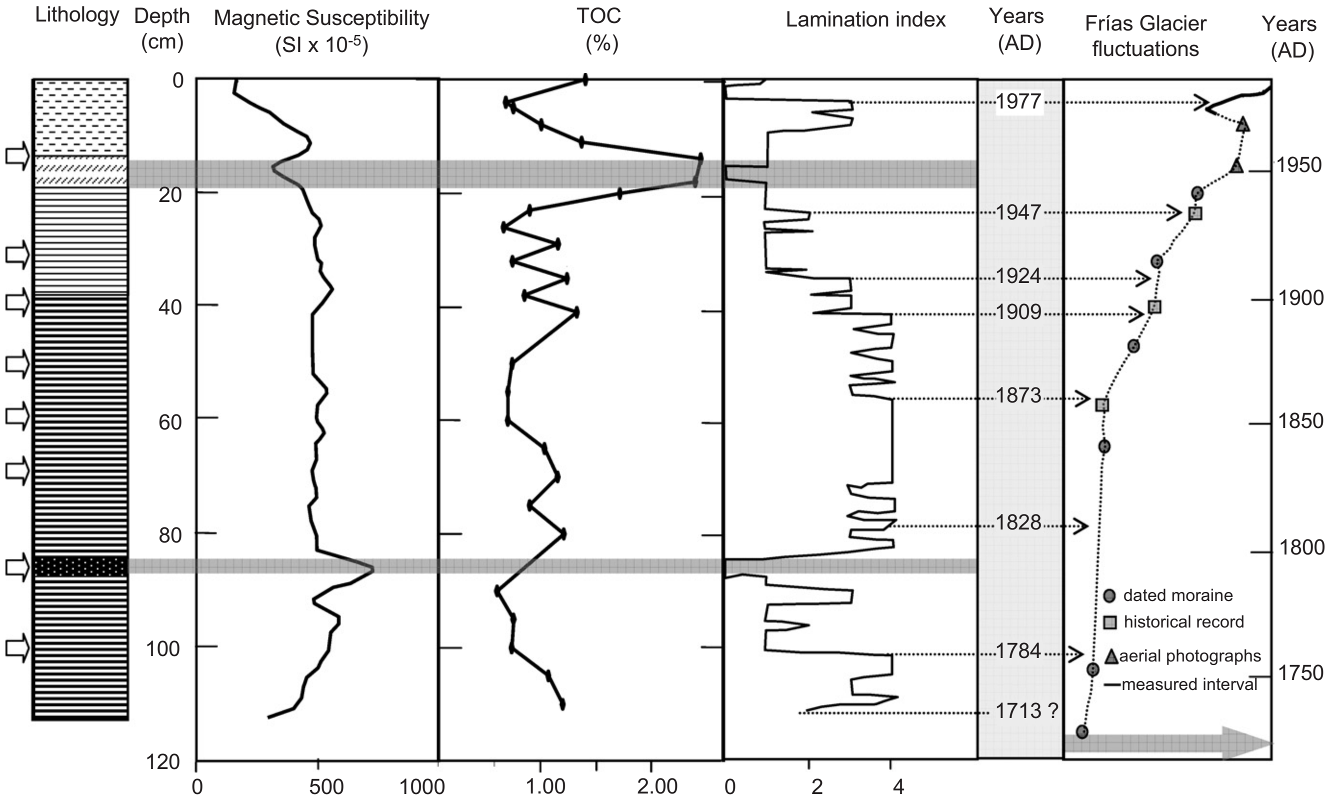

Fig. 4. Log of core F94-2 including main lithological units versus depth. Darker patterns indicate excellent development of lamination that is also expressed through the LI. Variations in physical properties (MS) and bulk geochemistry (percent TOC) show consistent patterns as highlighted by the shaded areas. White arrows indicate main tephra layers associated with regional volcanism. The chronology of Frías Glacier fluctuations is based on historical records, aerial photographs, tree-ring counts, ice-damaged trees and tree-ring index variations. Distances are relative to the position of the glacier terminus in summer 1986 and the gray arrow indicates glacier retreat (modified after Villalba et al., 1990).

the annual character of the lamination is to look in detail at its sedimentological features using a microstratigraphic approach. Fig. 5 shows a section of the core containing a very well-laminated interval. The SEM inspection of an epoxy-impregnated thin-section produced backscattered images that provided excellent grain-size and porosity information. These observations combined with detailed analyses of smear slides allowed us to formulate a model of an ideal varve that is summarized in Fig. 5. A gray layer composed of allochthonous organic matter and clastic material (mostly silt) is becoming distinctly more argillaceous towards the top.

The spring diatom bloom, which occurs most likely almost immediately after the snowmelt, is emphasized in the clastic coarse layer. Further increases in diatom remains account for summer and autumn productivity and they are commonly represented as pulses with slight differences in color. The thickness of the organic lamina is, therefore, the sum of autochthonous production within the lake and the amount of allochthonous material and is related to the primary production during the warm season. Despite the presence of autochthonous organic matter, clastic material remains dominant.

A second, light brown and finer layer with scarce to absent diatom frustules represents winter sedimentation. The accumulation of this lamina can be directly linked to glacier activity. Temperate glaciers increase the production of fine rock and mineral fragments by abrasion of the bedrock, so that glacial melt waters carry relatively large amounts of silt and clay-sized particles in suspension during summer, which are deposited in proglacial lakes. Because erosion rate increases with glacier size and thickness, and both are controlled by climatic parameters (such as mean summer temperature and winter precipitation) variations in the accumulated amount of the silt- and clay-sized mineral fraction in proglacial lake sediments provides a reliable high-resolution record of climate variations (Leemann and Niessen, 1994). The clear seasonality shown by the available meteorological data for the area (Fig. 2) supports the development of this model for varve formation. Additionally, snowfall dominates the winter season (Drago, 1973) and most of the catchment remains frozen, both limiting factors for the amount of sediment entering the lake during the cold season.

4.2. Searching for an independent chronology

An independent chronology for the uppermost sediments was achieved using the ^{137}Cs decay as shown in Fig. 6. The maximum peak of Cs activity in South America has been assigned to AD 1965 (Schuller et al., 2002), whereas no

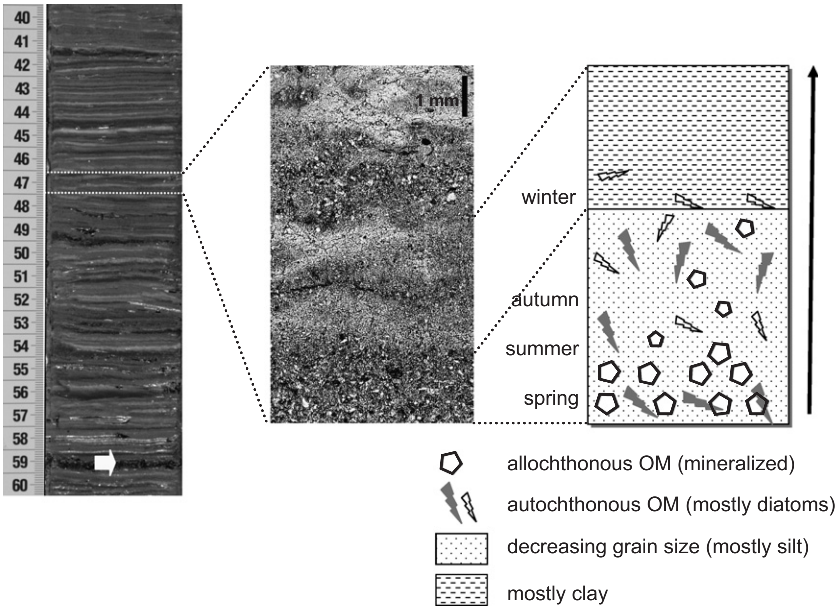

Fig. 5. Photograph of a nicely laminated section in core F94-2. The white arrow indicates a well-defined tephra layer. The schematic model on the right displays the interpreted sedimentary cycle of the seasonally deposited lamina in Lago Frías based on observations in smear-slides and impregnated thin sections. The SEM backscattered electron microphotograph in the center illustrates the regularity of the lamination at micro scale in a polished thin section.

increase in Cs activity is observed associated with the Chernobyl accident.

Additionally, the imprint in the sediments of some well-known historical events in the region confirms this chronology. Assuming a constant sedimentation rate the organic-rich layer observed between 20 and 16 cm can be dated at AD 1960. A major subduction related earthquake occurred in May–June that year that triggered a series of tsunami waves along the Chilean coast and formed mass-wasting deposits in lacustrine basins in both sides of the Andes (Chapron et al., 2006). In addition, results of the visual counting of the lamination in zoomed photographs between 10 and 5 cm combined with the ^{137}Cs peak confirm the annual character of the lamination.

Four ^{14}C radiocarbon samples were analyzed at the ETH-Zürich AMS facility. A macrofossil embedded in the organic-rich layer at 17 cm gave two possible calibrated (dendro-corrected) ages (2σ ranges) that are shown in Table 1. Due to the shape of the calibration curve in the region of interest, several true age ranges are possible. The 1794–1952 age, however, is the only one consistent with both Cs and varve chronologies. The three additional samples also shown in Table 1 were measured on bulk sediment, delivering ages that are far older than expected when considering the event stratigraphy proposed below. The causes for this discrepancy in radiocarbon ages are still elusive, since the lack of carbonates in the basin apparently rule out the classical hardwater effects (e.g., Gilli et al., 2005). The presence of hiatuses in the sedimentary sequence due to mass wasting events could account for these old ages. There is neither geophysical evidence (see core location in the seismic profile in Fig. 3c) nor sedimentological features in this core, however, which would point towards this option. Smear slides show a substantial amount of a dark-looking mineral fraction that may be a form of lignite, which is radiocarbon dead and has been a noted problem in other sites in Patagonia (Bösch, 2004; Moy, pers. comm.). Further systematic investigations are needed in order to understand the causes of this discrepancy.

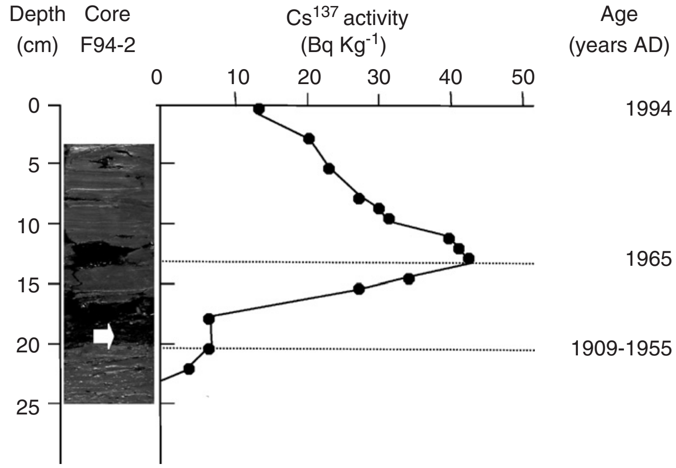

Fig. 6. Photo of the uppermost 25 cm of core F94-2 as well as the radioisotopic activity of the bulk sediments. The displayed ages are obtained from the maximum 137Cs peak that in this region of the world is attributed to 1965. The white arrow indicates the location of an AMS 14C age measured in a macrofossil at the base of the organic-rich layer.

4.3. Varve counting

Assuming the annual character of the lamination, varves were counted in the rest of the core using high-resolution

Table 1
Range finding radiocarbon samples were measured in both microfossil and bulk samples

Depth (cm)	Laboratory no.	Material remarks	AMS ^{14}C age (years BP)	Calibrated age (cal AD) 2σ	$\delta^{13}C$ (‰)
17	ETH-26210	Wood and leaves	170 ± 50	1669–1784 1794–1952	−30.2
63	ETH-26889	Bulk	1435 ± 80	465–482 533–871	−19.9
87	ETH-26211	Bulk	990 ± 70	984–1225	−24.4
90	ETH-26890	Bulk	1190 ± 60	724–739 771–1020	−22.4

All samples were measured at the ETH-Zürich AMS facility. Calibrated ages were calculated using the program CALIB Rev. 5.01 (Stuiver and Reimer, 1993) using the South Hemisphere correction (McCormac et al., 2004). See text for discussion.

photographs both visually and also using computer software. Fig. 7 shows a photograph of a well-laminated section where the gray-scale average intensity was measured. The raw data was further smoothed using an *n*-terms moving average in order to detrend the gray-scale signal. The difference between the raw and the smoothed signals provided a residual curve that was further thresholded and transformed in thickness. Instant events that are not related to the lamination, such as tephra layers and turbidites (Fig. 4), were manually deleted. Turbidites are mostly composed of dark and comparatively coarse reworked tephra and were easily identified in smear slides (Bösch, 2004).

Fig. 8 displays the variations in thickness of dark and light lamina separately as well as of the varves throughout the best laminated interval. An age of ca. AD 1713 was obtained for the base of the core using the counted varves. This age is older than the AD 1762 obtained when considering the position of the 1965 Cs peak and assuming an unrealistic uniform sedimentation rate down core. This discrepancy, however, is interpreted here as due to the variable sedimentation rates associated with fluctuating glacial activity throughout the studied time interval.

4.4. Comparison with other records and paleoclimate implications

A pioneer dendrochonological study in both front and lateral moraines in the Frías Glacier allowed not only to date but also to pinpoint cold intervals with higher rainfall and, thus, glacial re-advances (Villalba et al., 1990). Eight cold and rainy intervals were identified between AD 1703–1717, 1742–1777, 1826–1838, 1868–1873, 1900–1910, 1929–1935, and 1968–1977.

The associated glacier re-advances have been recorded as a better development and increasing thickness of lamination in the lacustrine record. A further comparison with the reconstructed fluctuations in the Frías Glacier is shown in Fig. 4 (after Villalba et al., 1990). While the first noticeable change in lamination is not exactly coincident with the two first cold and rainy intervals, there is significant agreement for the rest of the sequence, shown by the almost mirror image behavior of both curves. The observed change in lamination dated at AD 1784 would be associated with the tree-ring derived cold and rainy period ending in AD 1873 that is assigned to the LIA. A good agreement between records is also observed in the rest of the core as shown by less development of lamination during glacier retreat intervals. This correlation is particularly significant during the well-documented interval of formation of the 1968–1977 push-moraines (Rabassa et al., 1979) corresponding with increasing values of LI in the lacustrine sediments (Fig. 4). The remarkable coincidence between the sedimentological, geochemical and event stratigraphic data further validates the chronological model and confirms the use of varved sediments to reconstruct glacier variations in great detail.

The computer-assisted varve counting permitted separated measurements of the gray summer lamina from the light brown-winter lamina with a thickness varying from 0.2 to 4 mm, and 0.2 to 4.3 mm, respectively (Fig. 8). The excellent chronology allowed for a spectral analysis of the combined couples (i.e., varves) and these results are shown in Fig. 9. Main frequencies of changes in varve thickness are located between 2.5 and 3.0 years pointing towards a dominant ENSO signal. The two secondary, but statistically significant, frequencies centered at 16.4 and 10.4 years have previously been attributed to the TAD and the solar cycles, respectively. These results suggest a strong and variable influence of the ENSO phenomenon besides the seasonal precipitation changes during the studied interval. The latter would in turn produce glacial re-advances that are consistent with previous work in the region using both tree-rings and glacial moraines (Villalba et al., 1990, 1998). Moreover, recent investigations using lacustrine varved sequences at the same latitude on the western side of the Andes have shown comparable frequencies that have also been attributed to the ENSO phenomenon (Boës and Fagel, in press).

Previous studies have suggested that variations in solar activity may have affected the climate system (e.g., Haigh, 1996). In South America, its influence has been linked to the position of the mid-latitude storm tracks in southern Patagonia and northern Chile, see Gilli (2003), Van Geel et al. (2000), Grosjean et al. (1998), respectively). Moreover, Sonett and Trebisky (1986) have suggested the influence of

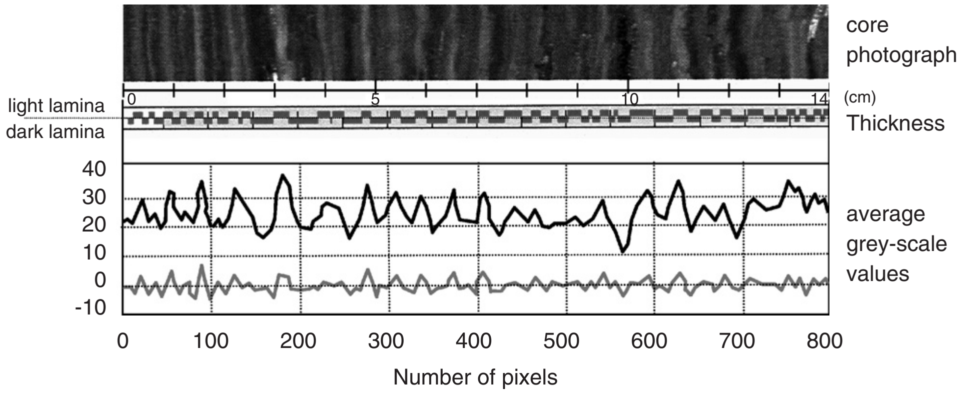

Fig. 7. Counting of the dark-light couples in high-resolution photographs was achieved using a specially designed computer-assisted system. The raw signal (uppermost black line) was smoothed using an n-terms moving average. The difference between these two signals provided a residual curve (gray line) that was further thresholded and transformed in thickness for both light and dark lamina. The scale in cm applies to both high-resolution core photograph and reconstructed varve thickness.

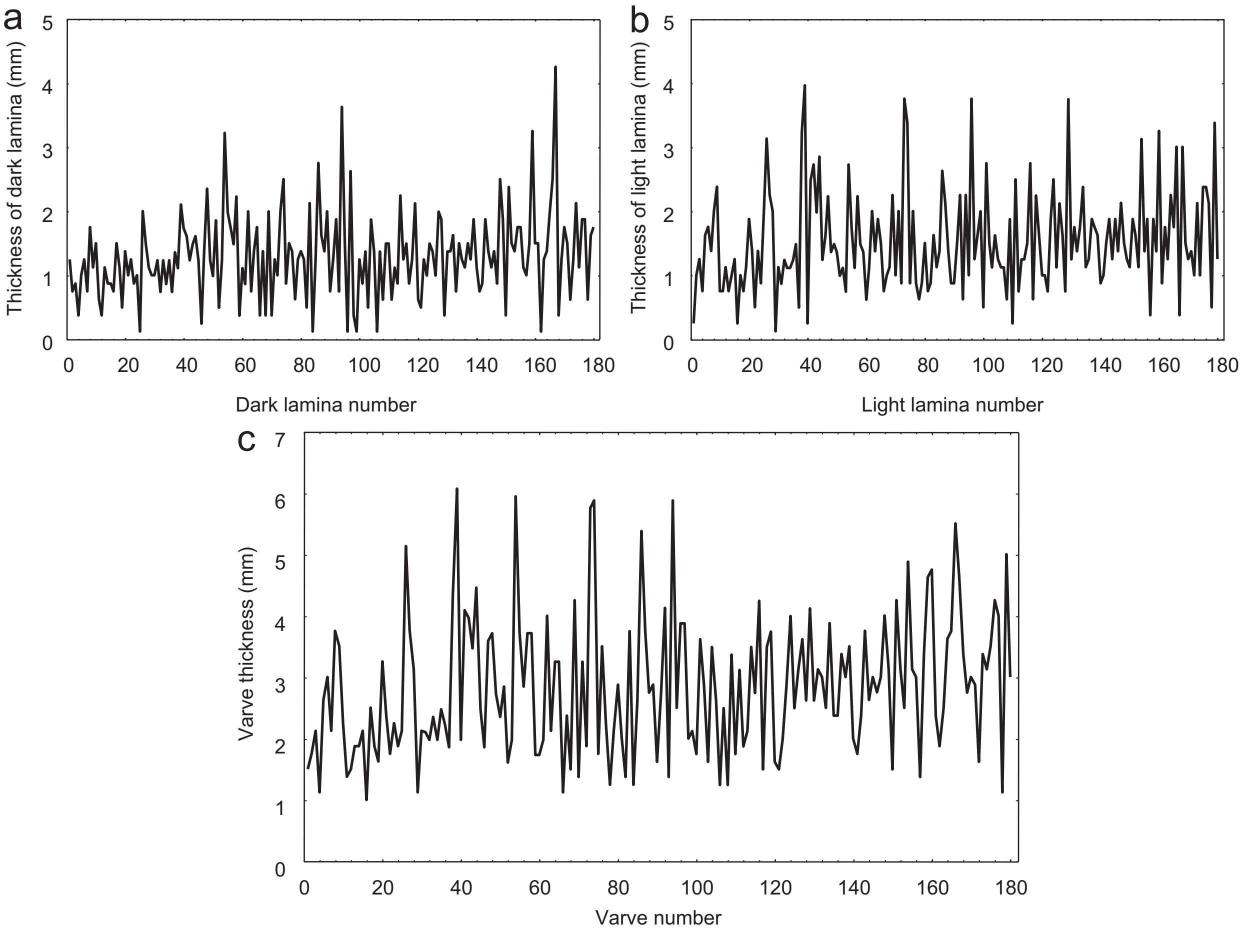

Fig. 8. Plots of thickness (mm) vs. dark lamina (a), light lamina (b) and varve number (c) for the best laminated core interval between 111.8 and 34.5 cm (refer to Fig. 4).

solar activity in varve thickness in old sedimentary sequences. More detailed analyses at a larger geographical scale are necessary in order to validate and understand the impact of solar cycles in Lago Frías sediments.

The climatic significance of the TAD frequencies observed at this latitude is even more puzzling. Today, most of the moisture at Lago Frías is coming from the west during the austral winter season (Figs. 1 and 2). ENSO and TAD precipitation teleconnections have been suggested as potential sources of interannual variations in the intensity of rains in the NW of Argentina (see white arrow in Fig. 1; Trauth et al., 2000). However, there is no evidence of a

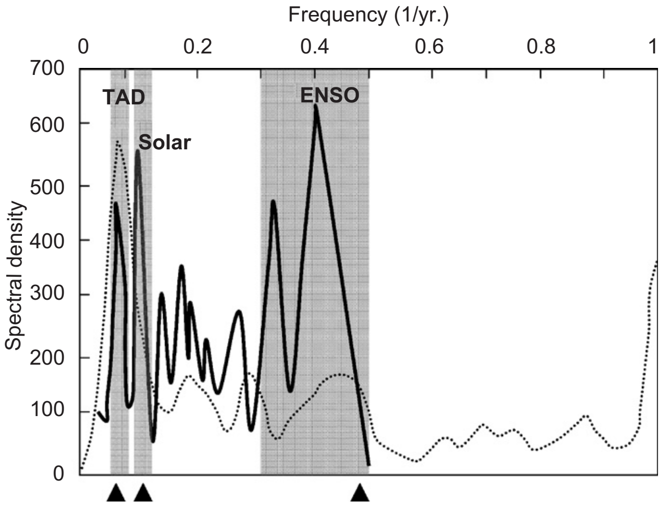

Fig. 9. The solid curve shows the spectral density of the varve thickness shown in Fig. 8c. Dominant frequency bands are centered at clear values suggesting a strong influence of ENSO. The dashed line displays the spectral density for a similar number of varves in NW Argentina (Trauth et al., 2000) whereas the black triangles designate the dominant frequencies of the tree-ring record close to the Frías Glacier (Villalba et al., 1990, 1998).

direct effect of this phenomenon during the LIA as far south as the study area. Villalba et al. (1998) noticed that the influence of high-latitude circulation on precipitation appears to be more significant during the 20th century. Comprehensive studies on the impact and potential teleconnections of TAD below 30°S are still needed in order to disentangle its influence in the Lago Frías record.

5. Conclusions

Results of the multiproxy study of Lago Frías sediments illustrate how coordinated seismic surveys and sediment coring offer the opportunity to recover optimal paleoclimate records. The retrieved laminated proglacial deposits reflect variations in the transport of glacially derived clay and silt to the basin. These variations can be directly linked to changes in climate during the last ca. 280 years.

The varved chronology combined with a consistent sedimentological model indicates a strong ENSO influence in the development of lamination. Combined with previous dendrochronological evidence, these new lacustrine data indicate variable cold and rainy intervals that in turn would have generated glacier re-advances. A similar mechanism has been proposed to explain recent glacier variations in western Norway associated with variations in the North Atlantic Oscillation Index (NAO; Nesje et al., 2001). The interplay with other secondary, but well-defined frequencies associated to both solar cycles and TAD, may also be involved in generating these glacier re-advances. The latter is consistent with data issued from tree-ring records that indicate that the recent increase of precipitation variability in northern Patagonia may reflect stronger interactions between middle and high-latitude atmospheric circulation in the Southern Hemisphere during the twentieth century.

Thus, the Lago Frías lacustrine record provides new insights into the complexity of the various forcing mechanisms behind the cooling during the LIA in this area of South America. It also points out the need to develop regional networks of well-understood lake systems with a reliable chronology. They will be critical evaluating the impact of the various mechanisms triggering environmental changes at different spatial and temporal scales.

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