Palaeogeography, Palaeoclimatology, Palaeoecology 281 (2009) 242–268

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Glacier fluctuations in extratropical South America during the past 1000 years

Mariano H. Masiokas [a,*], Andrés Rivera [b,c], Lydia E. Espizua [a], Ricardo Villalba [a], Silvia Delgado [a], Juan Carlos Aravena [d]

[a] Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), CCT-CONICET Mendoza, Argentina
[b] Centro de Estudios Científicos, Valdivia, Chile
[c] Departamento de Geografía, Universidad de Chile, Santiago, Chile
[d] Centro de Estudios Cuaternarios (CEQUA), Punta Arenas, Chile

ARTICLE INFO

Article history:
Received 14 August 2008
Accepted 8 August 2009
Available online 19 August 2009

Keywords:
Glacier records
Little Ice Age
Extratropical South American Andes

ABSTRACT

This paper presents an updated, extensive review of glacier fluctuations during the past 1000 years in the extratropical Andes of South America between ca. 17° and 55°S. Given the variety of environmental conditions and evidence available for glacier fluctuations across this wide latitudinal range, regional accounts are given for the Desert Andes (~17°–31°S), the Andes of central Chile and Argentina (31°–36°S), and the North (36°–45°S) and South (45°–55°S) Patagonian Andes. The techniques, dating limitations, and interpretations of the glacier records along this transect are also discussed. Information on glacier fluctuations in the Desert Andes is limited to the 20th century. Documentation on past glacier variations is more abundant in the Central Chilean-Argentinean Andes, but the number of chronologies dealing with glacier fluctuations prior to the 1900s is also limited. Most records indicate that glaciers were generally more extensive prior to the 20th century, with dates of maximum expansion ranging from the 16th to the 19th centuries. The number and extent of glaciers increase significantly in the Patagonian region, where the evidence available for dating glacier variations during the past centuries is more abundant and the dating control for glacier events is generally better than in the northern parts of the study area. For some Patagonian glaciers, maximum Little Ice Age (LIA) or post-LIA advances have been precisely dated by dendrogeomorphological determinations or *in situ* measurements. However, for most sites, the evidence available is still preliminary and there is considerable variability in the extent and timing of events related to the maximum LIA expansion identified in most areas between the 16th and 19th centuries. Evidence is starting to appear at a growing number of sites for glacier advances during the first half of the past millennium. These events were generally less extensive than the LIA maximum pulses. Despite the occurrence of several post-LIA readvances over the past 100–110 years, most areas in the Andes of extratropical South America have experienced a general pattern of glacier recession and significant ice mass losses. The differences in the glacier histories observed at local and regional scales probably reflect the inherent limitations associated with the glacier records and/or the dating techniques used in each case together with the varying dominance of precipitation, temperature and other climatic and non-climatic factors on glacier mass balance and glacier dynamics. These differences indicate that the late Holocene glacier history of southern South America is more complex than commonly assumed. The evidence discussed in this study highlights not only the immense potential for glaciological studies of this region but also a significant need for an increased number of detailed, well-dated records of glacier fluctuations.

1. Introduction

The Andes in the extratropical region of South America (ca. 17°–55°S) form an uninterrupted N–S mountain chain and contain over 23,000 km^2 of glaciers (Naruse, 2006), the largest glacierized area in the Southern Hemisphere outside Antarctica. Over this wide latitudinal range, glaciers can be found at elevations of over 6000 m in the high, arid Andes of northern Chile and Argentina and also at sea level in the humid southwestern portion of Patagonia and Tierra del Fuego (Fig. 1). Such a diversity of conditions supporting glacier ice underscores the potential of extratropical South America for the development of a great variety of glaciological investigations. However, despite numerous recent studies that have significantly increased our knowledge about glaciers in this region (see e.g. Casassa et al., 2002a), the late Holocene glacier history of extensive portions of this

* Corresponding author. Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), CCT-Mendoza CONICET, C.C. 330, (5500) Mendoza, Argentina. Tel.: +54 261 5244257; fax: +54 261 5244201.
E-mail address: mmasiokas@mendoza-conicet.gov.ar (M.H. Masiokas).

0031-0182/$ – see front matter
doi:10.1016/j.palaeo.2009.08.006

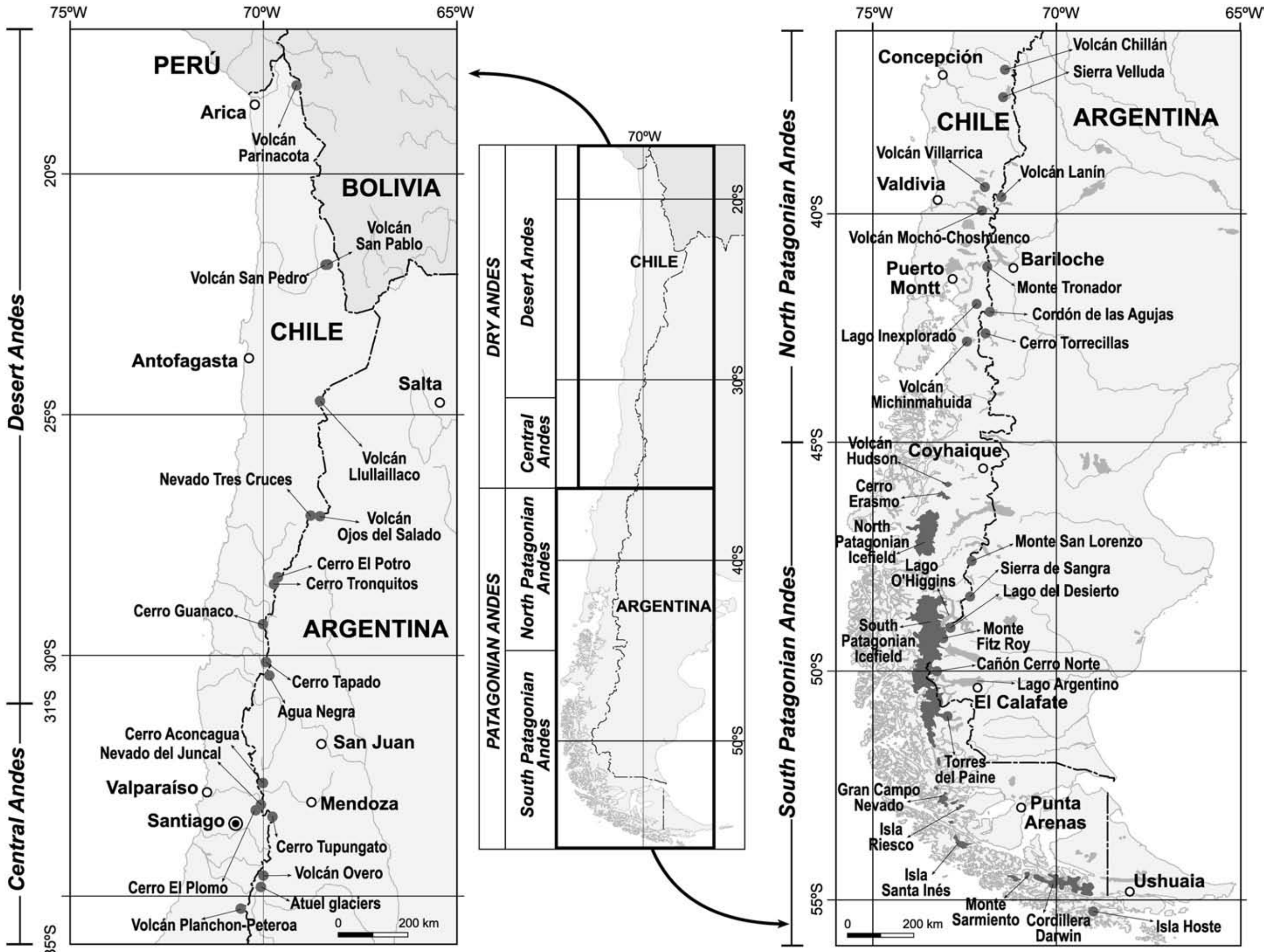

Fig. 1. Map of the Andean portion of extratropical South America showing the regional subdivisions (Desert Andes, Central Chilean–Argentinean Andes, and the North and South Patagonian Andes) and the location of the glacier sites mentioned in the text. The limits for the regional subdivisions are based on Lliboutry (1998).

mountain range remains relatively poorly known. This precludes, for example, the development of reliable regional glacier chronologies and the intercomparison with other glacierized areas for regional, hemispheric or global analyses. Reviews of the available evidence regarding late Holocene glacier fluctuations in the Andes of southern South America have been provided, among others, by Luckman and Villalba (2001) and Glasser et al. (2004). However, a comprehensive updated review for the entire extratropical portion of this continent that focuses specifically on the last millennium is not available.

In this paper we present and discuss an extensive, up to date compilation of evidence for glacier fluctuations in the Andes of Chile and Argentina over the past ~1000 years. This evidence is collectively presented here a) to demonstrate the type, usefulness and limitations of the information available and b) to provide a comprehensive database that will hopefully facilitate and promote further research in this region.

To facilitate the organization of this work and the interpretation of results, we have used the regional subdivisions proposed by Lliboutry (1998) with only minor modifications (Fig. 1). The Dry Andes (17°–36°S) are divided into the Desert Andes and the Andes of central Chile and Argentina ('Central Andes' sensu Lliboutry) covering the 17°–31°S and 31°–36°S latitudinal ranges, respectively. Further south, the Patagonian Andes are divided into the North Patagonian Andes between 36° and 45°S, and the South Patagonian Andes that contain all glaciers south of 45°S.

2. Geographic setting

Between ca. 17° and 35°S, the Andes can reach almost 7000 m in elevation but decrease gradually to an average of ca. 1500–2000 m at the southern tip of the continent. This mountain chain forms a formidable barrier to the prevailing westerly circulation and results in strong west–east climatic contrasts (Schwerdtfeger, 1976). Environmental conditions also show latitudinal and altitudinal gradients imposed by the main cordillera and by atmospheric circulation processes resulting from a relatively cold south-eastern Pacific, a warm south-eastern Atlantic Ocean, and the proximity to the Antarctic continent (see Garreaud et al., 2009-this issue, for further details). In general, the regional snow line decreases from north to south and from east to west (Nogami, 1972; Rabassa, 1981), but the degree of glacierization varies with topography and local climate ranging from small glacierets or snow patches on high isolated volcanoes and mountains in the north, to the extensive Patagonian icefields in the south (Aniya et al., 1997; Lliboutry, 1998; Rivera et al., 2007; Fig. 1).

Mean annual precipitation decreases from 400 mm in the highlands of Tarapacá (18°S) to less than 100 mm in the South American Arid Diagonal that crosses the Andes between 19 and 23°S (Messerli et al., 1998). The northern sector of the Desert Andes receives precipitation from the east in summer, but farther south (24–32°S), precipitation from the Pacific is more abundant and concentrated during the winter months. The Central Andes are characterized by a Mediterranean-type climate. Dry summers and wet winters are mainly the result of the northward–southward displacement of the high-pressure cell on the south-east Pacific Ocean, which generally inhibits precipitation during the warm season but allows the passage of the westerlies and a higher occurrence of frontal precipitation during the colder months (Rutllant and Fuenzalida, 1991). Total annual precipitation at sites above 2500 m ranges from less than 500 mm in the north (31°S) to as much as 2000 mm further south at around 36°S. At these latitudes the existence of numerous peaks that extend well above the elevation of the 0 °C isotherm (ca. 4000–3000 m over this latitudinal range) allow the development of important glacierized areas (Rivera et al., 2000).

Mean annual temperatures across Patagonia are mainly influenced by latitude and elevation. At 40°S along the Chilean coast mean annual temperatures vary around 12 °C but decrease to 6 °C at ca. 53°S (Miller, 1976). Precipitation regimes gradually change from a Mediterranean regime in northwestern Patagonia to a year-round regime in the southernmost sector of the continent. A typical west–east profile of precipitation at 40°S would show ca. 1500 mm yr^{-1} at the Chilean coast and about 3500 mm yr^{-1} at the main Andean divide, abruptly decreasing to ca. 300 mm yr^{-1} in the xeric Patagonian steppe, ca. 50 km to the east of the mountains (Miller, 1976; Villalba et al., 2003). Similar impressive west–east contrasts and dramatic changes in precipitation can be observed throughout the Patagonian Andes. At around 50°S annual precipitation totals can exceed 7000–8000 mm on the South Patagonian Icefield but decrease to ca. 200 mm at El Calafate, 70 km east of the icefield (Escobar et al., 1992; Warren and Sugden, 1993; Villalba et al., 2003).

3. Methods and limitations for reconstructing glacier fluctuations in the southern Andes during the past 1000 years

Given the wide variety of environments and climatic conditions found in the study area, different methods and sources of information have been used to study glacier fluctuations. Historical records (maps, drawings, photographs and written reports) of glaciers are generally available from the early 1900s/late 1800s. This material has provided, especially for the Central and Patagonian Andes, valuable information for documenting past glacier positions and for illustrating the long-term behaviour of glaciers in the cordillera (e.g. Espizua and Maldonado, 2007; Masiokas et al., 2008; Le Quesne et al., 2009-this issue). North of ~35°S, the high elevation and relative scarcity of datable organic material has yielded very few glacial chronologies covering the past centuries. In the Central Chilean–Argentinean Andes the maximum glacier extent of the last few centuries occurred during the commonly known “Little Ice Age” (hereafter LIA; Grove, 2004) and has been analyzed through morphological and stratigraphical studies complemented with radiometric age determinations of organic material associated with terminal and lateral moraines. Radiocarbon dates of basal samples from peat bogs inside these moraines have provided minimum age estimates for these deposits (Espizua, 2005). The Patagonian Andes contain a much larger number of glaciers and a greater variety of datable material (e.g. subfossil/living trees, lichens, organic sediments) associated with glacier deposits. This makes the dating of glacier events relatively easier and potentially more precise than in the Andes to the north, and has resulted in a significantly higher number of dated advances for the past 1000 years. Most of the advances that occurred during this interval have been dated using radiometric, dendrochronological and/or lichenometric methods. In some cases (e.g. Villalba et al., 1990) the tree-ring dating of material directly affected by glacier activity has provided precise, calendar-dated estimates for moraine formation. However, in most cases the available moraine ages are minimum age estimates based on the age of the oldest tree or lichen growing on these deposits, or maximum ages from radiocarbon dating of subfossil material buried by the moraines.

The glacier histories discussed below contain inherent limitations in both the dating techniques used and the glacier records themselves (see Porter, 1981, 2000; Luckman and Villalba, 2001; for detailed discussions). For example, when ages of glacier deposits are determined using the age of living trees or lichens growing on their surface, a common source of dating uncertainty is the estimation of the lag time between moraine stabilization and tree or lichen establishment (also known as “ecesis”, Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993). Ecesis estimates in studies of Patagonian glaciers range from a few years to several decades, but very few studies have used a direct, site-specific ecesis correction factor (see Koch and Kilian, 2005). Dates obtained from radiocarbon determinations for the past millennium may also be ambiguous and subject to errors of over 100 years (e.g. Porter 1981; Luckman and Villalba, 2001). As in many cases younger LIA advances overrode the evidence of earlier events, the surface record available for analysis is usually truncated. In addition, as the record from individual glaciers contains unique elements due to topography, debris cover, conditions at the glacier front or other factors, an adequate sample base of glacier histories is needed to provide a reliable regional picture of glacier fluctuations. Advances of surging and calving glaciers often complicate analyses of regional patterns of fluctuations as they generally respond to very specific, non-climatic factors (Warren, 1994; Warren and Rivera, 1994; Warren et al., 1995; Naruse and Skvarca, 2000; Rignot, et al., 2003; Benn et al., 2007). These issues result in reconstructions of glacier histories that usually vary in detail, quality and dating precision even within the last millennium. This should be taken into account when interpreting regional and local glacial histories (Luckman and Villalba, 2001).

The increasing detail and availability of satellite imagery during the past 30 years has provided very useful tools for the inventory and monitoring of glaciers, especially in numerous areas with difficult access in the extratropical Andes. However, extensive portions of this mountain range still lack detailed, up-to-date glacier inventories. The existing inventories are of variable degree of detail and have been developed based on field surveys, maps, aerial photographs and satellite imagery (e.g. Bertone 1960; Rabassa, 1981; Corte and Espizua, 1981; Espizua, 1982; Aguado, 1983; Cobos and Boninsegna, 1983; Valdivia, 1984; Aguado, 1986; Casassa, 1995; Aniya et al., 1996; USGS, 1998; Casassa et al., 2002b; Rivera et al., 2007; Schneider et al., 2007; Bown et al., 2008). For some areas, remote sensing techniques complemented with the detailed mapping and the dendro-geomorphological dating of moraines have provided quantitative information of changes in glacier extent during recent centuries (see e.g. Masiokas et al., 2009-this issue).

4. Desert Andes (17° to 31°S)

Glaciers are sparsely distributed on both sides of the Desert Andes between 17° and 31°S. At around 18°S there are a few cold-ice glaciers, often located on active volcanoes such as Volcán Parinacota (18°10′S). This volcano supports one of the biggest glacier areas with 6.6 km^2 of ice in 2003 (Fig. 1). Several summits rise well above the 0 °C isotherm between 19° and 27°S. However, the low precipitation is often insufficient to nourish glaciers, even at altitudes above 6000 m (Jenny and Kammer, 1996). Small active and inactive rock glaciers occur on Volcán San Pedro and Volcán San Pablo (21°53′S, Fig. 1). Payne (1998) reports an active rock glacier reaching a minimum altitude of 4525 m in that area. Garín (1987) inventoried several small snow fields and glacierets, some of them located near the summits of Volcán Llullaillaco at 24°43′S (Lliboutry, 1956; Grosjean et al., 1991) and Volcán Ojos del Salado at 27°05′S (Lliboutry et al., 1958) (Fig. 1). Between 27°S and 31°S, the greater winter precipitation levels and the existence of peaks reaching elevations higher than the modern snowline allow the occurrence of a larger number of glaciers. The Río Copiapó basin in Chile contains several glacierized peaks such as the Nevados Tres Cruces (27°06′S) with 1.1 km^2 of ice in 2000, Cerro El Potro (28°23′S) with 11 km^2 of ice in 1983 (Jenny and Kammer, 1996) and Cerro Tronquitos (28°30′S) with several small glaciers (Fig. 1).

Brüggen (1928), Lliboutry et al. (1958) and Mercer (1967) provide early descriptions and useful information for the assessment of historical variations of glaciers in the Desert Andes. In addition, the analysis of aerial photographs — the earliest flight dating from 1955 — and recent satellite images have allowed the identification of an important number of small glaciers and snow fields in this region. These ice masses have shown a general retreating pattern over recent decades at rates that vary between 4 and 35 $m yr^{-1}$ (Rivera et al., 2000). Glaciar Tronquitos (2.7 km^2 in 2002) is recording the largest glacier retreat in this area (Fig. 2a).

The upper basin of Río Huasco in Chile (~29°S, Fig. 1) contains about 15 km^2 of ice. Glaciar Guanaco (29°21′S; ca. 1.8 km^2 in 2005) is one of the

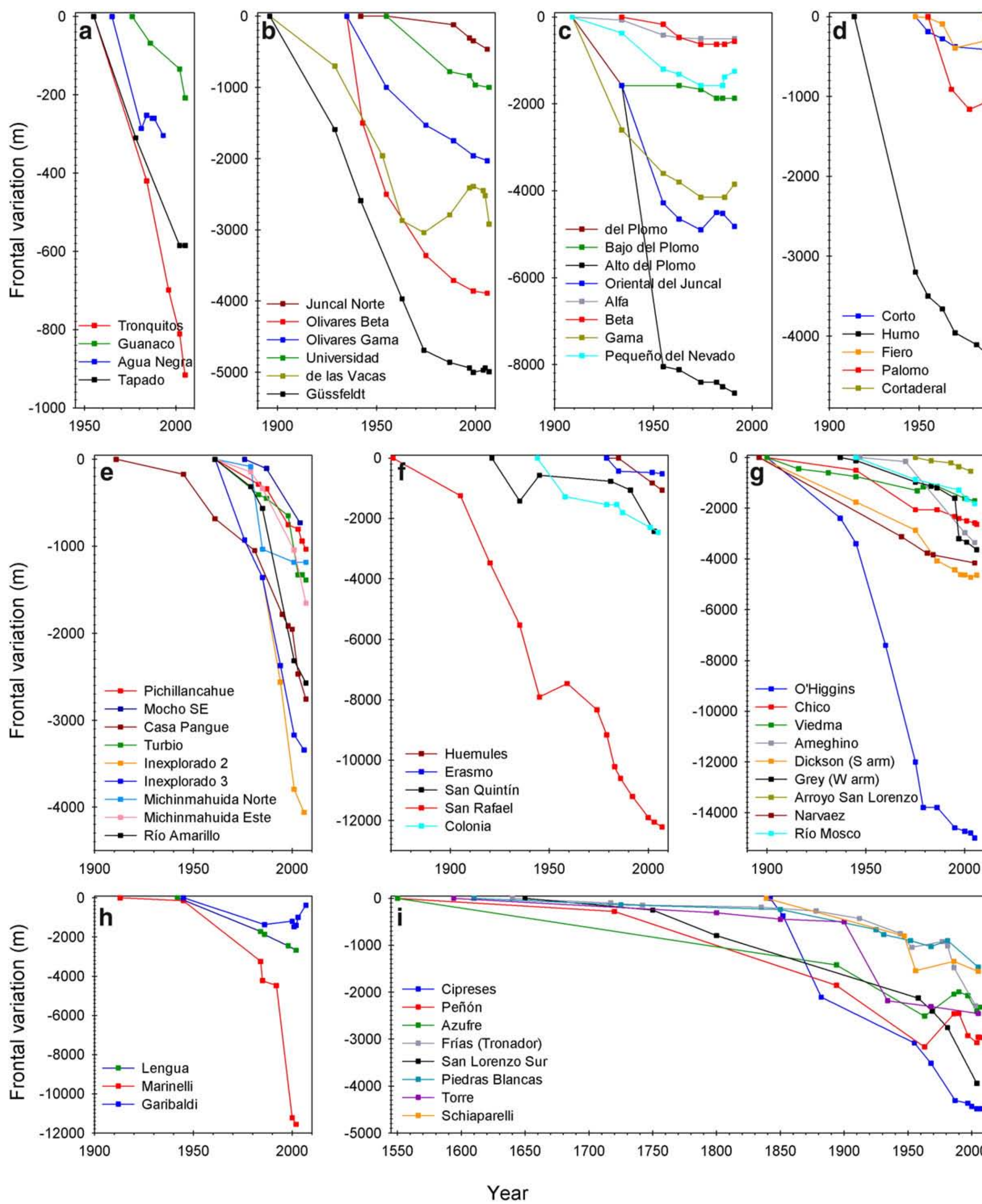

Fig. 2. Frontal variations of selected glaciers in the extratropical Andes of South America. (a) Desert Andes; (b–d) Central Chilean–Argentinean Andes; (e) North Patagonian Andes; (f–g) North and South Patagonian Icefields and surrounding glaciers; (h) Magallanes region. (i) shows the records longer than 150 years and includes glaciers from all regional subdivisions except the Desert Andes. Note that not all glaciers displayed in the figures are mentioned in the text (see Appendix A for details). Glaciers of known or suspected surging activity or those with clearly anomalous behaviour were not included (see text).

biggest glaciers in this area and, similarly to other smaller neighboring glaciers, has retreated at an average rate of about 7 m yr^{-1} during recent decades (Fig. 2a).

Espizua et al. (2006) focused on Los Amarillos, Guanaco (the Argentinean portion of the same glacier discussed above), Canito and Potrerillos glaciers in the Canito and Turbio basins in Argentina (29°20′S). These small glaciers (<1 km^2 in area) are between 1.2 and 1.7 km long and range between 5550 and 4775 m in elevation. Using aerial photographs from 1959 and more recent satellite imagery, Espizua et al. (2006) documented a general reduction in glacier area between 1959 and 2005. Glaciar Canito has shown the greatest relative reduction — approximately 33% of its area during this interval.

Colqui (1965) described the glaciers of the Quebrada de Agua Negra in Argentina (30°10′S) and drew the first map of this area using a phototheodolite. Glaciar Agua Negra is the most studied glacier of this area and is currently ca. 2.3 km long, 550 m wide on average, and extends from 4970 to 4600 m. Based on analyses of aerial photographs and a digital terrain model, Leiva (1999) estimated that this glacier retreated 286 m between 1965 and 1981, advanced 34 m between 1981 and 1984, showed little change from 1984 to 1988, and retreated slightly between 1988–1993 (Fig. 2a). Analysis of recent photographs shows a subsequent, noticeable reduction of this glacier despite the occurrence of several warm El Niño-Southern Oscillation (ENSO) episodes that generally bring heavy snow accumulation to the region (Leiva, 1999).

5. Central Chilean–Argentinean Andes (31°–36°S; 'Central Andes' sensu Lliboutry)

The number of glaciological studies in the Andes adjacent to Santiago (and in the Central Chilean Andes in general) has increased substantially in recent years. However, few glacier variations have been studied in detail. Glaciar Juncal Norte (33°S) in the Río Aconcagua basin, Chile, was first described in 1942 by Pfenniger (Lliboutry, 1956). The partially debris covered terminal portion of the glacier is ca. 2 km long, 500 m wide and 186 m thick (Rivera et al., 2001). This glacier has retreated at rates between 4 and 20 m yr^{-1} and lost 1.46 km^2 between 1955 and 2006 (Bown et al., 2008). Historical records dating from the 1940s (Lliboutry, 1956) are also available for glaciers on the southern flank of Nevados de Juncal in the upper part of the Río Maipo basin, Chile (Fig. 1). The biggest glacier in this area is Juncal Sur (22.7 km^2 in 2006), which experienced a sudden advance in 1946/47 during which the lower tongue expanded by ca. 1 km^2 (Fig. 3). This advance partially dammed Río Olivares, forming a small lagoon that had totally disappeared by 1954 (Lliboutry, 1956). Recent analyses indicate that the glacier has been receding almost continuously since 1947 with the greatest rates of recession at the beginning of the series (Fig. 3). The lower glacier surface thinned by ca. 1 m yr^{-1} from 1955 to 1997 (Rivera et al., 2002). In the same area, Glaciar Olivares Beta and Glaciar Olivares Gama had an area of 9.9 and 12.8 km^2 in 2006, respectively. According to Lliboutry (1956) both glaciers were still joined in 1935. Glaciar Olivares Beta has retreated almost 3.9 km between 1935 and 2006, whereas Glaciar Olivares Gama has retreated ca. 2 km over the same interval (Fig. 2b) and thinned by ca. 0.7 m yr^{-1} between 1955 and 1997 (Rivera et al., 2002). The longest record of historical variations in this region has been compiled for Glaciar Cipreses (34°33′S, Fig. 2i) in the Río Cachapoal basin, Chile. First described in 1842, this glacier had retreated almost 4.4 km by 2004 (Rivera et al., 2006b; Le Quesne et al., 2009-this issue). Röthlisberger (1986) describes at least four moraine systems on both margins of this glacier. Buried by the inner left lateral moraines he found a palaeosoil section that was dated to 625±

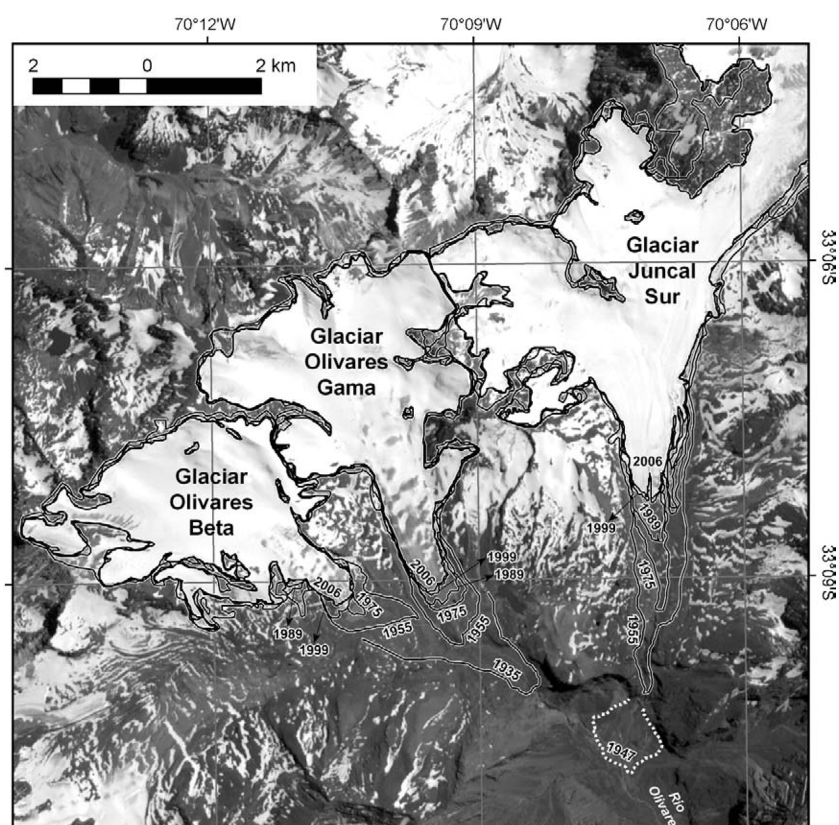

Fig. 3. Twentieth-century variations of the Olivares Beta, Olivares Gama and Juncal Sur glaciers in the upper Río Maipo basin, Central Chilean Andes.

155 ^{14}C yr BP and used to infer a glacier advance around or after that date. A subsequent advance in 1858 was documented by Pissis (1875). This event was roughly concurrent with a sudden advance of Glaciar Los Piuquenes in 1848 (some 30 km northeast of Glaciar Cipreses; Plagemann, 1887). The Piuquenes advance was considered a "surge" by Röthlisberger (1986) and according to Plagemann's description it was accompanied by a disastrous outburst flood. Lliboutry (1958) studied Glaciar Universidad (34°42′S; 70°49′W) in the Tinguiririca basin and reported a sudden advance of the glacier in 1943. After this event the glacier front receded approximately 2 km between 1945 and 2004 (Le Quesne et al., 2009-this issue; Rivera et al., 2002).

On the eastern slopes of the Central Chilean–Argentinean Andes, annual precipitation is lower, ranging from about 400 mm at 31°–33°S to 1000 mm at 35°–36°S (Ereño and Hoffmann, 1976). Many of the lower glacier tongues are partially or completely covered by debris. Glacier inventories for selected river basins between 31° and 34°S have been developed by Cobos (1981), Corte and Espizua (1981), Espizua (1982), and Aguado (1983, 1986). Glaciar Piloto Este, in the Río de las Cuevas basin (32°27′S), covers ca. 1.4 km^2 and ranges between 4800 and 4185 m in elevation. This glacier is the only ice mass with a mass balance record longer than 10 years in the Argentinean Andes (Leiva, 1999, Leiva et al., 2007). Starting in 1979, this record shows a predominance of negative annual net mass balances which have resulted in marked glacier shrinkage over the past three decades (Leiva et al., 2007).

Fluctuations of the east-facing Glaciar de las Vacas and Glaciar Güssfeldt, located 10 km east of Glaciar Piloto Este in the vicinity of Cerro Aconcagua (6959 m; Fig. 1), have been studied by Espizua and Maldonado (2007). Their study used a combination of historical information that includes photographs from many sources [including Fitz Gerald (1899) who photographed and drew a sketch map of both glaciers in 1896–1897], aerial photographs from 1963 and 1974, Landsat images, and field observations. Between 1896–1897 and 2005, Glaciar de las Vacas and Glaciar Güssfeldt have experienced a marked overall retreat only interrupted by minor advances or standstills (Figs. 2b and 4). Glaciar de las Vacas retreated ca. 3040 m between 1896 and 1974, advanced ca. 690 m between 1974 and 2003, and retreated slightly after 2003. Glaciar Güssfeldt retreated ca. 5000 m between 1896 and 1999 and showed little change during 1999–2005 (Espizua and Maldonado, 2007; see Espizua and Pitte, 2009-this issue, for more details). Glaciar Horcones Inferior (32°40′S), located below the south face of Cerro Aconcagua, is a well-documented case of a surging glacier. It experienced a rapid advance of several kilometers between 1984 and 1989 (Happoldt and Schrott, 1993; Unger et al., 2000; Llorens, 2002) and a new and more extensive surge event in 2004–2006 (Espizua et al., 2008).

The Río del Plomo basin (32°57′S, Fig. 1) was first studied by Helbling in 1909 who published a detailed 1:25,000 map based on a terrestrial photogrammetric survey (Helbling, 1919). Espizua (1986) reconstructed 20th-century glacier fluctuations in this basin using aerial photographs and the information provided by Helbling (1919) and Reichert (1929). She indicates that between 1909 and 1974 the glaciers in the Río del Plomo basin experienced a generalized retreating pattern (Fig. 2c). In 1909 Glaciar del Plomo was 16.5 km long and 15 m thick at its terminus which was at an altitude of 3160 m. The body of this glacier was originally formed by the confluence of four major valley glaciers, but between 1909 and 1934 the main glacier retreated ca. 1580 m and separated from one of its tributaries, Glaciar Grande del Juncal. Between 1934 and 1955 the recession of Glaciar del Plomo continued and glaciers Bajo del Plomo, Alto del Plomo and Oriental del Juncal were formed as independent ice bodies. Helbling (1919, 1935, 1940) indicates that Glaciar Grande

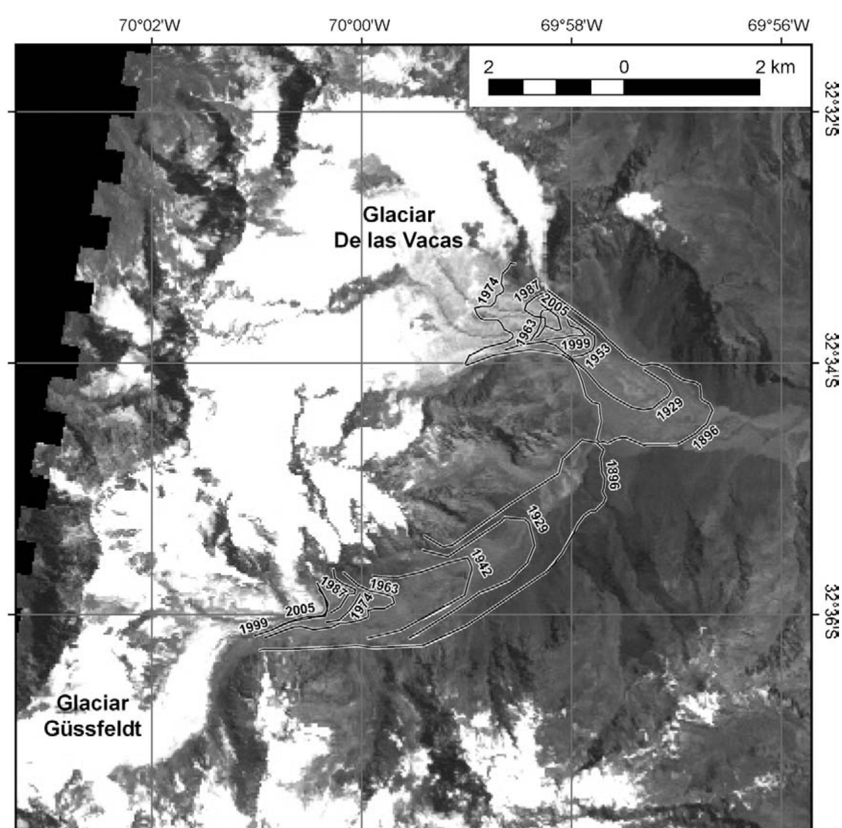

Fig. 4. Landsat 5 TM image showing the fluctuations between 1896 and 2005 of Las Vacas and Güssfeldt glaciers, Aconcagua region, Central Argentinean Andes (based on Espizua and Maldonado, 2007).

del Juncal advanced approximately 500–1000 m in 1910 whereas Espizua (1986) deduced another advance between 1934 and 1955 as the snout was about 140 m downvalley of the 1934 position in 1955. On January 10, 1934, a disastrous glacial lake outburst flood affected the human settlements located along the valley of Río Mendoza. The flood started in the tributary Río del Plomo valley by the sudden discharge of a 3 km-long lake dammed by Glaciar Grande del Nevado, which had advanced ca. 900 m beyond its 1912 position (Helbling, 1935, 1940). Based on aerial photographs, Espizua (1986) identified another advance of the glacier front of ca. 1050 m between 1963 and 1974. As other adjacent glaciers experienced a marked retreat over the 1909–74 period (Fig. 2c), Espizua (1986) suggested that the isolated advances of the Grande del Juncal and Grande del Nevado glaciers were glacier surges. The evolution of another, recent surge of Glaciar Grande del Nevado was documented using Landsat imagery. Following a sudden advance of ca. 2.7 km from its 1974 position, the glacier dammed Río del Plomo in November 1984 and created a new, 2.8 km-long lake that drained gradually through a natural subglacial tunnel in March 1985 (Espizua and Bengochea, 1990). Llorens and Leiva (1995) updated the mapping of glacier front positions in this area using satellite images and aerial photographs for the period 1974–1992. They report a relatively synchronous reactivation of the glaciers in this area starting in 1982–85 that lasted in some cases until 1991. Videla (1997) analyzed historical documents, photographs and field observations from the upper Río del Plomo valley. They did not recognize moraines or other glacial deposits outside the 1909 limit and suggested that glaciers in this area probably reached their Late Holocene maximum extent at the beginning of the 20th century. However, Espizua (1986) describes three terminal recessional moraines within 1 km of the 1909 glacier margin indicating older and more extensive advances.

Ferri Hidalgo et al. (2006) studied the fluctuations of several glaciers surrounding Cerro Tupungato (6800 m; 33°15′S; Fig. 1) using historical material from 1912, aerial photographs from 1963 and Landsat satellite imagery for the period 1987–2005. Their analyses showed that these glaciers have followed a general retreating pattern for most of the 20th century. This pattern appears to have slowed down in recent years as most glaciers have remained in nearly stable positions (Ferri Hidalgo et al., 2006). Llorens and Leiva (2000) also studied the Tupungato glaciers together with those on the nearby Cerro Tupungatito and Cerro San Juan using aerial photographs and satellite imagery for the period 1963–94. They report that the glaciers fronts advanced between 1982 and 1985 but retreated slightly between 1986 and 1993. Earlier advances for this area were reported by Lliboutry (1954, 1958), who identified a 1935 advance of ca. 5 km for Glaciar Río Museo (Tupungato massif), and a 1927 advance of 4–5 km for Glaciar Colina (south of Volcán San José, Marmolejo massif). Gargantini (2008) studied the 1963–2007 frontal variations of five glaciers in the Río Tunuyán Sur basin (33°40′S). He found that these glaciers have experienced an overall marked retreat but recorded readvances during 1987–1999.

Twentieth-century glacier fluctuations in the Río Atuel basin (34°20′–35°20′S, Fig. 1) were discussed by Cobos and Boninsegna (1983) based on historical information, aerial and field photographs and a detailed 1:2000 map. Groeber (1947, 1954) also studied the area and observed that in 1914 Glaciar Corto and Glaciar Humo were originally merged into a single terminal tongue, but by 1934 they had receded and separated. Cobos and Boninsegna (1983) estimate that Glaciar Humo retreated by ca. 3200 m between 1914 and 1947 (Fig. 2d). Groeber (1947, 1954) described Glaciar Fiero, also in the Atuel basin, as having in 1937 a tongue covered with detritus. Subsequent analyses at this site indicate that this glacier retreated between 1948 and 1970 and has continued retreating until recent times. The glacier located on the southwestern slope of Volcán Overo (4800 m, Fig. 1) also receded between 1948 and 1970 (Cobos and Boninsegna, 1983). Another glacier studied in the Atuel basin is Glaciar Laguna, which in 1914 was located only a few meters away from the shoreline of Laguna Atuel. This glacier showed a gradual retreat between 1914 and 1970 but advanced ca. 1400 m sometime between 1970 and 1982 (Cobos and Boninsegna, 1983). The magnitude of change and the fact that most glaciers in the basin retreated over this interval suggest that this recent Glaciar Laguna advance is probably a surging event. Le Quesne et al. (2009-this issue) document the continued recession of glaciers in this basin.

The glaciers in the Río Grande basin (~35°S) have attracted the attention of explorers and scientists since the end of the 19th century (Burckhardt, 1900; Gerth, 1931), but it was not until recently that glaciological studies started in this area. Glaciar El Peñón, located at Volcán Planchón–Peteroa (4138 m, Fig. 1), and Glaciar El Azufre have shown a complex history of fluctuations embedded in an overall retreating pattern between 1894–1897 and 2005 (Espizua and Maldonado, 2007). These glaciers retreated in 1894–1963, advanced between 1963 and 1986, remained nearly stationary between 1986 and 1990, retreated from 1990 to 2004 and remained nearly stable during 2004–2005 (see Figs. 2i and 5; and Espizua and Pitte, 2009). The occurrence and outline of the maximum LIA extent in El Azufre and El Peñón glaciers, and in the nearby Las Choicas and Las Damas valleys, have been determined from geomorphological analyses, radiocarbon determinations of basal peat samples, and field surveys of terminal and lateral moraines (Espizua, 2004; Espizua, 2005; Espizua and Pitte, 2009-this issue). Based on this evidence, the LIA maximum at these sites was tentatively dated to between 1550 and 1720, with a subsequent advance around 1830. The relatively similar dating, the freshness of the landforms and the proximity to the present glacier fronts led Espizua and Pitte (2009-this issue) to indicate that these advances could correspond to a relatively synchronous glacier reactivation during the LIA in the four valleys of the Río Grande basin.

6. The North Patagonian Andes (36°–45°S)

Interestingly, in the North Patagonian Andes, the available information for regional glacier fluctuations is more detailed and complete for the time of the last glacial maximum (see e.g. Denton, 1999 and references therein) than for the past few centuries. Very few studies have focused on glacial fluctuations of the last 1000 years (e.g. Rabassa et al., 1984; Villalba et al., 1990; Masiokas et al., in press) for which the available glacial evidence is usually relatively abundant, well preserved and most easily dated. There is, however, a relatively rich record of historical photographs of glaciers in this region that has been used successfully to document historical changes in glacier cover (e.g. Rabassa, 2007; Masiokas et al., 2008).

In northern Chilean Patagonia there has been a considerable reduction in glacier area over the past ~150 years. Philippi (1863) reported that glaciers at Nevados de Chillán (36°56′S, Fig. 1) had an area of ca. 30 km^2 in 1862 which had been reduced to ca. 6 km^2 in 2004 (Zenteno et al., 2004). Further south, the glaciers at Sierra Velluda (37°28′S, 71°25′W) were first surveyed in 1828 by Poeppig (1835) and a comparison of his drawings with photographs taken in 1950 also shows a marked reduction in glacier area (Poeppig, 1960). A systematic glacier mass balance program complemented with studies of frontal and surface elevation changes is presently been conducted at the glaciers in the active, ice-capped Villarrica (39°25′S) and Mocho–Choshuenco (39°55′S) volcanoes (Rivera et al., 2005a, 2006a, Fig. 1). These studies have determined a thinning rate of 0.81 ± 0.45 m yr^{-1} for Glaciar Pichillancahue–Turbio at Volcán Villarrica between 1961 and 2004 and an area loss of 13% between 1979 and 2005 (Fig. 2e). Glaciar Mocho at Volcán Mocho–Choshuenco has lost 17% of its area between 1976 and 2004 (Rivera et al., 2006a; Fig. 2e). At similar latitudes on the Argentinean side of Volcán Lanín (39°39′S, Fig. 1), a drastic ice mass loss of Glaciar Lanín Norte between 1896 and 2001 has been documented through the use of repeat photographs and historical documents (Masiokas et al., 2008).

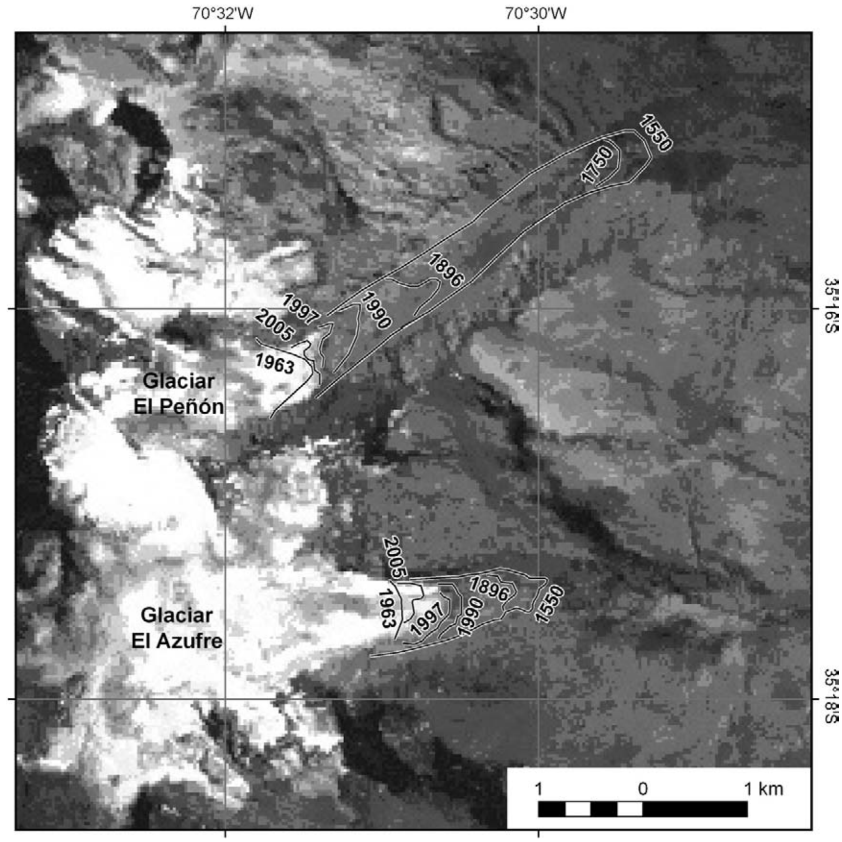

Fig. 5. Landsat 5 TM image showing the fluctuations since ~1550 of El Azufre and El Peñón glaciers, Río Grande basin, Central Argentinean Andes (based on Espizua and Maldonado, 2007).

Monte Tronador (41°10′S, Fig. 1) is covered by a thick icecap which feeds several glaciers that flow into Chile and Argentina. The first detailed glaciological study in this area was carried out in the late 1950s by Lawrence and Lawrence (1959), who dated the moraines of Glaciar Río Manso (41°12′S, 71°51′W) using tree-ring records and tephrochronology. Several subsequent studies have focused on the Tronador glaciers (e.g. Rabassa et al. 1978, 1984; Villalba et al. 1990; Bown, 2004; Bown and Rivera, 2007; Masiokas et al., in press) but a relatively detailed chronology of LIA and post-LIA fluctuations is available only for Glaciar Frías (41°09′S, 71°48′W) and Glaciar Río Manso (also known as Ventisquero Negro) on the Argentinean side of the mountain.

Villalba et al. (1990) used dendroglaciological techniques to develop a detailed chronology of fluctuations for Glaciar Frías during the past ~1000 years. Based on careful field surveys, air photo interpretation, and the tree-ring dating of living trees in the glacier forefield, they identified at least nine glacier events during the past millennium (Figs. 2i and 6). The maximum LIA extension was tree-ring dated to 1638–39 using an ice-scarred tree and other living trees growing on the moraine. Inside this peak LIA ridge, another living tree, that was also apparently impacted by ice ca. 1719–21, provided a precise limiting date for a younger moraine system. Villalba and collaborators found that increased annual growth of local *Fitzroya cupressoides* trees was positively correlated with cool and wet climatic conditions in this region. This relationship (wider rings during cool/wet periods) associated with the age of the oldest trees on inner moraines was used for dating subsequent readvances to ca. 1742–52, 1835–43, 1878–84, 1912–16 and 1941–43. A later readvance that culminated in 1976–77 was precisely identified from direct measurements of the ice front position (available for 1976–1986) and the tree-ring patterns of another ice-damaged tree (Fig. 6). Several *in situ* and reworked stumps were recently found buried within the most external LIA moraine and immediately outside an outermost pre-LIA moraine (assumed to have been formed before 1236 based on the age of the oldest tree sampled on this deposit; Villalba et al., 1990). This material is currently being processed and could provide key information to improve the dating of these outermost moraines.

Glaciar Castaño Overo (41°11′S, 71°49′W) is approximately 4 km south of Glaciar Frías. Until about the mid 1980s, the lower portion of the glacier was a regenerated ice cone below a 200 m high bedrock cliff. This cone has completely disintegrated in recent years (Rabassa, 2007; Masiokas et al., 2008). Rabassa et al. (1984) identified a series of terminal and lateral moraines downvalley of this cone on the south margin of the glacier. Using a tentative relationship based on the diameters of trees growing on these deposits, they concluded that the most extensive LIA event at this glacier occurred ca. 1818–29. Four sub-parallel moraine systems located inside these main LIA deposits were tentatively dated to ca. 1842, 1857, 1884 and 1902 (Rabassa et al., 1984). On the south side of the glacier cone Röthlisberger (1986) found a small in situ stump and some roots that were ^{14}C dated to “modern” times, suggesting that a recent glacier advance might have overridden these samples.

Masiokas et al. (in press) focused on Glaciar Río Manso and used field surveys, dendrochronology and the analysis of historical and aerial photographs to update earlier work by Lawrence and Lawrence (1959), Rabassa et al. (1984) and Röthlisberger (1986) and develop a well dated chronology of LIA and post-LIA glacier fluctuations at this site. The tree-ring dating indicates that the most extensive glacier expansion of the past several centuries took place between the late 1700s and the 1830–40s as the glacier thickened and advanced into adjacent forests. Tree-ring dating of overridden *in situ* snags on the inner flank of the north lateral moraine provides a maximum age of 1789 for this event and a tilted tree and

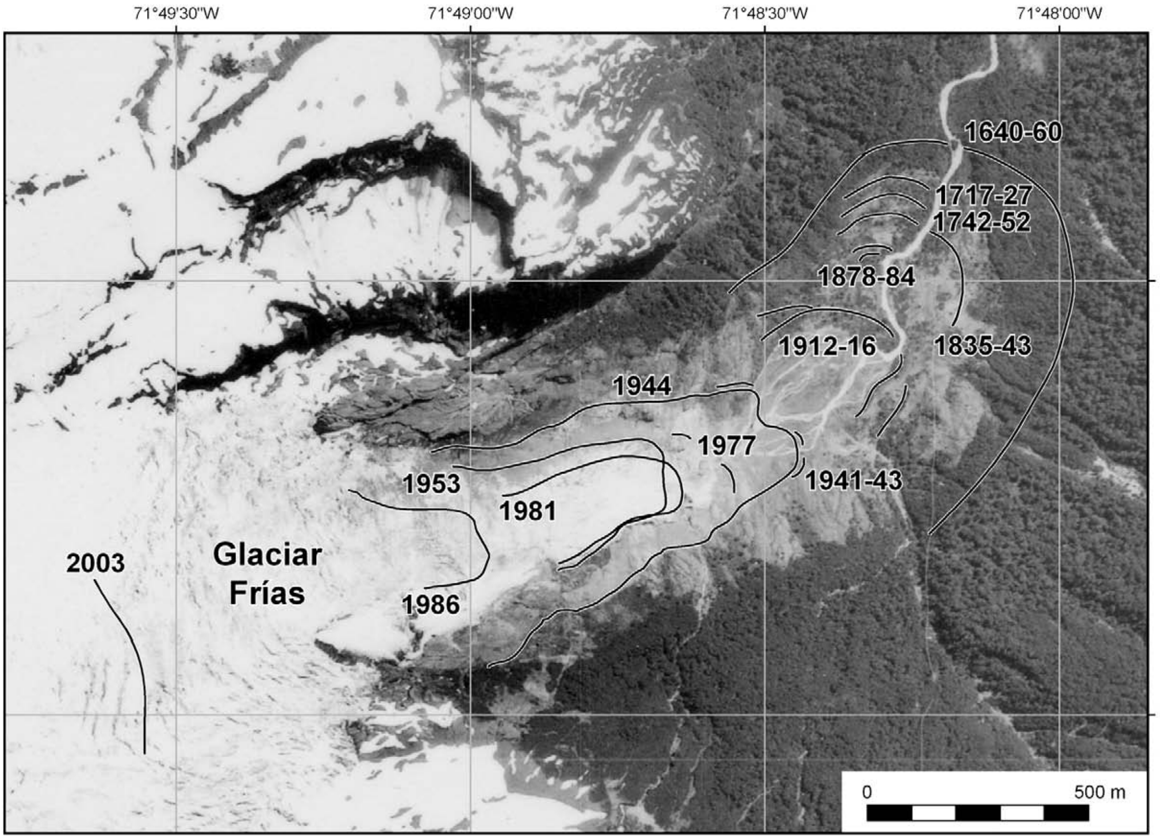

Fig. 6. Fluctuations of Glaciar Frías in the Monte Tronador area, North Patagonian Andes, during the past four centuries (updated to 2003 from Villalba et al., 1990).

stumps drowned by an ice marginal lake indicate that this glacier advance culminated in the 1840s. Living trees growing on this moraine indicate that the glacier was already in recession by the mid 1850s, providing closely bracketed dating control for this event. The only morphological evidence for earlier glacier activity at this site during the last millennium comes from a south lateral moraine section that is at least 300 years old (based on the oldest trees growing on its surface; Masiokas et al., in press). In addition, Röthlisberger (1986) reports ^{14}C dates from *in situ* stumps located on the proximal slope of the north lateral moraine and suggests that they indicate at least three glacier events occurring around (or soon after) 950, 600 and 300 ^{14}C yr BP. A series of moraine ridges on the southern flank of the glacier provided evidence for several post-LIA readvances that were tree-ring dated to ca. 1875, 1890, 1899, 1919, 1949, 1955, and during the mid 1970s. A more recent advance has been tentatively dated to the late 1990s (from aerial and field photographs; Masiokas et al., in press).

Despite the occurrence of several readvances during the 20th century, the Tronador glaciers have experienced an overall retreating trend over this interval, as documented by Masiokas et al. (2008) using photographs of early views of Frías, Castaño Overo and Río Manso glaciers (see also Rabassa 2007). On the Chilean side of Monte Tronador, old photographs dating back to 1898, aerial photographs and satellite images were used to reconstruct the frontal variations for Glaciar Casa Pangue: the total retreat amounts to 2.7 km between 1911 and 2007 (Rivera et al., 2002; Fernández et al., 2006; Rivera et al., 2008; Fig. 2e). The partially debris-covered lower tongue of the glacier (extending from ca. 1100 to 700 m) has thinned at a rate of 3.6 ± 0.6 m yr^{-1} between 1981 and 1998 (Bown and Rivera, 2007).

Information about LIA glacier fluctuations in the southern sector of the North Patagonian Andes is only available for Glaciar Esperanza Norte and Glaciar Torrecillas on the eastern side of the Andes. Esperanza Norte (42°15′S, 72°10′W) is a small, land terminating glacier located in the Cordón de las Agujas range (Fig. 1). Field surveys indicate up to eleven morainic systems in front of the glacier snout. Tree-ring dating of these moraines is currently in process and preliminary results suggest the outermost ridge has been formed in the early 17th century. Several *in situ* stumps that were uncovered by the proglacial stream were found immediately outside this outermost moraine. One of these stumps has been dated to 375 ± 40 ^{14}C yr BP, which provides complementary evidence for the dating of this event.

Glaciar Torrecillas (42°40′S, 71°55′W, Fig. 1) was first described by Colqui and Madejski (1952). The glacier forefield is characterized by the presence of well-defined lateral trimlines and at least nine, relatively recent moraine ridges. Preliminary results from tree-ring samples collected on these deposits have been presented by Masiokas et al. (2000) but have been complemented by more recent sampling. The results indicate that the outermost moraine associated with the most extensive LIA expansion formed before 1738. Garibotti and Villalba (2009) also studied this area and developed a chronosequence for the formation of the moraines using lichens of the species *Rhizocarpon*. Their analysis represents the first attempt to develop and apply lichenometric curves of this species for dating glacier fluctuations in the Patagonian Andes. Vegetated soil covering the surface of the outermost moraine hampered the use of lichens for dating this surface but samples from the inner ridges indicate they formed before 1735, 1755, 1891, 1900, 1906, and 1934, respectively. An additional, inner ridge has been dated to ca. 1937 based on historic photographs (Garibotti and Villalba, 2009). Several *in situ* stumps were found buried by glacial outwash approximately 600 m downvalley from the outermost moraine (Masiokas et al., 2000). The outer portion of one of these stumps dated to 440 ± 30 ^{14}C yr BP and provides additional, complementary evidence for the occurrence of an earlier, less extensive glacier advance that was apparently obliterated during the maximum LIA expansion.

In Chile, the southern portion of the North Patagonian Andes has several active volcanoes with glaciers in their calderas or on their flanks. However, most glaciers are associated with non-volcanic mountains, such as those near Lago Inexplorado (41°58′S, Fig. 1). Glaciar Inexplorado has shown an overall recession (with rates of up to 176 m yr^{-1}) since 1961 when it covered almost the entire upper valley of Río Blanco (Rivera et al., 2008). This glacier was formed by two main streams that separated after 1985 and were still receding in 2006, yielding total retreats between 1961 and 2006 of 3340 m and 4060 m for the southern and northern tongues, respectively (Glaciar Inexplorado 3 and 2, Fig. 2e). The glaciers on Volcán Michinmahuida (42°48′S; Fig. 1) have also shown noticeable recent retreats. Over the past three decades, this volcano has lost ca. 13% of its total glacierized area (from 93.3 km^2 in 1979 to about 81.4 km^2 in 2007). The largest glacier in this area is the south facing Glaciar Amarillo (Fig. 2e). Over the past two centuries, this glacier has been affected by several lahars during eruptive events of the volcano (González-Ferrán, 1995). Between 1961 and 1985, the lower tongue of Glaciar Amarillo was partially debris covered but is currently a stagnant ice mass detached from the main glacier body (Fernández et al., 2006; Fig. 2e).

7. The South Patagonian Andes (45°–55°S)

The southern portion of the Patagonian Andes supports a very large number of glaciers including three major icefields (Lliboutry, 1998; Fig. 1). The description of past glacier variations along this extended region is divided into five sub-regions to facilitate the interpretation of results.

7.1. Glaciers north of the North Patagonian Icefield

The region north of the North Patagonian Icefield contains many poorly known glaciers, such as those at Volcán Melimoyu, Volcán Maca and Volcán Hudson (González-Ferrán, 1995; Fig. 1). One of largest glacierized areas is located within the 10-km wide caldera of Volcán Hudson (45°54′S), which is the most active volcano in southern Chile (Stern, 1991). This volcano has experienced major eruptions in 1971 and 1991 that generated large lahars due to the melting and collapse of the ice (Naranjo et al., 1993). The main outlet is Glaciar Huemules which extends 8 km west from the caldera and is partially covered by ash and volcanic material from the recent eruptions (Fig. 2f). In 2005, the total area of Glaciar Huemules was ca. 65 km^2 — approximately 25% smaller than in 1979 — with most of the areal loss occurring after the 1991 eruption (Rivera et al., 2006c). Glaciar Erasmo (46°07′S) is located in a non-volcanic setting south of Volcán Hudson. This glacier has a size of approximately 45 km^2 and has lost ca. 15% of its area between 1979 and 2005 (Rivera et al., 2006c; see Fig. 2f for frontal retreat values).

7.2. The North Patagonian Icefield (NPI)

The first aerial photographs of the NPI (Fig. 1) were obtained in 1944/45 by the US Air Force. These photographs allowed the first complete compilation of the glaciers of the NPI (Keller, 1947; Lliboutry, 1956). This compilation has been subsequently updated and improved by Aniya (1988) and Rivera et al. (2007). According to Rivera et al. (2007) the NPI is formed by 70 glaciers with a total area of 3953 km^2 in 2001.

Glaciar Reichert (46°30′S, 73°35′W) and Glaciar Gualas (46°33′S, 73°39′W) are two contiguous outlet glaciers on the northwestern portion of the NPI. Harrison and Winchester (1998) provide a tree-ring based minimum age estimate of ca. 1876 (ecesis 6 years) for a conspicuous vegetation trimline observed at Glaciar Reichert. Trees growing on two moraines below this limit in front of the proglacial lake indicate that these deposits were free of ice by ca. 1930 and 1970. An additional readvance was tentatively dated to ca. 1953. At Glaciar Gualas, Harrison and Winchester (1998) obtained a similar exposure tree-ring date of ca. 1876 for an upper trimline and a 1909 date for another trimline below the 1876 feature. Glacier retreat from a third, lowest trimline was tree-ring dated to between 1954 and 1964, which may correspond to a minimum age estimate of 1961 for low moraine ridges on the northern shore of the proglacial lake. Remnants of an apparently earlier event were dated to ca. 1936; and a more recent advance of Glaciar Gualas was observed by Harrison and Winchester in 1994.

Glaciar San Rafael (46°41′S) is the lowest latitude tidewater glacier in the world. Antonio Vea named the proglacial lagoon ("Laguna San Rafael") in 1675 and provided the first historical reference to a glacier from the NPI (Casassa and Marangunic, 1987). The first rough map of the lagoon and the glacier dates from 1766 (García, 1889), and the first lithograph of the glacier was produced by Captain Simpson from the Chilean Navy in 1871 (Simpson, 1875). Steffen (1909, 1937) published some of the first glaciological studies of the NPI and Brüggen (1936) compiled ice front variations until 1935 based on the earliest photographs of Glaciar San Rafael taken by Martin Gusinde in 1921(Reichert, 1924). Although different studies show some discrepancies regarding the historical positions of this glacier (see Winchester and Harrison, 1996), the differences are relatively minor compared to the general agreement that the glacier has followed an overall retreating pattern over the past ~130 years. However, some advances have been identified within this retreating pattern. Heusser (1960) reported the advance of the glacier against trees in 1959, and Winchester and Harrison (1996) indicated a standstill or slight advance on the north side of the ice front in 1991–93. Araneda et al. (2007) published a new interpretation of the historical variations of this glacier, concluding that Glaciar San Rafael reached the LIA maximum extent around 1875. Figs. 2f and 7 show an updated record of historical positions for Glaciar San Rafael.

Glaciar San Quintín (46°52′S, 74°04′W; also known as Glaciar San Tadeo) is located to the south of Glaciar San Rafael and was first mapped by Darwin (1839). It has also been described by Reichert (1924) and Brüggen (1950). The moraines and frontal variations of this glacier were studied by Winchester and Harrison (1996), who tree-ring dated the LIA maximum advance to the mid-1800s. They also identified a subsequent advance sometime between 1935 and 1945 based on aerial photographs and earlier reports and observed that the glacier advanced over vegetated ground during 1991–93. After this short period of advance, the snout has experienced a strong thinning and has started to disintegrate in place (Fig. 2f; Aniya, 2001; Rivera et al., 2007).

On the northeastern side of the NPI, Aniya et al. (2007) identified three main moraine systems in front of Glaciar Exploradores (46°30′S; 73°10′W). No conclusive dating control was provided for the formation of the outermost moraine, but Aniya and collaborators used two radiocarbon dates of 870 ± 60 and 820 ± 60 ^{14}C yr BP obtained from wood embedded in the second moraine (six samples were collected) and a rough estimate of the age of an associated tree, to postulate that this moraine was formed between the 12th and 17th centuries. The innermost moraine system was apparently formed in two pulses: seven ^{14}C dates (ranging between 108 and 147 ^{14}C yr BP) obtained from organic material associated with the moraines indicate the first pulse occurred during the early-mid 19th century and aerial photographs suggest the latest pulse took place after 1944 (Aniya et al., 2007).

Harrison et al. (2007) studied Glaciar Calafate in the Río Leones valley (46°44′S, 73°05′W) and identified two moraines in front of the glacier. Minimum ages derived from a combination of lichen and tree-ring dates indicate that these deposits probably formed prior to 1871 and 1925, respectively. Glacier recession after 1925 led to the formation of a moraine-dammed lake that was affected in 2000 by a

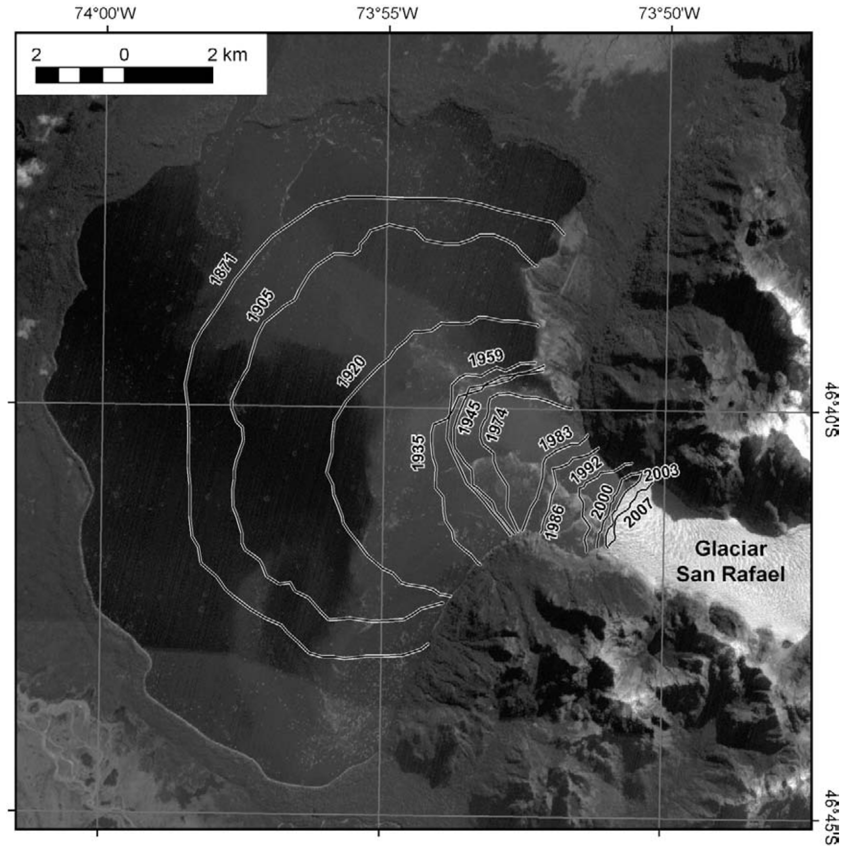

Fig. 7. Fluctuations of the tidewater Glaciar San Rafael, North Patagonian Icefield, Chile, during the past 136 years.

large rockfall which caused a catastrophic glacial lake outburst flood and deposited ca. 2 million m^3 of material along the Calafate and Río Leones valleys (Harrison et al., 2007). At the nearby Glaciar León, Harrison et al. (2008) used a combination of lichenometric, dendrochronological, cosmogenic and optically stimulated luminescence (OSL) techniques to provide a late-Holocene record of fluctuations for this calving glacier. Cosmogenic and OSL dates from a terminal moraine complex at the end of the 10-km long Lago Leones indicate glacier recession from these deposits after ca. 2500 yr BP. Three large, inner ridges were identified by bathymetric surveys on the lake floor between the lake-end moraine and the present glacier front. No dates are available for the outer two of these ridges but the inner one was identified as the LIA maximum extent and dated to ca. 1867 (using the age of a tree sampled on a small till-covered peninsula on the northern lakeshore ca. 3.5 km from the present ice front). As the glacier was in 1945 ca. 300 m from its 1991 position, Harrison et al. (2008) postulate that most of the post-LIA recession probably took place in the first half of the 20th century. They also identify a ca. 190 m advance of the ice front between 1994 and 1999 and a subsequent retreat of ca. 100 m for 1999–2000.

Radiocarbon dating of stumps in the forefield of Glaciar Soler (46°55′S, 73°09′W) provides one of the better indicators of "early LIA" glacier activity for this part of the Andes (Glasser et al., 2002). Seven samples of reworked wood collected from reworked glaciolacustrine sediments in front of the 1999 ice margin were dated to between 600 and 1015 ^{14}C yr BP and indicate that the glacier overrode the proglacial lake bed sometime during the earlier part of the past 1000 years. Two samples of trees with *in situ* roots plastered onto a large boulder immediately in front of the glacier were dated to 536 ± 40 and 782 ± 45 ^{14}C yr BP and, according to Glasser et al. (2002), constrain the period of glacier advance to between AD 1222–1342. Aniya and Naruse (1999) report a date of 270 ± 50 ^{14}C yr BP for tree leaves in a depression within the terminal moraine. They indicate that the LIA maximum advance occurred ca. AD 1650 but, given the context and type of evidence, this may not be a closely limiting dating control. More recent advances at Glaciar Soler were roughly dated to 1850, 1890, 1910, and 1940 using tree ages with an ecesis period of 50 years (Sweda, 1987).

Glaciar Nef (47°07′S, 73°11′W) is a 14-km-long outlet glacier on the eastern side of the NPI. This glacier has retreated ca. 3360 m between 1944 and 2000 (Aniya, 2001) which has led to the formation of a proglacial lake that is bordered by a complex moraine system comprising several moraine ridges. According to lichen dating estimates, Winchester et al. (2001) conclude that the outermost terminal ridge was formed before AD 1863. An additional minimum date of ca. AD 1884 was obtained for a ridge inside this outermost limit, and at least five more push ridges of decreasing height were identified between the 1884-limit and the lake shore. The innermost of these ridges beside the lake was dated using tree-rings and lichens to ca. 1935. The age of two mature trees growing along an older lateral moraine on the west valley side was extrapolated using the trees' diameter and an estimate of the number of missing rings from the pith. According to this preliminary evidence, Winchester et al. (2001) suggest that the lateral moraines may have been deposited prior to AD 1370.

Harrison and Winchester (2000) studied the variations of three adjacent glaciers (Colonia, Arenales and Arco) on the southeaster margin of the NPI (ca. 47°14′S, 73°15′W). Glaciar Arenales joins Glaciar Colonia from the west. At the junction of these two glaciers, lichen and tree ages on a lateral trimline to the west of the valley indicate that the ice was in recession by ca. AD 1883. Below this trimline there are four lateral moraines: lichens on the highest of these moraines suggest that this surface was ice free by 1970. Field examination of the morphological characteristics of the ice and sediments at the junction of these glaciers suggests that the Arenales tongue was advancing in 1996. Several additional tree-ring dates associated with the upper trimlines along the Colonia valley indicate a LIA maximum extent of Glaciar Colonia during the late 19th century. Lichen and tree-ring dates on fragments of inner, lateral and terminal moraines indicate minimum ages of ca. 1904, 1914–17, 1945–48 and 1980 for these deposits. A 90-m-high terminal moraine marks the maximum extent of Glaciar Arco during the LIA. Although it is uncertain when the glacier deposited this moraine, a lichen date on the moraine and trees growing on lateral trimlines indicate the ice was already in recession by AD 1881. A subsequent readvance ca. 1956 was identified from a tree-ring date obtained on the distal side of a recessional moraine located between Lago Arco and the present glacier snout (Harrison and Winchester, 2000).

7.3. The South Patagonian Icefield (SPI)

Aniya et al. (1997) determined the total area and frontal variations of the 48 major glaciers of the SPI (Fig. 1) between 1944 and 1986 using 1:250,000 preliminary maps, aerial photographs and satellite imagery. They found that the SPI and surrounding small glaciers had a total area of ca. 13,000 km^2 in 1986. Over the 1944–86 interval 42 glaciers retreated, 4 glaciers (HPS 13, HPS 15, Calvo and Spegazzini) were in equilibrium, and 2 glaciers (Pío XI and Moreno) increased in size. Other authors have extended this record using historical data and recent aerial photographs and/or satellite images of individual glaciers (Warren and Aniya, 1999; Aniya et al., 2000; Skvarca and De Angelis, 2002; Rivera and Casassa, 2004; Raymond et al., 2005). These analyses conclude that an overall pattern of retreat dominates the regional behavior of glaciers at the SPI.

On the Chilean side of the icefield, most glaciers have been retreating and thinning at very high rates during recent years. The few exceptions to this pattern are the Glaciar Trinidad (49°25′S), which was advancing against trees until 2000 (Rivera et al., 2002), and Glaciar Pío XI (49°08′S, 73°54′W), which was advancing until recent times. This glacier was first visited by Juan Ladrillero in AD 1558 and has the longest record of frontal variations in the SPI (King, 1839; AHMC, 1880). The first map of the glacier was prepared in 1830 (King, 1839). Since then, Glaciar Pío XI advanced approximately 7200 m to an initial maximum in 1928 (De Agostini, 1945), then retreated ca. 2450 m until 1945 (Rivera, 1992) when both arms of the glacier started advancing again for 11 km to reach their Holocene maximum extent in 1994 (Warren et al., 1997). At that time, the southern arm of the glacier was destroying trees that were more than 350 years old (Rivera et al., 1997a). Between 1995 and 1999, the glacier was relatively stable with an overall minor retreat. But by 2000 the glacier readvanced again reaching a position close to the 1994-maximum extent in 2008. The anomalous behavior of Pío XI has been associated with surging events (Rivera et al., 1997a,b) and, therefore, the frontal fluctuations are probably not directly related to climate (Warren et al., 1997).

Mercer (1970) visited the northwestern portion of the SPI in 1967–68 and studied the Late-Glacial and Holocene variations of several outlet glaciers (from north to south: Ofhidro Norte, Ofhidro Sur, Bernardo, Témpano and Hammick). Excellent descriptions and extensive evidence was provided for these glaciers. However, for the past 1000 years, Mercer reported evidence from a few sites only. At Glaciar Ofhidro Norte (48°26′S, 73°49′W) he described four moraines bounding a small proglacial lake; the innermost was treeless but the three outer moraines had trees that were 45, 50 and 105 years old. Allowing 70 years for the establishment of seedlings, he estimated the deposits were formed between about AD 1790 and 1850. In an inactive outwash plain about 700 m outside the outermost moraine, Mercer found stumps rooted in peat that had been exhumed by the proglacial stream. These stumps were ca. 3 m below the outwash surface. One sample was dated to 800 ± 95 ^{14}C yr BP, which provided strong evidence that a glacier advance was in progress around the early 1300s (Mercer, 1970).

Glaciar Bernardo (48°37′S, 73°54′W) was separated from Fiordo Bernardo by a 2-km wide outwash plain (Mercer, 1970). A narrow belt of small moraine ridges was described across the outwash between 500 and 600 m from the ice front position. As trees on the outermost ridge were ca. 115 years old (and between 75 and 85 years old in the inner ridges), Mercer estimated that the glacier reached the greatest extent around AD 1775 and fluctuated near this point for 35–45 years. Only 100 m from the 1968 ice front position, he found that stream erosion had exhumed rooted stumps of mature trees (up to 1.5 m in diameter) buried by outwash and covered with till. One sample was ^{14}C dated to 270 ± 90 yr BP. Mercer estimated that these trees were overridden by the glacier probably between the 15th and 18th centuries. The frontal moraines on the outwash plain continue as lateral moraines and several tilted, dead trees were found immediately outside the outermost ridge. Unfortunately, no living tree was found to provide a precise date for the tilting of these specimens. However, Mercer (1970) concluded that the late 18th century advance was probably the greatest of the recent centuries.

Along the south margin of the terminal, calving portion of Glaciar Témpano (48°43′S, 73°58′W), Mercer (1970) described four lateral moraines that formed in the past few centuries. According to aerial photographs, a fresh innermost ridge was close to the ice margin in 1945, whereas three outer ridges (with trees of up to 140 years old on the outermost deposit) were within 60 m distance from the inner moraine. Mature forest surrounds these moraines but along the forest trimline, Mercer found a tilted but still living *Pilgerodendron uviferum* tree. Examination of the growth rings patterns of this tree indicated that it was tilted during the moraine emplacement around AD 1760.

The last outlet glacier visited by Mercer on the northwest side of the SPI was Glaciar Hammick (also known as Glaciar Occidental; 48°50′S, 74°09′W). In 1968, the ice margin was about 50–200 m away from a massive, forested end moraine with a smaller moraine superposed on its inner face (Mercer, 1970). As trees on these two moraines were 150 and 60 years old, Mercer estimated that they were formed ca. AD 1750 and AD 1840, respectively. Four much smaller and treeless ridges (the outer two completely vegetated, the third partially vegetated and the innermost bare) were described between the outer moraines and the ice margin. Aerial photographs indicate that the glacier front was close to the inner ridge in 1945 but had receded by 20 to 60 m until 1968 (Mercer, 1970). Outside the 18th century moraine there is an older moraine with mature forest. Between these two ridges there is inactive outwash presumably associated with the most recent advance. Meltstream erosion had exhumed many *in situ* stumps that are less than 25 cm in diameter and reach about 2 m into the outwash. No date was reported for these stumps but Mercer indicates these trees were probably growing no more than a few centuries before the 18th century maximum. An additional set of much larger (up to 1.5 m in diameter) *in situ* stumps was also found in the area where the proglacial stream cuts through this moraine. These trees were buried by outwash and covered with till, but according to Mercer they were not related to the stumps in the outwash outside the moraine. A date of 2800 ± 100 ^{14}C yr BP from the outer portion of one of these stumps corroborates this assertion and indicates that the outwash that buried these larger trees is significantly older than the overlying 18th century moraine (Mercer, 1970).

In 1981 Röthlisberger visited several glaciers in the vicinity of Lago O'Higgins on the northeastern margin of the SPI (Fig. 1) and reported extensive evidence for past glacier activity in this area (Röthlisberger 1986). Reworked and *in situ* tree stumps, together with tephra layers and paleosoils directly affected by glacier deposits, were radiocarbon dated to obtain approximate dates for the occurrence of several Holocene glacier advances and volcanic eruptions in the region. However, we will concentrate on evidence for glacier advances during the past ~1000 years and, in particular, on evidence from *in situ* material. This material provides, compared to reworked material, more robust and accurate information about the specific timing and location of past glacier frontal positions (for further details see Röthlisberger, 1986). In front of the SPI outlet Glaciar Bravo (48°39′S, 73°12′W), Röthlisberger found up to six poorly preserved end moraine ridges. On the left proximal slope behind a bedrock outcrop and about 50–70 m above the ice surface and 80 m below the lateral trimline, he found the remnants of a buried forest with a 30–60 cm thick paleosol. Three *in situ* stumps were dated to 665 ± 80, 270 ± 100, and 165 ± 50 ^{14}C yr BP, which was interpreted as evidence for two separate glacier advances around 670 ^{14}C yr and 270 ^{14}C yr BP. Based on historical photographs (De Agostini, 1945) he also estimated a ~500 m glacier front recession between 1937 and 1981.

Further south from Glaciar Bravo, Röthlisberger visited Glaciar O'Higgins (48°55′S, 73°07′W). This glacier is a large outlet of the SPI and has a ~4 km-wide front that calves into Lago O'Higgins. The glacier front has experienced a drastic retreat of about 14.6 km between 1896 and 1995 (Fig. 2g; Casassa et al., 1997). There is a clear trimline that is at some points about 400 m above the lake level (Röthlisberger, 1986). Below this trimline, at about 9 km from the glacier front and 200 m above Lago O'Higgins, Röthlisberger found an impressive set of well-preserved reworked and *in situ* stumps (see Fig. 181, p. 241 in Röthlisberger, 1986). Two of these stumps were dated to 790 ± 55 and 345 ± 55 ^{14}C yr BP. Although they were apparently buried by glacial drift and may point to two different glacier events, Röthlisberger doubted the origin of these samples and suggested that this particular group of stumps might alternatively represent the remnants of a portion of forest that collapsed from the lateral slopes due to recent glacier shrinkage.

The frontal recession of Glaciar O'Higgins is one of the most impressive recent recessions of all outlet glaciers in the SPI (Fig. 2g, Casassa et al., 1997). This recession continued between 1995 and 2001, which opened a new bay between O'Higgins and GAEA glaciers (Rivera, 2004). Other Chilean glaciers with noticeable retreating patterns are Amalia and Jorge Montt (Rignot et al., 2003) and those in Torres del Paine National Park (especially the Dickson and Grey glaciers, Rivera and Casassa, 2004). In contrast, the SPI outlet Glaciar Chico has shown relatively minor recession (2.6 km during the 20th century, Fig. 2g; Rivera, 2004; Rivera et al., 2005b). Glaciar Viedma (Fig. 2g) is the biggest outlet flowing from the SPI into Argentina and was mapped in 1903 (Risopatrón, 1905) and in 1916 (Kölliker et al., 1917). This glacier has also shown a relatively little retreat over the 20th century (Rivera et al., 2008).

Glaciar Upsala (50°S, 73°20′W) has a 4 km-wide calving front in Lago Argentino and has thinned and retreated drastically during the 20th century (Aniya and Skvarca, 1992; Aniya et al., 1992; Naruse et al., 1995; Aniya et al., 1997; Warren and Sugden, 1993; Aniya, 1999). The late Holocene fluctuations of this glacier were first studied by Mercer (1965). More recent work has provided additional information that has modified Mercer's original glacial chronology for this site (Aniya, 1995; Aniya and Sato, 1995a). The available evidence suggests that Glaciar Upsala has experienced at least four major advances during the past 3000 years. The two older advances occurred ca. 2400–2200 years BP and ca. 1600–1400 years BP based on ^{14}C dating of subfossil wood and basal peat samples associated with moraines (Mercer, 1965; Aniya, 1995). Using tree-ring counts two later advances have been dated to between AD 1600 and AD 1760, and to the early 19th century (Mercer, 1965).

Glaciar Ameghino (50°25′S, 73°10′W) is another low-gradient eastern outlet glacier from the SPI (Figs. 2g and 8). Nichols and Miller (1951) described a series of terminal and lateral moraines in front of the glacier and a “small” moraine-dammed lake between the ice and the terminal moraine. They also described a clearly visible trimline at both sides of the valley about 150 m above the glacier level. Based on field surveys and tree-ring counts of trees growing inside the trimline, they estimated that these features formed at around the same time ca. AD 1870–1880 (Fig. 8). However, their most important finding was an *in situ* buried forest exposed by erosion of the proglacial stream in the valley bottom in front of the terminal moraine. Nichols and Miller suggested that these “hundreds of dead trees” were buried by glacial outwash during the formation of the lateral and terminal moraines. However, no radiocarbon dates were reported for the stumps. Aniya (1996) radiocarbon dated a tree that had been apparently crushed by the right lateral moraine at the trimline to 320 ± 80 ^{14}C yr BP, and dated this lateral trimline to about AD 1600–1700. He also identified remnants of three minor moraines outside the Nichols and Miller's terminal moraine (Fig. 8). One *in situ* stump, associated with the outermost of these three moraines, was ^{14}C dated to 380 ± 80 ^{14}C yr BP. Another exhumed (but not *in situ*) stump, assumed to be related to the buried forest described by Nichols and Miller (1951), was ^{14}C dated to 480 ± 80 ^{14}C yr BP. Therefore, Aniya (1996) dated the formation of the outermost moraine and the deposition of the glacial outwash that buried the forest to about AD 1500. Several living trees and more than 100 cross-sections from the buried forest were sampled by members of the Instituto Argentino de Nivologia y Glaciologia (IANIGLA, Mendoza) in 2000 and 2004. A preliminary floating chronology built from these stumps and several ^{14}C dates were presented by Masiokas et al. (2001). We have not been able yet to crossdate the floating tree-ring series with the oldest living trees sampled on the adjacent slopes outside the glacier forefield. The ^{14}C ages obtained from the outer portion of several stumps range between 315 ± 30 and 150 ± 30 ^{14}C yr BP (Fig. 8).

With a calving front ca. 5 km wide, Glaciar Perito Moreno (50°28′S, 73°02′W) is a major eastern outlet of the SPI. This glacier has experienced several readvances during the 20th century. This anomalous behaviour has attracted considerable scientific attention; Glaciar Perito Moreno is the most visited and one of the better studied glaciers in Argentina (e.g. Heim, 1951; Nichols and Miller, 1952; Lliboutry, 1953; Mercer, 1968; Warren, 1994; Warren et al., 1995; Skvarca and Naruse 1997; Skvarca et al. 2002, 2004). Based on several ^{14}C dates from peat samples in front of the glacier margin, Mercer (1968) concluded that the ice front has not advanced beyond its current position during the past 10,000 years. Aniya and Sato (1995b) dated an *in situ* stump at the south lateral trimline to 820 ± 80 ^{14}C yr BP and suggested that the glacier advance that affected this tree probably occurred during the 12th century.

Glaciar Frías (50°45′S, 73°05′W; homonymous to that described for the Tronador area at around 41°S), is located a few km to the south of Glaciar Perito Moreno. With about 9 km in length, it is one of the smallest outlet glaciers of the SPI. Mercer (1968, 1976) identified three recent moraines within one km from the present ice margin. Although the approximate age for these three younger moraines was not estimated, Mercer reported the age of some trees sampled on the deposits and on the glacier forefields. Based on this information and using an ecesis correction of 100 years (a value that Mercer used in several other glaciers in the region), we have estimated the formation of the three younger moraines to the mid-19th, early-19th, and mid-17th centuries. The recent variations of this glacier have been documented by Rivera and Casassa (2004). These authors determined a total area loss of 11% between 1945 and 2000 (5.9 km^2 in 1945) and a thinning rate of 1.4 m yr^{-1} between 1975 and 1995.

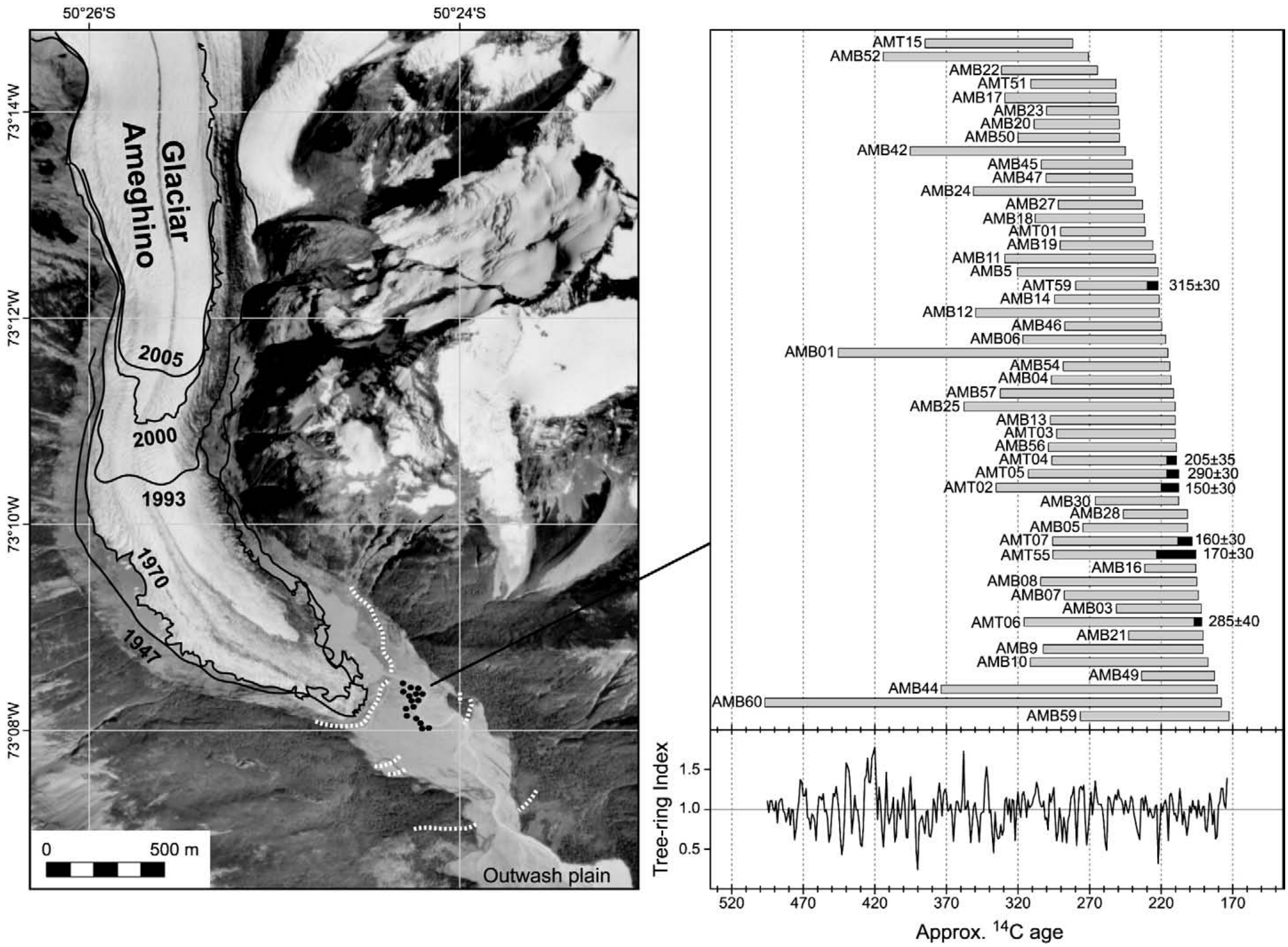

Fig. 8. (Left) Historical fluctuations of Glaciar Ameghino, South Patagonian Icefield, Argentina. The location of the buried in situ stumps (dots) and the main moraine ridges (white dotted lines) identified in front of the glacier are also indicated. (Right) Length of record, radiocarbon dates and mean tree-ring width chronology for *in situ* stumps buried by outwash at Glaciar Ameghino (modified from Masiokas et al., 2001).

Further south in the Torres del Paine area (Fig. 1), Marden and Clapperton (1995) describe a series of bare or partially vegetated recent moraines situated close to the modern glaciers. At the SPI outlet Glaciar Grey they provide minimum tree-ring dates for these moraines and indicate a main LIA extension around AD 1660 (100-year ecesis used). Dates of formation for younger deposits were estimated to ca. AD 1805, AD 1845 and AD 1890 (Marden and Clapperton, 1995). Twentieth-century frontal variations of Glaciar Grey and Glaciar Dickson (another SPI outlet glacier adjacent to Glaciar Grey) are shown in Fig. 2g.

7.4. Glaciers adjacent to the South Patagonian Icefield

Monte San Lorenzo (47°35′S, 72°21′W, 3706 m) is the third-highest summit in the Patagonian Andes and covers an area of approximately 25 km × 25 km astride the border between Chile and Argentina (Fig. 1). The Italian priest Alberto De Agostini explored this area in the early 1940s and provided excellent photographs of the glaciers and valleys in this region (De Agostini, 1945). Glacier San Lorenzo Sur (47°35′S, 72°20′W) is one of the largest ice bodies of Monte San Lorenzo and has shown a drastic thinning and frontal recession during recent decades (Fig. 2i). The glacier forefield has five well-defined moraine systems indicating at least five different glacier advances during the past 500 years. The innermost moraine ridge lacks vegetation for dendrochronological dating, but tree-ring dates from the four outer moraine systems indicate they were formed prior to AD 1665, AD 1769, AD 1819 and AD 1864 (García-Zamora et al., 2004). A similar study at glaciers Calluqueo, Río Tranquilo, and Arroyo San Lorenzo on the Chilean side of the mountain identified seven well-defined moraines dated to between ca. AD 1600 and the early 1900 s (Aravena, 2007). Glaciar Calluqueo has the most complete sequence of moraines with minimum age estimates dating to ca. AD 1652, 1683, 1715, 1742, 1760, 1845 and 1910. The lateral and terminal moraines formed by the five earliest advances were relatively similar in size. However, after ca. AD 1760 the glacier tongue experienced a huge downwasting of more than 100 m of the ice surface. Since 1940 the ice front has receded approximately 2500 m, and the rapid collapse of the lower portion of the glacier has resulted in the formation of a proglacial lake (Aravena, 2007). Fernández et al. (2006) report a continuous retreat for Glaciar Arroyo San Lorenzo between 1975 and 2003 (Fig. 2f).

In 1966 Mercer visited Glaciar Narváez (48°29′S, 72°24′W), located in the Sierra de Sangra about 50 km to the east of the northern tip of the SPI (Fig. 1). Mercer (1968) reported that the glacier had formed a 2 km-long proglacial lake behind a bare terminal moraine. He also indicated that, according to historical photographs

(Hatcher, 1903), the lake was just starting to form by AD 1897. At least two older moraines with immature forest cover were identified downvalley of this "bare" moraine, with 200 year-old trees on the outermost moraine. Based on this information, Mercer estimated that the bare, inner moraine probably formed about AD 1880, whereas the outer moraine formed during the 17th century. IANIGLA members visited this site in 2001 and found *in situ* stumps in a stream cut through a southern lateral moraine. This moraine was initially correlated with Mercer's 17th century glacier advance, but four ^{14}C dates obtained from the stumps (925 ± 30, 720 ± 35, 655 ± 30, and 645 ± 45 ^{14}C yr BP) seem to indicate that they were buried by an earlier event that probably occurred between the 12th and 14th centuries (Masiokas et al., 2001).

Röthlisberger (1986) visited Ventisquero Huemul (located in the vicinity of Glaciar O'Higgins and also known as Glaciar Mellizo Norte, Aniya et al., 1996) and identified up to seven moraine systems on the left margin of a ~1 km long proglacial lake and the vegetation trimline about 150–200 m above the ice surface. One *in situ* stump exposed by erosion on the left proximal slope was dated to 465 ± 65 ^{14}C yr BP and suggests a glacier advance after that time.

Masiokas et al. (2009) provide a detailed map and preliminary tree-ring dating of the main moraine ridges observed at three small, east facing glaciers located immediately to the west of Lago del Desierto, Argentina (49°04′S, 72°54′W; Fig. 1). Between eight and 10 moraine ridges were observed in front of these three glaciers, and minimum dates from trees sampled on selected moraines suggest the main LIA advances occurred in the early 17th century. Tree-rings from *in situ*, overridden material and living trees growing on the moraines provide well dated evidence for an advance in the early 17th century at all three glaciers. Two or three subsequent advances were identified at the Lago del Desierto glaciers. Living trees growing on the moraines indicate that most of them formed in the first half of the 20th century. Garibotti and Villalba (2009) developed a logarithmic lichen growth curve that allowed the dating of selected moraines at Glaciar Huemul (Glaciar Lago del Desierto II in Masiokas et al., 2009). Due to the lack of trees, dendrochronological dating of these moraines was not possible.

Masiokas et al. (2009) also present an updated compilation of available evidence for late Holocene glacier fluctuations at the Piedras Blancas and Torre glaciers, in the Monte Fitz Roy area (49°19′S, 73°01′W, Figs. 1 and 2i). Their study indicates that the LIA maxima at these sites occurred probably around the late 1500s–early 1600s. Conspicuous moraine ridges outside the LIA deposits suggests at least three earlier glacier events in this area. For the inner of these older deposits, Mercer (1965) provided a minimum age of 800 ± 85 ^{14}C yr BP derived from a basal peat sample collected immediately outside the moraine. The formation of the innermost moraines at Glaciar Torre was tree-ring dated to AD 1727, 1799, 1866 and during the late 19th century–early 20th century (see Masiokas et al., 2009). At Glaciar Piedras Blancas, three moraines were observed inside the main LIA deposits. The limited evidence available indicates that the innermost moraine was formed ca. 1931. Garibotti and Villalba (2009) sampled over 400 lichens on the Piedras Blancas forefield and concluded that the moraine located outside the 1931 limit was formed ca. 1904. A more recent readvance that occurred between 1968 and 1981 was identified from aerial photographs (Masiokas et al., 2009).

The Cañón Cerro Norte area (50°S, 73°15′W, Fig. 1) is a north–south valley located 5 km to the east of Glaciar Upsala. Mercer (1965) studied this area to examine the differences between a large low-gradient outlet glacier (Upsala), and two short steep glaciers that are not connected to the SPI. Four moraine systems were identified at Glaciar Dos Lagos. Assuming 100 years for ecesis and using the age of the oldest trees growing on the deposits as a reference, a massive moraine located about 500 m from the ice front position (measured in the 1960s) was dated to ca. AD 1760. The three innermost moraines were dated to around AD 1780, AD 1820 and the early 1900s. At the nearby Glaciar Cerro Norte, one *in situ* stump exposed by stream erosion was dated to 390 ± 85 ^{14}C yr BP. This date provides an age estimate for the formation of a large, forested moraine that has been almost completely covered by another younger 120 m-high moraine (Mercer, 1965).

Röthlisberger (1986) also provides evidence for Holocene advances at several small glaciers in the Torres del Paine area on the southwestern margin of the SPI (Fig. 1). On the right (west) margin of Glaciar Francés (51°01′S, 73°02′W) he found a palaeosoil exposed with many roots ca. 3 m below the lateral moraine crest. Two ^{14}C dates of 675 ± 45 and 235 ± 65 ^{14}C yr BP from samples of humic acid and *in situ* wood, respectively, were obtained from this cross-section. Accordingly, Röthlisberger suggested two separate glacier advances. A similar geomorphological setting was observed at Glaciar Perro (50°56′S, 73°06′W), where a palaeosoil and several overridden *in situ* stumps were found along a bedrock outcrop on the right lateral moraine ca. 30 m below the crest. Four ^{14}C dates (795 ± 80, 345 ± 100, 295 ± 75 and 260 ± 50 ^{14}C yr BP) were obtained from the stumps whereas two additional dates (1730 ± 80 and 205 ± 50 ^{14}C yr BP) resulted from samples of humic acid and embedded wood in the soil, respectively (Röthlisberger, 1986). The disparity of the dates and the location of the samples in a sheltered site led Röthlisberger to suggest the existence of different generations of trees and soils with different ages indicating separate advances around or after 1700, 800 and 400–200 years BP.

7.5. Glaciers in the Magallanes-Tierra del Fuego region

The administrative region of Magallanes in Chile contains many small icecaps and mountain glaciers that have been much less studied than the glaciers of the icefields further north (Fig. 1). Koch and Kilian (2005) studied the LIA fluctuations of Glaciar Lengua and used dendro-geomorphological analyses to date several moraine systems damming a small proglacial lake. Tree-ring dates (20-year ecesis used) indicate the main moraines were formed ca. AD 1628, 1872–75, 1886, 1902, 1912 and 1941. The dating of the advance in the 1870s was more precisely determined using death and tilt dates of trees associated with the moraine. An older, outermost moraine was also identified and tentatively dated to between the 13th and 15th centuries, assuming a correspondence with other glacial advances in Patagonia (Koch and Kilian, 2005).

Two additional glaciers recently studied in this region are Alejandro and Beatriz on Santa Inés Island (53°45′S, 72°30′W; Aravena, 2007). At these sites, several glacier advances were identified that produced well-defined, clearly separated frontal moraines. Using an ecesis of 32 years, tree-ring based minimum age estimates indicate that the main moraines at the flat valley of Glaciar Alejandro formed ca. AD 1675, 1758, 1794, 1843 and 1895 (Aravena, 2007). The moraine system at Glaciar Beatriz had fewer and younger moraines. The oldest advance was dated to ca. AD 1773. This advance overrode likely any evidence of earlier events since a prominent bedrock outcrop constricts the downvalley extent of ice. Subsequent advances are indicated by small moraines located on the inner slope of the oldest moraine. These were dated to ca. AD 1845, 1916 and 1945. A basal radiocarbon date of 5310 ± 80 ^{14}C yr BP from surface peat ca. 0.5 km outside the LIA limit of Glaciar Beatriz indicates that the LIA advance of this glacier was the most extensive in the last 5300 years (Aravena, 2007).

Other sites with significant glacier areas in the Magallanes region are the Monte Sarmiento massif and the Cordillera Darwin in Tierra del Fuego (Fig. 1). The Schiaparelli and Conway glaciers on the western side of Monte Sarmiento (54°27′S) were first described by King (1839; Rivera et al., 2008). Following his voyage in the "Beagle", Captain Fitz-Roy (1839) also published a lithograph of this mountain with a glacier that seems to have reached the ocean in AD 1836. Conway (1902) who first climbed Monte Sarmiento described the glacier as having retreated from the AD 1836 position behind densely vegetated moraines. In 1913, De Agostini (1959) also visited the area, took the first available photograph of the glacier and prepared a map using aerial photographs from 1945 (Lliboutry, 1956). Mercer (1967) argued that Fitz Roy incorrectly concluded that the glacier was reaching the ocean in 1836 because it was behind dense forest when Conway visited the area in early 20th century. Although Fitz Roy's 1836 lithography seems to be conclusive, a more detailed analysis of this site, including the tree-ring dating of trees growing on the frontal moraines is needed to resolve this question.

Strelin et al. (2008) studied the Holocene variations of Glaciar Ema (54°25′S, 70°44′W), on the eastern side of Monte Sarmiento. For the past 1000 years they identified an advance around 695 ± 95 ^{14}C yr BP based on dates from well-preserved wood embedded in till exposed in a stream cross-section. At least six subsequent events were identified during the second half of the last millennium. Three events were dated to ca. 379 ± 75, 335 ± 70, and 251 ± 70 ^{14}C yr BP based on wood samples within till, whereas soil development and tree size were used for tentatively dating three minor periods of glacier reactivation (or standstills during recession) to ca. 120–100, 100–70, and 70–60 yr BP (Strelin et al. 2008).

At Bahía Pía on the southern sector of Cordillera Darwin (54°40′S, 70°W), Kuylenstierna et al. (1996) identified three late Holocene glacier advances based mainly on sedimentological evidence. The dating of wood in a silt/sand layer within two till units provides evidence for a glacier advance prior to 940 ± 70 ^{14}C yr BP. An additional advance was inferred between this date and 675 ± 70 ^{14}C yr BP. This date was obtained from a basal gyttja and peat overlaying a bed of silt that, according to Kuylenstierna et al. (1996), was associated with the upper till mentioned above. Interestingly, no morphological evidence was found at Bahía Pía for glacier advances during the "classical" LIA period of the last centuries.

Holmlund and Fuenzalida (1995) studied the recent behavior of the glaciers in the Cordillera Darwin. They describe an interesting contrast between glaciers that are retreating on the northern and eastern flanks of the cordillera and glaciers that reached recently positions at or close to their Holocene maxima on the southern and western flanks. Glaciar Marinelli, located on the northern margin of Cordillera Darwin, has experienced a very noticeable retreat of 11.5 km between 1903 and 2002 and the collapse of the lower tongue of the glacier between 1992 and 2000 (Porter and Santana, 2003; Fig. 2h). In contrast, at least two south-facing glaciers on the southern edge of Cordillera Darwin were advancing in 2007: a glacier at Bahía Pía (54°26′S; Porter, personal communication), and Glaciar Garibaldi (54°40′S) which was advancing against trees in January 2007 (Figs. 2h and 9). It is interesting to note that (except for isolated examples such as Glaciar Perito Moreno and Glaciar Pío XI in the SPI, see above) the southern edge of Cordillera Darwin is the only region in the Patagonian Andes where several glaciers have been concurrently advancing in the last few years.

Past glacier fluctuations of four small cirque glaciers have been studied in the Cordón Martial, Cordillera Fueguina Oriental, Tierra del Fuego (54 47′S, 68 24′W; Strelin and Iturraspe, 2007). Assuming regional stratigraphic correlations and using the dating of glacier events at Glaciar Ema as a reference (see above), Strelin and Iturraspe indicate that the main LIA advances of glaciers at Cordón Martial occurred around 330 ^{14}C yr BP. Since that advance,

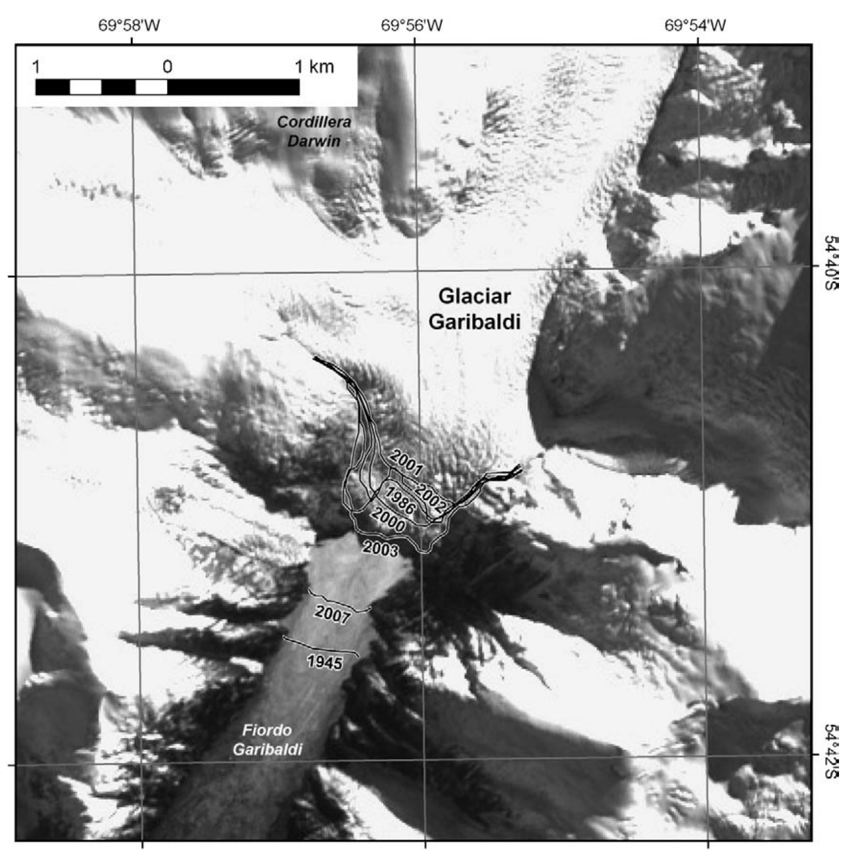

Fig. 9. Recent fluctuations of Glaciar Garibaldi at the southern edge of Cordillera Darwin, Tierra del Fuego, Chile. This glacier is one of the few ice masses currently advancing in southernmost South America.

glaciers have receded slowly until ca. 60 years ago, when the rate of glacier retreat accelerated. Between 1984 and 1998, Glaciar Martial Este lost about 0.64×10^6 m^3 of ice. Modelling results based on the annual mass balances recorded in Glaciar Martial Este since 1998 and future regional temperature projections for the region suggest that it is only Glaciar Martial Este, the largest of the four ice masses, that will survive the 21st century (Strelin and Iturraspe, 2007).

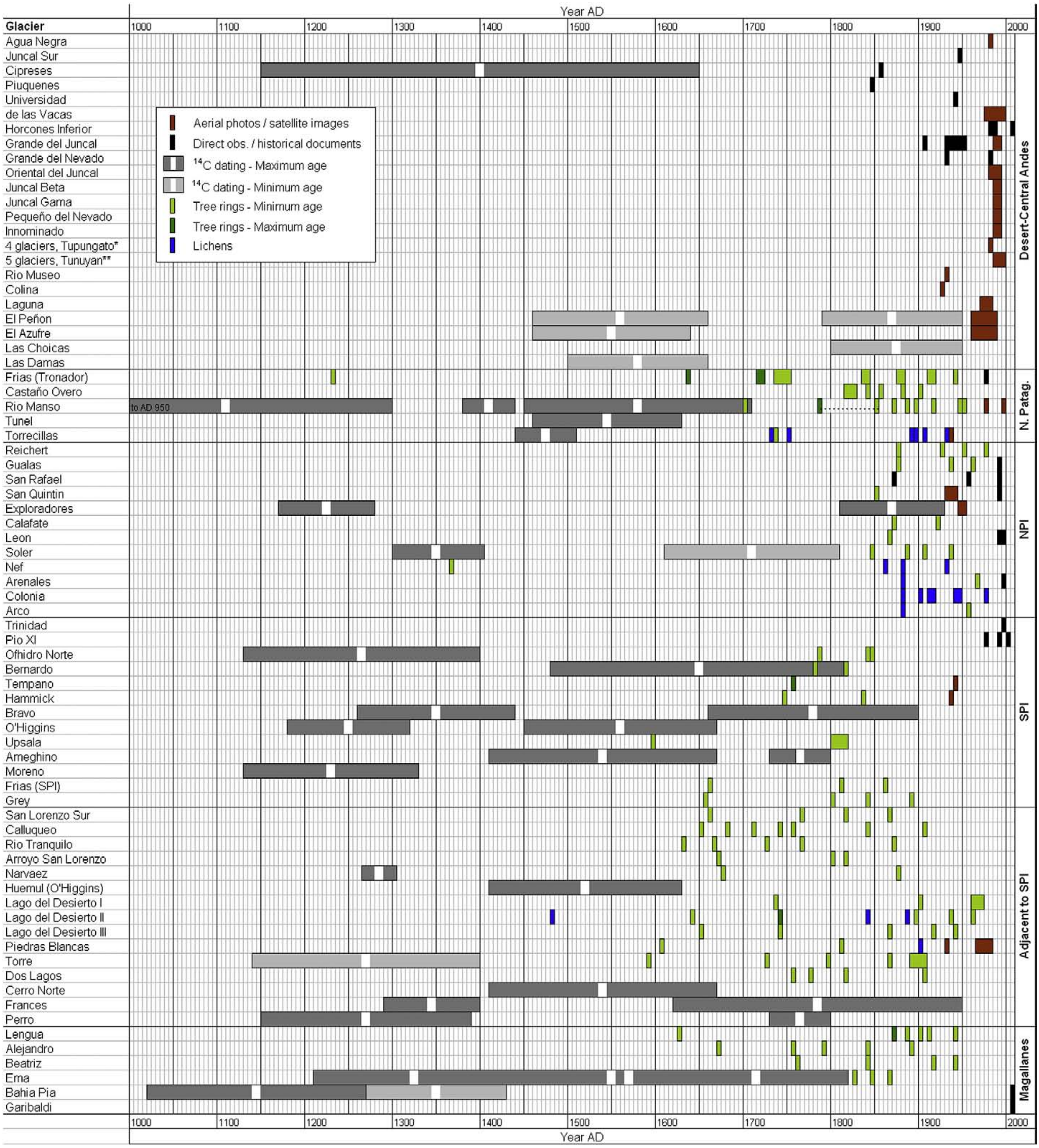

Fig. 10. Compilation of evidence for glacier advances over the past millennium in Andean South America between ca. 17° and 55°S (see Appendix B for details). The evidence is classified as follows: aerial photos and/or satellite imagery (brown bars); direct observations and/or historical documents (black bars); minimum and maximum radiocarbon dating (light and dark gray bars, respectively), showing 2σ uncertainty ranges and the most probable calibrated date as a white box; minimum and maximum tree-ring based estimations (light and dark green bars, respectively); lichen dates (blue bars). Note: (*) Four glaciers at Cerros Tupungato, Tupungatito, and San Juan (ca. 33°15′S); (**) Five glaciers in the Tunuyán Sur basin (ca. 33°40′S; see Appendix B).

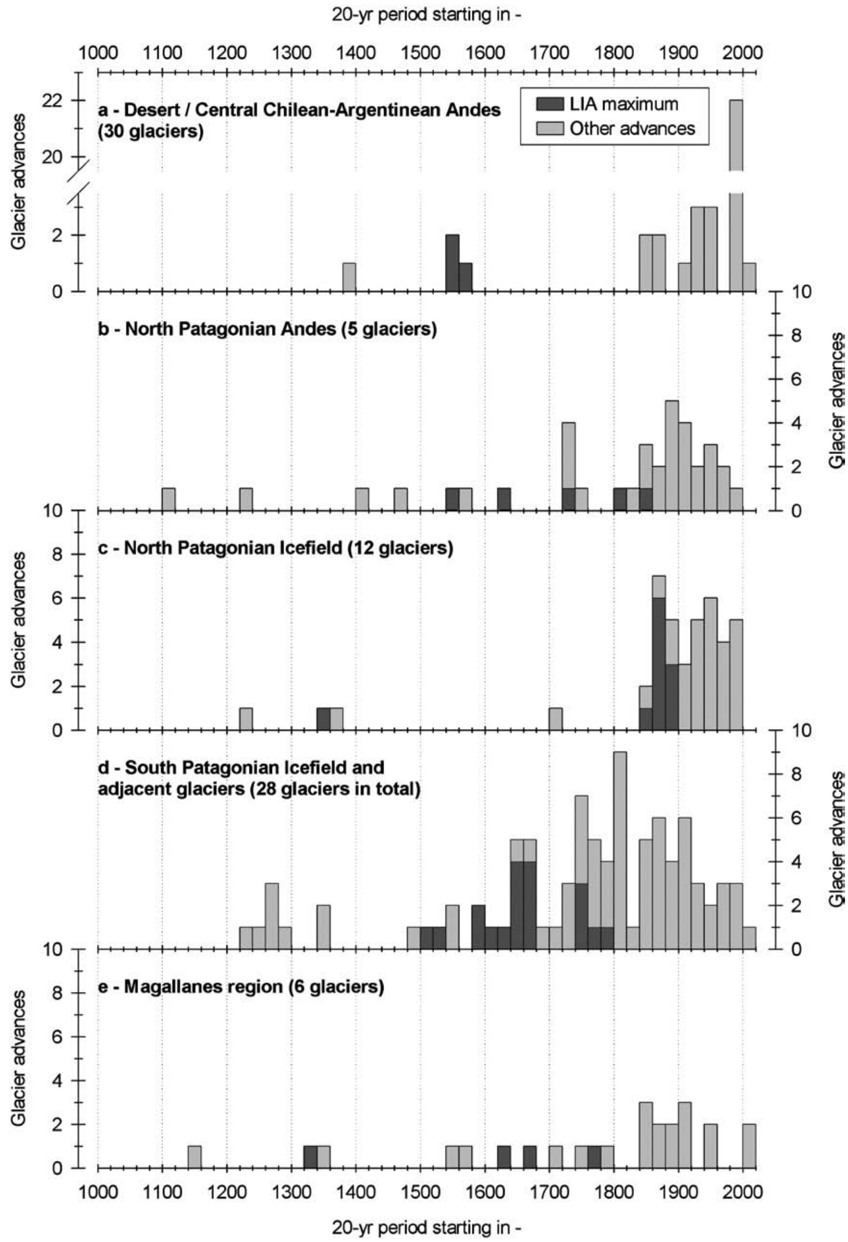

Fig. 11. Glacier advances in the extratropical Andes of South America during the past 1000 years. The diagram is based on Appendix B and Fig. 10 and events are grouped into 20-year periods. Advances identified by the original authors as the LIA maximum extent are indicated by dark gray bars, whereas other advances are indicated by light gray bars. For dates based on radiocarbon determinations we used the mid-point of the most probable calibrated age range (white boxes in Fig. 10). Except for (a), the histograms in (b–e) are portrayed using the same scale to show the relative differences in the number of dated glacier advances in each subregion.

8. Summary and conclusions

The Andes of extratropical South America contain an extensive glacierized area and an extremely rich variety of glaciers. Given the particular geographic location of this mountain range with respect to other glacierized landmasses in the Southern Hemisphere, this region has the potential to provide unique insights regarding the nature and mechanisms of past and present glacier variations and their relationships with atmospheric processes at local, regional and hemispheric-global scales. The extensive compilation of evidence on glacier variations discussed in this paper provides an updated overview of the type, quality and limitations of the data currently available. This is the first attempt to cover glacier variations of the past 1000 years both in Chile and Argentina between ~17° and 55°S. In some cases the evidence available is detailed enough to allow a relatively reliable reconstruction of glacier variations for most of this period, but in the majority of cases the evidence is rather limited and the history of fluctuations could be substantially improved with further detailed research at these sites. Thus, although not definitive, the information compiled in this review should be useful to gauge the current knowledge about late Holocene glacier fluctuations in southern South America and to promote and facilitate further related research in this region.

Figs. 10 and 11 and Appendix B summarize the information available on glacier advances for the past 1000 years and complement Fig. 2 which shows mainly frontal variations during the past ~100–150 years. Glacier fluctuations in the Desert Andes during the past millennium are virtually unknown as the information presently available starts only after ca. 1950 (Fig. 2a). This information indicates a general recession of glaciers during the second half of 20th century. The evidence for the Central Andes (sensu Lliboutry) includes a larger number of study sites but few glacier chronologies extend prior to 1900 (Figs. 2b–d, 10 and 11a). These chronologies indicate that glaciers were generally more extensive in earlier centuries, with dates of the LIA maximum expansion around the 16th century. Except for a few cases that are known for their surging activity, the majority of glaciers across the Central Andes have shown a generalized retreating pattern throughout the 20th century. There is a serious lack of long, good quality high elevation climate records across the extratropical Andes, but the recent glacier shrinkage observed in the Central Andes appears to have been mostly driven by regional warming and increased ablation rates combined with a long-term reduction in winter precipitation. Carrasco et al. (2005) found that since 1975 the 0 °C isotherm at these latitudes has risen ca. 122 ± 8 m in winter and 200 ± 6 m in summer. Falvey and Garreaud (2009) report a trend of ca. +0.25 °C/decade in mean annual temperatures for the period 1979–2006 using in situ and gridded datasets from locations above 500 m in elevation in the Andes between 17° and 37°S. In addition, central Chile precipitation (a variable closely related to winter snowpack levels in the mountains) shows a long-term decline over the past century (see e.g. Luckman and Villalba, 2001; Le Quesne et al., 2009-this issue). It is interesting to note, however, that after 1976 there has been a higher frequency of years with above-average winter snow accumulation in the mountains (commonly associated with warm El Niño events in the tropical Pacific, see e.g. Masiokas et al., 2006). This increase may explain the readvances observed during the last quarter of the 20th century (Figs. 10 and 11a) and has probably reduced to some extent a more drastic ice mass loss that would have otherwise occurred given the increases in temperatures reported for this portion of the Andes. The mass balance records of Glaciar Echaurren Norte and Glaciar Piloto Este start in 1975 and 1979, respectively, and are the longest direct records available for extratropical South America (see e.g. Casassa et al., 2006; Leiva et al. 2007). Over this period both records show years with positive mass balance associated with El Niño events but overall negative cumulative series, which is consistent with the glacier recession observed in this region (Rivera et al., 2006b).

Detailed, well-dated chronologies of fluctuations covering the past 1000 years in the North Patagonian Andes are also scarce (Figs. 2e, 10 and 11b). The available evidence indicates that glaciers in this region reached the maximum extent sometime between the 16th and 19th centuries during the LIA. After this period of maximum ice extent, several readvances have been identified (Fig. 11b) but glacier shrinkage has dominated and significant ice mass losses are clearly evident throughout this region. Masiokas et al. (2008) used hydroclimatic records from northwestern Patagonia and showed that glacier recession over the past century could be at least partially explained by a regional trend towards 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. This relationship has also been discussed by Villalba et al. (1990), who associated extended periods of cool/wet conditions — inferred from tree-ring records — with the formation of the main moraine systems at Glaciar Frías in the Tronador area (~41°S). Bown (2004) and Bown and Rivera (2007) presented analyses of surface climate records and 1958–2000 upper air temperatures (derived from radiosonde data from Puerto Montt, 41°26′S, 73°07′ W; ca. 95 km SW of Tronador). They found a significant warming aloft 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 shrinkage observed in northern Patagonia.

In the South Patagonian Andes, several glacier advances have been identified at a (growing) number of sites during the first half of the past millennium (Figs. 10 and 11c–e). The evidence for these earlier advances (based primarily on palaeosoils and/or subfossil wood material) has usually been found underneath or overridden by more extensive massive moraine systems that were generally emplaced between the 17th and 19th centuries during the peak LIA advances in this region. After the LIA, most glaciers in southern Patagonia have followed a marked retreating pattern that has continued until present times. Similar to the situation described further north, numerous glacier advances have occurred in the South Patagonian Andes during the past century but these readvances have not been sufficient to counteract the dominant pattern of glacier recession in this region (Figs. 2f–h, 10 and 11c–e). Villalba et al. (2003) showed that the southern tip of South America has warmed significantly over most of the 20th century and that this period has been the warmest for at least the past 400 years. This warming has very likely been a major forcing behind the widespread glacier recession but a decrease in precipitation is also usually discussed in the literature as an additional factor contributing to the recent ice mass loss observed in southern Patagonia (Rosenblüth et al., 1995; Rignot et al. 2003; Rivera, 2004). However, given the lack of good quality, long-term climatic data near glaciers, analyses of glacier–climate relationships in this portion of the Andes are tentative and the potential impacts of past and present climate changes on these ice masses are difficult to assess in detail. Recent important advances on this issue include the use of upper-air records derived from the NCEP-NCAR Reanalysis datasets to explain recent glacier changes (Rasmussen et al., 2007) or the detailed glaciological and meteorological modelling of conditions for some specific glacierized areas (Möller et al., 2007; Möller and Schneider, 2008).

From the regional histories described above it is possible to extract a broad, large-scale pattern of fluctuations characterized by isolated advances during the first half of the past millennium followed by a relatively synchronous glacier reactivation between the 17th and 19th centuries and widespread glacier shrinkage afterwards (see Figs. 2, 10 and 11). Embedded in this broad regional pattern of fluctuations it is possible to identify some interesting local and regional discrepancies. On a local scale, these discrepancies are probably the result of differences in topography, microclimate and conditions at the glacier fronts combined with the inherent limitations of the glacier records and/or the dating techniques used in the different studies. The cases of glacier surges (identified mainly during the 20th century, see above) constitute one of the most interesting and challenging issues from a glaciological and palaeoclimatic point of view because these records could potentially complicate the development of regionally representative glacier chronologies based on surficial evidence. The oscillations of many freshwater and tidewater calving glaciers, which are widely distributed in southern Patagonia and Tierra del Fuego, are also known to be influenced by non-climatic factors such as water depth, width of the calving front, and other site-specific factors (Warren, 1993, 1994; Warren and Rivera, 1994; Naruse and Skvarca, 2000; Rivera and Casassa, 2004; Benn et al., 2007). Volcanic activity is another potentially important factor influencing glacier behaviour on active ice-capped volcanoes throughout the extratropical Andes (Rivera et al., 2007). The dating of glacier events using radiocarbon data may also complicate the development of local (or regional) glacier histories. Given the low resolution of radiocarbon age determinations, it is currently difficult (if not impossible) to differentiate short-term glacier fluctuations on the basis of ^{14}C dates alone. This is especially true for the earlier part of the past millennium, when these data are the main source of information (see Fig. 10). Radiocarbon dating of glacier events of the past 3–4 centuries may also be problematic due to the non-linearity of the ^{14}C calibration curve (Porter, 1981).

Arguably the most important regional contrast found in this review is the difference in timing of the LIA maxima at the NPI compared to the SPI and glaciers further south and in surrounding areas (Fig. 11). The dating of trimlines and moraines associated with several NPI outlets showed consistently that the LIA maximum extent in this icefield occurred sometime during the 19th century. In contrast, for other glaciers in southern Patagonia the LIA maxima have been generally identified one to three centuries earlier (Fig. 11). As the NPI is located in a transitional position between two major climatic regimes in the north and south Patagonian Andes (Winchester and Harrison, 1996; Villalba et al., 2003), these differences may reflect the contrasting influences of these different regional climatic patterns. This contrasting behaviour may also reflect differences in the way and methods these glacier records were developed (i.e. through tree-ring or lichenometric age determinations, etc). Regardless of these potential confounding factors, the date of formation of the main LIA moraines are in most cases only known as minimum age estimates. There are very few cases where the occurrence of LIA advances have been estimated through closely bracketing dating controls (e.g. Villalba et al., 1990). Clearly, these issues require further research and attention as they could potentially influence future regional and larger-scale analyses of past and present glacier–climate relationships.

Despite these caveats, the wealth of glacier records gathered in this review shows some very interesting results and promising perspectives for multi-proxy climate reconstructions integrating, for example, the low-resolution information derived from the glacier records with other higher-resolution palaeoenvironmental indicators from the Andes (see other research papers presented in this Special Issue). The use of independent, complementary climate proxy records could help elucidate some interpretative problems regarding the temporal and spatial synchronicity of the main glacier and climate changes of the last millennium or help understand the main causes of the observed glacier changes from a broader perspective. However, as indicated by Luckman and Villalba (2001), there is still a significant need for a larger number of detailed, well-dated records of glacier fluctuations and a better understanding of the factors that control glacier mass balance if we are to use these records as palaeoclimatic indicators.

Acknowledgements

The research reported here has been supported by many sources. J.C. Aravena and A. Rivera were supported by FONDECYT grant 1080320, Centro de Ingeniería de la Innovación (CIN) and Centro de Estudios Científicos (CECS). CIN is funded by CONICYT and the Gobierno Regional de Los Ríos, Chile whereas CECS is funded by the Chilean Government through the Millennium Science Initiative and the Centers of Excellence Base Financing Program of CONICYT. This study was also supported by the Agencia Nacional de Promoción Científica y Tecnológica, Argentina, PICT 2002-10033, PICTR 2002-186, and the Projects CRN03 and CRN2047 from the Inter American Institute for Global Change Research (IAI). The latter project is funded by grant CRN II # 2060, which is supported by the US National Science Foundation (Grant GEO-0452325). We thank Comisión Nacional de Actividades Espaciales (CONAE, Argentina) for providing Landsat images. We are also grateful to Cesar Acuña, Fernando Ordenes, Francisca Bown, Pierre Pitte, Lidia Ferri Hidalgo and Claudia Bottero for their assistance in the preparation and compilation of tables and figures, and to Dr. Darío Trombotto (IANIGLA-CONICET) for help with the translation of Röthlisberger's notes from German to English. The comments and suggestions provided by Drs. Christoph Kull and Brian H. Luckman significantly improved the manuscript and are greatly appreciated.

Appendix A

Basic information for the Chilean and Argentinean glaciers depicted in Fig. 2.

Glacier in Fig. 2	Subregion—country	Lat. (S)	Long. (W)	Period
Tronquitos	Dry Andes—Chi	28.53	69.72	1955–2005
Guanaco	Dry Andes—Chi	29.35	70.02	1976–2005
Agua Negra	Dry Andes—Arg	30.15	69.80	1965–1993
Tapado	Dry Andes—Chi	30.13	69.92	1955–1978
Juncal Norte	Central Andes—Chi	33.03	70.10	1942–2006
Olivares Beta	Central Andes—Chi	33.13	70.18	1935–2006
Olivares Gama	Central Andes—Chi	33.13	70.17	1935–2006
Universidad	Central Andes—Chi	34.71	70.35	1955–2007
De Las Vacas	Central Andes—Arg	32.53	69.98	1896–2007
Güssfeldt	Central Andes—Arg	32.62	70.03	1896–2007
Del Plomo	Central Andes—Arg	33.03	70.00	1909–1934
Bajo del Plomo	Central Andes—Arg	33.00	69.97	1934–1974
Alto del Plomo	Central Andes—Arg	32.98	70.00	1934–1974
Oriental del Juncal	Central Andes—Arg	33.02	70.03	1934–1974
Alfa	Central Andes—Arg	33.07	70.05	1909–1974
Beta	Central Andes—Arg	33.08	70.05	1909–1974
Gama	Central Andes—Arg	33.10	70.03	1909–1974
Pequeño del Nevado	Central Andes—Arg	33.13	70.03	1909–1974
Corto	Central Andes—Arg	34.58	70.14	1948–2007
Humo	Central Andes—Arg	34.57	70.13	1914–2007
Fiero	Central Andes—Arg	34.61	70.16	1948–2007
Palomo	Central Andes—Chi	34.55	70.27	1955–2007
Cortaderal	Central Andes—Chi	34.64	70.26	1987–2007
Pichillancahue	N. Patag. Andes—Chi	39.43	71.87	1961–2007
Mocho SE	N. Patag. Andes—Chi	39.93	72.00	1976–2004
Casa Pangue	N. Patag. Andes—Chi	41.13	71.87	1911–2007
Turbio	N. Patag. Andes—Chi	39.42	71.88	1961–2007
Inexplorado 2	N. Patag. Andes—Chi	41.93	72.17	1961–2006
Inexplorado 3	N. Patag. Andes—Chi	41.98	72.20	1961–2006
Michinmahuida Norte	N. Patag. Andes—Chi	42.77	72.42	1961–2007
Michinmahuida Este	N. Patag. Andes—Chi	42.80	72.38	1961–2007
Río Amarillo	N. Patag. Andes—Chi	42.83	72.45	1961–2007
Huemules	S. Patag. Andes—Chi	45.88	72.97	1979–2007
Erasmo	S. Patag. Andes—Chi	46.12	73.17	1979–2007
San Quintín	S. Patag. Andes—Chi	46.85	73.80	1921–2003
San Rafael	S. Patag. Andes—Chi	46.68	73.80	1871–2007
Colonia	S. Patag. Andes—Chi	47.23	73.25	1944–2005
O'Higgins	S. Patag. Andes—Chi	48.88	73.25	1900–2005
Chico	S. Patag. Andes—Chi	49.08	73.15	1900–2006
Viedma	S. Patag. Andes—Arg	49.45	73.22	1900–2005
Ameghino	S. Patag. Andes—Arg	50.42	73.17	1947–2005
Grey (western arm)	S. Patag. Andes—Chi	50.93	73.27	1937–2006
Dickson (southern arm)	S. Patag. Andes—Chi	50.78	73.17	1896–2006
Arroyo San Lorenzo	S. Patag. Andes—Chi	47.55	72.32	1975–2003
Narváez	S. Patag. Andes—Arg	48.48	72.40	1896–2005
Río Mosco	S. Patag. Andes—Chi	48.45	72.43	1945–2005
Lengua	Magallanes—Chi	52.73	73.12	1942–2002
Marinelli	Magallanes—Chi	54.53	69.57	1913–2002
Garibaldi	Magallanes—Chi	54.67	69.93	1945–2007
Cipreses	Central Andes—Chi	34.56	70.37	1842–2007
Peñón	Central Andes—Arg	35.27	70.57	1550–2007
Azufre	Central Andes—Arg	35.28	70.55	1550–2007
Frías	N. Patag. Andes—Arg	41.15	71.80	1640–2003
San Lorenzo Sur	S. Patag. Andes—Arg	47.58	72.33	1650–2004
Piedras Blancas	S. Patag. Andes—Arg	49.26	72.98	1610–2005
Torre	S. Patag. Andes—Arg	49.32	73.04	1594–2005
Schiaparelli	Magallanes—Chi	54.38	70.83	1839–2005

Appendix B

Summary of the evidence for glacier advances in extratropical South America for the past 1000 years. The glaciers have been ordered following the sequence used in the text. Notes: (1) Dates for glacier advances derived from radiocarbon determinations are reported as 2σ calibrated calendar age ranges rounded to the nearest decade. All ^{14}C dates were calibrated using the program CALIB 5.0.1 (Stuiver and Reimer, 1993) and the Southern Hemisphere calibration dataset SHCal04 (McCormac et al., 2004). When calibration resulted in two or more non-overlapping calendar age segments, we report the segment with the highest associated probability. (*) Where multiple ^{14}C dates are available for the same deposit/event in a forefield, a pooled mean and standard deviation estimate from all samples were calculated prior to calibration using CALIB 5.0.1. (2) The evidence is abbreviated as follows: (AP—SI) aerial photos and/or satellite imagery; (OBS) direct observations and/or historical documents; (PSO) palaeosoil buried/overridden by glacier deposits; (BPS) basal peat sample; (ISS) *in situ* stump buried/overridden by glacier deposits; (RWS) stump reworked by glacier deposits (TRD) tree-ring dating of deposits; (LI) lichenometric determination. (3) Type of date obtained: (Adv) advance around indicated date; (Max) maximum age for deposits; (Min) minimum age for deposits.

Glacier	Dated period of glacier advance (1)	Evidence (2)	^{14}C age BP (code)	Comments (3)	Reference
Desert — Central Chilean–Argentinean Andes					
Agua Negra (30°10′S)	1981–84	AP–SI		Adv	Leiva (1999)
Juncal Sur (33°S)	1946–47	OBS		Adv	Lliboutry (1956)
Cipreses (34°33′S)	1150–1650	PSO	625 ± 155 (Hv-10915)	Max	Röthlisberger (1986)
	1858	OBS		Adv	Pissis (1875)
Piuquenes (34°S)	1848	OBS		Adv (surge?)	Plagemann (1887)
Universidad (34°42′S)	1943	OBS		Adv (surge?)	Lliboutry (1958)
de las Vacas (32°30′S)	1974–99	AP-SI		Adv	Espizua and Maldonado (2007)
Horcones Inferior (32°40′S)	1984–89	AP–SI		Adv - Surging glacier	Various refs. (see text)
	2005–06	OBS			
Grande del Juncal (32°57′S)	ca. 1910	OBS		Adv (surges?)	Various refs. (see text)
	1934–55				
	1985–91	AP–SI			
Grande del Nevado (32°57′S)	1933–34	OBS		Adv – Surging glacier	Various refs. (see text)
	1984–85	OBS			
Oriental del Juncal	1982–91	AP–SI		Adv	Llorens and Leiva (1995)
Juncal Beta	1986–91	AP–SI		Adv	Llorens and Leiva (1995)
Juncal Gama	1986–91	AP–SI		Adv	Llorens and Leiva (1995)
Pequeño del Nevado	1985–91	AP–SI		Adv	Llorens and Leiva (1995)
Innominado	1986–91	AP–SI		Adv	Llorens and Leiva (1995)
4 glaciers at Cerros Tupungato, Tupungatito, and San Juan (ca. 33°15′S)	1982–85	AP–SI		Adv	Llorens (2002)
Río Museo (34°S)	1935	OBS		Adv	Lliboutry (1958)
Colina (34°S)	1927	OBS		Adv	Lliboutry (1958)
5 glaciers in the Tunuyán Sur basin (ca. 33°40′S)	1987–99	OBS		Adv	Gargantini 2008
Laguna (34°S)	1970–82	AP–SI		Adv (surge?)	Espizua (1986)
El Peñón (35°S)	1460–1660	BPS	340 ± 50 (GD-12764)	Min	Espizua and Pitte (2009-this issue)
	1790–1950	BPS	150 ± 65 (GD-15831)	Min	
	1963–86	AP–SI		Adv	Espizua and Maldonado (2007)
El Azufre (35°S)	1460–1640 (*)	BPS	400 ± 60 (LP-930); 350 ± 60 (LP-1442)	Min	Espizua (2005)
	1963–86	AP–SI		Adv	Espizua and Maldonado (2007)
Las Choicas (35°S)	1800–1950	BPS	80 ± 60 (BETA-125198)	Min	Espizua (2004); Espizua and Pitte (2009-this issue)
Las Damas (35°S)	1500–1660 (*)	BPS	360 ± 40 (CURL-5948); 230 ± 60 (BETA-119845)	Min	Espizua (2004); Espizua and Pitte (2009-this issue)
North Patagonian Andes					
Frías (41°09′S)	1236	TRD		Min	Villalba et al. (1990)
	1638–39	TRD		Max	
	1719–21	TRD		Max	
	1742–52	TRD		Min	
	1835–43	TRD		Min	
	1878–84	TRD		Min	
	1912–16	TRD		Min	
	1941–43	TRD		Min	
	1976–77	OBS-TRD		Adv	
Castaño Overo (41°11′S)	1818–29	TRD		Min	Rabassa et al. (1984)
	1842	TRD		Min	
	1857	TRD		Min	
	1884	TRD		Min	
	1902	TRD		Min	
Río Manso (41°12′S)	950–1300	ISS	940 ± 110 (Hv-11800)	Max	Röthlisberger (1986)
	1380–1440 (*)	ISS	620 ± 50 (Hv-12865); 585 ± 50 (Hv-12864)	Max	
	1450–1710	ISS	300 ± 85 (HV-11799)	Max	
	1701	TRD		Min	Masiokas et al. (in press)
	1789–1850s	TRD		Bracketing dates	
	1875	TRD		Min	
	1890	TRD		Min	
	1899	TRD		Min	
	1919	TRD		Min	

Glacier	Dated period of glacier advance (1)	Evidence (2)	^{14}C age BP (code)	Comments (3)	Reference
North Patagonian Andes					
Río Manso (41°12′S)	1949	TRD		Min	
	1955	TRD		Min	
	Mid 1970 s	AP-TRD		Min	
	Late 1990 s	AP-OBS		Adv	
Esperanza Norte (42°15′S)	1460–1630	ISS	375 ± 40 (NSRL-12467)	Max	This study
Torrecillas (42°40′S)	1440–1510	ISS	440 ± 30 (NSRL-11093)	Max	Masiokas et al. (2000)
	1735	LI		Min	Garibotti and Villalba (2009)
	1738	TRD		Min	This study
	1755	LI		Min	Garibotti and Villalba (2009)
	1891	LI		Min	
	1900	LI		Min	
	1906	LI		Min	
	1934	LI		Min	
	1937	OBS		Adv	
North Patagonian Icefield					
Reichert (46°32′S)	1876	TRD		Min	Harrison and Winchester (1998)
	1930	TRD		Min	
	1953	TRD		Min	
	1970	TRD		Min	
Gualas (46°35′S)	1876	TRD		Min	Harrison and Winchester (1998)
	1909	TRD		Min	
	1936	TRD		Min	
	1954–64	TRD		Min	
	1994	OBS		Adv	
San Rafael (46°41′S)	1875	OBS		Adv	Araneda et al. (2007)
	1956	OBS		Adv	Heusser (1960)
	1991–93	OBS		Adv	Winchester and Harrison (1996)
San Quintín (46°52′S)	1851	TRD		Min	Winchester and Harrison (1996)
	1935–45	AP-OBS		Adv	
	1991–93	OBS		Adv	
Exploradores (46°30′S)	1170–1280 (*)	RWS	870 ± 60; 820 ± 60. No codes available	Probable maximum ages, but evidence is poorly described and documented	Aniya et al. (2007)
	1810–1930 (*)	RWS and other organic sediments	7 samples: 108 to 147 ^{14}C yr BP. No error terms or codes available. We used a 30-year standard deviation for all samples.		
	1944	AP		Adv	
Calafate (46°44′S)	1871	LI-TRD		Min	Harrison et al. (2007)
	1925	LI-TRD		Min	
León (46°44′S)	1867	TRD		Min	Harrison et al. (2007)
	1994–99	OBS		Adv	
Soler (46°55′S)	1300–1410 (*)	ISS	536 ± 40 (SRR-6605); 782 ± 45 (SRR-6608)	Max	Glasser et al. (2002)
	1610–1810	Leaves on depression	270 ± 50 (N/A)	Min	Aniya and Naruse (1999)
	1850	TRD		Min	Sweda (1987)
	1890	TRD		Min	
	1910	TRD		Min	
	1940	TRD		Min	
Nef (47°07′S)	1370	TRD		Min	Winchester et al. (2001)
	1863	LI		Min	
	1884	LI		Min	
	1935	LI-TRD		Min	
Arenales (ca. 47°14′S)	1883	LI-TRD		Min	Harrison and Winchester (2000)
	1970	LI		Min	
	1996	OBS		Adv	
Colonia (ca. 47°14′S)	1883	TRD		Min	Harrison and Winchester (2000)
	1904	LI–TRD		Min	
	1914–17	LI–TRD		Min	
	1945–48	LI–TRD		Min	
	1980	LI–TRD		Min	
Arco (ca. 47°14′S)	1881	LI–TRD		Min	Harrison and Winchester (2000)
	1956	TRD		Min	
South Patagonian Icefield					
Trinidad (49°25′S)	2000	OBS		Adv	Rivera et al. (2002)
Pío XI (49°08′S)	1928	OBS		Adv	Various refs. (see text)
	1994	OBS		Adv	
	2008	OBS		Adv	Rivera, personal observation
Ofhidro Norte (48°30′S)	1130–1400	ISS	800 ± 95 (I-3827)	Max	Mercer (1970)
	1790	TRD		Min	
	1845	TRD		Min	
	1850	TRD		Min	

(*continued on next page*)

Glacier	Dated period of glacier advance (1)	Evidence (2)	^{14}C age BP (code)	Comments (3)	Reference
Bernardo (48°40′S)	1480–1820	ISS	270 ± 90 (I-3824)	Max	Mercer (1970)
	1775	TRD		Min	
	1825	TRD		Min	
Témpano (48°47′S)	1760	TRD		Max	Mercer (1970)
	1945	AP		Adv	
Hammick (48°50′S)	1750	TRD		Min	Mercer (1970)
	1840	TRD		Min	
	1945	AP		Adv	
Bravo (48°39′S)	1260–1440	ISS	665 ± 80 (Hv-10899)	Max	Röthlisberger (1986)
	1660–1900 (*)	ISS	270 ± 100 (Hv-10900); 165 ± 50 (Hv-11556)	Max	
O'Higgins (48°53′S)	1180–1320	ISS?	790 ± 55 (Hv-11558)	Probable maximum ages, but origin of samples uncertain	Röthlisberger (1986)
	1450–1670	ISS?	345 ± 55 (Hv-10905)		
Upsala (49°42′S)	1600	TRD		Min	Mercer (1965)
	1820	TRD		Min	
Ameghino (50°25′S)	1430–1670	ISS	380 ± 80 (NU-658)	Max	Aniya (1996)
	1730–1800 (*)	ISS	315 ± 30 (NSRL-11092); 290 ± 30 (NSRL-11086); 285 ± 40 (NSRL-11090); 205 ± 35 (NSRL-11085); 170 ± 30 (NSRL-11091); 160 ± 30 (NSRL-11087); 150 ± 30 (NSRL-11084)	Max	Masiokas et al. (2001)
Moreno (50°30′S)	1130–1330	ISS	800 ± 80 (NU-355)	Max	Aniya and Sato (1995b)
Frías-SPI (50°41′S)	1660	TRD		Min	Mercer (1968, 1976)
	1810	TRD		Min	
	1860	TRD		Min	
Grey (50°49′S)	1660	TRD		Min	Marden and Clapperton (1995)
	1805	TRD		Min	
	1845	TRD		Min	
	1890	TRD		Min	
Glaciers adjacent to SPI					
San Lorenzo Sur (47°35′S)	1665	TRD		Min	García-Zamora et al. (2004)
	1769	TRD		Min	
	1864	TRD		Min	
	1819	TRD		Min	
Calluqueo (47°35′S)	1652	TRD		Min	Aravena (2007)
	1683	TRD		Min	
	1715	TRD		Min	
	1742	TRD		Min	
	1760	TRD		Min	
	1845	TRD		Min	
	1910	TRD		Min	
Río Tranquilo (47°35′S)	1632	TRD		Min	Aravena (2007)
	1669	TRD		Min	
	1726	TRD		Min	
	1770	TRD		Min	
	1873	TRD		Min	
Arroyo San Lorenzo (47°35′S)	1675	TRD		Min	Aravena (2007)
	1802	TRD		Min	
	1820	TRD		Min	
Narváez (48°29′S)	1270–1310 (*)	ISS	925 ± 30 (NSRL-12461); 720 ± 35 (NSRL-12460); 655 ± 30 (NSRL-12462); 645 ± 45 (NSRL-12463)	Max	Masiokas et al. (2001); This study
	1880	TRD		Min	Mercer (1968)
	1680	TRD		Min	
Huemul-Mellizo Norte (48°34′S)	1410–1630	ISS	465 ± 65 (Hv-10894)	Max	Röthlisberger (1986)
Lago del Desierto I (49°04′S)	1740	TRD		Min	Masiokas et al. (2009-this issue)
	1901	TRD		Min	
	1905	TRD		Min	
	1975	TRD		Min	
Lago del Desierto II-Huemul (49°04′S)	1481	LI		Min	Masiokas et al. (2009-this issue); Garibotti and Villalba (2009)
	1645	TRD		Min	
	1743	TRD		Max	
	1841	LI		Min	
	1886	LI		Min	
	1900	TRD		Min	
	1936	TRD		Min	
	1964	TRD		Min	
Lago del Desierto III (49°04′S)	1655	TRD		Min	Masiokas et al. (2009-this issue)
	1734	TRD		Min	
	1867	TRD		Min	
	1920	TRD		Min	
	1945	TRD		Min	

Glacier	Dated period of glacier advance (1)	Evidence (2)	^{14}C age BP (code)	Comments (3)	Reference
Piedras Blancas (49°15′S)	1610	TRD		Min	Masiokas et al. (2009-this issue);
	1815	TRD		Min	Garibotti and Villalba (2009)
	1904	LI		Min	
	1931	OBS		Adv	
	1968–81	AP		Adv	
Torre (49°24′S)	1140–1400	BPS	800 ± 85 (I-984)	Min	Mercer (1965)
	1594	TRD		Min	Masiokas et al. (2009-this issue)
	1727	TRD		Min	
	1799	TRD		Min	
	1866	TRD		Min	
	1910	TRD		Min	
Dos Lagos (49°47′S)	1760	TRD		Min	Mercer (1965)
	1780	TRD		Min	
	1820	TRD		Min	
	1910	TRD		Min	
Cerro Norte (49°47′S)	1410–1670	ISS	390 ± 85 (I-989)	Max	Mercer (1965)
Francés (51°01′S)	1290–1400	PSO	675 ± 45 (Hv-10844)	Max	Röthlisberger (1986)
	1620–1950	PSO	235 ± 65 (HV-11984)	Max	
Perro (50°56′S)	1150–1390	ISS	795 ± 80 (HV-10887)	Max	Röthlisberger (1986)
	1730–1800 (*)	ISS-PSO	345 ± 100 (HV-10886); 295 ± 75 (HV-11554); 260 ± 50 (HV-11555); 205 ± 50 (HV-11986)	Max	
Magallanes region					
Lengua (52°44′S)	1628	TRD		Min	Koch and Kilian (2005)
	1872–75	TRD		Max	
	1886	TRD		Min	
	1902	TRD		Min	
	1912	TRD		Min	
	1941	TRD		Min	
Alejandro (53°45′S)	1675	TRD		Min	Aravena (2007)
	1758	TRD		Min	
	1794	TRD		Min	
	1843	TRD		Min	
	1895	TRD		Min	
Beatriz (53°45′S)	1773	TRD		Min	Aravena (2007)
	1845	TRD		Min	
	1916	TRD		Min	
	1945	TRD		Min	
Ema (54°25′S)	1210–1440	RWS	695 ± 95 (UA-13425)	Max	Strelin et al. (2008)
	1430–1670	RWS	379 ± 75 (UA-13419)	Max	
	1450–1680	RWS	335 ± 70 (UA-13420)	Max	
	1610–1820	RWS	251 ± 70 (UA-13424)	Max	
	1830	TRD		Min	
	1850	TRD		Min	
	1870	TRD		Min	
Bahía Pía (54°40′S)	1020–1270	RWS	940 ± 70 (UA-4886)	Max	Kuylenstierna et al. (1996)
	1270–1430	BPS	675 ± 70 (UA-4884)	Min	
	2007	OBS		Adv	Porter, pers. comm.
Garibaldi (54°40′S)	2007	OBS		Adv	Rivera, personal observation

References

Aguado, C., 1983. Inventario de glaciares y morenas de la cuenca del Río San Juan, sector sur, cuenca del Río de los Patos. San Juan, Argentina. IANIGLA-CONICET, Mendoza. (Unpublished).

Aguado, C., 1986. Inventario de glaciares y morenas en la cuenca del Río San Juan, sector centro y norte: cuencas de los ríos Blanco, Calingasta, Ansilta y Castaño. Provincia de San Juan, Argentina. IANIGLA-CONICET, Mendoza. (Unpublished).

AHMC, 1880. Espedición de Juan Ladrillero (1557 a 1559). Anuario Hidrográfico de la Marina de Chile 4, 453–525.

Aniya, M., 1988. Glacier inventory for the Northern Patagonia Icefield, Chile, and variations 1944/45 to 1985/86. Arctic and Alpine Research 20 (2), 179–187.

Aniya, M., 1995. Holocene glacial chronology in Patagonia: Tyndall and Upsala glaciers. Arctic and Alpine Research 27, 311–322.

Aniya, M., 1996. Holocene variations of Ameghino Glacier, southern Patagonia. The Holocene 6, 247–252.

Aniya, M., 1999. Recent glacier variations of the Hielos Patagonicos, South America, and their contribution to sea-level change. Arctic, Antarctic and Alpine Research 31 (2), 165–173.

Aniya, M., 2001. Glacier variations of Hielo Patagónico Norte, Chilean Patagonia, since 1944/45, with special reference to variations between 1995/96 and 1999/2000. Bulletin of Glacier Research 18, 55–63.

Aniya, M., Naruse, R., 1999. Late-Holocene glacial advances at Glaciar Soler, Hielo Patagonico Norte, South America. Transactions, Japanese Geomorphological Union 20, 69–83.

Aniya, M., Sato, H., 1995a. Holocene glacial chronology of Upsala Glacier at Peninsula Herminita, southern Patagonia. Bulletin of Glacier Research 13, 83–96.

Aniya, M., Sato, H., 1995b. Morphology of Ameghino Glacier and landforms of Ameghino Valley, southern Patagonia. Bulletin of Glacier Research 13, 69–82.

Aniya, M., Skvarca, P., 1992. Characteristics and variations of Upsala and Moreno Glaciers, southern Patagonia. Bulletin of Glacier Research 10, 39–53.

Aniya, M., Naruse, R., Shizukuishi, M., Skvarca, P., Casassa, G., 1992. Monitoring recent glacier variations in the Southern Patagonian Icefield, utilizing remote sensing data. International Archives of Photogrammetry and Remote Sensing 29 (B7), 87–94.

Aniya, M., Sato, H., Naruse, R., Skvarca, P., Casassa, G., 1996. The use of satellite and airborne imagery to inventory outlet glaciers of the Southern Patagonian Icefield, South America. Photogrammetric Engineering and Remote Sensing 62, 1361–1369.

Aniya, M., Sato, H., Naruse, R., Skvarca, P., Casassa, G., 1997. Recent glacier variations in the Southern Patagonia Icefield, South America. Arctic and Alpine Research 29 (1), 1–12.

Aniya, M., Dhakal, A., Park, S., Naruse, R., 2000. Variations of Patagonian Glaciers, South America, using RADARSAT and Landsat images. Canadian Journal of Remote Sensing 26 (6), 501–511.

Aniya, M., Barcaza, G., Iwasaki, S., 2007. Recent glacier advances at Glaciar Exploradores, Hielo Patagónico Norte, Chile. Bulletin of Glaciological Research 24, 49–57.

Araneda, A., Torrejón, F., Aguayo, M., Torres, L., Cruces, F., Cisternas, M., Urrutia, R., 2007. Historical records of San Rafael glacier advances (North Patagonian Icefield): another clue to 'Little Ice Age' timing in southern Chile? The Holocene 17, 987–998.

Aravena, J.C., 2007. Reconstructing climate variability in southern Chilean Andes. Ph.D. Dissertation, University of Western Ontario, London, Ontario, Canada, 220 pp.

Benn, D.I., Hulton, N.R.J., Mottram, R.H., 2007. 'Calving laws', 'sliding laws' and the stability of tidewater glaciers. Annals of Glaciology 46, 123–130.

Bertone, M., 1960. Inventario de los glaciares existentes en la vertiente Argentina entre los paralelos 47°30′ y 51° S. Instituto Nacional del Hielo Continental Patagónico, Publicación No. 3, Buenos Aires, 104 pp.

Bown, F., 2004. Cambios climáticos en la Región de Los Lagos y respuestas recientes del Glaciar Casa Pangue (41°08′S). MSc Thesis, Universidad de Chile, Santiago, 131 pp.

Bown, F., Rivera, A., 2007. Climate changes and glacier responses during recent decades in the Chilean Lake District. Global and Planetary Change 59, 79–86.

Bown, F., Rivera, A., Acuña, C., 2008. Recent glacier variations at the Aconcagua basin, central Chilean Andes. Annals of Glaciology 48, 43–48.

Brüggen, J., 1928. La glaciación actual y cuaternaria de la cordillera de los Andes. Anales de la Universidad de Chile, tercer trimester, pp. 601–684.

Brüggen, J., 1936. Informe geológico sobre la Región de Ofqui. Boletín del Dpto. de Minas y Petróleo 52, 197–208.

Brüggen, J., 1950. Fundamentos de la Geología de Chile. Instituto Geográfico Militar, Santiago, Chile.

Burckhardt, C., 1900. Profils géologiques transversaux de la Cordillère Argentino–Chilienne. Stratigraphie et tectonique. Anales del Museo de La Plata, Sec. Geología y Mineralogía, Tomo II. InLa Plata, Argentina.

Carrasco, J., Quintana, J., Casassa, G., 2005. Changes of the 0 °C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. Hydrological Sciences Journal 50 (6), 933–948.

Casassa, G., 1995. Glacier inventory in Chile: current status and recent glacier variations. Annals of Glaciology 21, 317–322.

Casassa, G., Marangunic, C., 1987. Exploration history of the Northern Patagonia Icefield. Bulletin of Glacier Research 4, 163–175.

Casassa, G., Brecher, H., Rivera, A., Aniya, M., 1997. A century-long record of Glacier O'Higgins, Patagonia. Annals of Glaciology 24, 106–110.

Casassa, G., Rivera, A., Aniya, M., Naruse, R., 2002a. Current knowledge of the Southern Patagonia Icefield. In: Casassa, G., Sepúlveda, F., Sinclair, R. (Eds.), The Patagonian Icefields. A Unique Natural Laboratory for Environmental and Climate Change Studies. Kluwer Academic/Plenum Publishers, New York, pp. 67–83.

Casassa, G., Smith, K., Rivera, A., Araos, J., Schnirch, M., Schneider, C., 2002b. Inventory of glaciers in Isla Riesco, Patagonia, Chile, based on aerial photography and satellite imagery. Annals of Glaciology 34, 373–378.

Casassa, G., Rivera, A., Schwikowski, M., 2006. Glacier mass-balance data for southern South America (30 S–56 S). In: Knight, P.G. (Ed.), Glacier Science and Environmental Change. Blackwell, Oxford, UK, pp. 239–241.

Cobos, D., 1981. Inventario de glaciares, Cuenca del Río Atuel. Evaluación de los recursos hídricos sólidos de la Cordillera de los Andes IANIGLA-CONICET, Mendoza, Argentina. (Unpublished).

Cobos, D., Boninsegna, J.A., 1983. Fluctuations of some glaciers in the upper Atuel River basin, Mendoza, Argentina. IANIGLA-CONICET: Quaternary of South America and Antarctic Península 1, 61–82.

Colqui, B.S., 1965. Repertorio actualizado sobre información recogida en glaciares argentinos. Acta Geológica Lilloana 7, 63–78.

Colqui, B.S., Madejski, M.E., 1952. Contribución al estudio del glaciar Torrecillas (Lago Menéndez, Chubut). Meteoros 2, 209–214.

Conway, M., 1902. Aconcagua and Tierra del Fuego. Cassell and Company Ltd., London.

Corte, A.E., Espizua, L.E., 1981. Inventario de glaciares de la cuenca del Río Mendoza. IANIGLA-CONICET, Mendoza, Argentina, pp. 5–62. 19 planos.

Darwin, C., 1839. Narrative of the surveying voyages of His Majesty's Ships Adventure and Beagle between the years 1826 and 1836, describing their examination of the southern shores of South America, and the Beagle's circumnavigation of the globe. Journal and Remarks III, 1832–1836.

De Agostini, A., 1945. Andes Patagónicos, In: Kraft, Guillermo (Ed.), Viajes de Exploración a la Cordillera Patagónica Austral, Segunda edición. Buenos Aires. 445 pp.

De Agostini, A., 1959. Esfinges de Hielo. Escalada de los Montes Sarmiento e Italia en la Tierra del Fuego. Editorial ILTE, Torino, 235 pp.

Denton, G., 1999. Glacial and vegetational history of the southern Lake District of Chile — preface. Geografiska Annaler 81A (2), 105–106.

Ereño, C.E., Hoffmann, J.A., 1976. El régimen pluvial de la Cordillera Central. Departamento de Geografía, Buenos Aires.

Escobar, F., Vidal, F., Garin, C., 1992. Water balance in the Patagonia Icefield. Bulletin of Glacier Research 4, 109–120.

Espizua, L.E., 1982. Glacier and moraine inventory on the eastern of Cordón del Plata and Cordón del Portillo, Central Andes, Argentina. In: Evenson, E., Sclüchter, C., Rabassa, J. (Eds.), Tills and Related Deposits Genesis/Petrology/Application/Stratigraphy. INQUA Symposia on the Genesis and Lithology of Quaternary Deposits, USA 1981/Argentina 1982. A.A. Balkema, Rotterdam, pp. 381–395.

Espizua, L.E., 1986. Fluctuations of the Rio del Plomo glaciers. Geografiska Annaler 68A, 317–327.

Espizua, L.E., 2004. Holocene glacier variations in the Las Choicas and Las Damas valleys, Mendoza, Argentina. 2nd International Symposium on Mass Balance of Andean Glaciers, Glacier Shrinkage in the Andes and Consequences for Water Resources. Huaraz, Peru. 6–9 July, 2004.

Espizua, L.E., 2005. Holocene glacier chronology of Valenzuela Valley, Mendoza Andes, Argentina. The Holocene 15 (7), 1079–1085.

Espizua, L.E., Bengochea, J.D., 1990. Surge of Grande del Nevado Glacier (Mendoza, Argentina) in 1984: its evolution through satellite images. Geografiska Annaler 72A (3–4), 255–259.

Espizua, L.E., Maldonado, G.I., 2007. Glacier fluctuations in the Central Andes of Mendoza, Argentina from 1894/1896 to 2005. In: Scarpati, O.E., Jones, A.A. (Eds.), Environmental Change and Rational Water Use. Orientación Gráfica Editora S.R.L., Buenos Aires, pp. 353–366.

Espizua, L.E., Pitte, P., 2009. The Little Ice Age advances in the Central Andes (350S), Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology. 281, 345–350 (this issue).

Espizua, L.E., Ferri-Hidalgo, L. Gargantini, H., Pitte, P., 2006. Ambiente y Procesos glaciales y periglaciales en Lama-Veladero, San Juan, Argentina. Subsecretaría de Minería de la Provincia de San Juan, 57 pp., 13 mapas. (Unpublished).

Espizua, L.E., Pitte, P., Ferri Hidalgo, L., 2008. Horcones Inferior glacier surge. In: Fluctuations of Glaciers for 2000–2005. Vol. IX. Prepared by World Glacier Monitoring Service, (WGMS) ICSU (FAGS)-IUGG (IACS)-UNEP-UNESCO-WMO, pp. 41–42.

Falvey, M., Garreaud, R.D., 2009. Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). Journal of Geophysical Research 114 (D04102), 1–5. doi:10.1029/2008JD010519.

Fernández, A., Rivera, A., Ramírez, C., 2006. Variaciones recientes de glaciares entre 41 S y 49 S y su relación con los cambios climáticos. Revista Geográfica 139, 39–69.

Ferri Hidalgo, L., Espizua, L., Pitte, P., 2006. Glacier fluctuations at Cerro Tupungato. Abstracts from the International Symposium Reconstructing Past Regional Climate Variations in South America Over the Late Holocene: A New PAGES Initiative. Malargüe, Mendoza, Argentina, p. 73.

Fitz Gerald, E.A., 1899. The Highest Andes. A record of the first ascent of Aconcagua and Tupungato in Argentina and the exploration of the surrounding valleys. Methuen & Co., London. 390 pp.

Fitz-Roy, R., 1839. Narrative of the surveying voyages of His Majesty's Ships Adventure and Beagle between the years 1826 and 1836, describing their examination of the southern shores of South America, and the Beagle's circumnavigation of the globe, volume II. Proceedings of the Second Expedition, 1831–36, Under the Command of Captain Robert Fitz-Roy. Henry Colburn, London. 695 pp.

García, J., 1889. Diario del viaje i navegación hechos por el Padre José García, de la Compañía de Jesús, desde su misión de Cailín, en Chiloé, hacia el Sur, en los años 1766 i 1767. Anuario Hidrográfico de la Marina de Chile 14, 3–43.

García-Zamora, G., Villalba, R., Delgado, S., Trombotto, D., Masiokas, M., Calí, S., Ripalta, A., Hernandez, J., 2004. Glacier fluctuations during the past centuries in the Argentinean sector of Cerro San Lorenzo (47°40′S), southern Patagonia. 2nd Symposium on Mass Balance of Andean Glaciers, Glacier Shrinkage in the Andes and Consequences for Water Resources. Huaraz, Peru. July 6–9 2004.

Gargantini, H., 2008. Fluctuaciones de los glaciares de la cuenca del Tunuyán Sur. Trabajo de Licenciatura en Ciencias Geológicas, Facultad de Ciencias Exactas, Físicas y Naturales. Universidad Nacional de San Juan. Registro 9084, 52 pp.

Garibotti, I.A., Villalba, R., 2009. Lichenometric dating using *Rhizocarpon* subgenus *Rhizocarpon* in the Patagonian Andes, Argentina. Quaternary Research 71, 271–283.

Garín, C., 1987. Inventario de glaciares de los Andes Chilenos desde los 18° a los 32° de latitud sur. Revista de Geografía Norte Grande 14, 34–48.

Garreaud, R., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. Palaeogeography, Palaeoclimatology, Palaeoecology. 281, 180–195 (this issue).

Gerth, E., 1931. Contribuciones a la estratigrafía y paleontología de los Andes Argentinos. Quinta parte: La Estructura Geológica de la Cordillera Argentina entre el Río Grande y el Río Diamante en el Sud de la Provincia de Mendoza. Actas de la Academia Nacional de Ciencias, Tomo X, Entrega 2da. Córdoba, Argentina, pp. 125–172.

Glasser, N.F., Hambrey, M.J., Aniya, M., 2002. An advance of Soler Glacier, North Patagonian Icefield, at ca. AD 1222–1342. The Holocene 12, 113–120.

Glasser, N.F., Harrison, S., Winchester, V., Aniya, M., 2004. Late Pleistocene and Holocene palaeoclimate and glacier fluctuations in Patagonia. Global and Planetary Change 43, 79–101.

González-Ferrán, O., 1995. Volcanes de Chile. Instituto Geográfico Militar, Santiago, Chile. 635 pp.

Groeber, P., 1947. Observaciones geológicas a lo largo del meridiano 70°. 2 Hojas: Sosneado y Maipú. Sociedad Geológica Argentina, Revista 2 (II), 1–174.

Groeber, P., 1954. Bosquejo paleogeográfico de los glaciares del Diamante y Atuel. Buenos Aires, Asociación Geológica Argentina, Revista IX (2), 89–108.

Grosjean, M., Messerli, B., Schreier, H., 1991. Seehochstände. Bodenbildung und Vergletscherung im Altiplano Nordchiles: Ein interdisziplinärer Beitrag zur Klimageschichte der Atacama. Erste Resultate. Bamberger Geographische Schriften 11, 99–108.

Grove, J.M., 2004. Little Ice Ages: Ancient and Modern (2 vols). Routledge, London. 718 pp.

Happoldt, H., Schrott, L., 1993. Horcones Inferior. Fluctuations of glaciers 1985–1990. IAHS (ICSI)–UNEP–UNESCO, Vol. V.

Harrison, S., Winchester, V., 1998. Historical fluctuations of the Gualas and Reicher glaciers, North Patagonian Icefield, Chile. The Holocene 8 (4), 481–485.

Harrison, S., Winchester, V., 2000. Nineteenth and twentieth century glacier fluctuations and climatic implications in the Arco and Colonia Valleys, Hielo Patagónico Norte, Chile. Arctic, Antarctic and Alpine Research 32 (1), 55–63.

Harrison, S., Winchester, V., Glasser, N.F., 2007. The timing and nature of recession of outlet glaciers of Hielo Patagónico Norte, Chile, from their Neoglacial IV (Little Ice Age) maximum positions. Global and Planetary Change 59, 67–78.

Harrison, S., Glasser, N., Winchester, V., Haresign, E., Warren, C., Duller, G.A.T., Bailey, R., Ivy-Ochs, S., Jansson, K., Kubik, P., 2008. Glaciar León, Chilean Patagonia: late-Holocene chronology and geomorphology. The Holocene 18 (4), 643–652.

Hatcher, J.B., 1903. Narrative of the Princeton University Expedition to Patagonia, March 1896 to September 1897. Princeton University Press, Princeton. 314 pp.

Heim, A., 1951. Informe sobre un estudio glaciológico en el Parque Nacional Los Glaciares. Adm. Gral. de Parques Nacionales, Buenos Aires.
Helbling, R., 1919. Beiträge zur Topographischen Erschliessung der Cordilleras de los Andes zwischen Aconcagua und Tupungato. Sonderabdruck aus dem XXIII Jahresbericht des Akademischen Alpenclub Zürich 1918. . 77 pp.
Helbling, R., 1935. The origin of the Río Plomo ice-dam. The Geographical Journal 8 (1), 41–49.
Helbling, R., 1940. Ausbruch eines Gletschersees in den argentinischen Anden und aussergewöhnliche Gletscherschwankungen im Allgemeinen. Schweizerische Bauzeitung 115 (11), 121–128.
Heusser, C.J., 1960. Late-Pleistocene environments of the Laguna de San Rafael area, Chile. Geographical Review 50 (4), 555–577.
Holmlund, P., Fuenzalida, H., 1995. Anomalous Glacier responses to 20th century climatic changes in Darwin Cordillera, Southern Chile. Journal of Glaciology 41 (139), 465–473.
Jenny, B., Kammer, K., 1996. Jungquartäre Vergletscherungen. In: Amman, C., Jenny, B., Kammer, K. (Eds.), Climate Change in den trockenen Anden. Geographisches Institut Universität Bern, Geographica Bernensia, G46, pp. 1–80.
Keller, C., 1947. La región del Hielo Continental frente al lago Buenos Aires. Revista Chilena de Historia y Geografía 110, 309–335.
King, P., 1839. Narrative of the surveying voyages of His Majesty's Ships Adventure and Beagle between the years 1826 and 1836, describing their examination of the southern shores of South America, and the Beagle's circumnavigation of the globe, volume I. Proceedings of the first expedition, 1826–30, under the command of Captain P. Parker King, Henry Colburn, London. 597 pp.
Koch, J., Kilian, R., 2005. “Little Ice Age” glacier fluctuations, Gran Campo Nevado, southernmost Chile. The Holocene 15, 20–28.
Kölliker, A., Kühn, F., Reichert, A., Tomsen, A., Witte, L., 1917. Patagonia: Resultados de las expediciones realizadas en 1910 a 1916. Sociedad Científica Alemana, Buenos Aires. 2 vols., 430 pp.
Kuylenstierna, J.L., Rosqvist, G.C., Holmlund, P., 1996. Late-Holocene glacier variations in the Cordillera Darwin, Tierra del Fuego, Chile. The Holocene 6, 353–358.
Lawrence, D.B., Lawrence, E.G., 1959. Recent glacier variations in southern South America. American Geographical Society Southern Chile Expedition Technical Report, Office of Naval Research Contract 641(04), New York, USA.
Le Quesne, C., Acuña, C., Boninsegna, J.A., Rivera, A., 2009. Historical glacier variations in the central Andes of Chile and Argentina and long-term precipitation variability reconstructed from tree-rings. Palaeogeography, Palaeoclimatology, Palaeoecology 281, 334–344.
Leiva, J.C., 1999. Recent fluctuations of the Argentinean glaciers. Global and Planetary Change 22, 169–177.
Leiva, J.C., Cabrera, G.A., Lenzano, L.E., 2007. 20 years of mass balances on the Piloto glacier, Las Cuevas river basin, Mendoza, Argentina. Global and Planetary Change 59, 10–16.
Lliboutry, L., 1953. More about advancing and retreating glaciers in Patagonia. Journal of Glaciology 2 (13), 168–172.
Lliboutry, L., 1954. Le massif du Nevado Juncal (Andes de Santiago). Ses pénitents et ses glaciers. Revue de géographie alpine 42 (3), 465–495.
Lliboutry, L., 1956. Nieves y glaciares de Chile. Fundamentos de Glaciología. Ediciones de la Universidad de Chile, Santiago, Chile, 472 pp., maps.
Lliboutry, L., 1958. Studies of the shrinkage after a sudden advance, blue bands, and wave ogives on Glaciar Universidad (central Chilean Andes). Journal of Glaciology 3 (24), 261–272.
Lliboutry, L., 1998. Glaciers of Chile and Argentina. In: Williams, R.S., Ferrigno, J.G. (Eds.), Satellite Image Atlas of Glaciers of the World: South America. USGS Professional Paper 1386-I, Online version 1.02.
Lliboutry, L., Gonzalez, O., Simken, J., 1958. Les Glaciers du Desert Chilien. Extrait des Comptes Rendus et Rapports, Assemblee Generale de Toronto 1957 (Gentbrugge 1958), Tome IV, 291–300.
Llorens, R.E., Leiva, J.C., 1995. Glaciological studies in the high Central Andes using digital processing of satellite images. Mountain Research and Development 15 (4), 323–330.
Llorens, R., Leiva, J.C., 2000. Recent glacier fluctuations in the Southern Andes. In: Smolka, P.P., Volkheimer, W. (Eds.), Southern Hemisphere Paleo-and Neoclimates. Key Sites, Methods, Data and Models. Springer, pp. 143–149.
Llorens, R.E., 2002. Glacier advances or glaciar retreats in the Argentine Central Andes. In: Trombotto, D., Villalba, R. (Eds.), IANIGLA, 30 Years of Basic and Applied Research on Environmental Sciences. Zeta Editores, Mendoza, Argentina, pp. 177–180.
Luckman, B.H., Villalba, R., 2001. Assessing the synchroneity of glacier fluctuations in the western cordillera of the Americas during the last millennium. In: Markgraf, V. (Ed.), Interhemispheric climate linkages. Academic Press, London, pp. 119–140.
Marden, C.J., Clapperton, C.M., 1995. Fluctuations of the South Patagonia Icefield during the last glaciation and the Holocene. Journal of Quaternary Science 10, 197–210.
Masiokas, M., Casteller, A., Villalba, R., Trombotto, D., Ripalta, A., Hernandez, J., Lázaro, M., 2000. Latitudinal differences in glacier fluctuations across Patagonia: a dendrogeomorphological approach to characterize climate variability in the southern Andes during the past 1000 years (PATAGON-1000). Abstracts from the International Conference on Dendrochronology for the Third Millennium. Mendoza, Argentina, p. 176.
Masiokas, M., Villalba, R., Delgado, S., Trombotto, D., Luckman, B., Ripalta, A., Hernandez, J., 2001. Dendrogeomorphological reconstruction of glacier variations in northern Patagonia during the past 1000 years. In: Kaennel Dobbertin, M., Bräker, O.U. (Eds.), Abstracts from the International Conference on Tree Rings and People. Davos, Switzerland, p. 177.
Masiokas, M., Villalba, R., Luckman, B., Le Quesne, C., Aravena, J., 2006. Snowpack variations in the central Andes of Argentina and Chile, 1951–2005: large-scale atmospheric influences and implications for water resources in the region. Journal of Climate 19, 6334–6352.
Masiokas, M., Villalba, R., Luckman, B., Lascano, M., Delgado, S., Stepanek, P., 2008. 20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia. Global and Planetary Change 60, 85–100.
Masiokas, M.H., Luckman, B.H., Villalba, R., Delgado, S., Skvarca, P., Ripalta, A., 2009. Little Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del Desierto areas, south Patagonian Andes, Argentina. Palaeogeography, Palaeoecology. 281, 351–362 (this issue).
Masiokas, M.H., Luckman, B.H., Villalba, R., Delgado, S., Rabassa, J., in press. Little Ice Age fluctuations of Glaciar Río Manso in the north Patagonian Andes of Argentina. Quaternary Research.
McCarthy, D.P., Luckman, B.H., 1993. Estimating ecesis for tree-ring dating of moraines: a comparative study from the Canadian Cordillera. Arctic and Alpine Research 25, 63–68.
McCormac, F.G., Hogg, A.G., Blackwell, P.G., Buck, C.E., Higham, T.F.G., Reimer, P.J., 2004. SHCal04 Southern Hemisphere calibration 0–11.0 cal kyr BP. Radiocarbon 46, 1087–1092.
Mercer, J.H., 1965. Glacier variations in Southern Patagonia. Geographical Review 55, 390–413.
Mercer, J.H., 1967. Southern Hemisphere Glacier Atlas. Technical report 67-76-ES, Earth Science laboratory, US Army Natick Lab., Mass., 325 pp.
Mercer, J.H., 1968. Variations of some Patagonian glaciers since the Late-Glacial. American Journal of Science 266, 91–109.
Mercer, J.H., 1970. Variations of some Patagonian glaciers since the Late-Glacial: II. American Journal of Science 269, 1–25.
Mercer, J.H., 1976. Glacial history of southernmost South America. Quaternary Research 6, 125–166.
Messerli, B., Ammann, C., Geyh, M., Grosjean, M., Jenny, B., Kammer, K., Vuille, M., 1998. The problem of the “Andean dry diagonal”: current precipitation, Late Pleistocene snow line, and lake level changes in the Atacama Altiplano (18 S–28 S/29 S). Bamberger Geographische Schriften 15, 17–34.
Miller, A., 1976. The climate of Chile. In: Schwerdtfeger, W. (Ed.), World Survey of Climatology. Climates of Central and South America, vol. 12. Elsevier, Amsterdam, pp. 113–145.
Möller, M., Schneider, C., Kilian, R., 2007. Glacier change and climate forcing in recent decades at Gran Campo Nevado, southernmost Patagonia. Annals of Glaciology 46, 136–144.
Möller, M., Schneider, C., 2008. Climate sensitivity and mass balance evolution of Gran Campo Nevado Ice Cap, southwest Patagonia. Annals of Glaciology 48, 32–42.
Naranjo, J., Moreno, H., Banks, N., 1993. La erupción del Volcán Hudson en 1991 (46 S), Región XI, Aysén, Chile. SERNAGEOMIN, Boletín 44, 1–50.
Naruse, R., 2006. The response of glaciers in South America to environmental change. In: Knight, P. (Ed.), In Glaciers and Earth's Changing Environment. Blackwell, Oxford, UK, pp. 231–238.
Naruse, R., Skvarca, P., 2000. Dynamic features of thinning and retreating Glaciar Upsala, a lacustrine calving glacier in Southern Patagonia. Arctic, Antarctic and Alpine Research 32 (4), 485–491.
Naruse, R., Aniya, M., Skvarca, P., Casassa, G., 1995. Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. Annals of Glaciology 21, 297–303.
Nichols, R.L., Miller, M.M., 1951. Glacial geology of Ameghino Valley, Lago Argentino, Patagonia. Geographical Review 41, 274–294.
Nichols, R.L., Miller, M.M., 1952. Advancing glaciers and nearby simultaneously retreating glaciers. Journal of Glaciology 2 (11), 41–50.
Nogami, M., 1972. The snow-line and climate during the last glacial period in the Andes Mountains. The Quaternary Research 2, 11.
Payne, D., 1998. Climatic implications of rock glaciers in the arid Western Cordillera of the Central Andes. Glacial Geology and Geomorphology, rp03/1998 http://ggg.qub.ac.uk/ggg/papers/full/1998/rp031998/rp03.htm.
Philippi, R., 1863. Exkursion nach den Bädern und dem Neuen Vulkan von Chillan in Chile, im Spätsommer 1862 gemacht. Petermann's Geographische Mitteilungen, pp. 241–257.
Pissis, J.A., 1875. Atlas de la Geografía Física de la República de Chile. Instituto Geográfico de Paris, Ch. Delagrave, Paris.
Plagemann, A., 1887. Das andine Stromgebiet des Cachapoal. Petermanns Geogr. Mitteilungen. Heft III, Gotha. pp. 65–82.
Poeppig, E., 1835. Reise in Chile, Peru und auf dem Amazonestrome, während der Jahre 1827–1832. Volume 1, xviii + 466 pages. (Reprinted 1960 in single volume with plates and atlas: xvii + 464 pages. Stuttgart: F. A. Brockhaus Komm.-Gesch.)
Poeppig, E., 1960. Un testigo en la alborada de Chile (1826–1829). Zig-Zag, Santiago, Versión castellana, notas e ilustraciones de Carlos Keller, 507 pp.
Porter, S.C., 1981. Glaciological evidence of Holocene climatic change. In: Wigley, T.M.L., Ingram, M.J., Farmer, G. (Eds.), Climate and History. Cambridge Univ. Press, Cambridge, pp. 82–110.
Porter, S.C., 2000. Onset of neoglaciation in the Southern Hemisphere. Journal of Quaternary Science 15 (4), 395–408.
Porter, C., Santana, A., 2003. Rapid 20th century retreat of Ventisquero Marinelli in the Cordillera Darwin Icefield. Anales del Instituto de la Patagonia 31, 17–26.
Rabassa, J., 1981. Inventario de glaciares y cuerpos de nieve permanentes en los Andes Patagónicos septentrionales, Argentina. Octavo Congreso Geológico Argentino, Actas 4, 109–122.
Rabassa, J., 2007. Global climate change and its impacts on the glaciers and permafrost of Patagonia, Tierra del Fuego and the Antarctic Peninsula. In: Leite, P., Costa, W., Hidalgo, L. (Eds.), A Contribution to Understanding the Regional Impacts of Global Change in South America. Institute of Advanced Studies IEA/USP, São Paulo, Brazil, pp. 21–39.

Rabassa, J., Rubulis, S., Suarez, J., 1978. Los glaciares del Monte Tronador: Buenos Aires. Anales de Parques Nacionales 4, 259–318.
Rabassa, J., Brandani, A., Boninsegna, J.A., Cobos, D.R., 1984. Cronología de la "Pequeña Edad del Hielo" en los glaciares Río Manso y Castaño Overo, Cerro Tronador, Provincia de Río Negro. Noveno Congreso Geológico Argentino, Actas 3, 624–639.
Raymond, C., Neumann, T., Rignot, E., Echelmeyer, K., Rivera, A., Casassa, G., 2005. Retreat of Tyndall Glacier, Patagonia, over the last half century. Journal of Glaciology 51 (173), 239–247.
Rasmussen, L.A., Conway, H., Raymond, C.F., 2007. Influence of upper air conditions on the Patagonia icefields. Global and Planetary Change 59, 203–216.
Reichert, F., 1924. La exploración de la Cordillera Central Patagónica desconocida entre los paralelos 46°30′ hasta 47°30′. Anales de la Sociedad Argentina de Estudios Geográficos, vol. 1. GAEA, Cerro San Valentín, pp. 3–23.
Reichert, F., 1929. La exploración de la Alta Cordillera de Mendoza. Círculo Militar, Biblioteca del Oficial. Buenos Aires, Argentina, 400 pp.
Rignot, E., Rivera, A., Casassa, G., 2003. Contribution of the Patagonian icefields of South America to global sea level rise. Science 302, 434–437.
Risopatrón, L., 1905. La Cordillera de los Andes, entre las latitudes 46 i 50 s. Imprenta Cervantes, Santiago. 233 pp.
Rivera, A., 1992. El Glaciar Pío XI: avances y retrocesos, el impacto sobre su entorno durante el presente siglo. Revista Geográfica de Chile Terra Australis 36, 33–62.
Rivera, A., 2004. Mass balance investigations at Glaciar Chico, Southern Patagonia Icefield, Chile. PhD thesis, University of Bristol, UK, 303 pp.
Rivera, A., Casassa, G., 2004. Ice elevation, areal, and frontal changes of glaciers from National Park Torres del Paine, Southern Patagonia Icefield. Arctic, Antarctic and Alpine Research 36 (4), 379–389.
Rivera, A., Aravena, J.C., Casassa, G., 1997a. Recent fluctuations of Glaciar Pío XI, Patagonia: discussion of a glacial surge hypothesis. Mountain Research and Development 17 (4), 309–322.
Rivera, A., Lange, H., Aravena, J.C., Casassa, G., 1997b. The 20th century advances of Glaciar Pio XI, Chilean Patagonia. Annals of Glaciology 24, 66–71.
Rivera, A., Casassa, G., Acuña, C., Lange, H., 2000. Variaciones recientes de glaciares en Chile. Revista de Investigaciones Geográficas 34, 29–60.
Rivera, A., Casassa, G., Acuña, C., 2001. Mediciones de espesor en glaciares de Chile centro-sur. Revista Investigaciones Geográficas 35, 67–100.
Rivera, A., Acuña, C., Casassa, G., Bown, F., 2002. Use of remotely sensed and field data to estimate the contribution of Chilean glaciers to eustatic sea-level rise. Annals of Glaciology 34, 367–372.
Rivera, A., Bown, F., Casassa, G., Acuña, C., Clavero, J., 2005a. Glacier shrinkage and negative mass balance in the Chilean Lake District (40 S). Hydrological Sciences Journal 50 (6), 963–974.
Rivera, A., Casassa, G., Bamber, J., Kääb, A., 2005b. Ice elevation changes of Glaciar Chico, southern Patagonia, using ASTER DEMs, aerial photographs and GPS data. Journal of Glaciology 51, 105–112.
Rivera, A., Bown, F., Mella, R., Wendt, J., Casassa, G., Acuña, C., Rignot, E., Clavero, J., Brock, B., 2006a. Ice volumetric changes on active volcanoes in southern Chile. Annals of Glaciology 43, 111–122.
Rivera, A., Acuña, C., Casassa, G., 2006b. Glacier variations in central Chile (32 S–41 S). In: Knight, P.G. (Ed.), Glacier Science and Environmental Change. Blackwell, Oxford, UK, pp. 246–247.
Rivera, A., Bown, F., Acuña, C., Clavero, J., Naranjo, J.A., Rignot, E., 2006c. Volcán Hudson glacier responses after recent plinian eruptions. Southern Chile. IGS International Symposium on Earth, and Planetary Ice-Volcano Interactions, Reykjavík, Iceland, 19–23 June. Abstract 45A005.
Rivera, A., Benham, T., Casassa, G., Bamber, J., Dowdeswell, J., 2007. Ice elevation and areal changes of glaciers from the Northern Patagonia icefield, Chile. Global and Planetary Change 59, 126–137.
Rivera, A., Bown, F., Acuña, C., Ordenes, F., 2008. Chilean glaciers as indicators of climate change. Terra Glacialis 11, 193–207.
Rosenblüth, B., Casassa, G., Fuenzalida, H., 1995. Recent climate changes in western Patagonia. Bulletin of Glacier Research 13, 127–132.
Röthlisberger, F., 1986. 10, 000 Jahre Gletschergeschichte der Erde. Verlag Sauerländer, Aarau.
Rutllant, J., Fuenzalida, H., 1991. Synoptic aspects of the central Chile rainfall variability associated with the Southern Oscillation. International Journal of Climatology 11, 63–76.
Schneider, C., Schnirch, M., Acuña, C., Casassa, G., Kilian, R., 2007. Glacier inventory of the Gran Campo Nevado Ice Cap in the Southern Andes and glacier changes observed during recent decades. Global and Planetary Change 59, 87–100. doi:10.1016/j.gloplacha.2006.11.023.
Schwerdtfeger, W., 1976. The atmospheric circulation over Central and South America. In: Schwerdtfeger, W. (Ed.), Climates of Central and South America. World Survey of Climatology, 12. Elsevier, pp. 1–12.
Sigafoos, R.S., Hendricks, E.L., 1969. The time interval between stabilization of alpine glacial deposits and establishment of tree seedlings. U.S. Geological Survey Professional Paper 650-B, 89–93.
Simpson, E., 1875. Esploraciones hechas por la Corbeta Chacabuco en los archipiélagos de Guaitecas, Chonos i Taitao. Anuario Hidrográfico de la Marina de Chile 1, 3–166.
Skvarca, P., De Angelis, H., 2002. Fifteen year changes of Southern Patagonia Icefield glaciers, Argentina–Chile, detected from Landsat TM mosaics. Proceedings of the 29th International Symposium on Remote Sensing of Environment (29th ISRSE). 8–12 April 2002, Buenos Aires, Argentina (on CD-ROM).
Skvarca, P., Naruse, R., 1997. Dynamic behavior of Glaciar Perito Moreno, southern Patagonia. Annals of Glaciology 24, 268–271.
Skvarca, P., De Angelis, H., Naruse, R., Warren, C.R., Aniya, M., 2002. Calving rates in fresh water: new data from southern Patagonia. Annals of Glaciology 34, 379–384.
Skvarca, P., Naruse, R., De Angelis, H., 2004. Recent thickening trend of Glaciar Perito Moreno, southern Patagonia. Bulletin of Glaciological Research 21, 45–48.
Steffen, H., 1909. Viajes de Esploracion i Estudio en la Patagonia Occidental: 1892–1902. Anales de la Universidad de Chile, vol. I. Imprenta Cervantes, Santiago. 409 pp.
Steffen, J., 1937. El Istmo de Ofqui en la Patagonia Occidental. Anales de la Universidad de Chile 22 (23), 22–70.
Stern, C., 1991. Mid-Holocene tephra on Tierra del Fuego (54 S) derived from the Hudson volcano (46 S): evidence for a large explosive eruption. Revista Geológica de Chile 18, 139–146.
Strelin, J., Iturraspe, R., 2007. Recent evolution and mass balance of Cordón Martial glaciers, Cordillera Fueguina Oriental. Global and Planetary Change 59, 17–26.
Strelin, J., Casassa, G., Rosqvist, G., Holmlund, P., 2008. Holocene glaciations in the Ema glacier valley, Monte Sarmiento massif, Tierra del Fuego. Palaeogeography, Palaeoclimatology, Palaeoecology 260, 299–314.
Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.
Sweda, T., 1987. Recent retreat of Soler Glacier, Patagonia, as seen from vegetation recovery. Bulletin of Glacier Research 4, 119–124.
Unger, C., Espizua, L.E., Bottero, R., 2000. Untersuchung von Gletscherständen im Tal des Río Mendoza (Zentralargentinische Anden) — Kartierung eines Surge-Vorstosses des Horcones Inferior. Zeitschrift für Gletscherkunde und Glazialgeologie 36 (1), 151–157.
USGS, 1998. Satellite image atlas of glaciers of the world: South America. In: Williams, R., Ferrigno, J. (Eds.), U.S. Geological Survey Professional Paper, vol. 1386-I. U.S. Government Printing Office, Washington DC, USA, 1206 pp.
Valdivia, P., 1984. Inventario de Glaciares, Andes de Chile Central (32°–35° lat. S). Hoyas de los ríos Aconcagua, Maipo, Cachapoal y Tinguiririca. Jornadas de Hidrología de Nieves y Hielos en América del Sur: Programa Hidrológico Internacional, Santiago de Chile, 1, pp. 6.1–6.24.
Videla, M.A., 1997. Neoglacial advances in the Central Andes, Argentina, during the last centuries. In: Rabassa, J., Salemme, M. (Eds.), Quaternary of South America and Antarctic Peninsula, vol. 10 (1994). A.A. Balkema, Rotterdam, Brookfield, pp. 55–70.
Villalba, R., Leiva, J.C., Rubulis, S., Suarez, J.A., 1990. Climate, tree rings and glacier fluctuations in the Rio Frias Valley, Rio Negro, Argentina. Arctic and Alpine Research 22 (3), 215–232.
Villalba, R., Lara, A., Boninsegna, J.A., Masiokas, M., Delgado, S., Aravena, J.C., Roig, F.A., Schmelter, A., Wolodarsky, A., Ripalta, A., 2003. Large-scale temperature changes across the southern Andes: 20th-century variations in the context of the past 400 years. Climatic Change 59, 177–232.
Warren, C., 1993. Rapid recent fluctuations of the calving San Rafael Glacier, Chilean Patagonia: climatic or non-climatic? Geografiska Annaler 75A (3), 111–125.
Warren, C.R., 1994. Freshwater calving and anomalous glacier oscillations: recent behaviour of Moreno and Ameghino glaciers, Patagonia. The Holocene 4, 422–429.
Warren, C., Sugden, D., 1993. The Patagonian Icefields: a glaciological review. Arctic, Antarctic and Alpine Research 25 (4), 316–331.
Warren, C., Rivera, A., 1994. Non-linear climatic response of calving glaciers: a case study of Pío XI Glacier, Chilean Patagonia. Revista Chilena de Historia Natural 67, 385–394.
Warren, C., Aniya, M., 1999. The calving glaciers of southern South America. Global and Planetary Change 22, 59–77.
Warren, C.R., Sugden, D.E., Clapperton, C.M., 1995. Asynchronous response of Patagonian glaciers to historic climate change. Quaternary of South America and the Antarctic Peninsula 9, 89–108.
Warren, C., Rivera, A., Post, A., 1997. Greatest Holocene advance of glaciar Pío XI, Chilean Patagonia: possible causes. Annals of Glaciology 24, 11–15.
Winchester, V., Harrison, S., 1996. Recent oscillations of the San Quintín and San Rafael glaciers, Patagonian Chile. Geografiska Annaler 78A, 35–49.
Winchester, V., Harrison, S., Warren, C.R., 2001. Recent retreat Glaciar Nef, Chilean Patagonia, dated by lichenometry and dendrochronology. Arctic, Antarctic and Alpine Research 33 (3), 266–273.
Zenteno, P., Rivera, A., García, R., 2004. Glacier inventory of the Itata basin derived from satellite imagery: historical trends and recent variations at Nevados de Chillán volcano (36°56′S–71°20′W). VIII International Earth Sciences Congress, Santiago, 18–28 October 2004.