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ARTICLE IN PRESS
GLOBAL-01235; No of Pages 16
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ScienceDirect
GLOBAL AND PLANETARY CHANGE
Global and Planetary Change xx (2007) xxx–xxx
www.elsevier.com/locate/gloplacha

20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia

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Received in revised form 5 July 2006; accepted 5 July 2006

Abstract

This paper documents the occurrence of significant glacier and hydroclimatic changes in northwestern Patagonia during the past century. Drastic, widespread glacier recession is documented by repeat photography of some of the earliest glacier images from southern South America. Linear trends in regionally-averaged annual and seasonal temperature and precipitation records indicate significant warming and decreasing precipitation over the 1912–2002 interval. A climatic index is developed, based on winter precipitation and summer temperature records, that mimics glacier mass balance relationships and shows a strong negative trend which agrees with the drastic glacier recession shown by the photographic comparisons. Short positive periods of this climatic index broadly correspond with known evidence of glacier advances in the region. Regionally-averaged mean annual streamflow records east of the mountains were used in an independent verification check of the climatic series used in this study. This regional runoff record shows a strong negative trend, remarkable similarities with the climatic index, and highly significant positive (negative) correlations with the regional precipitation (temperature) series. This highlights the existence of a strong, regionally coherent hydroclimatic signal across this region and supports the utility of these records as environmental indicators for northwestern Patagonia between ca. 38° and 45°S. Given the significant socio-economic importance of rivers and glaciers in this area, further research is needed to evaluate the full range of natural hydroclimate variability and improve understanding of potential impacts of the future warmer and drier climates projected for this region.

Keywords: North Patagonian Andes; repeat photography; glacier recession; hydroclimatic variability

1. Introduction

In many mountainous areas of the world glaciers are critical sources of fresh water that crucially contribute to the sustainability of socio-economic activities such as hydroelectric power generation, agriculture, and tourism (e.g. Coudrain et al., 2005). In such regions long, complete instrumental climate records are usually scarce. Glaciers can provide a longer term perspective for the study of climatic variations (e.g. Klok and Oerlemans, 2004), and are considered key indicators for the early detection of global climate changes (Oerlemans, 1994; Dyurgerov and Meier, 2000; Oerlemans, 2001; Hoelzle et al., 2003; Oerlemans, 2005; Haeberli, 2005).

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doi:10.1016/j.gloplacha.2006.07.031

Please cite this article as: Masiokas, M.H. et al. 20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia. Global and Planetary Change (2007), doi:10.1016/j.gloplacha.2006.07.031

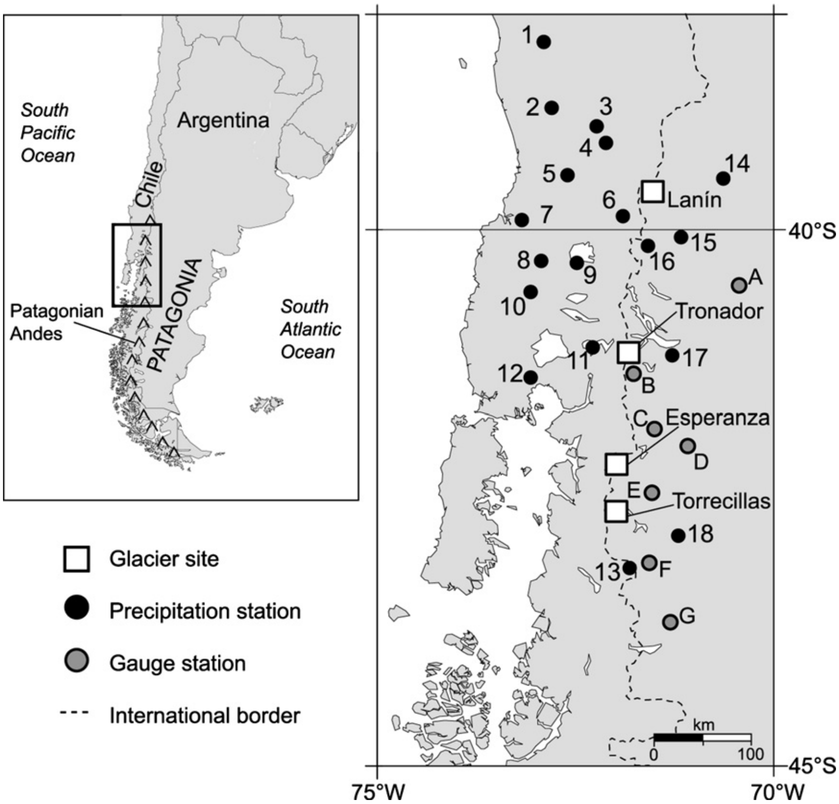

Fig. 1. Map of northwestern Patagonia showing the location of the glacier sites (white squares), the precipitation (black dots) and streamflow gauge stations (grey dots) used in this study. Mean monthly temperature anomalies for the grid cell between 40°–45°S and 70°–75°W grid cell were obtained from the CRUTem2v gridded dataset (Jones and Moberg, 2003). The codes for precipitation and streamflow gauging stations are described in Tables 1 and 2, respectively.

The Patagonian Andes (Fig. 1) contain over 20,000 km^2 of glaciers, by far the largest glacierized area in South America. Glaciers are mostly concentrated south of 45°S, with the Northern and Southern Patagonian Icefields covering ca. 4200 and 13,000 km^2, respectively (Aniya, 1988; Aniya et al., 1996). Unfortunately, the absence of long (>10 yr) annual mass balance records in this region seriously hampers the study of interannual glacier variations and the assessment of the relative influence of the main climate variables on glacier mass balance (Warren and Sugden, 1993; Rivera et al., 2000). Nevertheless, the marked recession of Patagonian glaciers during the 20th century has generally been linked with the combined effect of increasing temperatures and decreasing precipitation (Rosenblüth et al., 1995, 1997; Rivera et al., 2000, 2002; Villalba et al., 2003, Rivera, 2004; Villalba et al., 2005). Recent studies by Bown (2004) and Rivera et al. (2005) suggest that the drastic ice mass loss observed during the past four decades in the northern Patagonian Andes might also be related to the significant tropospheric warming trend observed in radiosonde records in the region (e.g. Aceituno et al., 1993). However, few studies have analyzed the short-term (i.e. sub-decadal) climate variations during the last century and their influence on local glacier behavior (particularly related to periods of glacier advance) is still poorly understood. Most previous glacier studies have focused on the large glaciers of the southern Patagonian Andes: the potential contribution of the relatively small glaciers located north of 45°S to studies of past and present climate changes in the region has not been fully exploited.

In this paper we present selected paired photographs documenting glacier recession in the north Patagonian Andes[1] over the past 110 yr. In most cases, these include the earliest known photographs for these glaciers and are part of a recent compilation of such materials by Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA) to study climate and glacier fluctuations in this region. We have also analyzed updated, homogenized climate records from 1912–2002 for stations between 39°S and 45°S to develop a simple

[1] Considered here as the portion of the Andes between 38°S and 45°S.

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climatic index or “mass balance proxy” based on April–September (long winter) precipitation and October–March (long summer) temperature series. Given the lack of mass balance records for this region, this index provides a rough measure of the relative magnitude of the accumulation and ablation seasons in any given year. Comparison of available glacier history with decadal-scale variations in this climatic index provides insight into the causes of glacier fluctuations in this region during the 20th century. The reliability of the regional climatic series developed in this study was also assessed by comparison with independently measured streamflow records from rivers east of the Andes. As river discharge is mainly fed by winter precipitation, close agreement between these variables provides mutual verification of the quality of these records.

2. Study area

The north Patagonian Andes (Fig. 1) form an effective topographic barrier to the westerly air masses that dominate circulation in this region, resulting in steep precipitation gradients across the mountain range. At ca. 40°–41°S, the main cordillera experiences over 4000 mm precipitation per year (Prohaska, 1976) whereas the xeric Patagonian steppe, less than 100 km east of the Andes, receives less than 200 mm/yr (Veblen and Lorenz, 1988; Villalba et al., 2003). Mean annual temperatures vary from ca. 11 °C at the Chilean coast to ca. 8 °C at the forest–steppe limit in Argentina (Prohaska, 1976; Miller, 1976). Although absolute minimum temperatures in this region can fall below −15 °C, mean temperatures for the coldest month (July) vary between 4°–8 °C in Chile and 2°–4 °C in Argentina. Mean temperatures for the warmest month (January) range from 14° to 18 °C in both regions (Prohaska, 1976). These mild environmental conditions and the lower elevations of the north Patagonian Andes limit the glacierized area to relatively small glaciers on the highest peaks and volcanoes along the mountain range (Lliboutry, 1998).

Twentieth-century glacier changes in the north Patagonian Andes have been studied using aerial photographs, satellite imagery, historical documents, tree-ring records and field measurements (e.g. Rabassa et al., 1978; Villalba et al., 1990; Rivera et al., 2002; Bown, 2004; Rivera et al., 2005). However, and in contrast to the south Patagonian Andes (i.e. south of 45°S), few preliminary glacier inventories are available for this area. Lliboutry (1998) estimated that glaciers covered approximately 300 km^2 between 35°S and 45°S and occurred mainly west of the continental divide. The relatively small size of glaciers in this area makes them particularly sensitive to synoptic changes in climate (Oerlemans and Fortuin, 1992), and thereby valuable sources of information for the study of hydroclimatic variations in this region.

Rivers originating in the north Patagonian Andes have a huge socio-economic importance at regional and national scales as sources of fresh water for domestic consumption, irrigation, industries, hydroelectric generation, and recreational activities. For example, 51.8% of Argentina’s total hydroelectric generation in 2003 was based on the rivers flowing from the north Patagonian Andes (Secretaría de Energía, 2004). On the Chilean side, the multi-million dollar salmon farming industry closely depends on fresh water volumes from the mountains to regulate the salinity and oxygen of the estuarine environments where the farming structures are located (Lara et al., 2005). No data are available that document the direct contribution of glacier melt to streamflow for these rivers. However, given the relatively small number and volume of glaciers in this area, this contribution is likely to be relatively small compared with snowmelt except for headwater reaches of rivers fed directly by glaciers. Fortunately a remarkably good database of mean monthly discharges exists for most of the rivers east of the Andes. In some cases the available records extend for almost 90 yr with few missing months and are some of the longest, most complete runoff records in South America. Of particular relevance for the purposes of this study, these records can be used as an independent check to verify the reliability of the limited climatic information available for this area.

3. Data and methods

3.1. Repeat ground photography

Historical records represent a valuable tool to study glacier fluctuations because they can provide precise information about past glacier volumes and frontal positions (e.g. Zumbühl and Holzhauser, 1988). Paired with recent photographs, these historical documents can also be used to show, in a simple yet powerful way, the impacts of recent climate changes on these remote, climate-sensitive environments (Hamilton, 1965; Rogers et al., 1984). The beauty and remoteness of the Patagonian Andes have attracted explorers, climbers and researchers since the beginning of the 20th century, and a relatively good collection of historical documents exists for some specific areas (e.g. Kölliker et al., 1917; De Agostini, 1945). Many publications contain maps, site descriptions and terrestrial photographs that can be used to establish the former position of the glaciers. For example, the detailed 1856 drawing of the Frías valley

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and Mount Tronador (Fonck and Hess, 1857), and a picture of Frías Glacier taken by De Agostini in the 1930s were used by Villalba et al. (1990) to complement their tree-ring based chronology of ice front positions at this site.

Until recently these valuable documents have not been analyzed or compiled into an accessible regional database that could facilitate glaciological and environmental studies in Patagonia. In the late 1990s, IANIGLA began to collect available scientific and non-scientific bibliographic materials concerning Patagonian environments and compile the historical documents (photographs, maps, diagrams, notes, etc) for glaciers in Patagonia. In order to evaluate the changes in glacier areas, volumes, and ice front positions, this initiative was complemented, whenever possible, by repeat photography of the same views. This expanding database now contains several hundred historical documents and sets of paired photographs showing glacier change over the last century. We selected six glaciers between 39°S and 43°S for which good quality comparative photographs are available. Fig. 2 shows the earliest known photographs for these

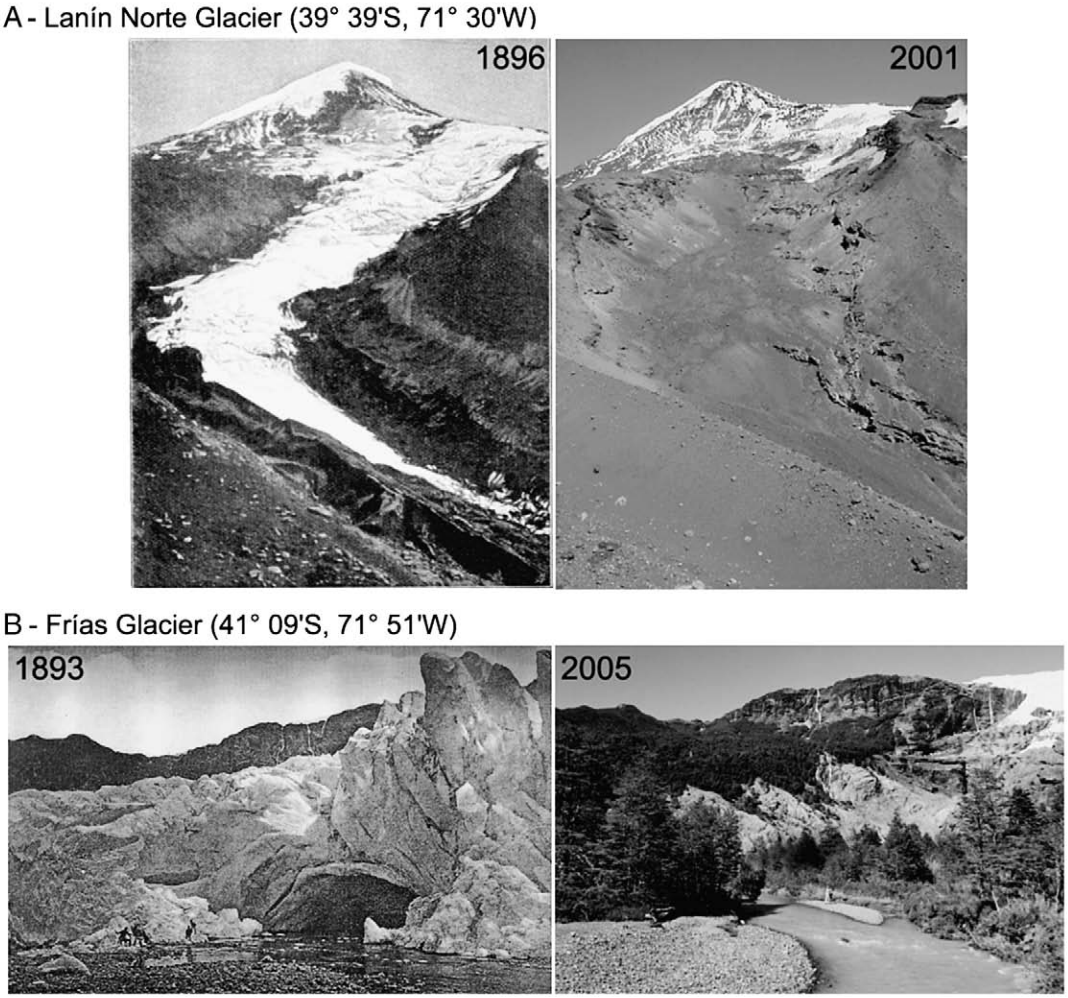

Fig. 2. Photographic comparisons showing changes in six selected glaciers of the north Patagonian Andes between 39° and 43°S. (A) The Lanín Norte Glacier in 1896 (Hauthal, 1904) and 2001. (B) The Frías Glacier in the Tronador Area has receded markedly between 1893 (Steffen, 1909) and 2005. (C) The Castaño Overo Glacier in the Tronador Area shown in 1936 (Jakob, 1936) and 2005. (D) The southernmost of the Argentinean glaciers in the Tronador Area, the Ventisquero Negro (also known as Río Manso Glacier) has thinned markedly between 1937 (Jakob, 1937) and 2005. Note the ice-covered proglacial lake in the foreground. (E) The Esperanza Norte Glacier is located in a largely unexplored portion of the north Patagonian Andes around 42°S and has receded drastically between 1948 (Neumeyer, 1949) and 2001. (F) The Torrecillas Glacier, a conspicuous feature of Parque Nacional Los Alerces, has thinned and retreated markedly during the past century. The photograph on the left was taken by F.P. Moreno in 1899 and is courtesy of Museo de la Patagonia, Bariloche, Argentina. Although it is not exactly matched (it was not at hand when we visited the area), we have included this view to assess the glacier changes over an extended period. The view in the middle was published by Koutche and Ladvocat (1937).

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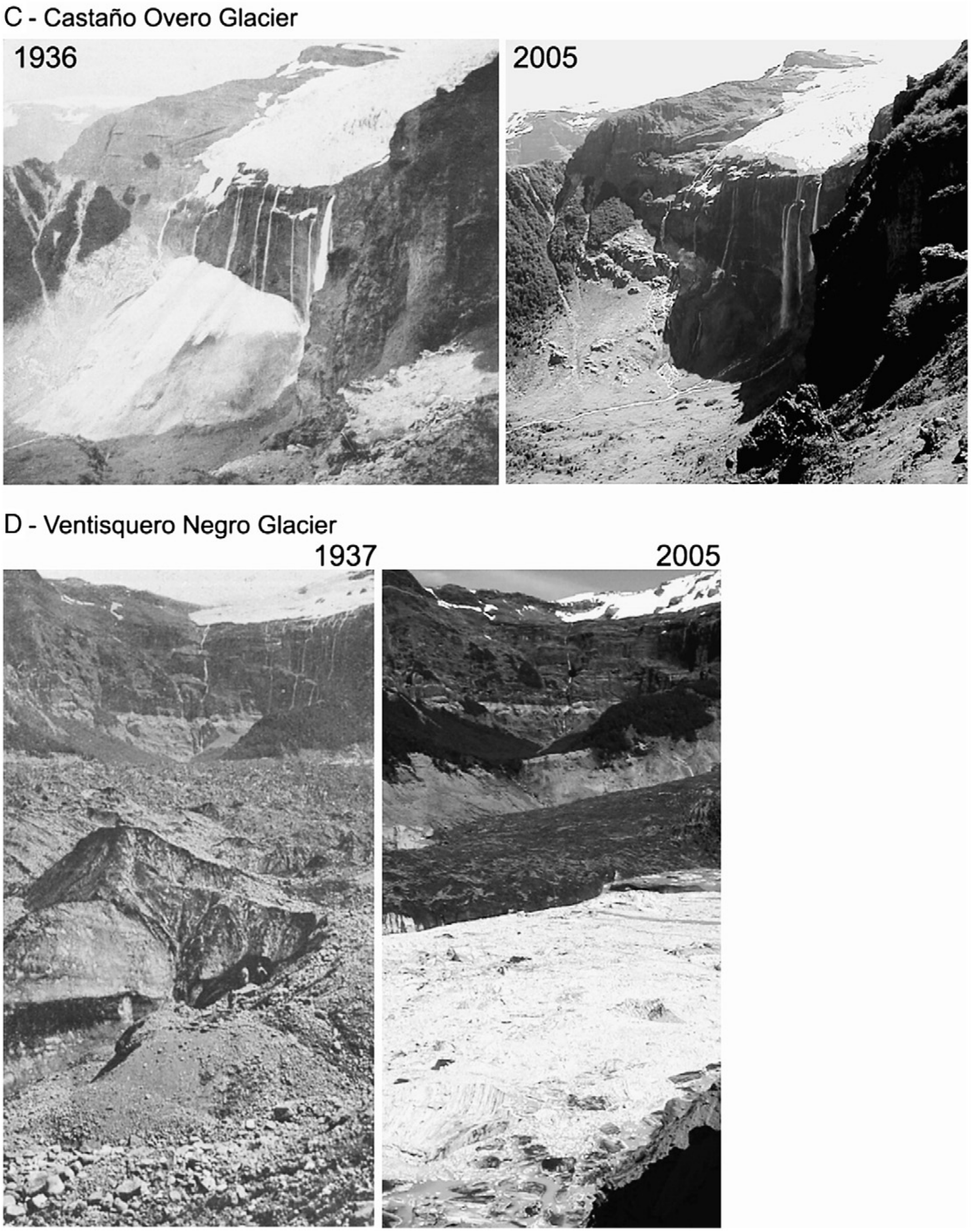

Fig. 2 (*continued*).

glaciers and includes some of the earliest documented glacier positions in Patagonia.

3.2. Climate records

The poor quality of climatic data and the inadequate spatial distribution of meteorological stations in Patagonia limit the characterization of climatic variability of this region (Rosenblüth et al., 1997). Furthermore, it is very difficult and often impossible to obtain the station metadata (data about the stations' histories) to evaluate possible non-climatic variation or inhomogeneities in the records. We have compiled climate data from several sources to obtain a relatively complete, updated climatic

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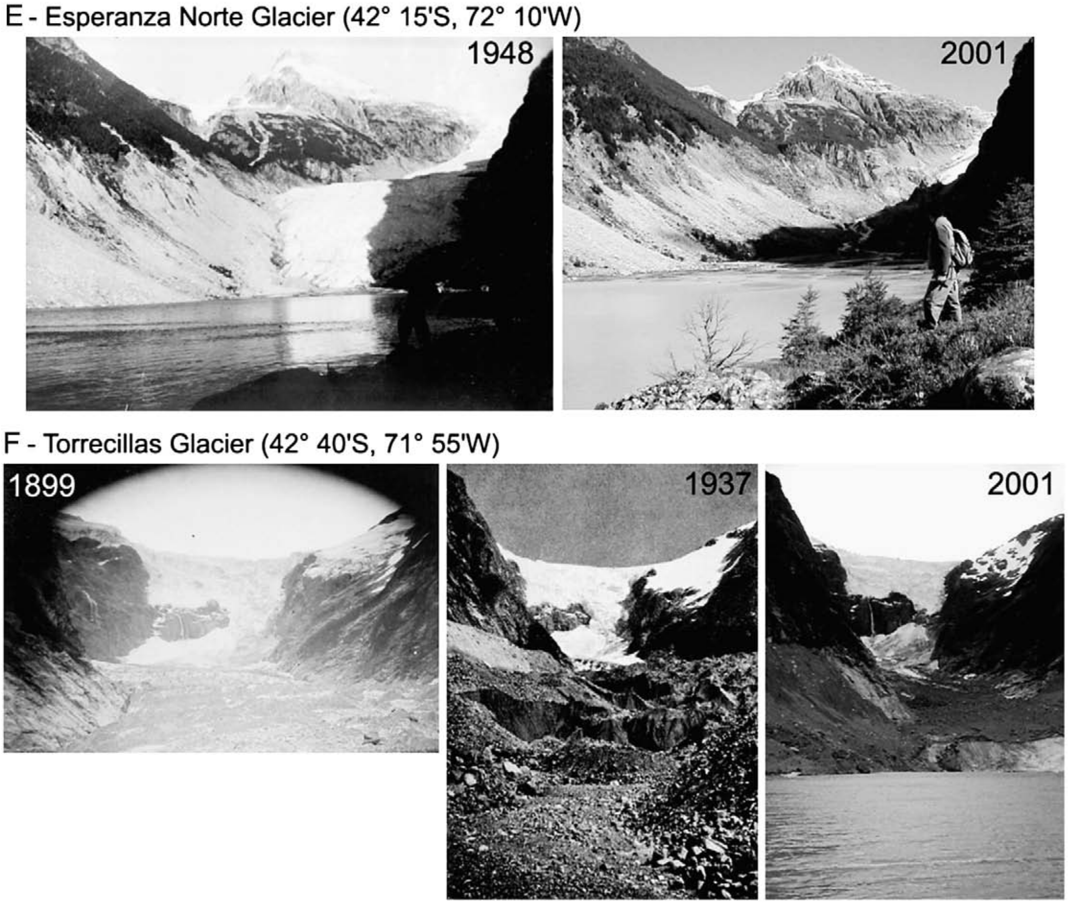

Fig. 2 (*continued*).

dataset for the region. Mean monthly temperature series were obtained for the 40°–45°S and 65°–70°W grid cell from the CRUTem2v dataset (Jones and Moberg, 2003, Climatic Research Unit, UK, http://www.cru.uea.ac.uk/). These are homogenized data from land stations only expressed as anomalies from the 1961–1990 reference period. These monthly records were averaged into annual (April–March), cold season (April–September), and warm season (October–March) temperature anomaly series for the analysis of two hypothetical 'accumulation' and 'ablation' seasons over the 1912–2002 period. Each year or season is identified by the year of the earliest month (e.g. the 2002 yr runs from April 2002 to March 2003).

Monthly total precipitation records for sites between 38°S and 44°S were obtained from Version 2 of the Global Historical Climatology Network (Vose et al., 1992), and various institutions in Chile and Argentina (Table 1). Since many of these records are short or incomplete, we selected 18 stations that provided the most complete (<7% missing) and longest (> 30 yr) records covering the 1961–1990 interval (Fig. 1 and Table 1). Missing months were estimated by linear regression using reference series created from up to 10 neighboring stations significantly correlated with the candidate series. These reference series were also used to evaluate potential inhomogeneities (see Pittock, 1980) in the data for each station. The Alexandersson ratio test (Alexandersson, 1986) was used to identify the location, evaluate the statistical significance, and obtain adjustment coefficients of potential inhomogeneities. Given the absence of metadata for these precipitation stations, each series was adjusted only when the ratio test reached the 95% critical level. Following Jones and Hulme (1996), annual and seasonal totals for each station were converted to percentages of their 1961–1990 mean and averaged to create a set of annual, cold season and warm season precipitation series from 1912 to 2002 for the region.

In the absence of long, complete climatic data from high elevation sites, most of the climatic records used in this analysis come from lowland stations that are distant from the mountain range and therefore their representativeness may be questioned. To address this issue we

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Table 1
Stations used to develop regionally-averaged series of annual and seasonal precipitation variations for northwestern Patagonia between 38° and 44°S. Data sources: (GHCN) Global Historical Climatology Network Version 2 (Vose et al., 1992); (DGA) Dirección General de Aguas, Chile; (DMC) Dirección Meteorológica de Chile; (ENDESA) Empresa Nacional de Electricidad, Chile; (AIC) Autoridad Interjurisdiccional de Cuencas de los Ríos Neuquén, Limay y Negro, Argentina

Station (code in Fig. 1)	Latitude (S) Longitude (W)	Elev. (m)	Period	1961–90 annual mean (mm)	Apr–Sep contrib. to annual totals (%)	Data source
Lumaco (1)	38° 09′ 72° 54′	60	Jan 1948–Dec 2001	1352.2	72.9	DGA
Temuco (2)	38° 48′ 72° 48′	114	Jan 1912–Apr 2003	1147.2	72.5	GHCN
Los Laureles (3)	38° 59′ 72° 14′	190	Jan 1947–Dec 2001	2021.8	72.9	DGA
Flor del Lago (4)	39° 09′ 72° 07′	300	Jan 1961–Dec 2001	2592.1	74.3	DMC
Purulón (5)	39° 28′ 72° 36′	95	Jan 1936–Dec 2000	2145.9	75.9	DMC
Puerto Fuy (7)	39° 52′ 71° 54′	596	Jan 1961–Dec 1996	4297.4	70.7	ENDESA
Valdivia (6)	40° 00′ 73° 06′	19	Jan 1912–Apr 2003	1953.7	77.0	GHCN
Río Bueno (8)	40° 18′ 72° 56′	70	Jan 1940–Dec 2000	1126.3	72.6	DMC
Lago Ranco (9)	40° 18′ 72° 30′	79	Jan 1931–Dec 2000	1938.1	69.8	DMC
Osorno (10)	40° 36′ 73° 04′	65	Jan 1961–Dec 2001	1325.2	72.9	DMC
Punta Huano (11)	41° 08′ 72° 17′	200	Jan 1961–Dec 2000	3146.2	71.0	DMC
Puerto Montt (12)	41° 24′ 73° 06′	81	Jan 1907–Apr 2003	1770.7	65.1	GHCN
Futaleufú (13)	43° 12′ 71° 49′	317	Jan 1961–Dec 2001	2073.4	70.0	DMC
Ea. Campo Grande (14)	39° 30′ 70° 38′	960	Jan 1947–Dec 1998	471.9	77.2	AIC
Ea. Collún Co (15)	40° 04′ 71° 10′	875	Jan 1912–Dec 1998	900.2	80.4	AIC
Ea. Quechuquina (16)	40° 09′ 71° 35′	640	Jan 1957–Dec 1998	2145.9	75.9	AIC
Bariloche (17)	41° 12′ 71° 12′	840	Jan 1931–Apr 2003	802.5	79.0	GHCN
Esquel (18)	42° 54′ 71° 12′	785	Jan 1916–Apr 2003	497.9	73.1	GHCN

correlated the annual regional temperature and precipitation series with 1969–1995 annual records from the Mascardi meteorological station (41° 16′S, 71° 39′W, 842 m). Although this record was too short to be included in the regional climate series, this station is 15 km east of the Tronador glaciers (Fig. 2B–D) and is thought to be representative of climate conditions that influence these glaciers (Rabassa et al., 1978; Villalba et al., 1990). Thus, the Mascardi records provide a partial validation of the regional temperature and precipitation series. In addition we performed a Principal Component Analysis (PCA) on the 18 annual precipitation records to evaluate the strength of the climatic signal on both sides of the mountain range.

3.3. Construction of the regional climatic index, 1912–2002

The lack of long glacier mass balance records seriously hampers the analysis of interannual and interdecadal climatic impacts on glacier behavior in the Patagonian Andes (see e.g. Hodge et al., 1998; McCabe et al., 2000; Rasmussen and Conway, 2004; Nesje, 2005 for some Northern Hemisphere examples). We therefore developed a regional climatic index (or ‘mass balance proxy’) which estimates the relative magnitude of surrogates for winter accumulation (cold season precipitation) and summer ablation (warm season mean temperatures) in the study area. The regional winter anomaly series was developed by averaging anomalies (*Z* scores) of the April–September precipitation totals from the individual stations, each standardized to the 1961–1990 mean. The October–March gridded temperature records were also converted to *Z* scores. The climatic index was developed by subtracting the temperature anomalies from the precipitation anomalies such that relatively wet winters and cool summers result in positive indices (overall 'positive' mass balance conditions in the region), and vice versa. In years when heavy winter precipitation was followed by warm summers the climatic index is close to zero.[2] In developing these proxies the choice of specific months and length of season is somewhat arbitrary and only intended to provide a simple yet reasonable surrogate for the relative importance of accumulation vs. ablation in any given year. It is not known for example whether precipitation or temperature variability is the more significant driver of mass balance variations in this region: obviously, as additional north Patagonian glacier mass balance data become available (e.g. Rivera et al., 2005), more realistic selection and weighting for these proxies can be developed. We compared the smoothed, low-frequency (i.e. decadal or longer) variations in the regional climatic index with the periods of glacier advances that have been reported for this region during the 20th century (such data are only available for the Tronador Area at around 41°10′S, Fig. 1). Although preliminary and largely qualitative, this exercise provided the first assessment of the potential influence of decadal climate variations on glacier behavior in northwestern Patagonia. Given the small size of these glaciers (7–19 km^2; Rabassa et al., 1978) we expect them to have a relatively short response time to climate fluctuations (Johannesson et al., 1989). However, the possible influence of non-climatic, site-specific factors (such as bed topography, debris cover, etc) at individual glaciers, coupled with the small sample size and inherent limitations in dating glacier deposits (Porter, 1981) suggest such comparisons should be interpreted cautiously.

3.4. Relationship between regional streamflow records and climate

The northwestern Patagonian climate usually has dry summers and wet winters: 65–80% of annual precipitation falls between April and September (Table 1). Therefore the climatic index described above may also be used as a measure of the balance between winter moisture input and summer evapotranspiration in a given basin. In addition, and given the relatively small glacierized area in the north Patagonian Andes, variations in this index should be strongly related to the discharge of local rivers that are mainly fed by winter precipitation. Therefore agreement between the independent estimates of regional river discharges and regional climatic records should provide an additional test of the quality and consistency of these records.

Mean monthly discharges were obtained for seven important rivers between 40° and 44°S that have the longest and most complete flow records in Patagonia (Fig. 1 and Table 2). Missing monthly values in each gauge station were estimated using a reference series created from those remaining streamflow records significantly correlated with the candidate series. The gauge station records for the Futaleufú and Limay rivers (discontinued in 1976 and 1990 respectively due to dam construction) were updated with data from active gauging stations upstream from the original sites. Subsequently, mean annual (April–March) streamflow records were expressed as percentages of their 1961–1990 mean and averaged to create a regional streamflow series for 1903–2004. Simple correlation analyses were used to evaluate the strength of the relationships between the regionally-averaged streamflow record, the climatic index, and the annual and seasonal temperature and precipitation composites from the study area. The statistical significance of these correlations was estimated using an 'effective sample size' based on the lag-1 autocorrelation of the raw data (Dawdy and Matalas, 1964). The statistical significance of least-squares linear trends in these regional records was assessed following a conservative approach which also accounts for the temporal autocorrelation in these time series (the AdjSE + AdjDF approach, Santer et al., 2000).

4. Results

4.1. Photographic comparisons

Fig. 2 includes some of the earliest documented glacier positions in Patagonia and clearly indicates that glacier recession has been a generalized phenomenon in the north Patagonian Andes during the past century. However, the large temporal gap between observations (>100 yr in some cases) indicates that these images can only be used as endpoints of the sequence of glacier variations during this time frame. In addition to the marked glacier front retreats of, for example, the Lanín Norte and Frías glaciers (Fig. 2A and B), some of the

[2] However, in the absence of mass balance data, the climatic index should be interpreted cautiously. The mean climate index over the 1961–1990 period is simply a reference level and does not imply a zero net balance.

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Table 2
Streamflow records used in this study. Mean annual discharges refer to an April–March water year and were obtained mostly from Subsecretaría de Recursos Hídricos (SSRH, 2004). Notes: (†) April 1990–September 2005 completed with data from Aluminé (at Huechahue), Chimehuin (at Puesto Confluencia), Caleufú (at Puesto Córdoba) and Limay Superior (at Villa Llanquín); (‡) April 1976–September 2005 from Futaleufú Embalse (43° 07′S, 71° 39′W, 320 m); data from E. Flamenco (personal communication), and Compañía Administradora del Mercado Mayorista Eléctrico (CAMMESA), http://memnet2.cammesa.com/

River (basin area in km^2)	Gauge station (code)	Latitude (S) Longitude (W)	Elevation (m)	Period of record (% missing)	Mean annual discharge (m^3 s^{-1})
Limay (26400)	Paso Limay (A)	40°32′ 70°26′	538	Apr 1903–Sep 2005 (†)	717.3
Manso (750)	Los Alerces (B)	41°23′ 71°46′	728	Apr 1951–Mar 2003 (1.7)	44.7
Quemquemtreu (650)	Escuela No. 139 (C)	41°54′ 71°30′	750	Apr 1956–Mar 2003 (1.6)	9.5
Chubut (1200)	El Maitén (D)	42°06′ 71°10′	680	Apr 1943–Mar 2003 (0.8)	19.5
Carrileufú (580)	Cholila (E)	42°30′ 71°32′	535	Apr 1957–Mar 2003 (2.3)	48.4
Futaleufú (4650)	Balza Garzón (F)	43°09′ 71°34′	320	Apr 1948–Sep 2005 (‡)	277.7
Carrenlufú (1500)	La Elena (G)	43°42′ 71°18′	802	Apr 1954–Mar 2003 (1.5)	33.3

less steep glaciers (e.g. Ventisquero Negro, Fig. 2D) have lost ice mass mainly by thinning. Overall, these comparisons reveal that over the past century the climate conditions in the region have clearly favored ablation over accumulation in the mass balance of these glaciers.

4.2. Climate changes in northwestern Patagonia, 1912–2002

A series of long, homogeneous annual, cold season, and warm season regionalized temperature and precipitation records between 1912–2002 were used to complement the photographic comparisons and analyze the possible climatic influence in this noticeable ice mass loss. Despite the broad spatial extent and inherent low-elevation nature of these climatic series, the regionalized climate records revealed a strong coherent signal that provides a reliable indicator of climatic conditions across northwestern Patagonia (Fig. 1). These records are significantly correlated (r=0.87 for temperature; 0.86 for precipitation, $p<0.01$) with the 1969–1995 records from the higher elevation Mascardi station, ca. 15 km east of the Tronador glaciers (Fig. 2B–D). In addition, even though annual precipitation totals vary from over 4000 mm to less than 500 mm (Table 1), a Principal Component Analysis performed on the 18 precipitation records indicates that 62.9% of the variance in these records can be explained by the first Principal Component over the 1961–1995 common interval.

The linear trend analyses performed on the annual (April–March), cold season (April–September), and warm season (October–March) regional temperature and precipitation series (Table 3) showed that these variables have experienced opposite long-term patterns between 1912 and 2002. Annual and seasonal gridded temperature records showed similar, statistically significant positive linear trends of around +0.056 °C per decade even after a marked adjustment to the degrees of freedom due to the serial correlation in their regression residuals. Highly significant negative linear trends were found for the equivalent precipitation records with cold season

Table 3
Linear trend analysis for regional temperature, precipitation, climatic index, and streamflow variations in northwestern Patagonia between 1912 and 2002. The lag-1 autocorrelation coefficient in the regression residuals of each series (r_1) was used to calculate an 'effective sample size' (n_{eff}) and estimate the statistical significance (t test) of linear trends (Santer et al., 2000). Notes: *(**) significant at the 0.05 (0.01) confidence level

Variable	r_1	n_{eff}	Linear trend (values per decade)
Temperature Apr–Mar	0.386	40	+0.056 °C**
Temperature Apr–Sep	0.360	43	+0.056 °C*
Temperature Oct–Mar	0.202	60	+0.056 °C**
Precipitation Apr–Mar	0.040	84	−4.67%**
Precipitation Apr–Sep	0.025	89	−4.89%**
Precipitation Oct–Mar	0.031	86	−3.71%**
Climate Index	0.095	75	−0.399 Z scores**
Runoff Apr–Mar	0.145	68	−3.91%**

totals showing the steepest decrease at −4.89% per decade (Table 3).

Temperatures in the northwestern Patagonian region have experienced a marked interannual variability and distinctive low-frequency (decadal-scale) patterns within this long-term trend (Fig. 3A). The highest warm season temperatures occurred in 1943 (average anomaly of +0.82 °C) with extended warmer temperatures between 1950 and the early 1960s, and again between the late 1970s to about 1990. It is interesting to note that, although the post-1990 values have remained warmer than the long-term mean, they have not reached the extreme levels of the early 1940s in this region. Intervals of extended below-average temperatures occurred during the first three decades in these series and again between the mid 1960s and mid 1970s when the two coldest years on record (1970 and 1975) reached −0.87 °C below the mean. The analysis of annual (April–March) values revealed very similar low-frequency patterns throughout the century. In their analysis of the temperature record from 1930/33–1990/92, Rosenblüth et al. (1997) and Villalba et al. (2003) reported an overall cooling trend between the 1950s and mid 1970s that they considered to be the most noticeable feature of recent climate in northwestern Patagonia west of the Andes. This negative trend is also observed in the records from stations east of the Andes, but their overall trend is positive and non significant. Our results indicate that, when records from

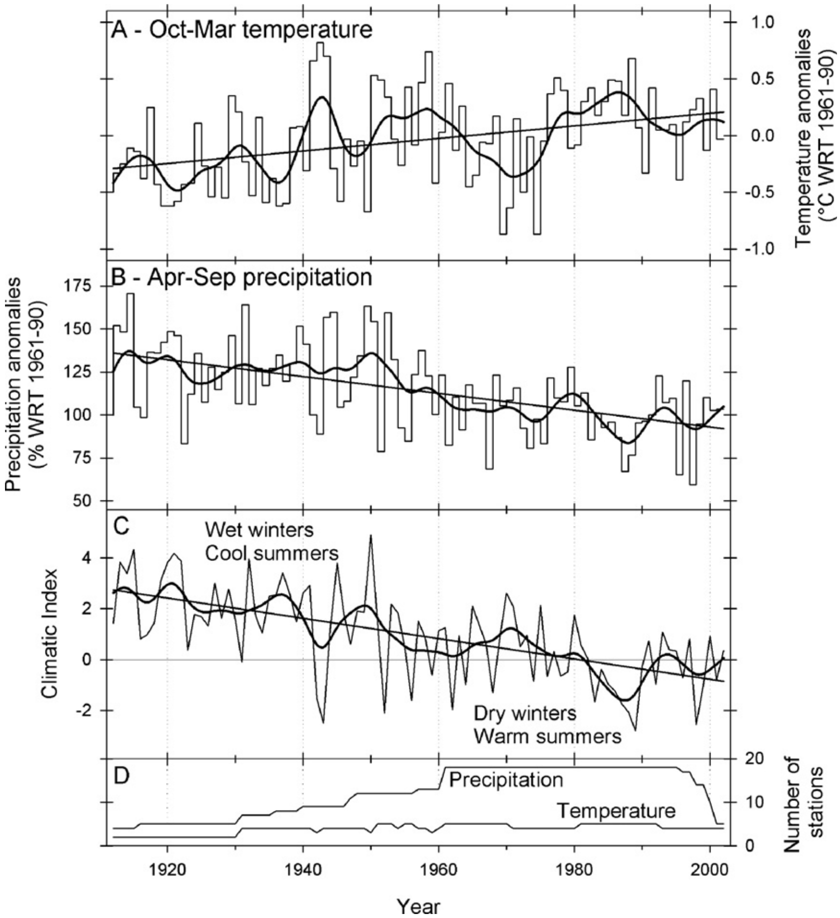

Fig. 3. (A) Warm season (October–March) temperature variations in the northwestern Patagonian region between 1912 and 2002 (CRUTem2v grid cell bounded between 40°–45°S and 70°–75°W), expressed as anomalies (°C) with respect to the 1961–1990 reference period. (B) Cold season (April–September) precipitation variations for the study area. Adjusted totals for the 18 selected stations between 38° and 44°S were converted to percentages of their 1961–1990 mean and subsequently averaged to create this regional record. (C) Regional climatic index calculated as the difference between the standardized anomalies (Z scores) of cold season precipitation totals and warm season mean temperatures. In general, positive values are interpreted as the result of wet winters being followed by cool summers, and vice versa. Least squares linear trends and smoothed (10-yr, 50% cutoff spline) versions of each climatic series are shown to highlight the low-frequency patterns in these records. (D) Number of stations contributing to the regionally-averaged temperature and precipitation series in any given year.

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both sides of the Andes are analyzed over the 1912–2002 period, this cooling trend is insufficient to counteract the overall warming trend observed across the region (Fig. 3A).

Above-average cold season precipitation totals dominate the first four decades of the regional series and culminate around the mid 1950s. Subsequently there is a strong decrease in winter totals, interrupted by short periods of increased precipitation around 1970, 1980, and the mid 1990s (Fig. 3B). The extended below-average interval between 1983 and 1992 is the most conspicuous feature of the later portion of the regional series. The two driest years on record are 1998 (averaging 59.5% of the 1961–1990 precipitation) and 1996 (65.3%, Fig. 3B). As the cold season totals average between 65% and 80% of the annual (April–March) total (Table 1) these two series are almost identical, highlighting the strong influence of winter totals on annual precipitation variations at interannual and interdecadal timescales.

4.3. Localized glacier advances and their relationship with the regional climatic index

The climatic index based on these standardized precipitation and temperature series (Fig. 3C) shows a strong negative trend that broadly agrees with the dramatic ice mass losses seen in Fig. 2. Between 1912 and 2002, the linear trend is −0.399 standardized anomalies per decade, significant at the 0.01 level (Table 3). Within this long-term pattern, several extended intervals of positive and negative indices are also evident. Positive values (i.e. wet winters followed by cold summer conditions) dominate the series until 1941, when a sharp drop to strongly negative anomalies occurs. Beginning in 1944, a short-lived period of positive values culminates in 1950 with the highest index (+4.89) in this time series. From 1950 until the late 1980s, annual values show a sharp declining trend interrupted by periods of positive values between the mid 1960s and 1970s. One of the most intriguing features of this time series is the interval of successive negative indices between 1983 and 1990, with 1989 being the lowest (−2.80) on record. Subsequently winter precipitation and summer temperature anomalies are roughly balanced and the resulting index values oscillate around zero with an overall mean of −0.12.

The decadal patterns in the regional climatic index show a fair correspondence with known periods of 20th-century glacier advances in the region (Fig. 4 and Table 4). The smoothed regional climatic index shows peaks in the early 1920s, 1940s and 1950s which roughly precede moraine formation at the Frías and Ventisquero Negro Glaciers (Table 4). The best documented glacier readvances in the Tronador Area (identified mainly from field studies, Table 4) started in the early 1970s and ended in 1977. This short-lived interval of glacier advance closely follows the peak in the climatic series around 1970 (Fig. 4). To our knowledge, no evidence has been reported for glacier advances during the 1990s in response to the slight increase in the climatic index evident at that time. On the contrary, most sources indicate accelerating retreating rates following the 1970–1977 advance, with the strongest glacier mass loss occurring during recent years (e.g. Rivera et al., 2005). However, the slight positive climate index

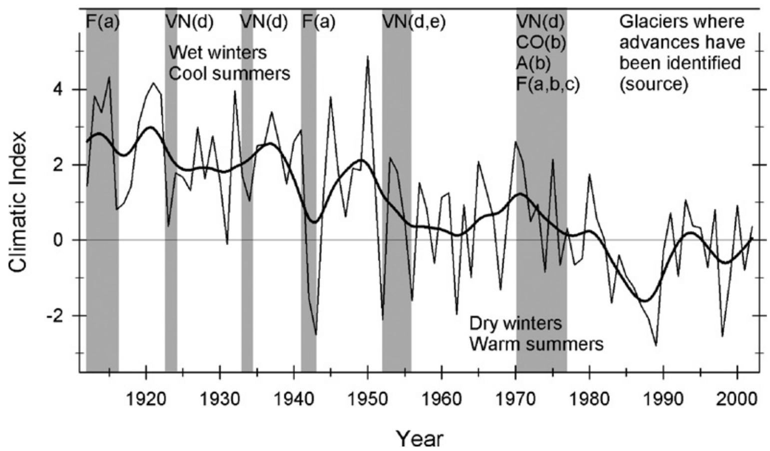

Fig. 4. Comparison between the regional climatic index and glacier advances identified in the Tronador Area (41°10′S) during the 20th-century. A 10-yr, 50% cutoff spline (thick line) is shown to emphasize the low-frequency patterns in the climatic series. The shaded bars are approximate dates for observations of glacier advances. Glacier abbreviations are (F) Frías Glacier; (VN) Ventisquero Negro; (CO) Castaño Overo Glacier; (A) Alerce Glacier. The bracketed lower case letters refer to sources listed in Table 4.

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Table 4
Glacier advances identified in the Tronador Area (41°10′S) during the 20th century. Sources: (a) Villalba et al., 1990; (b) Rabassa et al., 1978; (c) Rabassa et al., 1979; (d) Rabassa et al., 1984; (e) Lawrence and Lawrence, 1959

Glacier	Date of advance	Supporting evidence (source)
Frías	1912–1916	Age of trees growing on frontal and lateral moraines. 8–13-yr ecesis estimated (a)
	1941–1943	
	1970–1977	Tree-ring patterns in ice-scarred living tree (a)
		In situ measurements of glacier front position (b, c)
Alerce	1975–1977	In situ measurements of glacier front position (b)
Castaño Overo	ca. 1902	Age estimations for trees growing on right lateral moraine (d)
	1970–1974	In situ measurements, frontal position of regenerated ice cone (b)
	1976–1977	
Ventisquero Negro	1896–1902	Age of trees growing on right lateral moraines. 14-yr ecesis estimated (d)
	1923–1924	
	ca. 1933	
	1952–1956	Age of trees growing outside right lateral moraine. 14-yr ecesis, estimated (d)
		Tree-ring patterns in ice-scarred living tree (e)
	ca. 1975	Field observations and air photographs (d)

values after 1990 do not necessarily imply a positive mass balance (see discussion above), but simply indicate conditions during the 1990s were similar to the mean over the 1961–1990 reference interval. It is possible that the glaciers may be adjusting to a new (i.e. post-1977) mean state (likely with a higher Equilibrium Line Altitude) in response to the overall warmer and drier conditions during recent decades.

4.4. Regional streamflow variations and relationships with climate records

The PCA and intercorrelation tests performed on the annual discharge of seven Argentinean rivers in the north Patagonian Andes (Table 2) confirmed the existence of a strong regional hydroclimatic signal in this area. The only significant Principal Component explains 76.8% of the variance in the annual series over the 1957–2003 common interval. Significant ($p<0.05$) positive correlations were found for all possible pairs of rivers (average $r=0.73$, range 0.53–0.89). In addition, this regionally-averaged streamflow record shows a strong positive correlation ($r=0.77$, $p<0.01$) with the regional climatic index series and remarkable similarities at interannual and interdecadal scales (Fig. 5). Regional annual streamflow variations show a highly significant negative trend (−3.9% decade^{-1}, $p<0.01$) over the 1912–2002 period (Table 3). Correlations between the averaged streamflow series and the annual and seasonal temperature and precipitation records revealed the opposite influence of these variables on river discharges in the region. Statistically significant positive

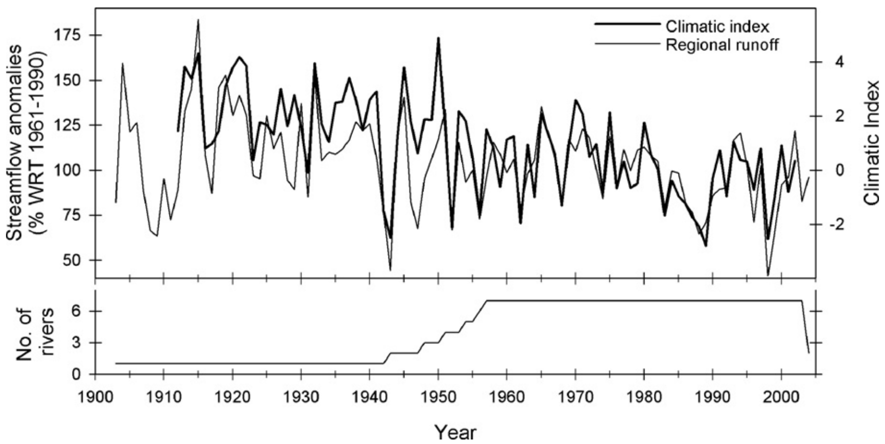

Fig. 5. Comparison between the regional climatic index (thick line) and the average of seven annual (April–March) river records from the eastern side of the north Patagonian Andes (thin line), expressed as percentages from their 1961–1990 mean flows. The lower diagram shows the number of gauge stations used in the computation of the regional streamflow series on any given year.

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Table 5
Paired correlations between the annual (April–March) streamflow record and annual and seasonal (April–September, October–March) precipitation and temperature series for the northwestern Patagonian region between 1912 and 2002. The statistical significance (*t* test) of the correlations was estimated after accounting for the serial correlation in the intervening time series (Dawdy and Matalas, 1964). Notes: *(**) Significant at the 0.05 (0.01) confidence level

		Precipitation			Temperature		
		Apr–Mar	Apr–Sep	Oct–Mar	Apr–Mar	Apr–Sep	Oct–Mar
Runoff Apr–Mar		0.820**	0.798**	0.480**	−0.375**	−0.262*	−0.332**
Precipitation	Apr–Mar		0.937**	0.620**	−0.247*	−0.141	−0.252*
	Apr–Sep			0.315**	−0.187	−0.116	−0.181
	Oct–Mar				−0.280*	−0.133	−0.313**
Temperature	Apr–Mar					0.800**	0.781**
	Apr–Sep						0.250*

(negative) correlations with the regional precipitation (temperature) series were found for all three seasons analyzed (Table 5). However, the strongest correlations (up to +0.82) occurred with precipitation records, especially with annual and cold season totals. The highest negative correlations ($r = -0.375$) were found with the annual temperature series (Table 5).

5. Discussion and conclusions

The preliminary analyses presented here indicate major changes in the climate of northwestern Patagonia over the last century with noticeable impacts on glaciers and river discharge in the region. Conservative linear trend analyses revealed a strong, highly significant tendency towards drier and warmer conditions over the 1912–2002 period. Over this interval, averaged warm season (October–March) temperatures have increased by 0.056 °C per decade, whereas cold season (April–September) precipitation records (on average ca. 73.5% of annual totals) have declined at a rate of 4.89% per decade (Fig. 3AB and Table 3). Although clearly apparent in the gridded temperature records used in this study, the previously identified cooling trend between the 1950s and the mid 1970s for northwestern Patagonia west of the Andes (Rosenblüth et al., 1997; Villalba et al., 2003) is insufficient to counteract the overall warming tendency observed in the entire region over the 1912–2002 period. The comparison with independently measured climate and streamflow records suggests that these regional temperature and precipitation series can be regarded as reliable indicators of climatic conditions for northwestern Patagonia between ca. 38° and 45°S.

The small size of glaciers in the north Patagonian Andes and their relatively short response time to climate fluctuations makes them particularly suitable to complement studies of recent climate changes in this part of the world. The comparison of past and present glacier front positions from repeated ground photography (Fig. 2) provides powerful baseline information about the long-term behavior of local ice masses. The good quality paired photographs from six glaciers between 39°S and 43°S document the strong glacier recession over the past century in this region and corroborate the highly significant trends towards warmer and drier conditions over the 20th century based on regionalized temperature and precipitation records. A simple climatic index derived from these records provides a crude proxy for glacier mass balance that is consistent with the observed glacier recession in the region (Fig. 3C). Although this climatic index shows a marked negative trend over the complete record, multi-year periods of positive values (i.e. wet winters followed by cool summers) roughly coincide with known periods of glacier advance during the 20th century (Fig. 4 and Table 4). For example, the well-documented interval of glacier advances culminating in 1976–1977 probably took place in response to consecutive years of relatively wet and cool conditions during the early 1970s, implying a relatively short (less than a decade) glacier response time to climate. However, these tentative conclusions are drawn on the limited, presently available database. Recent and ongoing glaciological studies (e.g. Bown, 2004; Rivera et al., 2005) may ultimately provide more comprehensive data to evaluate the relationships between glaciers and synoptic changes in climate in this area.

The climatic index developed in this paper is strongly correlated with regional streamflow records derived from the seven longest and most complete records from the north Patagonian Andes in Argentina, confirming the validity of this index and highlighting the regional nature of the changes observed in these variables. Correlation with precipitation and temperature series provides further insight into the climate-runoff relationships in the

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region, indicating a strong regional pattern of discharge primarily controlled by precipitation variability over the last century. These preliminary findings have interesting implications for the evaluation of the relative importance of possible future changes in precipitation and temperatures in this region.

Results from several coupled atmosphere–ocean general circulation models (Cubasch et al., 2001; Bradley et al., 2004) suggest that the temperature and precipitation trends observed in northwestern Patagonia will probably continue well into the 21st century. Although further work is needed to evaluate the potential hydrological and socio-economic impacts of such predictions, an improved knowledge of recent (i.e. 20th-century) climate variability in this area will be of crucial importance for future water resource management programs and regional development initiatives.

Acknowledgments

We would like to thank Christoph Kull for inviting us to participate in this special issue. Comments from two anonymous reviewers significantly improved this manuscript and are greatly appreciated. This research was supported by the Argentinean Agency for the Promotion of Science and Technology (grant PICTR02–186), and the CRN03 Project of the Inter American Institute for Global Change Research (IAI). We are grateful to Darío Trombotto, Pepe Hernández, Alberto Ripalta, and Salvador Calí (IANIGLA, Mendoza), Club Andino Bariloche and Museo de la Patagonia (Bariloche), and Biblioteca Perito Moreno (Parques Nacionales, Buenos Aires, Argentina) for their assistance in developing the photographic database. We also thank Rocío Urrutia (Universidad Austral de Chile, Valdivia) for providing most of the Chilean precipitation records, and Eduardo Flamenco (INTA Castelar, Argentina) for the updated streamflow data. The GHCN v.2 precipitation records were obtained from the Climate Explorer website (http://climexp.knmi.nl) of the Royal Netherlands Meteorological Institute (KNMI). Regional hydroclimatic series were analyzed utilizing the AnClim and ProClimDB software packages available at http://www.klimahom.com/software.

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