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Climate changes and recent glacier behaviour in the Chilean Lake District

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Abstract

Atmospheric temperatures measured at the Chilean Lake District (38°–42°S) showed contrasting trends during the second half of the 20th century. The surface cooling detected at several meteorological stations ranged from −0.014 to −0.021 °C a^{-1}, whilst upper troposphere (850–300 gpm) records at radiosonde of Puerto Montt (41°26′S/73°07′W) revealed warming between 0.019 and 0.031 °C a^{-1}. Regional rainfall data collected from 1961 to 2000 showed the overall decrease with a maximum rate of −15 mm a^{-2} at Valdivia st. (39°38′S/73°05′W). These ongoing climatic changes, especially the precipitation reduction, seem to be related to El Niño–Southern Oscillation (ENSO) phenomena which has been more frequent after 1976. Glaciers within the Chilean Lake District have significantly retreated during recent decades, in an apparent out-of-phase response to the regional surface cooling. Moreover, very little is known about upper troposphere changes and how they can enhance the glacier responses. In order to analyse their behaviour in the context of the observed climate changes, Casa Pangue glacier (41°08′S/71°52′W) has been selected and studied by comparing Digital Elevation Models (DEMs) computed at three different dates throughout the last four decades. This approach allowed the determination of ice elevation changes between 1961 and 1998, yielding a mean thinning rate of -2.3 ± 0.6 m a^{-1}. Strikingly, when ice thinning is computed for the period between 1981 and 1998, the resulting rate is 50% higher (-3.6 ± 0.6 m a^{-1}). This enhanced trend and the related area loss and frontal retreat suggests that Casa Pangue might currently be suffering negative mass balances in response to the upper troposphere warming and decreased precipitation of the last 25–30 yr, as well as debris cover would not prevent the glacier from a fast reaction to climate forcing. Most of recent glaciological studies regarding Andean glaciers have concentrated on low altitude changes, namely frontal variations, however, in order to better understand the regional glacier changes, new data are necessary, especially from the accumulation areas.

Keywords: climate change; ENSO; Chilean Lake District; glacier fluctuations; ice thinning

1. Introduction

The atmospheric warming observed in Chile during the 20th century is thought to has driven the fluctuations of glaciers, which have been suffering frontal retreats, area shrinkage and ice thinning in recent decades (Casassa, 1995; Rivera et al., 2002). Rosenblüth et al. (1997) reported that mean surface temperatures measured at several stations in northern and southern Chile experienced warming rates between 0.013 and 0.02 °C a^{-1} in the period 1933–1992. However, when atmospheric warming was analysed for the most recent period between 1960 and 1992, the resulting trends were doubled (Rosenblüth et al., 1997). This higher warming seems to be correlated with changes experienced by the tropical Pacific Ocean after 1976, when a shift in the global climatic system was detected,

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increasing the mean global temperatures by 0.2 °C as well as the frequency of negative ENSO events (Giese et al., 2002).

Despite the above general warming, stations located within the Chilean Lake District (38–42°S, Fig. 1) recorded atmospheric cooling, particularly Puerto Montt (41°26′S/

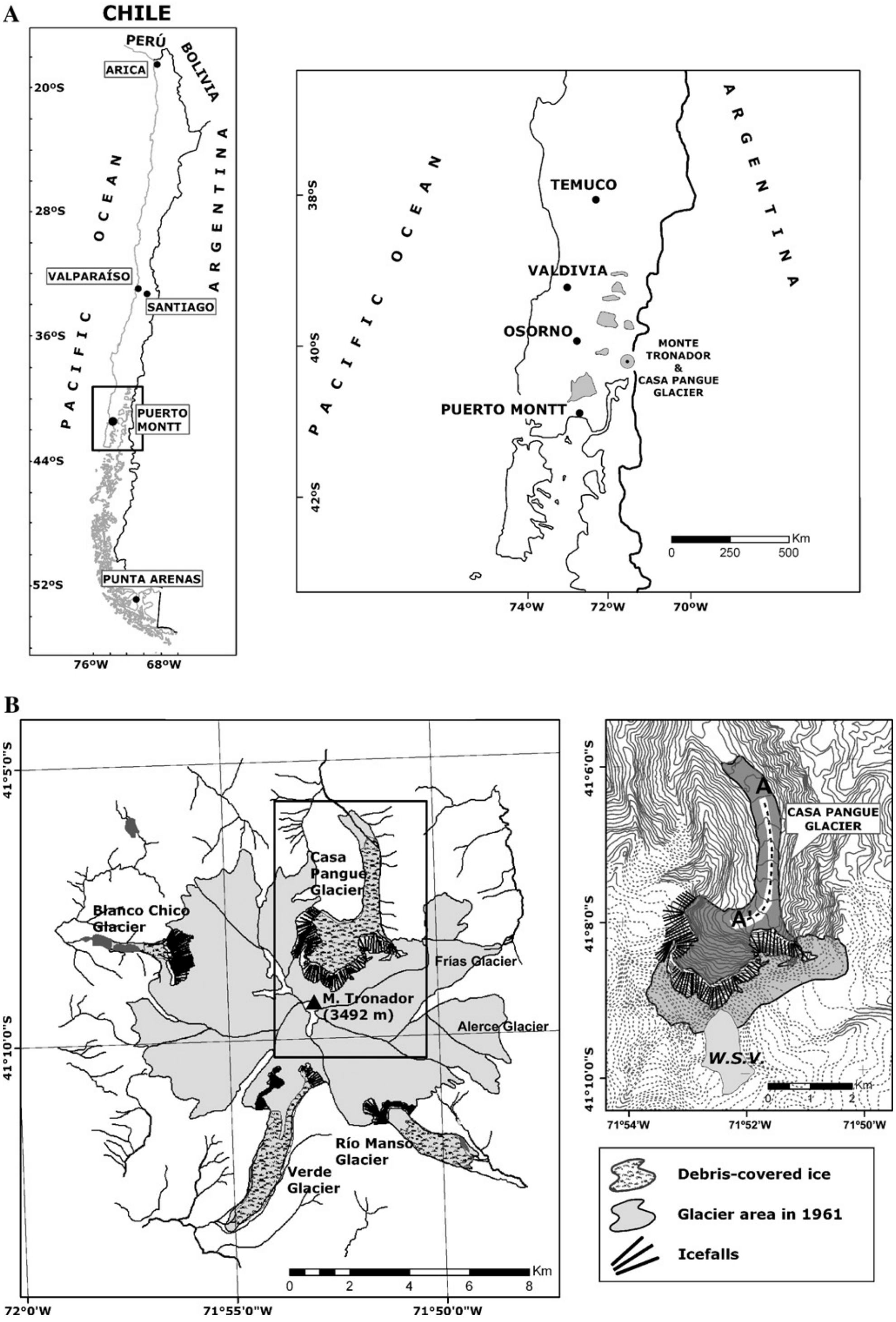

Fig. 1. Map of the Chilean Lake District, with location of the meteorological stations discussed in the text (A), and Monte Tronador with main glaciers (B). Inset shows the topographic profile used to analyse ice elevation changes on Casa Pangue glacier.

73°07′W) where the surface temperature trend yielded -0.011 °C a^{-1} between 1960 and 1992 (Rosenblüth et al., 1997). The decrease in temperatures was assumed to be affecting the lower troposphere only, when Aceituno et al. (1993) detected warming above the 850 gpm level within the same period of time, in synchronicity with an intensified greenhouse effect (Karoly, 1987).

Inter-annual precipitation variability in Central Chile has been linked to ENSO phenomena, with a positive relationship to sea surface temperature anomalies during winter between 32 and 38°S, while this relation is negative in the region south of 38°S during the following summer (Montecinos and Aceituno, 2003). This is due to the seasonal shift of the subtropical anticyclone as well as the reinforcement of its southern tip, blocking western frontal systems, which are the main source of precipitation in this part of the country (Rutllant and Fuenzalida, 1991). As a result, a decrease in summer precipitation has been observed in the Chilean Lake District, i.e., during the mature phase of El Niño events (Montecinos and Aceituno, 2003).

Glaciers located within the Chilean Lake District have experienced frontal retreats during recent decades, in both the Chilean western side of the Andes (Rivera et al., 2000) and the eastern Argentinean side (Villalba et al., 1990; Leiva, 1999), suggesting that they do not respond linearly to surface temperature changes. Glacier–climate interactions are well known to date, where the equilibrium line altitude (ELA) is closely connected to precipitations and air temperatures, rising when the annual mass balance of a glacier is negative and dropping when this balance is positive (Benn and Evans, 1998). The response time, or the time taken by a glacier to adjust to a change in its mass balance, may be solved by two basic parameters, i.e. ice thickness and ablation at the terminus (Paterson, 1994). Thus, according to the ice thickness for Casa Pangue glacier (41°08′S/71°52′W, Fig. 1) estimated by Rivera et al. (2001) and ablation rates on temperate maritime climates (Paterson, 1994), the response time should yield ~15 yr.

In this context, surface and upper atmosphere instrumental data collected from 1950 to 2000 at meteorological stations located between 38°S and 42°S of Chile have been analysed in order to estimate temperature and precipitation multidecadal trends. Simultaneously, the glacier fluctuations were studied based upon data collected for Casa Pangue, one of the largest glaciers of Mount Tronador (Fig. 1). This is a regenerated valley glacier with a debris-covered ablation area, located at the foot of icefalls falling from the head of the basin (Lliboutry, 1956; Rabassa et al., 1981). Supraglacial debris can have a strong influence on glaciers by isolating them from atmospheric heat, and thus, reducing ablation (Nakawo and Young, 1982; Benn and Evans, 1998). For instance, this effect has been reported in Himalaya, with thinning rates being smaller where the surface is not bare-ice (Nakawo et al., 1999). However, Casa Pangue glacier seems to react quickly to climate change, showing a significant frontal retreat during recent decades (Rivera et al., 2002).

With all the above, the main aim of this paper is the analysis of regional climatic series of temperatures (surface and troposphere) and precipitation, in order to interpret the behaviour of Casa Pangue glacier.

2. Methods

2.1. Climate trends detection in meteorological records

We analysed monthly mean surface temperatures and precipitation data between 1950 and 2000 at meteorological stations located between 38° and 42°S (<200 m asl), as well as upper air temperatures obtained at Puerto Montt radiosonde station (41°26′S/73°07′W) from 1958 to the year 2000 (Fig. 1). These stations are operated and maintained by the Chilean Meteorological Office (Dirección Meteorológica de Chile, DMC), who provided the data. The bi-monthly anomalies of the Multivariate ENSO Index (Wolter and Timlin, 1998) were also analysed within the same period of time.

Temperature and precipitation records were normalised and linear trends over the time series were obtained from the least-squares method. For statistical significance, a two-tailed *t*-Student test was applied to the series (Rosenblüth et al., 1997).

A smoothing filter was applied to the series in order to reduce inter-annual variability and obtain long-term trends (Carrasco et al., 2002). The filter was based upon an exponential curve (Essenwanger, 1986) applied forward and backward in time. The selection of the smoothing coefficient was based on the observed variability for the original series. For an input series *xt*, the curve is obtained with Eqs. (1) and (2):

$$y_t = cx_t + (1-c)y_t - 1 \quad t = 2,3,\ldots,N \tag{1}$$

$$z_t = cy_t + (1-c)z_t + 1 \quad t = (N-1),(N-2),\ldots,2,1 \tag{2}$$

where:

y_t	intermediate stage (forward)
z_t	final stage (backward)
c	smoothing coefficient

For the initialisation of the process, y_1 was taken as the average of the first ten values of x_t, and final value of backward stage, z_n, corresponds to the last value of forward stage, y_n.

2.2. Determination of ice elevation changes

Ice elevation changes of Casa Pangue glacier (Fig. 1) were obtained by comparing DEMs (Digital Elevation Models) acquired at different dates, being referred to the unchanging non-ice surrounding terrain, the "bedrock control" (Krimmel, 1999).

A 30 m grid size DEM was generated based on interpolation of 50 m-interval digital contour lines from the regular cartography published by Instituto Geográfico Militar of Chile (IGM). This cartography was photogrammetrically derived by IGM from vertical aerial photographs acquired in 1961 (DEM-1961). The interpolation procedure applied to the contour lines is the Triangular Irregular Network (TIN), available at Idrisi32 commercial software. Within this interpolation method, known attributes, i.e. contour lines, are employed to generate a set of non-overlapping triangles (Burrough and McDonnell, 2000).

The vertical RMS (Root Mean Square) error of DEM-1961 was estimated to yield:

$$\sqrt{17^2 + 9^2} = \pm 19\,\mathrm{m}.$$

The first source of this error (17 m) was the inaccuracy of the Classified I regular cartography, in terms of the American Society for Photogrammetry and Remote Sensing. Following Falkner (1995) this is calculated as one third of the contour interval. The second error source (9 m) was the inaccuracy added by the interpolation method. This has been estimated from the "jack-knifing" procedure (Lythe et al., 2001), when a truncated DEM, generated by interpolation of an uncomplete set of contour lines was compared to a DEM computed with the whole data set. This step allowed to determine the mean variability for this type of model.

Two further DEMs (30 m pixel size) were created by means of traditional photogrammetry by H. Brecher, Ohio State University, USA, employing a Kern DSR-11 analytical stereo-plotter instrument. Input data were vertical photographs acquired in 1981 and 1998 aerial surveys (DEM-1981 and DEM-1998 respectively). Ground Control Points (GCPs), provided by IGM, were selected from distinguishable rock outcrops and summits and marked on the photographs. Then, thousands of points on the stereomodels were measured every 30 m based upon the GCPs and the camera calibration parameters (fiducial marks coordinates and focal lens distance).

Ideally, vertical error for these kinds of models may derive from rock height differences as being compared with a "true" surface, e.g., an accurate topographic map. However, data collected over rock areas was scarce and the total error was then determined adopting the inaccuracies acquired during the DEMs generation. Thus, the estimated RMS error of DEM-1981 and DEM-1998 is ±8 m, derived from the inaccuracy of the GCPs (5 m) as well as the overall uncertainties added by the aerophotogrammetrical restitution (6 m).

Table 1
Mean annual temperature (°C a^{-1}) and precipitation (mm a^{-2}) trends

Meteorological station	Latitude (S)/ Longitude (W)	Elevation (m)	Air temperature 1950–2000 (°C a^{-1})	Precipitation 1961–2000 (mm a^{-2})
Temuco	38°45′/ 72°38′	114	−0.014**	−1.1
Valdivia	39°38′/ 73°05′	19	−0.019**	−15.0**
Osorno	40°36′/ 73°04′	65	0.004	−6.5*
Puerto Montt	41°26′/ 73°07′	90	−0.021**	−14.1**

Notes: **significant to 1%; *significant to 5%.

All DEMs were geolocated and projected to UTM coordinates using the worldwide datum WGS 1984 (NIMA, 1997) and mean sea level altitude reference, allowing their direct comparison. Due to the lack of stereoscopic vision on snow-covered surfaces at the accumulation area of the glacier (up to 3000 m asl), DEMs were compared in the ablation area from an altitude of ~700 to 1050 m asl, fully covered with supraglacial debris, providing a suitable study with the available data. The ice elevation changes were calculated along a topographic profile following the central flow line of the glacier (A–A′), where vertical errors are minimised (Fig. 1, inset).

3. Results

3.1. Climate change

3.1.1. Surface cooling and decrease in rainfall

The surface temperature series obtained between 1950 and 2000 confirm the cooling trend detected for most of the regional stations until the early 1990s (Rosenblüth et al., 1997). The only exception was observed at Osorno, located 100 km inland from the Pacific Ocean where no statistically significant trend was obtained. The maximum cooling was observed at Puerto Montt, located at the sea side at an inner bay (Fig. 1, Table 1).

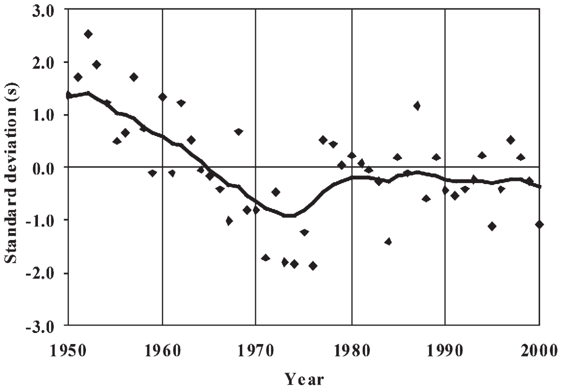

Fig. 2. Composite of annual mean temperature anomalies in the Chilean Lake District (Temuco, Valdivia, Osorno and Puerto Montt). The smoothed line is an exponentially-filtered curve ($c=0.25$).

The smoothed trend ($c=0.25$) of the regional temperature composite shows that the cooling is better defined in the first half of the study period, with a steep negative curve from the 1950s to the 1970s. Conversely, temperatures during the last two decades, although exhibiting a negative trend, seem to be more stable with values around the long-term mean (Fig. 2).

Regarding the annual precipitation, decreasing trends are found during the last four decades, although a large spatial/temporal variability has been observed for the analysed stations. A maximum reduction was detected at Valdivia and Puerto Montt, whereas at Temuco, only 200 km northwards, the trend is negligible (Table 1).

Fig. 3 presents the annual precipitation anomalies at Puerto Montt, where a more defined trend was possible to be found throughout the study period. The smoothed curve was based on a damping coefficient of 0.11, which allowed to shallow a large inter-annual variability. The ENSO Index anomalies were smoothed with similar coefficient, being related to precipitation trend more directly. In general terms, the monotonically rainfall decrease is appreciated between 1961 and 2000. However, no strong precipitation trend appears until early 1970s, in synchronicity with negative ENSO Index anomalies prevailing from 1950 to the mid 1970s, when the positive (cold) phase events were more frequent. After the 1970s precipitation series showed a significant decrease, with the strongest negative anomalies during the 1990s, whereas the ENSO Index showed positive values, indicating more frequent occurrence of El Niño events. The above suggests that precipitation may be negatively related to the ENSO Index described by Wolter and Timlin (1998), as well as El Niño events may arise as the main control on the reduction of precipitation.

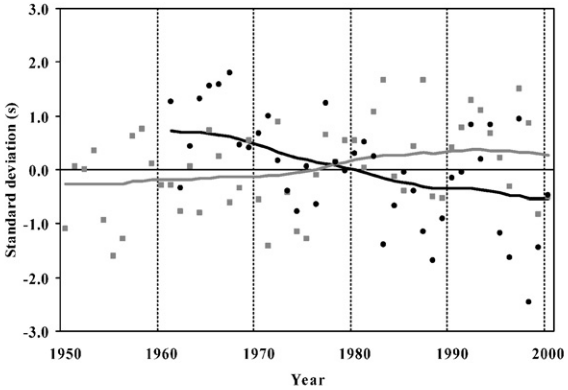

Fig. 3. Annual precipitation (Puerto Montt, black) and Multivariate ENSO Index (grey) anomalies. The smoothed line is an exponentially-filtered curve with a coefficient of 0.11, in order to reduce the high inter-annual rainfall variability.

Table 2
Mean annual temperature (°C a^{-1}) trends at Puerto Montt radiosonde station

Geopotential height level (gpm)	Height (m)	Air temperature 1958–2000 (°C a^{-1})
850	1500	0.019**
700	3000	0.031**
500	5500	0.021*
300	9000	0.023**
150	14000	−0.007
100	16000	−0.020*

Notes: **significant to 1%; *significant to 5%.

3.1.2. Upper atmosphere temperature changes

Upper atmospheric data at Puerto Montt radiosonde station showed temperature increases at different tropospheric levels between 1958 and 2000, suggesting that the cooling have prevailed only in the near-surface layers of the atmosphere (Aceituno et al., 1993). The warming appears especially at 700 gpm (0.031 °C a^{-1}). On the other hand, geopotential levels above the tropopause (150 gpm and 100 gpm) indicate stratospheric cooling (Table 2).

Fig. 4 presents temperature trends at 850 gpm and 700 gpm levels (1500 m to 3000 m) between 1958 and 2000. During the 1960s, both levels showed small variations, however during the 1970s a sharp increase in temperatures was observed at both atmospheric levels in synchronicity with the 1976 global climatic shift (Giese et al., 2002). The 1990s decade is the warmest of the 42-year period.

3.2. Ice elevation changes

Extreme ice elevation changes between specified dates are shown in Table 3 for Casa Pangue glacier. The average

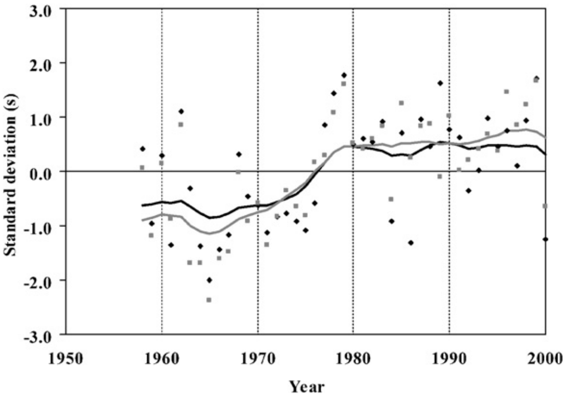

Fig. 4. Annual mean temperature anomalies at 850 (black) and 700 (grey) gpm levels from Puerto Montt radiosonde station. The smoothed line is an exponentially-filtered curve ($c=0.25$).

value between 1961 and 1981 was −1.2±1.1 m a^{-1}, when the smallest frontal variations were observed by Rivera et al. (2002). In the second period (1981–1998), the ice thinning rates were three times higher, yielding a mean value of −3.6±0.6 m a^{-1}. The frontal retreat of the glacier during this recent period accelerated to a maximum rate of −51 m a^{-1}, being also observed the highest area change at lower altitude (Table 3). Over the entire study period, the average elevation change was −2.3±0.6 m a^{-1}.

Plotting all ice elevation changes versus altitude (Fig. 5), it is appreciated a linear spatial pattern between the 700 and 1050 m, with higher rates of thinning at lower altitude and its decrease with increasing elevation. Because of the frontal retreat taking place at the glacier terminus, which has been occasionally calving into a proglacial lagoon since 1981, the maximum thinning rates are observed at ~750 m. From 800–850 m, they decrease roughly towards the accumulation area of the glacier.

4. Discussion and conclusions

During the second half of the 20th century, surface temperatures in the Chilean Lake District experienced a decrease in the range of −0.014 to −0.021 °C a^{-1}. These rates appear larger than those given by Rosenblüth et al. (1997) for the period between 1960 and 1992, suggesting that the lower atmospheric cooling was a key feature during the 1950s. Conversely, the troposphere height levels analysed above 850 gpm showed warming, especially from the 1970s onward.

Table 3
Casa Pangue glacier ice elevation, areal and frontal changes

Period	Ice elevation change		Areal change (km^2) (Fernández, 2003)	Frontal variation (m a^{-1}) (Rivera et al., 2002)
	Minimum (m a^{-1})	Maximum (m a^{-1})		
1961–1981	−0.1±1.1	−2.9±1.1	−0.19	−18
1981–1998	−1.7±0.6	−5.3±0.6	−0.47	−51
1961–1998	−1.6±0.6	−3.4±0.6	−0.66	−33

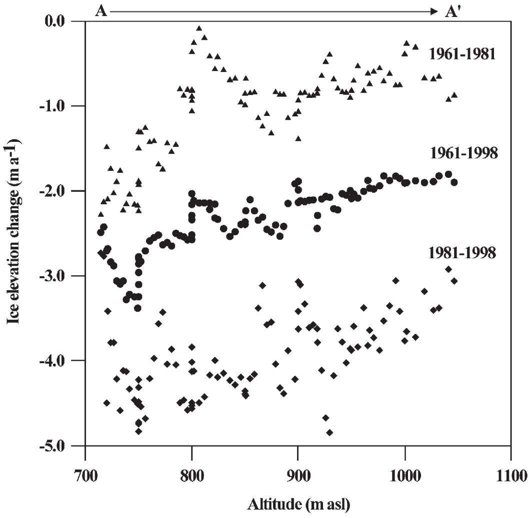

Fig. 5. Ice elevation changes between specified dates in the ablation area of Casa Pangue glacier based upon the topographic profile described in Fig. 1.

A decreasing precipitation trend was observed within the whole study period, especially during the last two decades, which was coincident with the change in the Multivariate ENSO Index, suggesting that the Pacific variability at the interdecadal timescale might be the background climate phenomenon as indicated by Giese et al. (2002). This implies that the most recent reduction in precipitation may be related to a more frequent negative phase of ENSO (El Niño) as has been observed after 1976.

The increase in temperature at different tropospheric levels (between 300 and 850 gpm) together with a decrease in precipitation arises as the most significant regional climatic trends, and therefore it is possible to presume that both the accumulation and ablation areas of the glaciers must be significantly affected, with smaller amounts of snowfall and higher ablation.

Temperature increase above 1500 m means that the ELA is probably shifting upwards, and therefore the accumulation area is shrinking or the net accumulation is becoming progressively smaller, which should be generating negative mass balances. The ablation area seems to respond with high thinning rates, frontal retreat and ice surface loss, all of which accelerated since the 1980s. Thus, the cooling trend observed in the available surface meteorological data does not appear relevant on the glacier behaviour, as being likely affected through increased sensible heat transfer and absorption of shortwave radiation explained under a warmer and drier climate. Debris cover at Casa Pangue is not enough to minimise its response to climate change, suggesting a delay time even as fast as it is reported for another bare-ice glaciers in Southern Chile (Rivera et al., 1997). Moreover, the thinning pattern described for Casa Pangue glacier is very similar to the curves estimated for many glaciers in Patagonia (Rignot et al., 2003), suggesting high ablation in a negative mass balance context.

Unfortunately, the DEMs generated based upon aerial photographs did not cover all the glacier due to lack of stereoscopic vision at the accumulation area, which might also be affected by warming trends detected in the radiosonde data. The thinning curves obtained here suggest that this may still be observed at higher altitude, however, this signal will arise under the errors of the DEMs, meaning that a more accurate survey technology will be necessary for these higher areas in order to estimate the possible elevation changes. One possibility is the use of geodetic quality GPS receivers during direct measurement campaigns. The main problem of using this technology in Mount Tronador is the rough topography of the mountain, resulting in logistical and mountaineering constraints. A more likely but expensive approach could be the use of laser altimetry sensors mounted onboard aircrafts, which have been successfully used in Patagonia and other glaciers of the Northern Hemisphere (Thomas et al., 2003).

Considering that this debris-covered glacier has been thinning at high rates during recent decades, even under the effect of the surface cooling, it can be speculated that in the future the glacier retreat will be enhanced in response to an increase in surface temperatures, as suggested by the trends observed at Puerto Montt during the 1990s. However, further research and new data will be necessary in order to fully understand the processes taking place in the area, especially if the observed climate changes can quantitatively account for the glacier retreat, or alternatively if another mass balance component (recent calving?) is affecting the glacier thinning.

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