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# Glacier changes in the Pascua-Lama region, Chilean Andes (29° S): recent mass-balance and 50-year surface-area variations

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2307

## Abstract

Since 2003, a monitoring program has been conducted on several glaciers and glacierets in the Pascua-Lama region of the Chilean Andes (29° S/70° W; 5000 m a.s.l.), permitting the study of glaciological processes on ice-bodies in a subtropical, arid, high-elevation area where no measurements were previously available. In this paper we present: (i) 6 years of glaciological surface mass-balance measurements from 4 ice-bodies in the area, including a discussion of the nature of the studied glaciers and glacierets and characterization of the importance of winter mass-balance to annual mass-balance variability; and (ii) changes in surface-area of 20 ice-bodies in the region since 1955, reconstructed from aerial photographs and satellite images, which show that ice-bodies have lost  $44 \pm 21\%$  of their 1955 surface-area, and that the rate of surface-area shrinkage increased in the late 20th century. From these datasets we present an interpretation of inter-decadal glacier changes, which appear to be linked to El Niño Southern Oscillation and to the Pacific Decadal Oscillation.

## 1 Introduction

In the arid to semi-arid subtropical region of Chile and Argentina (27° S to 33° S), the evolution of the cryosphere (including glaciers, rock glaciers and seasonal snow cover) is a major concern for local populations due to the impact on water resources. Previous hydrological (e.g. Favier et al., 2009) and climatological (e.g. Masiokas et al., 2006; Vuille and Milana, 2007) studies carried out in this region highlight the lack of knowledge of glaciological processes at high elevation. The Pascua-Lama region (29° 19' S, 70° 01' W) is very close to the arid diagonal, and coincides with an apparent northerly limit of glaciation in Chile; north from this area glaciers are almost absent until the intertropical zone. Glacier mass-balance measurements are not available in the vicinity of the Pascua-Lama region. The nearest study sites from this subtropical region are found on Echaurren Glacier, Chile, 33°35' S (Escobar et al., 2000), on Piloto Glacier,

2308

Argentina, 32°27' S (Leiva et al., 2007) and ~1500 km north on Zongo and Chacaltaya glaciers in the Bolivian intertropical Andes, ~16° S (e.g. Wagnon et al., 1999; Francou et al., 2003). Climate conditions are considerably drier in the Pascua-Lama region than those observed 450 km south on Echaurren Glacier or on the Argentinian side of the Andean divide on Piloto Glacier (Falvey and Garreaud, 2007; Favier et al., 2009). As a consequence, glaciological processes are likely to be different in this transition zone and studying the glaciers of this region is crucial to understand the role of glaciers in the hydrological cycle. Paleoglaciological studies (e.g. Kull et al., 2002; Ginot et al., 2006) can offer until now only limited knowledge of current local mass-balance processes, patterns and relationship with local climatology. Previous work on glacier variations and relationship between glaciers and climate in this transition zone consists of four studies. In 1999, Leiva showed that the terminus of the Agua Negra Glacier in Argentina (30°10' S, 69°50' W) changed little from 1981 to 1997. Rivera et al. (2002) used aerial photographs to determine that Tronquitos Glacier (28°32' S, 69°43' W) retreated by 0.52 km<sup>2</sup> over the 1955–1984 period which represents –11.4% of its 1955 surface-area. At Cerro Tapado summit (30°08' S, 69°55' W), Ginot et al. (2006) obtained a record of net accumulation over the 20th century from an ice core drilled down to the bedrock, which showed large interannual variability but no significant trend. Finally, Nicholson et al. (2009) showed in a recent inventory that the total extent of glacierized area in this region is very small. These studies need to be complemented in order to gain an understanding of glacier behaviour and its relation to present and future climate conditions.

Glacier monitoring of several glaciers and glacierets in the Pascua-Lama region was initiated in 2003. The term “glacieret” defines an ice-body formed primarily by blowing or avalanching snow, which shows no surface signs of flow (World Glacier Monitoring Service, WGMS).

This paper focuses first on the results of the glacier mass-balance monitoring program in the Pascua-Lama region to better understand the climate/glacier relationship within this subtropical zone. Then it documents glacier changes over the last 50 years,

2309

both of which represent significant additions to glaciological databases such as WGMS and GLIMS (Global Land Ice Measurements from Space, [www.glims.org](http://www.glims.org)). Finally, glacier changes over the last fifty years are discussed within the context of regional climate. The contribution of glacier ablation to the hydrological regime of the watershed is examined by Gascoin et al. (2010).

## 2 Study area

### 2.1 Pascua-Lama glaciers/glacierets network

Figure 1 shows the studied ice bodies in the Pascua-Lama region located in the highest part of the Huasco River basin (southern part of the Chilean Región de Atacama). A small number of ice-bodies shows surface features indicative of flow and can be deemed glaciers, while the others are more properly referred to as glacierets. Their distribution is mainly controlled by topography, with all ice bodies being found on the southern slopes of the highest summits, spanning a range of 4780–5485 m a.s.l (Nicholson et al., 2009). This distribution is a consequence of shading from solar radiation and the redistribution of snow by predominantly northwesterly winds to the leeward side of peaks and crestlines. All ice-bodies have relatively smooth, gently sloping surfaces and ice flow, where it exists, is minimal ( $2.0 \pm 1.2 \text{ m a}^{-1}$  for 2008, Golder Associates, 2009). Their surface-area ranges from 0.04 to 1.84 km<sup>2</sup> in 2007 and the ice is generally thin except in the case of a few larger glaciers like Estrecho, Ortigas 1 or Guanaco where it reaches ~120 m (Table 1). All these ice-bodies are comprised of cold ice and are thought to be cold-based throughout; depth-averaged ice temperature measured in an ice-core borehole drilled at 5161 m a.s.l. in the central part of Guanaco Glacier in November 2008 was –6.2 °C, and basal temperature at 112.5 m depth was –5.5 °C (Ginot, personal communication, 2009).

2310







higher than for mid-latitudes glaciers where summer mass-balance is the main control on interannual mass-balance variations, e.g. in the French Alps, winter mass-balance explains only 10–15% of the annual mass-balance variability (Vallon et al., 1998; Rabatel et al., 2008). This characteristic of Pascua-Lama ice-bodies may result from both the higher variability of winter mass-balance (72%) and lower variability of summer mass-balance (41%) in this subtropical area compared to mid-latitudes. Similar conclusions can be drawn when comparing the results obtained on Pascua-Lama ice-bodies with glaciers of the Arctic region where the variability of summer mass-balance is the dominant factor in the annual mass-balance variability (Koerner, 2005).

#### 4.1.5 Causes of higher summer ablation on glacierets

Comparison of winter mass-balance and summer mass-balance between the glacierets and Guanaco Glacier shows that the more negative annual mass-balance of the glacierets (Sect. 4.1.2) is mainly due to a more negative summer mass-balance ( $B_s = -1.86 \pm 0.46$  m w.e. for the glacierets and  $B_s = -0.73 \pm 0.26$  m w.e. for Guanaco). This more negative summer mass-balance might be partly attributable to the distribution of stakes on the glacierets extending to a lower elevation compared to the glacier, but as the altitude-dependence of ablation is very weak (Sect. 4.1.3; Fig. 4), and temperatures are persistently sub-zero at this elevation, additional explanations to an elevation-driven temperature-dependent contrast between the ice-bodies are needed. Possible causes of enhanced ablation on the glacierets are stronger edge effects, lower surface albedo due to natural dust deposition and penitents which are all more evident on the glacierets than the glacier. Comparison of measured summer ablation and penitent height at 28 ablation stakes on the 6 ice-bodies showed a significant correlation ( $r^2 = 0.64$ ,  $\rho < 0.01$ ) between these variables. The systematic observation of penitents on the glacierets in summer is probably related to dust deposits on their whole surface as they are small ice-bodies and therefore a larger portion of their surfaces can be influenced by dust deposition from the unglaciated surroundings. Laboratory results (Bergeron et al., 2006) have demonstrated that surfaces covered with dusted

2317

snow form penitents more readily, and have penitents with larger peak separations than clean-snow surfaces. They also suggest that high intensity of radiation for near-infrared and infrared wave-lengths are crucial at the start of penitent growth; these wavelengths are likely to be higher at the border of the ice-bodies due to a larger emission from heated surrounding rocks (e.g. Francou et al., 2003). Unlike the glacierets, we observed that on Guanaco Glacier most of the surface is not covered by penitents. The role of penitents has been discussed in several studies (e.g. Lliboutry, 1954; Corripio and Purves, 2005). Lliboutry (1954) mentions that melting is the main ablation process in a field of penitents. Thus, by creating and maintaining conditions more favourable to melting, the presence of penitents could partly explain the more negative summer mass-balance on the glacierets.

## 4.2 Glacier surface-area changes

Surface-area changes of 6 glaciers and 14 glacierets in the Pascua-Lama region have been reconstructed from the mid-20th century using aerial photographs and satellite images (see Sect. 3). Results are presented in Table 4. Over the whole period, the mean surface-area loss for all the ice-bodies reaches  $44 \pm 21\%$ , with a maximum of 79% for Toro 2 glacieret and a minimum of 9% for Ortigas 1 glacier. The loss is much larger for the glacierets ( $54 \pm 16\%$ ), than for the glaciers ( $19 \pm 9\%$ ).

The aerial photographs and satellite images used allow analysis of 3 periods of evolution: 1955/56–1978 (23/22 years), 1978–1996 (18 years), and 1996–2007 (11 years). Other aerial photographs exist, e.g. 1981, but they were taken in spring when snow cover precludes the identification of glacier outlines. Figure 6 shows the annual surface-area loss for each period, expressed as a function of the 1955/56 surface. The first period shows a mean annual surface-area loss for all the ice-bodies of  $1.09 \pm 0.73\% \text{ a}^{-1}$  ( $1.37 \pm 0.63\% \text{ a}^{-1}$  for the 14 glacierets and  $0.27 \pm 0.22\% \text{ a}^{-1}$  for the 6 glaciers). Over the second period, mean annual surface-area loss falls to  $0.47 \pm 0.46\% \text{ a}^{-1}$  ( $0.56 \pm 0.49\% \text{ a}^{-1}$  for the 14 glacierets and  $0.18 \pm 0.14\% \text{ a}^{-1}$  for the 6 glaciers). During the last period, mean annual surface-area loss for all the

2318

ice-bodies increases to over twice the rate of the first period, at  $2.34 \pm 1.32\% \text{ a}^{-1}$  ( $2.74 \pm 1.20\% \text{ a}^{-1}$  for the 14 glacierets and  $0.96 \pm 0.61\% \text{ a}^{-1}$  for the 6 glaciers).

Glacierets consistently experienced a greater percentage surface-area loss over all the periods than glaciers. In addition, the scatter between individual glaciers is more pronounced with increasing mean surface-area loss (Fig. 6), suggesting that topographic factors also influence the surface-area changes.

### 4.3 Possible causes of glacier evolution since 1955

Figure 7 presents the mean surface-area loss of all the studied ice-bodies in parallel with glaciological, climatological data series and PDO variations. The PDO is a pattern of Pacific climate variability that shifts phase at a multi-decadal time scale (20 to 30 years). The PDO is detected as positive/warm or negative/cool phases (red/blue boxes on Fig. 7). The most recent regime shifts occurred in 1946 (change to negative phase), 1977 (change to positive phase), and 1998 (change to negative phase). The last shift although commonly accepted is still debated in the climate community mainly because if the lack of perspective on the data sets and because it does not appear to be as strong as the previous changes.

According to Escobar and Aceituno (1998) and Quintana and Aceituno (2010), precipitation in the Chilean subtropical zone is linked to PDO phase. A positive PDO phase is associated with frequent and intense El Niño events, which are in their turn associated with high precipitation amounts, whereas a negative phase is associated with numerous La Niña events and so with precipitation deficits. Quintana and Aceituno (2010) showed that during the 1950s, 1960s and 1970s, the frequency of humid years was abnormally low, but this changed into abnormally high frequency of humid years during the 1980s and the early 1990s, becoming low again during the late 1990s and early 2000s.

In Fig. 7, we present the cumulative annual mass-balances of Echaurren Glacier between 1975 and 2009 and the PDO data between 1955 and 2009. These data reveal

2319

an overall agreement between the PDO and mass-balance variations. Actually, this link reflects the relationship between the annual mass-balance at Echaurren Glacier and precipitation (Escobar et al., 2000). Although the period considered is short, annual mass-balance series from Echaurren and Guanaco glaciers are significantly correlated ( $r^2 = 0.75$ ,  $\rho < 0.01$ ). Note that this correlation analysis includes a highly positive annual mass-balance for the year 2002–2003 estimated on Pascua-Lama ice-bodies from GPR profile differencing (e.g.  $B_a = 1.2 \text{ m w.e.}$  on Guanaco Glacier with an uncertainty of 15%, J. Schmok, personal communication, 2008). Despite the lower accuracy of this method to determine annual mass-balance in comparison with the glaciological method, this estimated positive annual mass-balance value on Guanaco Glacier is in good agreement with the highly positive annual mass-balance measured using the glaciological method for the same year on Echaurren Glacier:  $B_a = 2.06 \text{ m w.e.}$

On a longer time scale, surface-area changes of the small Pascua-Lama ice-bodies show close agreement with the cumulative annual mass-balance record of the larger Echaurren Glacier, located 450 km further South. The cumulative mass-balance of Echaurren Glacier was quasi-stable between 1975 and 1993, in agreement with the low rate of surface-area loss recorded on the Pascua-Lama ice-bodies and the positive phase of the PDO index. Since the late 1990s, Echaurren Glacier has shown generally negative mass-balance values associated with a negative PDO phase and in agreement with more pronounced glacier surface-area loss in the Pascua-Lama region as well as negative measured annual mass-balances during recent years (Sect. 4.1). It is thus not surprising that the surface-area retreat appears to be related to the PDO. Indeed, although limits of the periods considered for the glacier surface-area changes (imposed by the available aerial photos and satellite images) do not strictly match the PDO shifts, a first qualitative insight reveals good consistency between the rate of glacier surface-area change and PDO regime. The first and third periods, characterized by greater surface-area loss, correspond to a negative phase of the PDO, while the second period, associated with lower rate of surface-area change, corresponds to a positive phase of the PDO. Note that the recent negative phase since 1998 is not so

2320



strong as the 1955–1976 negative phase, showing for example a pronounced peak in precipitation during the hydrological year 2002–2003.

Since precipitation is driven by the PDO and represents a key factor at Echaurren Glacier (Escobar et al., 2000), we analysed precipitation variability in the study area. Figure 7 shows precipitation anomalies at two high elevation sites located close to the Pascua-Lama region (El Indio Mine; 3870 m a.s.l.; about 50 km south; and La Laguna; 3130 m a.s.l.; about 100 km south). Although longer time-series would be advantageous for this analysis, during the positive PDO phase (1977–1998), both series contain several years with positive precipitation anomalies sometimes in excess of 2 standard deviations. Mass-balance time series at Pascua-Lama are too short for statistical comparison with precipitation records. However, despite the large distance between both sites, Echaurren Glacier mass-balance is significantly correlated with La Laguna precipitation series ( $r^2 = 0.62$ ,  $\rho < 0.01$ ) and El Indio precipitation series ( $r^2 = 0.44$ ,  $\rho < 0.01$ ). These findings strengthen our hypothesis of a link between Pascua-Lama ice-bodies changes and precipitation over recent decades.

In contrast, no link between glacier surface-area loss and temperature evolution over the last 50 years emerges. Figure 7 shows the summer (November to March) temperature anomaly at the 500 mb pressure level (approximately the elevation of the ice-bodies) for the Pascua-Lama region computed from NCEP/NCAR reanalysis data. Both summer and annual averages of NCEP/NCAR 500 mb temperature reanalysis data present a slight, but not statistically significant, positive trend ( $+0.19^\circ\text{C}/\text{decade}$  for summer temperature over the 1958–2007 period). Although the last decade shows the strongest mean annual surface-area loss for all the studied ice-bodies and more consistently positive temperature anomalies, we observed that the highest summer temperature anomalies (2003 and 2006) are associated with the positive annual mass-balances observed on Pascua-Lama ice-bodies. Despite the lack of summer mass-balance data for the year 2002–2003, the summer mass-balance values measured for 2005–2006 suggest that ablation was reduced on the 4 ice-bodies. This is probably related to the fact that, as mentioned above, Pascua-Lama ice-bodies are found at an

2321

altitude above the  $-2^\circ\text{C}$  annual isotherm and so melting remains limited and hence, glacier surface-area loss does not seem to be closely related to temperature evolution over the last 50 years. However, if the trend of rising summer temperatures is confirmed in the next decades, the increase in melting at glacier surface could increase the mass loss and consequently the rate of glacier retreat in this region.

All these considerations support the hypothesis that, in this region of the Andes, glacier surface-area changes over recent decades were mainly driven by the observed decreasing trend in precipitation (Santibañez, 1997; CONAMA, 2007), rather than temperature changes.

## 5 Conclusions

Results from a new glacier mass-balance monitoring program and the reconstruction of glacier surface-area changes since the mid-20th century on glaciers and glacierets in the sub-tropical Andes of Chile ( $29^\circ\text{S}$ ) have been presented in this study. This monitoring allows us to improve our knowledge and understanding of the behaviour of glaciers under semi-arid, high-elevation conditions.

- Under such climatological and geographical conditions, where air temperature remains negative year-round due to the high elevation, glacier annual mass-balance is more strongly linked to variability in precipitation than air temperature.
- The average glacier surface-area recession for the 20 studied ice-bodies in the region over the 1955–2007 period was  $44 \pm 21\%$  of the 1955 area. After the first period, 1955–1978, annual equivalent glacier surface-area recession rate slowed down between 1978 and 1996, and has accelerated since the late 1990s to reach a rate as high as experienced during the 1955–1978 period.
- The mass-balance record of Echaurren Glacier shows notable similarities to mass-balance and surface-area changes at Pascua-Lama despite the fact that the ice-bodies are 450 km apart.

2322



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2325

**Table 1.** Geographical and topographical characteristics of the monitored glaciers in the Pascua-Lama region (in 2007).

	Glaciarete Toro 1	Glaciarete Toro 2	Glaciarete Esperanza	Glaciar Guanaco	Glaciar Estrecho	Glaciar Ortigas 1	Glaciarete Ortigas 2
Location (UTM19S, WGS 84)	6 754 775 N 401 085 E	6 755 055 N 400 530 E	6 755 010 N 399 340 E	6 753 070 N 401 495 E	6 758 580 N 401 600 E	6 748 600 N 397 800 E	6 748 000 N 398 900 E
Surface area (km <sup>2</sup> )	0.071	0.066	0.041	1.836	1.303	0.874	0.071
Max. elevation (m a.s.l.)	5235	5200	5145	5350	5485	5225	5245
Min. elevation (m a.s.l.)	5080	5025	4965	4985	5030	4775	4975
Max thickness (m) <sup>a</sup>	20	12	36	120	–	–	–
Aspect	SSW	SSW	S	SSE	SE	SW	S
Number of ablation stakes <sup>b</sup>	(5) 9	(5) 5	4	(5) 14	(7) 14	(4) 9	1
First year of mass- balance survey	2003	2003	2003	2003	2005	2005	2007

<sup>a</sup> 2004

– means no data are available

<sup>b</sup> In brackets = sites measured by Golder Associates S.A. (2003–2005), the other numbers represent the number of stakes measured by CEAZA.

2326

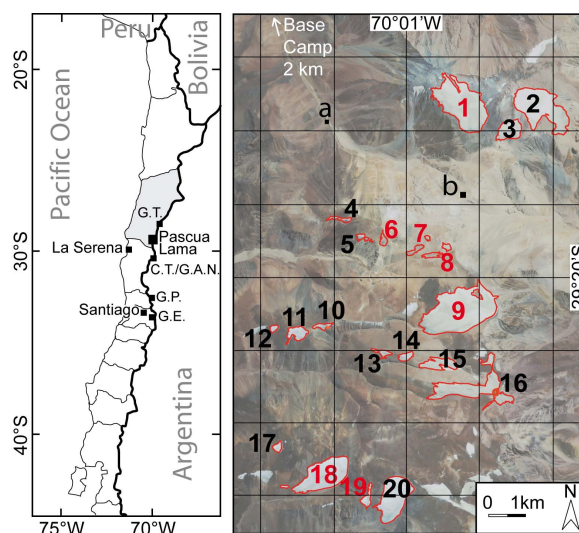


**Table 4.** Surface-area of 20 glaciers in the Pascua-Lama region and their change since the mid-20th century. Numbers of the first column refer to Fig. 1. The GLIMS Id for each glacier has been generated using the GlimsView software available on [www.glims.org](http://www.glims.org). Underlined values correspond to 1956.

N°	GLIMS Id.	Local Name	Glacier surface area in 2007 (km <sup>2</sup> )	Loss between 1955/56 and 2007
1	G289986E29298S	Estrecho	1.303 ± 0.030	-26 ± 6%
2	G290006E29297S	Los Amarillos	1.077 ± 0.024	-33 ± 5%
3	G289999E29303S	Amarillo	0.286 ± 0.011	-34 ± 8%
4	G289953E29325S		0.049 ± 0.007	-64 ± 9%
5	G289957E29329S		0.038 ± 0.006	-60 ± 12%
6	G289963E29330S	Esperanza	0.041 ± 0.005	-78 ± 5%
7	G289976E29330S	Toro 2	0.066 ± 0.007	-79 ± 4%
8	G289981E29332S	Toro 1	0.071 ± 0.010	-72 ± 6%
9	G289985E29348S	Guanaco	1.836 ± 0.027	-15 ± 4%
10	G289932E29352S		0.053 ± 0.006	-48 ± 11%
11	G289939E29352S		0.140 ± 0.006	-48 ± 8%
12	G289946E29351S		0.030 ± 0.003	-53 ± 9%
13	G289963E29358S		0.048 ± 0.006	-63 ± 10%
14	G289969E29359S		0.071 ± 0.005	-42 ± 12%
15	G289980E29360S		0.205 ± 0.013	-33 ± 8% <sup>a</sup>
16	G289986E29367S	Cañitos	0.810 ± 0.040	-22 ± 9% <sup>a</sup>
17	G289933E29381S		0.048 ± 0.005	-30 ± 15%
18	G289948E29387S	Ortigas 1	0.873 ± 0.020	-9 ± 5%
19	G289957E29394S	Ortigas 2	0.071 ± 0.010	-57 ± 9%
20	G289966E29393S		0.757 ± 0.017	-9 ± 3%

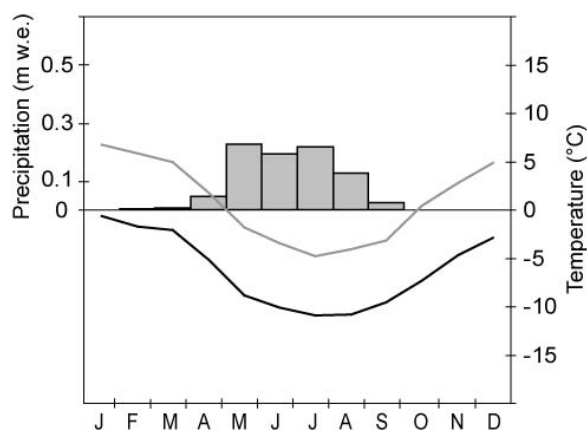
<sup>a</sup> = loss between 1978 and 2007

2329



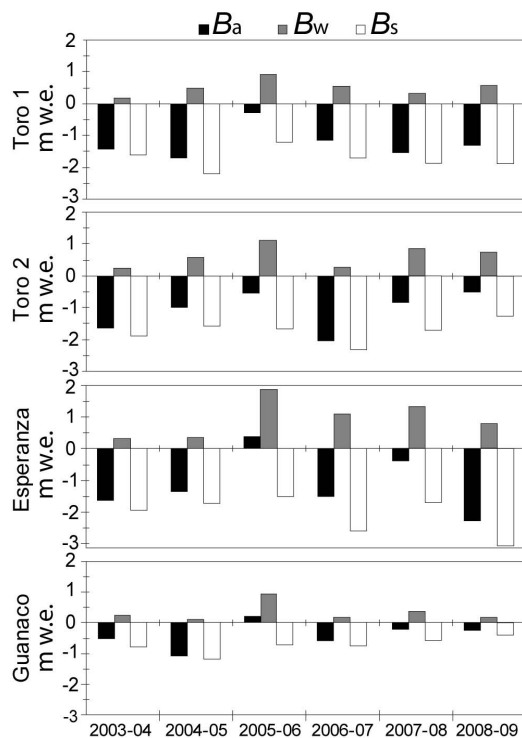
**Fig. 1.** Location of the Pascua-Lama region in the administrative *Región de Atacama* (in grey on the left map). On the left, the central and northern parts of Chile (G.T. = Glaciar Tronquitos, C.T. = Cerro Tapado, G.A.N. = Glaciar Agua Negra, G.P. = Glaciar Piloto, G.E. = Glaciar Echaurren). On the right, glaciers studied by CEAZA in the Pascua-Lama region are numbered in red: 1 = Estrecho, 6 = Esperanza, 7 = Toro 2, 8 = Toro 1, 9 = Guanaco, 18 = Ortigas 1, and 19 = Ortigas 2. For all the numbered glaciers, surface-area evolution since the mid-20th century has been reconstructed (refer to Table 4). Black squares indicate “La Olla” (a) and “Frontera” (b) weather stations. Some glaciers of the area were not considered as they were not covered by the aerial photographs (for example north from glacier 2, east from glacier 20 or west from glacier 18).

2330



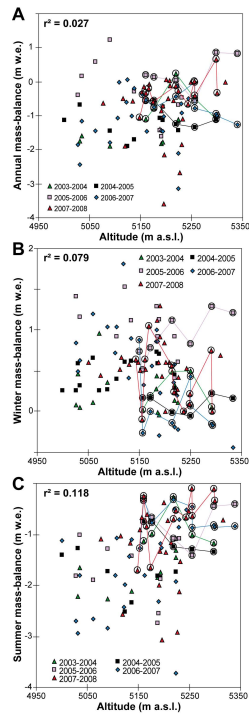
**Fig. 2.** Mean annual cycle (2001–2009) of monthly average precipitation (grey bars) and of monthly average temperature (lines) recorded in the Pascua-Lama area. Precipitation comes from manual measurements at Pascua-Lama Mine base camp (~3800 m a.s.l.). Temperatures are recorded at “La Olla” (grey line; “a” on Fig. 1; 3975 m a.s.l.) and “Frontera” weather stations (black line; “b” on Fig. 1; 4927 m a.s.l.).

2331



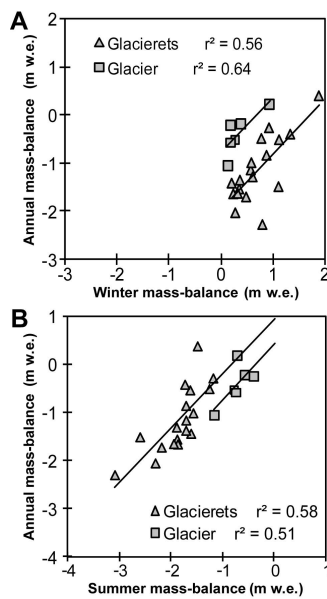
**Fig. 3.** Annual mass-balance ( $B_a$ ), winter mass-balance ( $B_w$ ) and summer mass-balance ( $B_s$ ) over the 2003–2009 period on Toro 1, Toro 2, Esperanza and Guanaco (in m w.e.).

2332



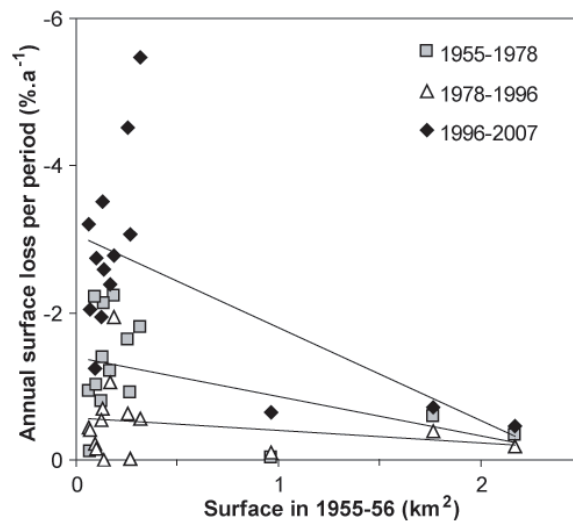
**Fig. 4.** (a) Comparison of annual mass-balance measurements with altitude on Toro 1, Toro 2, Esperanza and Guanaco ice-bodies over the 2003–2008 period. (b) Same comparison but with winter mass-balance measurements. (c) Same comparison but with summer mass-balance measurements. Lines and circles highlight measurements made on Guanaco Glacier for each year.  $r^2$  values shown are for the linear best fit of stakes measured on all 4 ice bodies.

2333



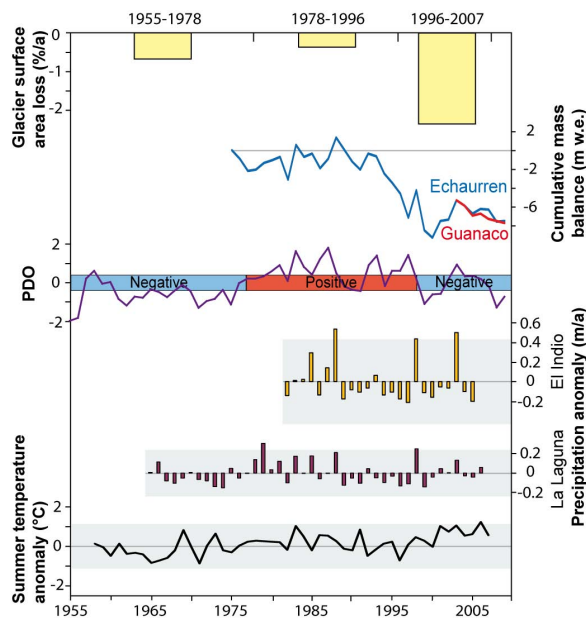
**Fig. 5.** (a) Comparison of annual mass-balances and winter mass-balances computed on Toro 1, Toro 2, Esperanza glacierets and Guanaco Glacier between 2003 and 2009. (b) Same comparison with summer mass-balances.

2334



**Fig. 6.** Annual surface-area loss per period for 6 glaciers and 14 glacierets of the Pascua-Lama region in percent of their 1955–1956 surface-area. Error-bars are not shown for legibility of the graph; lines plotted are linear best fits for each period.

2335



**Fig. 7.** Glacier surface-area loss (average per period of all the studied ice-bodies) compared with: (1) Echaurren (blue line) and Guanaco (red line) glaciers cumulated annual mass-balance; (2) annual variation of the PDO (violet line) and its negative/positive phases (blue/red boxes); (3) precipitation anomaly recorded at El Indio Mine and La Laguna dam; and (4) summer temperature anomaly of NCEP/NCAR 500 mb temperature reanalysis data. Grey boxes for precipitation and temperature anomalies data represent the  $\pm 2$  standard deviations interval.

2336