Recent glacier mass balance calculations at Volcán Mocho-Choshuenco (40ºS), Chilean Lake District

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Abstract The majority of glaciers in the Chilean Lake District (38º–42ºS) have experienced shrinking and ice thinning during recent decades, presumably in response to climatic changes as observed at nearby meteorological stations. One of these glaciers is the southeastern basin of Volcán Mocho-Choshuenco (39°55′S, 72°02′W), a dormant volcano which has not experienced fumarolic activity since 1864. In order to analyse the glacier response to climatic conditions affecting this region, a monthly based mass balance programme was initiated in 2003. This paper presents new results and discusses the mass balance method applied during recent years. The 2004/2005 glacier average net mass balance yielded +0.36 ± 0.07 m w.e. year^{-1} (metres of water equivalent per year) with a winter balance of +4.04 m w.e. year^{-1} and a summer balance of –3.73 m w.e. year^{-1}. This positive mass balance is analysed in comparison to El Niño Southern Oscillation (ENSO) phenomena observed during recent years, as well as previous mass balance results.

Key words Chilean Lake District; climate changes; glacier mass balance; ice-capped volcanoes; precipitation

INTRODUCTION

The great majority of glaciers in the Chilean Lake District (Fig. 1(a)) are located on active volcanic cones (Rivera *et al.*, 2000), most of them showing retreating frontal tongues and ice thinning (Rivera *et al.*, 2002). Volcanic activity has been considered an important factor affecting glacier behaviour, especially when geothermal activity is enhancing ice melting at the bedrock (Björnsson, 1998). Glaciers are also considered an important factor when risk assessments are carried out on ice-capped active volcanoes, especially because of lahar generation during eruptive processes (Naranjo & Moreno, 2004). As a result of these glacier–volcano interactions, some glaciers might have experienced strong retreats due to volcanic activity (Casassa *et al.*, 2004), while other glaciers have been protected by thick ash-debris layer deposits which are insulating the ice from direct solar radiation (Rivera *et al.*, 2005).

This paper presents the mass balance results obtained for the 2004/2005 period at Volcán Mocho-Choshuenco (39°55′S, 72°02′W, Fig. 1), an active volcano during the Holocene but inactive in historical times since 1864 (González-Ferrán, 1995; Rodríguez *et al.*, 1999), having an important glacier over its depression or "caldera" (Echegaray, 2005).

This is the second year of mass balance data at the southeastern glacier since a monthly based monitoring programme was initiated in 2003. This glacier was selected
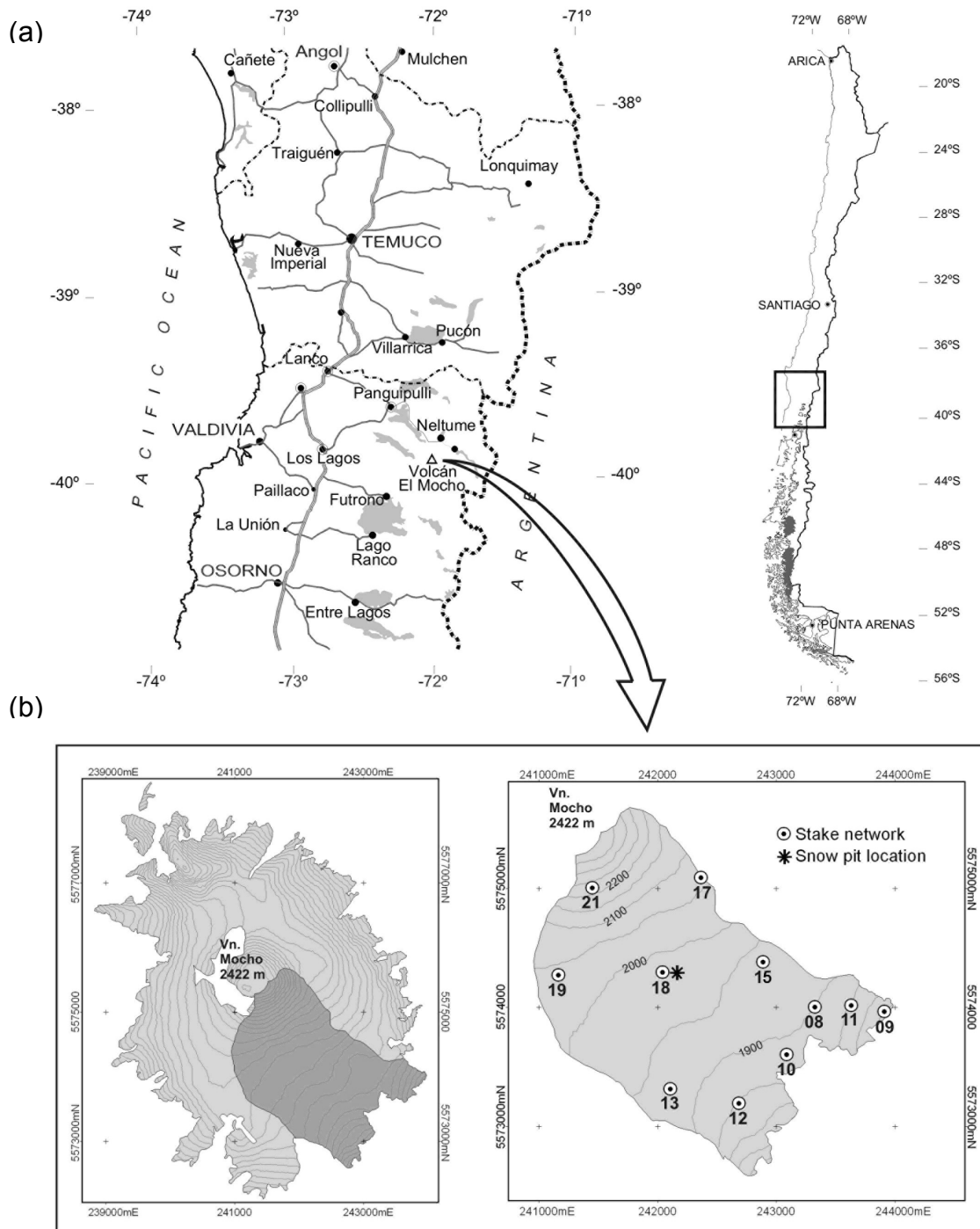
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Fig. 1 Map of the Chilean Lake District showing the location of Volcán Mocho-Choshuenco (a). On (b), the ice limits of the whole volcano and the southeastern glacier are based on SRTM and geodetic GPS data (left). The stake network for mass balance measurements and snow pit location are shown on the right-hand side. Contour lines are expressed in m a.s.l. and coordinates in UTM-WGS 1984 system for all figures.

because of its accessibility and logistic facilities, being considered representative of glaciers located over volcanoes without present activity (Rivera *et al.*, 2005). The "glaciological" method was employed to account for the annual net glacier mass

balance, where a relatively dense stake-network was installed on the glacier and snow pits are periodically dug for measuring snow densities and surface snow structures.

Weather seasonality and maritime environment have been considered important factors when studying glacier mass balance (Holmlund & Schneider, 1997). Precipitation throughout the year in this part of the country varies according to the changing frequency of wind circulation and frontal systems from the Pacific Ocean. Thus, the annual as well as seasonal mass balances are estimated and compared with year to year fluctuations of precipitation and temperature, in order to discuss possible relationships between climatic trends and glacier responses.

METHODS

Glacier site and mass balance data collection

Glacier ice basins at Volcán Mocho-Choshuenco have been determined based upon SRTM data (Shuttle Radar Topography Mission) of 2000 and several geodetic quality GPS surveys carried out since 2003. The main glacier of the volcano was located in the southeastern flank of the cone, with a total area of 5.1 km^2 (Rivera *et al.,* 2005). However, due to deformations still remaining on steeper slopes of the volcanic cone, new resampling procedures were carried out recently with to date available data, allowing a more accurate determination of glacier area as 4.8 km^2 (Rivera *et al.,* 2006) (Fig. 1(b)).

Mass balance data have been collected almost continuously since the programme was initiated by Centro de Estudios Científicos in early 2003. A Chilean bamboo (coligüe) stake network was installed from the summit at 2422 m to 1750 m a.s.l., covering representative sectors of the glacier. Frequently many stakes located on steep flanks and at high altitude were missing due to strong westerly winds, or were buried beneath the surface because of avalanches and high snowfall affecting the volcano especially during the early ablation season. At lower sites, some coligües were complemented with 10 m-PVC (plastic) stakes drilled into the ice using a steam drill (Heucke, 1999). Some of these stakes drilled into the ice were totally covered by snow during the winter, but they emerged on the surface of the glacier during the summer season, allowing an annual estimation of ablation at each site. A total of 11 stakes were finally used for the analysis (Fig. 1(b)), where snow heights were measured on a monthly basis. Some missing snow-height values were derived by means of simple linear regression (>75% variance) between existing stakes.

In order to convert height differences (m) between successive dates into gains or losses of mass units, snow densities were measured throughout the year, mainly at a snow pit dug around stake #18 (Fig. 1(b)). Volume and weight of snow samples, as well as temperature and stratigraphic data were registered every 10 cm down to 100–120 cm depth using a 500 cm^3 metal device and a digital balance. Additionally, in late winter surface density measurements (upper 140-cm layer) were carried out with a "Mount Rose" sampling tube (Model 3600 "Federal") in every stake, including #18 (Fig. 1(b)). The inaccuracies of the snow pit data, when compared with Mount Rose densities at stake #18 at similar dates and depths were estimated to be 10%. Snow pit measurements were then used to calibrate density values per site/per date based on the resulting ratio of stake #18 and the snow pit data (Table 1).

Table 1 Surface snow/firn density (%) in September 2004 obtained with the "Mount Rose" sampling tube at several stakes and calculated density ratio with respect to stake #18.

Stake	Altitude (m a.s.l.)	Density (%)	Density ratio (density of stake/density of stake #18)
8	1917	45.0	1.02
9	1723	45.0	1.02
10	1908	45.0	1.02
11	1846	45.0	1.02
12	1853	54.5	1.24
13	1947	53.2	1.21
15	1947	50.0	1.14
17	2074	44.4	1.01
18	2013	44.0	1.0
19	2050	53.7	1.22
21	2169	47.3	1.08

Calculation of average glacier net mass balance

The hydrological year in this region of the country spans between the beginning of May and the end of the following April (Rivera *et al.*, 2005). The "combined" net mass balance ($B_{n\ Combined}$) (Østrem & Brugman, 1991) for hydrological year 2004/2005, was calculated by the algebraic sum of the total annual accumulation (B_c) and ablation (B_a) considering the glacier as a whole. Due to the strong weather seasonality observed in this part of the country, the mass balance was separated into two main periods, i.e. the net winter and summer balances, B_w and B_s, respectively. The winter period was established when most of the accumulation takes place (May–October), with October marking the threshold between positive and negative height measurements, and the summer period being defined to take place between November and April, characterised by strong ablation and negligible accumulation.

According to Paterson (1994), the mass gain or loss of a glacier is an equivalent volume of water (w.e.) per area relative to the previous summer surface. Thus, the glacier average mass balance components mentioned above, e.g. net balance ($\overline{b_{n\ Combined}}$), net accumulation ($\overline{b_c}$), net ablation ($\overline{b_a}$), net winter balance ($\overline{b_w}$) and net summer balance ($\overline{b_s}$) are computed by dividing annual values of the whole glacier by the total area (A).

In order to obtain mass balance components (accumulation and ablation) for the glacier as a whole from discrete annual accumulated values obtained at each stake, several interpolation methods were applied, such as the Inverse Distance Weight (IDW), Triangular Irregular Network (TIN), Kriging and Bi-Cubic Spline. All these methods were based upon SRTM data for 2000 at 90-m resolution. The best interpolation method was determined using a "jack-knifing" procedure (Lythe *et al.*, 2001), yielding 15% inaccuracies on average when the TIN method was used.

RESULTS

In Table 1 density results obtained in September 2004 (spring time) are shown by using the "Mount Rose" device at 11 stakes. In all cases density values at stakes were

larger than the density at stake #18 and therefore, show ratios >1.0. Stakes located at lower altitude show generally higher density values, especially on the ablation season where ice density is expected (~90%), whilst upper sites show smaller but more homogeneous density ratio data throughout the year.

Accumulation obtained at stakes ranged from 3.0 to a maximum of 5.4 m w.e. year^{-1} (Table 2). The stakes were spatially distributed generally following a west–east trend, with maximum values near the western edge of the glacier at higher elevations (Fig. 2(a). At the steep summit cone (#21) accumulation decreases due to frequent snow avalanches. Minimum accumulation was detected on the lowermost northeastern side of the glacier.

Table 2 Mass balance components measured at the 11 stakes used for this study.

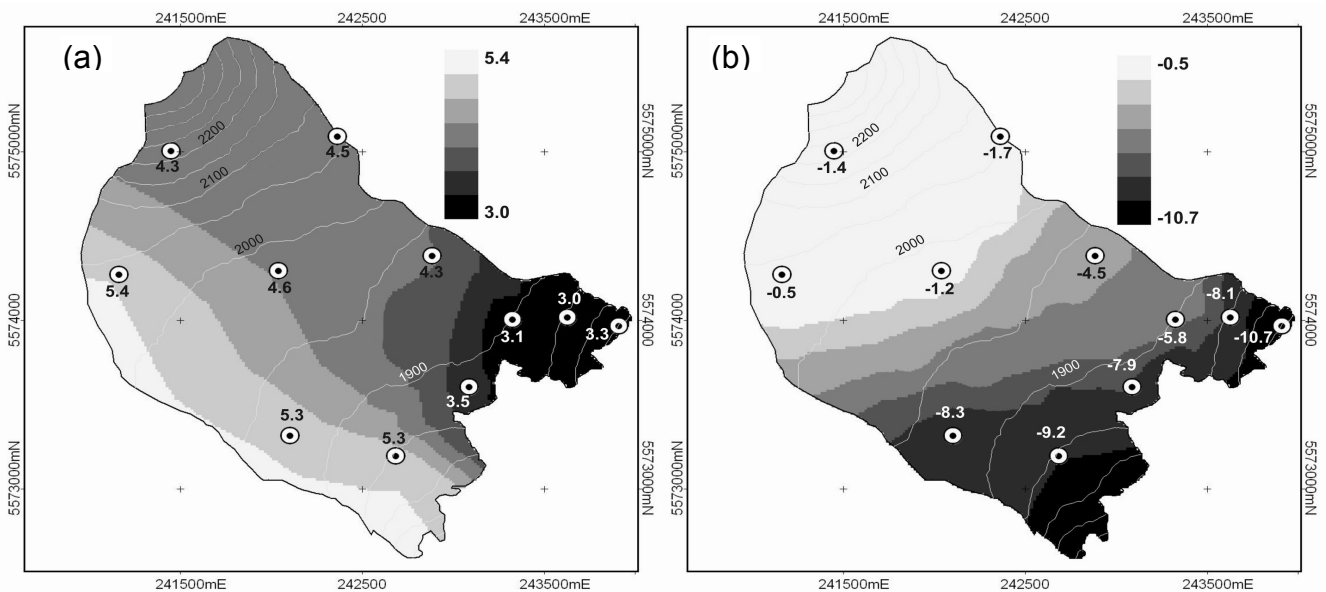| Stake	Altitude (m a.s.l.)	Accumulation (m w.e. year^{-1})	Ablation (m w.e. year^{-1})	Net winter balance (m w.e. year^{-1})	Net summer balance (m w.e. year^{-1})	Net balance (m w.e. year^{-1})
8	1917	3.1	−5.8	3.0	−5.7	−2.7
9	1723	3.3	−10.7	2.7	−10.1	−7.4
10	1908	3.5	−7.9	3.3	−7.7	−4.4
11	1846	3.0	−8.1	2.7	−7.8	−5.1
12	1853	5.3	−9.2	5.1	−9.0	−3.9
13	1947	5.3	−8.3	4.7	−7.7	−3.0
15	1947	4.3	−4.5	4.0	−4.2	−0.2
17	2074	4.5	−1.7	3.9	−1.1	2.8
18	2013	4.6	−1.2	3.9	−0.5	3.4
19	2050	5.4	−0.5	4.5	0.4	4.9
21	2169	4.3	−1.4	4.1	−1.2	2.9

Fig. 2 Annual net accumulation (a) and ablation (b) in m w.e. year^{-1}. Individual values represent observations at each stake for all figures.

As expected, ablation measurements show a strong dependency on altitude, with the extreme negative value at lowermost stake #9 (–10.7 m w.e. year⁻¹) decreasing upstream up to a minimum of –0.5 m w.e. year⁻¹ at stake #19 (Table 2). On steep flanks, some mass losses are enhanced by avalanches (Fig. 2(b)).

Seasonal mass balance components calculated per each stake are shown in Table 2. The winter balance showed a similar distribution to the annual accumulation, i.e. higher positive values at the southern side (>5 m w.e. year⁻¹) and progressive decrease towards the glacier front to the northeast (Fig. 3(a)). The summer balance showed negative values for almost the whole glacier area ranging from nearly "zero" m w.e. year⁻¹ up to –10 m w.e. year⁻¹, except by the surroundings of stake #19 where there are small positive accumulations (Fig. 3(b)).
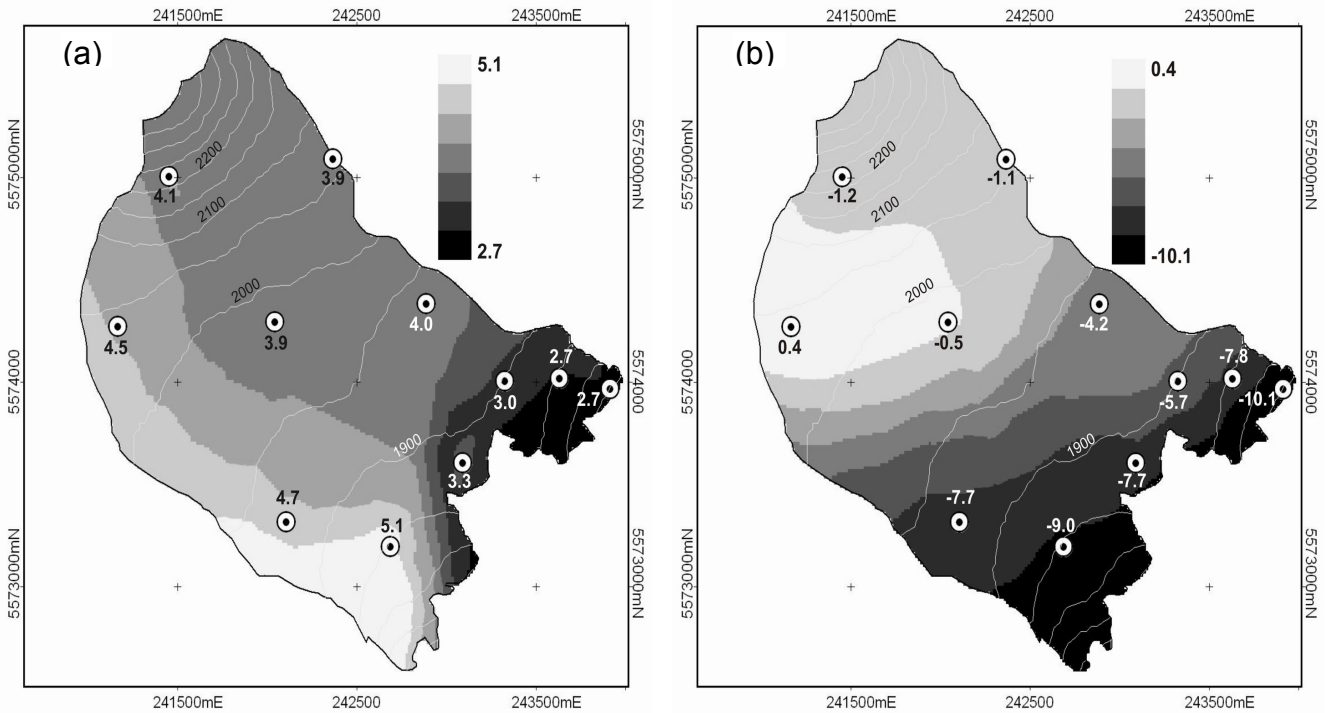

Fig. 3 Annual net winter (a) and summer (b) balance in m w.e. year⁻¹.

An average net mass balance of +0.36 ± 0.07 m w.e. year⁻¹ was obtained at Volcán Mocho-Choshuenco in 2004–2005, with net accumulation and ablation of +4.48 and –4.12 m w.e. year⁻¹, respectively. The 20% uncertainty assigned to the net mass balance was calculated based upon the Root Mean Square (RMS) of independent errors, e.g. the snow-pit density measurements (10%) (Harper & Bradford, 2003), the stake-height field measurements (5%) and the selected interpolation method (15%). If the algebraic sum of seasonal balances is taken into account, a net mass balance of +0.31 ± 0.06 m w.e. year⁻¹ is obtained, which is statistically equal to the net mass balance obtained by subtracting accumulation and ablation.

The Equilibrium Line Altitude (ELA) was estimated at 1961 ± 11 m a.s.l. defining an Accumulation Area Ratio (AAR) of 0.56.

Comparison to previous mass balance data

The final mass balance results are shown in Fig. 4. Table 3 summarizes average glacier values compared to the same parameters measured in 2003/2004 at glacier Mocho as well as Echaurren Norte, a glacier surveyed since the 1970s in central Chile.
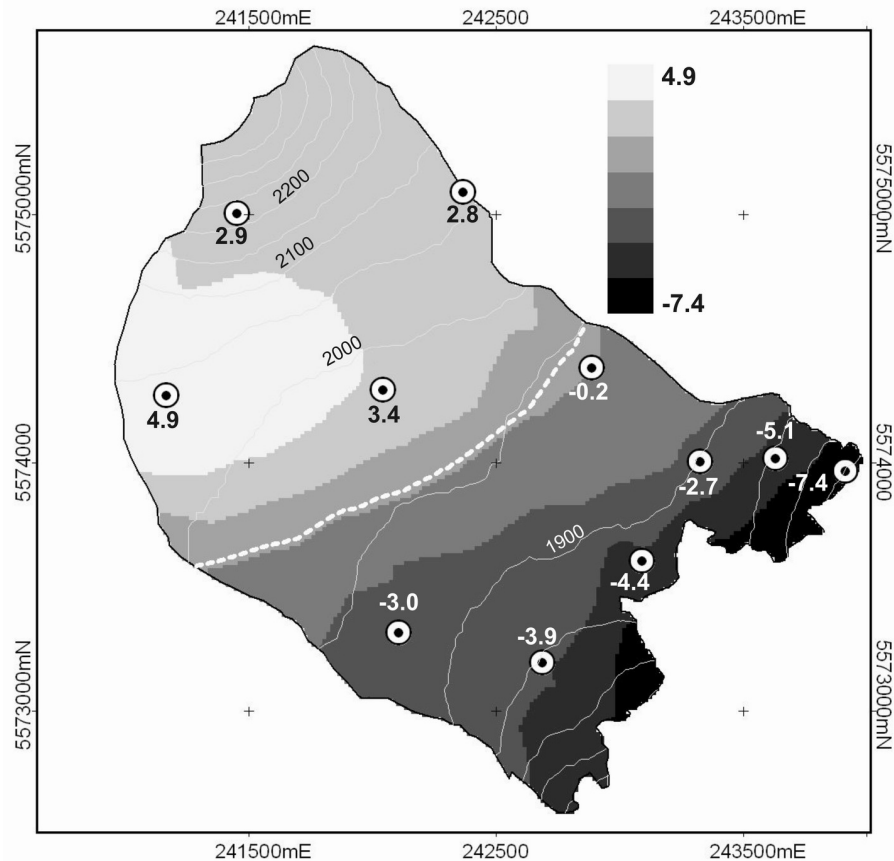

Fig. 4 Annual net mass balance in m w.e. year^{-1}. ELA location is shown as a dashed-white line.

Table 3 Average mass balance values at Glacier Mocho for the 2004/2005 period and its comparison with previous mass balance data.

Period	2003–2004		2004–2005
	Gl. Echaurren (33ºS)	Gl. Mocho (40ºS)	Gl. Mocho (40ºS)
Net accumulation (m w.e. year^{-1})	2.0	2.59	4.48
Net ablation (m w.e. year^{-1})	–2.57	–3.47	–4.12
Net winter balance (m w.e. year^{-1})	n/d	n/d	4.04
Net summer balance (m w.e. year^{-1})	n/d	n/d	–3.73
Net mass balance (m w.e. year^{-1})	–0.57	–0.88 ± 0.18	0.36 ± 0.07
ELA (m a.s.l.)	n/d	1956 ± 53	1961 ± 11
AAR	n/d	0.52	0.56
Sources	DGA, personal communication	Rivera *et al.*, 2005	This study

The most significant change experienced by the glacier between 2003/2004 and 2004/2005 was the higher accumulation rates in the latter period, which resulted in a positive annual mass balance. Higher ablation values were also detected in 2004/2005, particularly at lower altitudes, suggesting that 2004/2005 experienced a steeper mass balance gradient.

The ELA between both periods did not experience a significant change; however the AAR experienced a small increment from 0.52 to 0.56, which supports a more positive balance as measured during the last hydrological year.

DISCUSSION AND CONCLUSIONS

Long-term climate trends along the coast in southern Chile have shown a general near surface atmospheric warming, except for cooling detected in the Lake District (Rosenblüth *et al.,* 1997). However, in atmospheric levels above 850 hPa geopotential height (approximately at an altitude of 1500 m a.s.l., representing the mean elevation of glaciers in this region), temperatures exhibited a positive trend (Aceituno *et al.*, 1993; Bown & Rivera, 2007). Annual precipitation in the Chilean Lake District showed negative trends during the second half of the 20th century (Bown & Rivera, 2007), with the strongest decreases at Valdivia (–15 mm year^{-2}, 39º38′S) and Puerto Montt (–14 mm year^{-2}, 41º26′S).

These tropospheric warming and rainfall deficits, suggest negative long term glacier mass balances in the region. In spite of that, inter-annual variability could play an important role, especially in connection to El Niño Southern Oscillation (ENSO) events (Quintana, 2004).

The rainfall inter-annual variability in the Chilean Lake District has been teleconnected to the latitudinal migration of the southeastern Pacific Ocean anticyclonic cell (Montecinos & Aceituno, 2003), with reinforcement (weakness) of the southern edge of the anticyclonic cell during El Niño (La Niña) years, provoking dry (wet) summers. During recent years, however, ENSO phenomena have not shown any strong events, as illustrated by Sea Surface Temperature (SST) anomalies in El Niño region 3.4 (Trenberth, 1997) and the Southern Oscillation Index (Díaz & Markgraf, 2000). While a strong La Niña phase took place in 1999–2000, neutral and weak-to-moderate conditions have alternated thereafter, with the current period 2004–2005 being estimated as a weak El Niño year (Table 4).

Therefore these weak atmospheric–oceanic interactions are probably not the main driving factors affecting the glacier mass balance in the Chilean Lake District since 2003, and the occurrence of a negative mass balance in Glacier Mocho during 2003/2004 and a positive mass balance during 2004/2005, are probably responding to inter-annual variability of precipitation and temperature not related to ENSO. This behaviour is very distinctive when compared to the mass balance records obtained in central Chile, where the mass balance of Glacier Echaurren Norte is strongly dependent on the occurrence of ENSO events (Escobar *et al.*, 1995). For instance, during the moderate-weak El Niño year 2002/2003 the mass balance yielded +2.06 m w.e. year^{-1}, whereas in neutral ENSO year 2003/2004 the mass balance was –0.57 m w.e. year^{-1} (DGA, personal communication).

Table 4 Mean Sea Surface Temperatures (SST) in Region 3.4 and Southern Oscillation Index (SOI) standard deviations during the last 5 years*.

Year	Mean SST standard deviation Region 3.4	Mean SOI standard deviation	Classification
1999–2000	−1.08	0.70	Strong Niña
2000–2001	−0.42	0.60	Neutral
2001–2002	0.16	−0.28	Neutral
2002–2003	0.87	−0.80	Weak/moderate El Niño
2003–2004	0.29	−0.13	Neutral
2004–2005	0.61	−0.74	Weak Niño

* Monthly SST and SOI standard deviations obtained from NOAA-CIRES Climate Prediction Center and Australian Bureau of Meteorology, respectively. Annually-mean standard deviations and event classification obtained by this study.

Table 5 Annual precipitation in 2003 and 2004 at selected Chilean Lake District meteorological stations and deficit/surplus relative to the 1961–1990 climatological mean*.

Meteorological station	2003		2004	
	Precipitation (mm)	Deficit/surplus (%)	Precipitation (mm)	Deficit/surplus (%)
Temuco	917	−17	1149	4
Valdivia	1703	−6	1721	−5
Osorno	1075	−15	1290	2
Puerto Montt	1286	−24	1458	−14

* National Meteorological Office, personal communication.

The precipitation regime in the Chilean Lake District showed a clear deficit during 2003, especially significant in Puerto Montt, whilst 2004 exhibited "normal" behaviour (Table 5). No clear trends were observed regarding temperature between both years. However, the summer of 2004 was particularly dry and warm due to abnormal synoptic conditions, which were blocking frontal systems coming from the west, while the summer of 2005 was also dry, but not especially warm (National Meteorological Office, personal communication).

The above characterization of meteorological variables indicates that in the absence of strong ENSO events in the Pacific Ocean, the mass balance of Glacier Mocho is presumably more sensitive to rainfall variability and summer temperatures. Considering the synoptic circulation in this part of the country, the appearance of strong ENSO events should be reflected in opposed ways between central Chile and the Chilean Lake District, with positive (negative) mass balance in central Chile (Lake District) during El Niño years and *vice versa*.

Although measurements at the glacier located on Volcán Mocho-Choshuenco started only in 2003, the mass balance results seem to evidence climate driving factors. This suggests that volcanic activity plays a minor role on the glacier behaviour.

In spite of the above, further data are strongly needed to determine more accurate mass balance changes, as well as the relationships with climatic factors.

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