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Glacier shrinkage and negative mass balance in the Chilean Lake District (40°S)

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Abstract Ice-capped volcanoes of the Chilean Lake District have shown significant glacier retreat during recent decades, probably in response to tropospheric warming and precipitation decrease. Volcán Mocho-Choshuenco (39°55′S, 72°02′W) is one of the main active volcanoes in this part of the country. A mass balance programme was initiated on its southeastern glacier in 2003, in view of its representative conditions as an ice body that is presumably not affected by current volcanic activity. The glaciers of this volcano have been retreating and shrinking in recent decades; by 2003 there had been a reduction of 40% of the original area of 28.4 km^2 in 1976. A maximum decrease of area was observed in the most recently analysed period, a rate of 0.45 km^2 year^{-1} between 1987 and 2003. The glacier average net mass balance of 2003/04 yielded –0.88 m w.e. (water equivalent) per year (±0.18), with an average net accumulation and ablation of 2.59 and –3.47 m w.e. per year, respectively. This is the first direct measurement of glacier mass balance in southern Chile, where very little is known about glacier variations and glacier–volcano interactions.

Key words climatic changes; Chilean Lake District; glacier variations; ice-capped active volcanoes; mass balance

Rétrécissement glaciaire et bilan massique négatif dans la Région des Lacs du Chili (40°S)

Résumé Les volcans à calotte glaciaire de la Région des Lacs du Chili ont présenté un recul glaciaire significatif durant les dernières décennies, probablement en réponse au réchauffement troposphérique et à la diminution des précipitations. Le Volcan Mocho-Choshuenco (39º44ºS, 72º02ºW) est l'un des principaux volcans actifs de cette partie du pays. Un programme de bilan massique a été initié en 2003 pour ce glacier du sud-est, compte tenu de ses conditions représentatives d'un massif glaciaire qui n'est vraisemblablement pas affecté par une activité volcanique actuelle. Les glaciers de ce volcan ont présenté un recul et un rétrécissement durant les dernières décennies. En 2003, la réduction atteignait 40% par rapport à la surface initiale de 28.4 km^2 en 1976. Une diminution maximale de la surface a été observée à la fin de la période analysée, avec un taux de 0.45 km^2 an^{-1} entre 1987 et 2003. Le bilan massique glaciaire net moyen de 2003/04 atteint –0.88 m e.e. (équivalent eau) an^{-1} (±0.18), avec une accumulation et une ablation nettes moyennes respectivement de 2.59 et –3.47 m e.e. par an. Il s'agit là de la première mesure directe de bilan massique glaciaire dans le sud du Chili, où les variations glaciaires et les interactions glacier–volcan sont peu connues.

Mots clefs changements climatiques; Région des Lacs du Chili; variations glaciaires; volcans actifs recouverts de glace; bilan massique

INTRODUCTION

The great majority of glaciers of the Chilean Lake District have been retreating and shrinking during recent decades (Rivera *et al.*, 2002). These glaciers are located on active volcanic cones where frequent ash deposition and lava flows have affected them by reducing the ice areas and covering them with thick ash layers, which usually

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insulate the ice and reduce the ablation (Adhikary *et al.*, 2002). The presence of glaciers on active volcanoes represents an important issue in terms of hazards associated with glacio–volcanic interactions taking place during eruptions. Sudden melting of snow and ice due to lava or pyroclastic flows could generate large volumes of water, which flow downstream as a debris flow known as lahar (Johannesson, 2002; Cas & Wright, 1987).

In order to distinguish volcanic and climatic effects on the glacier responses, two ice-capped volcanoes located within 60 km in the Chilean Lake District were selected to initiate a research project. One of these volcanoes (Volcán Villarrica) has frequent and recent volcanic eruptions (Moreno, 1993; Clavero & Moreno, 1994), whilst the other (Volcán Mocho-Choshuenco) is an active volcano without significant recent volcanic activity (González-Ferrán, 1995).

Although ice-covered volcanoes are widespread in the Andean range, and especially in the southern Andes (González-Ferrán, 1995; Simkin & Siebert, 1994), as yet there has not been any detailed study in the Andes that has focused on the interaction of volcanic and glacial systems. In Iceland, for instance, where active volcanoes are closely related to glacial activity, it has been shown that both geological and geo-environmental systems have strong relationships (Sigmundsson, 1991; Sigvaldason, 2000; Björnsson *et al.*, 2001; Maclennan *et al.*, 2002). At a small time scale, active geothermal systems at ice-capped volcanoes can enhance icemelt, especially at the base of glaciers (Björnsson, 1998), sometimes generating catastrophic floods associated with eruptions, that are known as jökulhlaups (Matthews & Clague, 1993), and also the main type of lahars produced in southern Chile (Moreno, 1993; Naranjo & Moreno, 2004). This effect has already been observed at the Guallatiri Volcano in northern Chile, where the glacier has completely melted in two fumarolic areas in the last decades, whereas glaciers on top of other active volcanoes without superficial geothermal field have remained more stable in recent years (Clavero, 2002).

Volcán Mocho-Choshuenco (39°55′S, 72°02′W, Fig. 1) generated large explosive eruptions during the Holocene, triggering laharic flows over the ice cap. However, since 1864 it has been considered a dormant complex without eruptive activity (Rodríguez *et al.*, 1999). At present, the volcano has an important ice field over the volcanic depression or "caldera" (Echegaray, 2005). In May 2003 a mass balance programme was initiated on the southeastern glacier of this volcano because of its optimal access, logistic facilities and the well-defined ice basin. In addition to these considerations, it is estimated that this glacier is representative of regional non-volcanic glacier responses to climate changes due to the very low activity of the volcanic cone. The variation of the ice front throughout recent decades has also been determined. Thus, the lack of mass balance data from southern Chile is significantly improved in the Lake District, contributing to the knowledge of regional glacier climatic responses on ice-covered volcanoes.

The surface mass balance of a glacier is mainly controlled by the amount of solid precipitation, as well as the amount of ablation taking place on the glacier, both factors depending on temperature, precipitation, altitude, aspect, slope, albedo, wind, etc. The volcanic activity can also affect the mass balance due to changes in albedo caused by ash deposition and lava flows, which can change the amount of ablation at the surface (Shiraiwa *et al.*, 2001). In order to estimate the glacier surface mass balance, several 4-m coligüe (Chilean bamboo) and some 10-m PVC stakes have been monitored

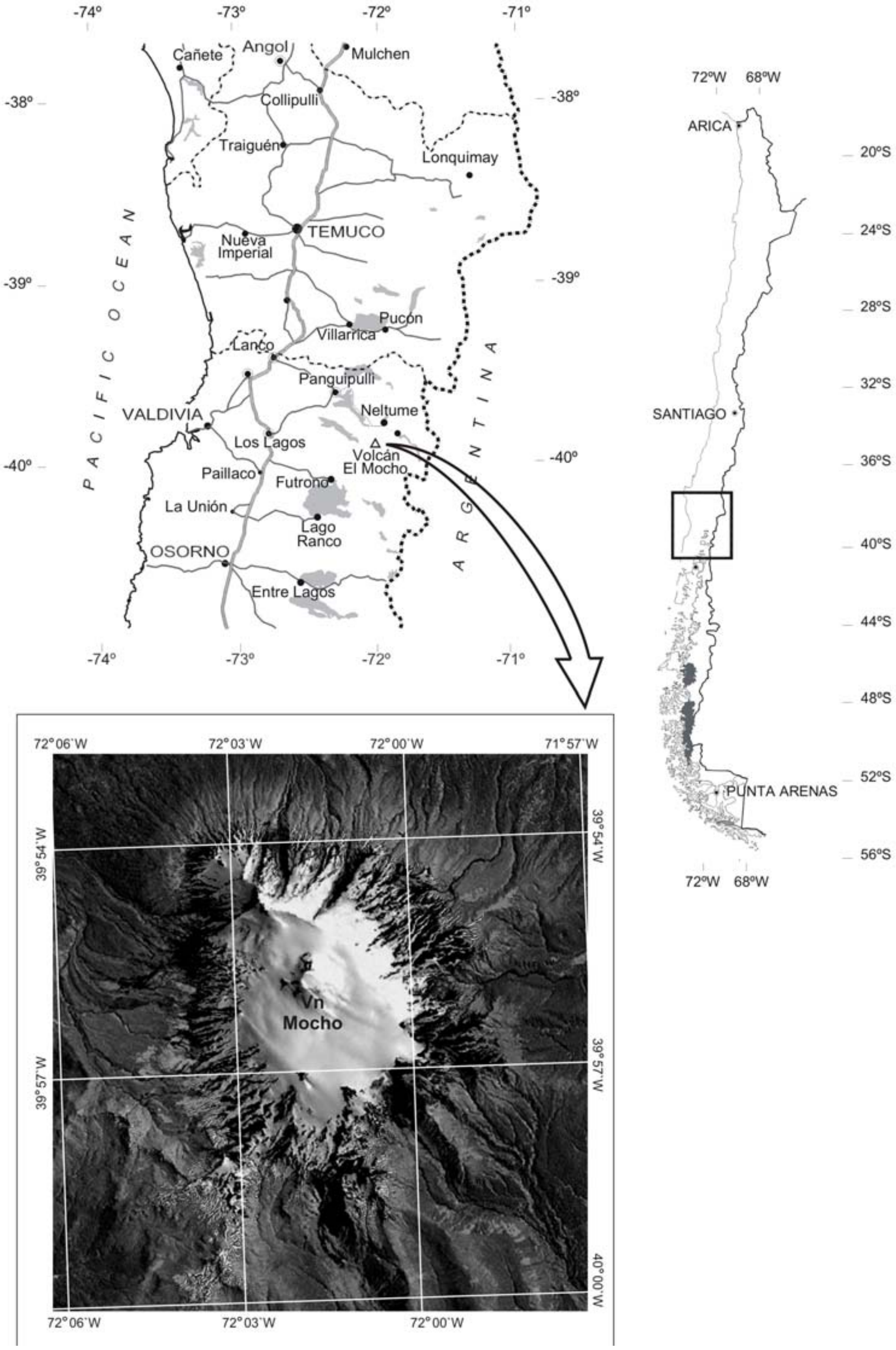

Fig. 1 Location map of the Chilean Lake District with an inset showing the 2003 ASTER image of Volcán Mocho-Choshuenco.

monthly, including snow height variations, snow densities and surface topography measurements, following the "combined" method (Østrem & Brugman, 1991). This is the first programme of this type in the Lake District of southern Chile, where very little glacier information is available, particularly on glacier–volcano interactions.

METHODS

Frontal variations

The frontal variations of the glacier were determined through digital analysis of satellite images (Table 1) which were georectified using the satellite orbital parameters, and were orthorectified using SRTM topography data. A false colour composite Landsat MSS image was generated based on bands 1, 2 and 3. The ratio between bands 4 and 5 of Landsat TM was used to distinguish snow and ice surfaces (Paul *et al.*, 2002). A false colour composite ASTER image was also generated based on bands 1, 2 and 3Nadir. Tens of tie-points were selected from visible channels, in order to connect all images yielding horizontal errors smaller than the pixel size of each image, and allowing determination of significant areal changes between dates.

Ice basin delineation and surface topography

The delineations of the main ice divides of the volcano were obtained based upon SRTM data as well as geodetic quality GPS data obtained in the field (Fig. 2). The

Table 1 Satellite images.

Sensor	Path	Row	Pixel size (m)	Date
MSS	249	88	57 × 79	1976/04/02
TM	232	88	28.5	1987/02/09
ASTER	232	88	15	2003/03/24

MSS: Landsat Multi Spectral Scanner; TM: Landsat Thematic Mapper; ASTER: Advanced Space-borne Thermal Emission and Reflection Radiometer.

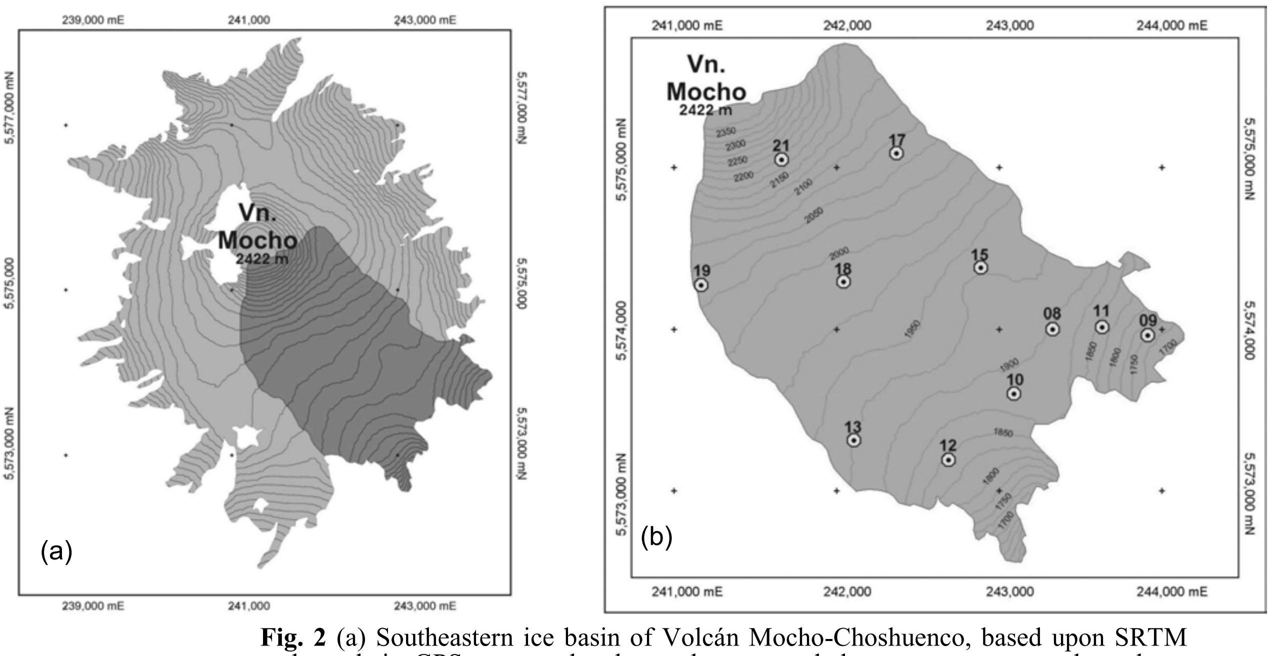

Fig. 2 (a) Southeastern ice basin of Volcán Mocho-Choshuenco, based upon SRTM and geodetic GPS topography data, where mass balance measurements have been carried out, and (b) location of the stakes used for this study. Contour lines are in m a.s.l. Universal Transversal Mercator (UTM) World Geodetic System (WGS) 1984 co-ordinates in m.

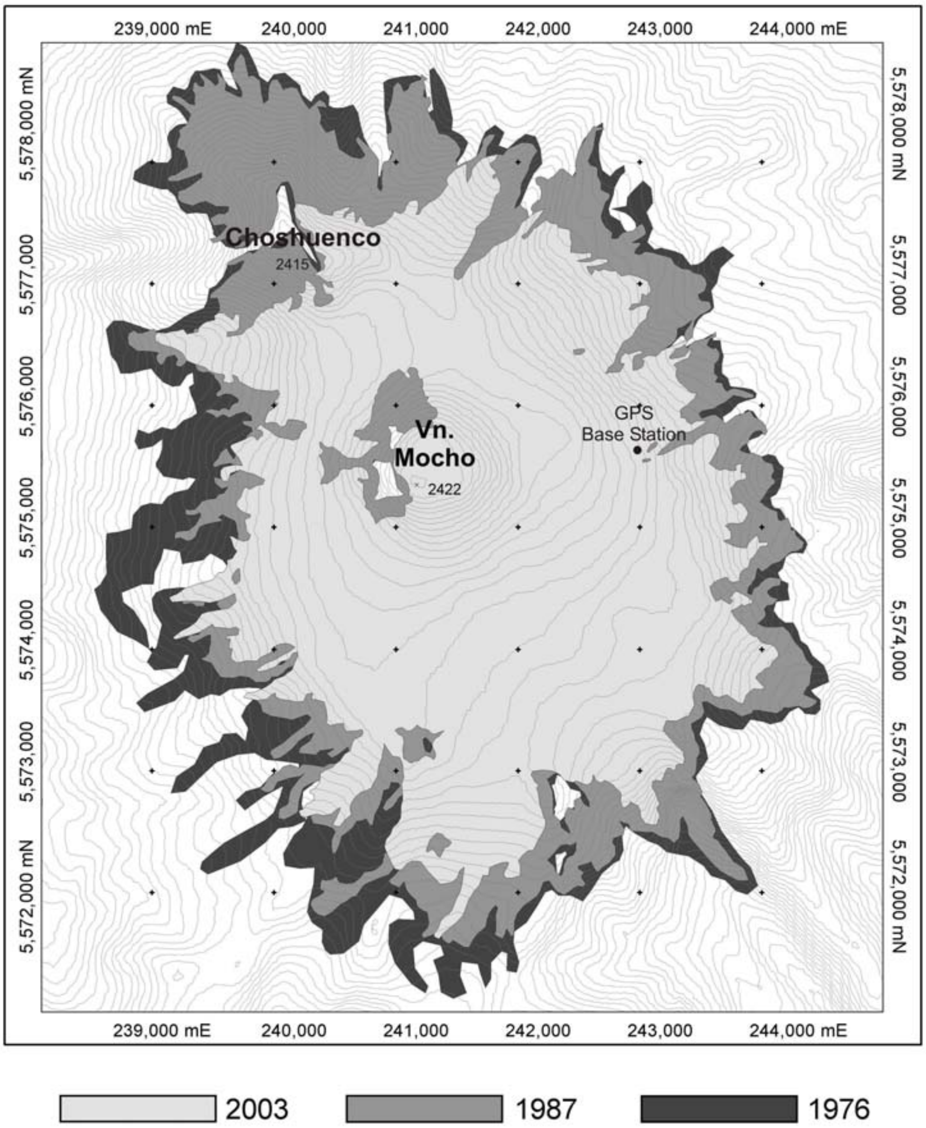

Fig. 3 Volcán Mocho-Choshuenco glacier extension in 1976, 1987 and 2003.

surface topography of the glacier was surveyed using JAVAD dual frequency GPS receivers, model Lexon-GD. Two of these receivers were used in each campaign; a base station was located on a rock outcrop (Fig. 3), where the GPS antenna was attached to a metal pin fixed to a hole drilled into the rock. The second receiver was configured in a "stop-and-go" mode, to record data whilst personnel were moving around the glacier.

Mass balance measurements

The mass balance of a non-calving glacier, such as the glaciers of Volcán Mocho-Choshuenco, can be defined as the annual algebraic sum of the total accumulation (B_c) and ablation (B_a). The "combined" net mass balance (Østrem & Brugman, 1991) at the end of the balance year, or hydrological year, defined for the Chilean Lake District as between April and May, is the net mass balance for that year (B_n). This annual change in mass is expressed as an equivalent volume of water (w.e.) per unit area relative to the previous summer surface of a glacier (Paterson, 1994). The average net balance ($\overline{b_n}_{\,Combined}$), net accumulation ($\overline{b_c}$) and net ablation ($\overline{b_a}$) of a glacier is defined by dividing B_n, B_c and B_a respectively, by the total area of the glacier (A).

Annual accumulation and ablation on Volcán Mocho-Choshuenco have been measured on the southeastern glacier since May 2003 on a monthly basis. A network of coligüe stakes was installed from the summit (2413 m a.s.l.) to an altitude of 1750 m a.s.l. near the glacier front, in order to include a wide range of aspects and slopes within the glacier (Fig. 2). Snow densities were also measured every month at snow pits dug at stake 18 and occasionally at the summit. In each pit, snow samples were collected every 20 cm vertically, using a 500 cm^3 metal device, and were weighed with a digital balance. Snow temperatures were also measured every 20 cm depth with a digital thermometer equipped with a 5-cm probe. Snow stratigraphy was recorded for each level including the presence of ice layers, sediments, ice pipes and columns. Discrete measurements of snow densities were performed at each stake in August 2004 using a stainless steel snow sampling tube (Model 3600 “Federal” also called Mount Rose), allowing estimation of densities of the snow/firn layer to a depth of 2 m. These discrete measurements were used to calibrate the snow densities assigned to each stake based upon the snow pit data.

Long (~10 m) plastic stakes were installed in the lower ablation area using a Heucke steam drill (Heucke, 1999). In the accumulation area and especially in the winter, some stakes were lost due to high snow accumulation. However, several stakes could be monitored year-round, particularly at lower altitude. Occasionally, stakes disappeared due to avalanches or strong winds, especially at the summit where very few stakes survived the inclement weather conditions. Missing snow height measurements were substituted using regression analysis of data obtained from the existing stakes.

In order to obtain the mass balance for the glacier as a whole, the discrete values obtained from the stake network were interpolated using an inverse distance weight (IDW) method, available in IDRISI-32 software. For this purpose an SRTM 90-m pixel size model was used, allowing calculation of $\overline{b_c}$, $\overline{b_a}$ and $\overline{b_n}$.

RESULTS

Glacier area changes

Assuming a worst-case ice margin delineation error of ±0.5 pixel size for each date (Table 1) multiplied by the ice-area perimeter length of only the changed portion (Williams *et al.*, 1997), a total ice-area loss of 11.5 ± 2.5 km^2 was determined between 1976 and 2003 (Table 2), representing 40.5% of the 1976 area. A possible acceleration of the area shrinkage was also estimated for the most recent period, where the area changes were 15% higher than during the previous period (Table 2).

Most of the ice changes between 1976 and 1987 took place around the western margin of the volcano, where several small tongues retreated. However, in the period 1987–2003 all the margins of the volcano experienced ice recession, especially at the Choshuenco summit, where most of the ice disappeared (Fig. 3).

Table 2 Glacier area changes 1976–2003 on Volcán Mocho-Choshuenco.

Year	Area (km^2)	Area change (km^2 $year^{-1}$)
1976	28.4	
1987	24.2	–0.39 ± 0.24
2003	16.9	–0.45 ± 0.08

Mass balance

The net annual accumulation obtained on the glacier (Fig. 4) ranges from 1.2 to 4.8 m w.e. $year^{-1}$. The average net accumulation yielded 2.6 m w.e. $year^{-1}$ (Tables 3 and 4). The maximum accumulation was obtained around stake 19, which is located near the ice divide with the western glaciers of the volcano, where most of the snowfall takes place in response to the predominant westerly frontal systems. Snow accumulation here is not strongly affected by the topographic barrier generated by the volcanic cone; therefore, snow drift from the western side of the volcano must be an important accumulation factor around this stake. In this sense, both slope and aspect are important in order to determine the amount of accumulation around the volcano. The steep

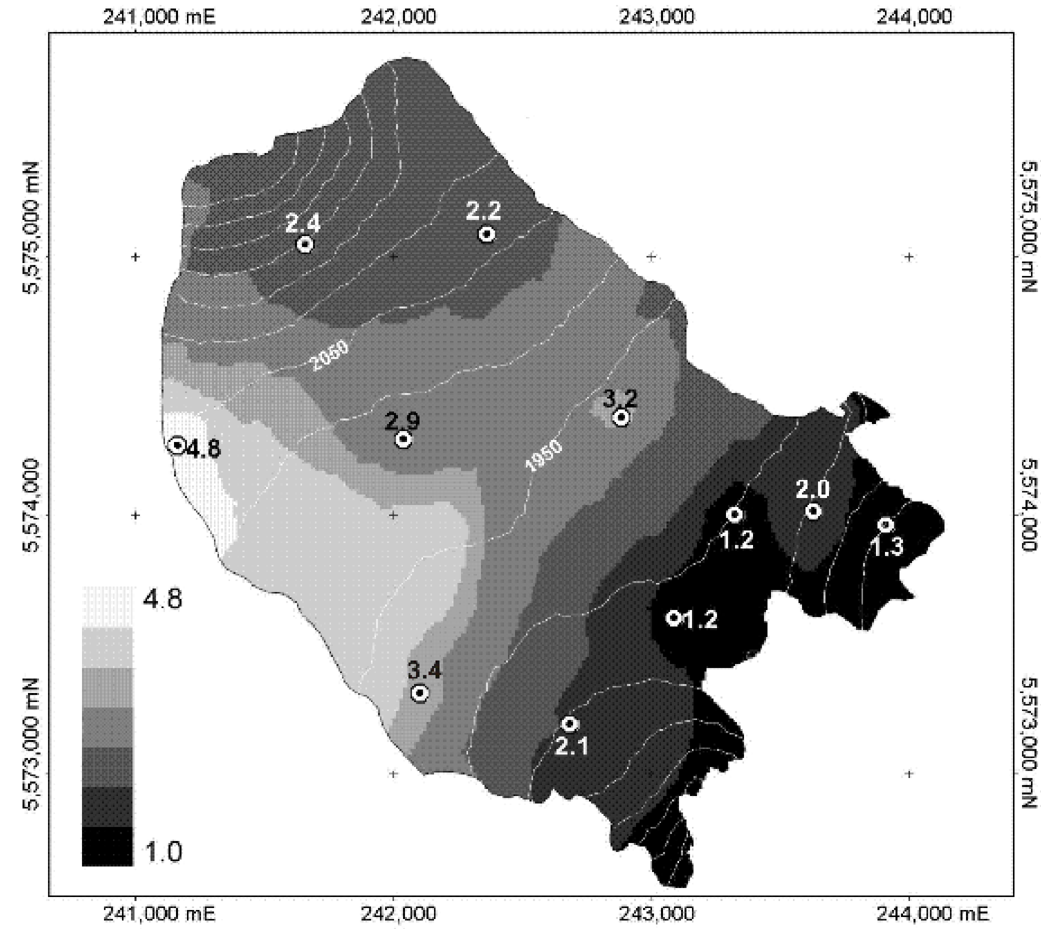

Fig. 4 Annual net accumulation (m w.e. $year^{-1}$). Individual values represent the accumulation measured at each stake. Contour lines show surface topography based upon SRTM data in m a.s.l. UTM WGS-1984 co-ordinates in m.

Table 3 Mass balance components measured at each stake.

Stake	Altitude (m a.s.l.)	Accumulation (m w.e. year^{-1})	Ablation (m w.e. year^{-1})	Net balance (m w.e. year^{-1})
1*	2416			
8	1917	1.2	–4.7	–3.5
9	1723	1.3	–7.6	–6.3
10	1908	1.2	–4.2	–3.0
11	1846	2.0	–6.5	–4.5
12	1853	2.1	–6.1	–4.0
13	1947	3.4	–4.6	–1.1
15	1947	3.2	–3.4	–0.1
17	2074	2.2	–1.1	1.1
18	2013	2.9	–1.2	1.7
19	2050	4.8	–2.1	2.7
21	2169	2.4	–1.6	0.9

* This and other stakes were frequently lost due to avalanches and strong winds.

Table 4 Mass balance results for hydrological year 2003/04.

Glacier area (km^2)	5.1
Maximum altitude (m a.s.l.)	2422
Minimum altitude (m a.s.l.)	1603
Maximum length (km)	3.3
ELA (m a.s.l.)	1956 ± 53
Accumulation Area ratio (AAR)	0.52
Average net ablation (m w.e. year^{-1})	–3.47
Average net accumulation (m w.e. year^{-1})	2.59
Average net balance (m w.e. year^{-1})	–0.88 ± 0.18
Mass balance gradient (year^{-1})	0.015

slopes surrounding the main cone are affected by snow avalanches generating reduced accumulation. However, the stakes located on flat areas are receiving more snow due to wind redistribution from the west to the east. The stakes located at lower altitudes on the east are receiving progressively less accumulation, as expected.

The net ablation on the glacier is shown in Fig. 5. The maximum ablation yielded –7.6 m w.e. year^{-1} around the lowest altitude stake (stake 9), near the frontal tongue of the glacier. The minimum ablation was measured at stake 17 (2074 m a.s.l., Table 3), in an area located in the rain shadow of the main cone.

The net balance of the glacier is shown in Fig. 6, and the main resulting parameters of the analysis are shown in Table 4. In general, the net mass balance has a direct relationship with altitude; lower areas on the glacier show negative values and higher areas positive values. However, the maximum balance was not obtained at the summit as expected, due to the strong wind redistribution and snow avalanches. The equilibrium line altitude (ELA) of the glacier was located at 1956 ± 53 m a.s.l., which defines an accumulation area ratio of 0.52. A mass balance gradient was calculated for the glacier using SRTM data and the net balance assigned to each pixel of the ice basin, yielding 0.015 year^{-1}, which is similar to other estimates derived for

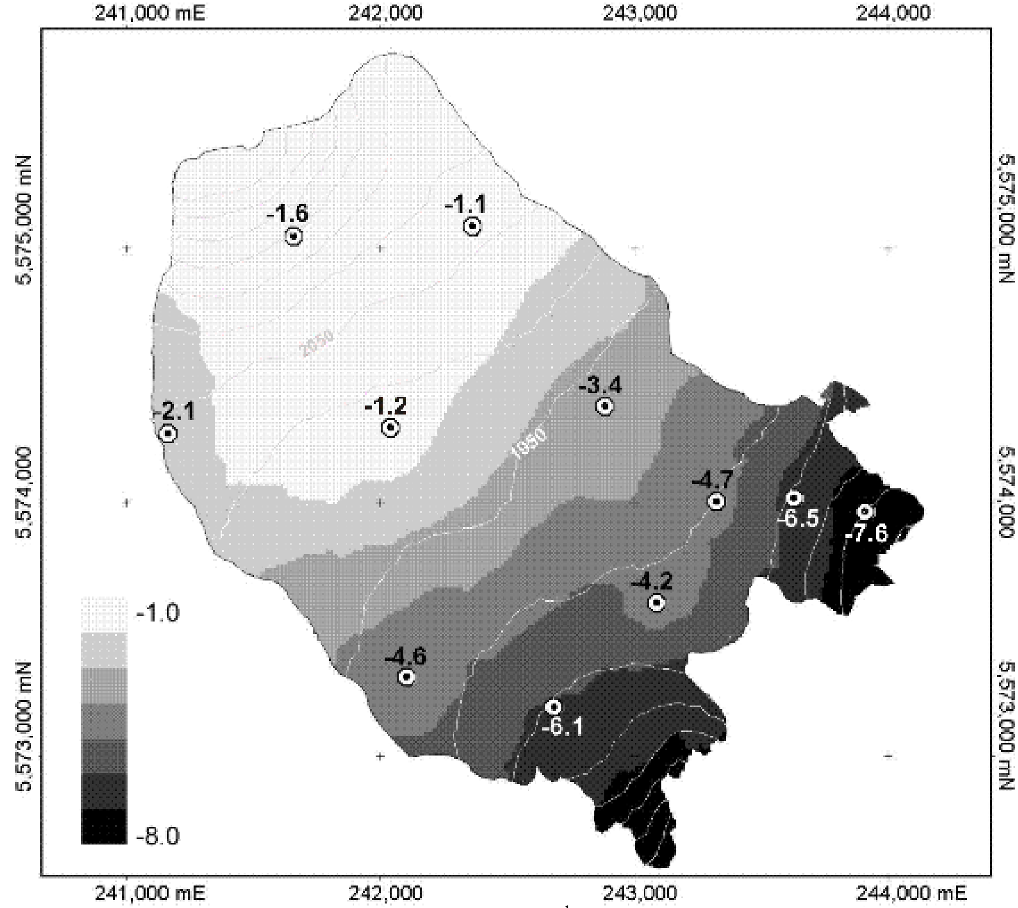

Fig. 5 Annual net ablation (m w.e. year^{-1}). Individual values represent ablation measurements at each stake. Contour lines show surface topography based upon SRTM data in m a.s.l. UTM WGS-1984 co-ordinates in m.

Patagonian glaciers (Naruse *et al.*, 1995). The plot of net mass balance *vs* altitude for each pixel within the glacier (Fig. 7) shows a linear trend from the minimum altitude up to the foot of the main cone, where two patterns are observed: one with smaller net balance values towards the summit, and the other with maximum positive values towards the ice divide with the western flank of the glacier.

The average net balance of the glacier yielded –0.88 ± 0.18 m w.e. year^{-1} for the period 2003/2004; the error, an estimated 20% of the total mass balance, comprises uncertainties in stake height measurements, snow density sampling biases (Harper & Bradford, 2003) and the interpolation method applied to discrete values.

DISCUSSION AND CONCLUSIONS

Atmospheric warming has been observed at several stations in Chile during recent decades, especially between 1960 and 1992 (Rosenblüth *et al.*, 1997), when increasing temperature trends of 0.02–0.04°C year^{-1} in Arica-Punta Angeles (18–33°S) and 0.021–0.025°C year^{-1} in Puerto Aysén-Punta Arenas (45–53°S) were obtained. However, the Chilean Lake District (39–42°S, Fig. 1) was affected by surface

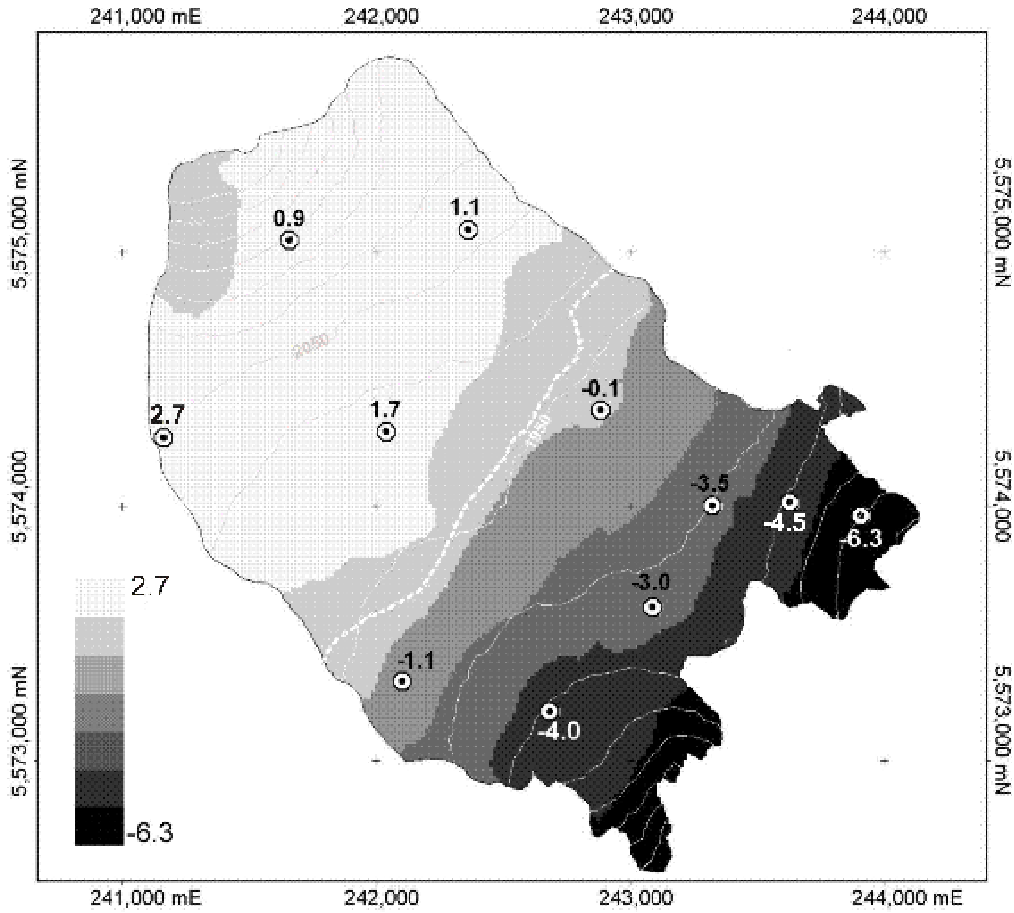

Fig. 6 Annual net mass balance (m w.e. year^{-1}). Individual values represent annual net balance observed at each stake. Contour lines show surface topography based upon SRTM data in m a.s.l. The ELA of year 2003/04 is shown as a dotted white line. UTM WGS-1984 co-ordinates in m.

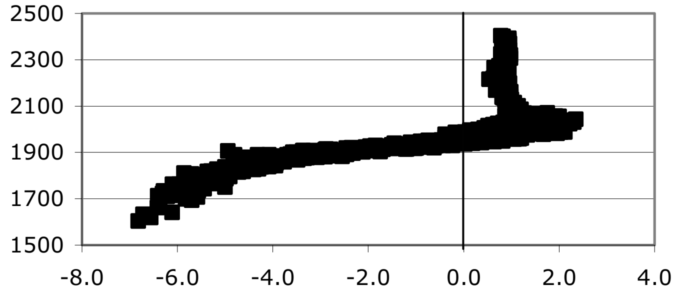

Fig. 7 Glacier net mass balance 2003/04 in m w.e. year^{-1} (x-axis) *vs* altitude in m a.s.l. (y-axis). Dots represent single pixel values for the whole glacier area based upon the interpolation model. The ELA of the glacier for this year was located at 1956 ± 53 m a.s.l.

atmospheric cooling between 1960 and 1992, particularly at Puerto Montt (41°26′S), where the temperature trend yielded –0.011°C year^{-1} (Rosenblüth *et al.*, 1997). This temperature decrease affected only the lower troposphere, as warming was detected above the 850 hPa atmospheric level from the early 1960s until the late 1980s (Aceituno *et al.*, 1993; Carrasco *et al.*, 2002). This atmospheric level (850 hPa) approximately represents the minimum altitude of the regional glaciers. Therefore an increase in ablation at progressively higher altitudes is expected to have taken place in recent decades.

On the other hand, most of the stations of the Chilean Lake District have shown a decrease in annual amounts of precipitation during the second half of the 20th century. For example Valdivia (39°38′S/73°05′W, 19 m a.s.l.) exhibited a trend of –15 mm year^{-1} between 1961 and 2000, whilst Puerto Montt (41°26′S, 73°07′W, 90 m a.s.l.) showed –14 mm year^{-1} during the same period (Bown & Rivera, 2005).

Both climatic trends: the decrease in precipitation and upper atmosphere warming, are affecting the glaciers, explaining the area shrinkage and frontal retreats as was described for other glaciers of this part of the country by Rivera *et al.* (2002). The influence of ashes originating from the nearby Volcán Villarrica on the glacier dynamics of Volcán Mocho-Choshuenco are presumably negligible, because the predominantly westerly winds spread volcanic material ejected by Volcán Villarrica towards the east, and not to the south, where Volcán Mocho-Choshuenco is located. Therefore, due to the lack of volcanic activity at Volcán Mocho-Choshuenco, the observed ice-area changes on this volcano are thought to be driven mainly by climatic factors. In this sense, the negative mass balance for year 2003/04 could be partially explained by the pluviometric deficits of 22% and 31% (relative to the 1960–1991 mean) observed during the relatively dry year of 2003 at the Valdivia and Osorno meteorological stations (40°36′S, 73°04′W, 69 m a.s.l.), respectively (Chilean Meteorological Office, personal communication).

It will be necessary to maintain the mass balance monitoring programme for several years at Volcán Mocho-Choshuenco in order to estimate the trends and representativeness of the results obtained for the 2003/04 period. Direct measurements need to be complemented with indirect satellite observations, as well as modelling studies, in order to improve our understanding of the glacier dynamic and the interactions with the volcano. In the mean time it is possible to conclude that this glacier has proved to be a good site for glaciological studies, and that its mass balance is responding to non-volcanic factors.

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REFERENCES

Aceituno, P., Fuenzalida, H. & Rosenblüth, B. (1993) Climate along the extratropical west coast of South America. In: *Earth System Responses to Global Change: Contrasts between North and South America* (ed. by H. A. Mooney, E. R. Fuentes & B. I. Kronberg) (Elsevier Science & Technology Books), 61–69. Academic Press Inc., San Diego, California, USA.

Adhikary, S., Yamaguchi, Y. & Ogawa, K. (2002) Estimation of snow ablation under dust layer covering a wide range of albedo. *Hydrol. Processes* **16**, 2853–2865.

Björnsson, H. (1998) Hydrological characteristics of the drainage system beneath a surging glacier. *Nature* **395**, 771–774.

Björnsson, H., Rott, H., Gudmundsson, S., Fisher, A., Siegel, A. & Gudmundsson, M. (2001) Glacier–volcano interactions deduced by SAR interferometry. *J. Glaciology* **47**(156), 58–70.

Bown, F. & Rivera, A. (2005) Climate changes and recent glacier behaviour in the Chilean Lake District. *Global Planet. Change*. (in press)

Carrasco, J., Casassa, G. & Rivera, A. (2002) Meteorological and climatological aspects of the Southern Patagonia Icefield. In: *The Patagonian Icefields. A Unique Natural Laboratory for Environmental and Climate Change Studies* (ed. by G. Casassa, F. Sepúlveda & R. Sinclair), 29–41. Series of the Centro de Estudios Científicos, Kluwer Academic/Plenum Publishers, New York, USA.

Cas, R. & Wright, J. (1987) *Volcanic Successions: Modern and Ancient.* Unwin & Hyman, London, UK.

Clavero, J. (2002) Evolution of Parinacota Volcano and Taapaca Volcanic Complex, central Andes of northern Chile. PhD Thesis, University of Bristol, Bristol, UK.

Clavero, J. & Moreno, H. (1994) Licán and Pucón ignimbrites: evidences of postglacial explosive basaltic-andesite eruptions from Villarrica Volcano, southern Andes, 39º25'S. In: *Proceedings of the VII Chilean Geologic Congress*, Concepción, Chile, 250–254.

Echegaray, J. (2005) Geological and geochemical evolution of the Mocho-Choshuenco Volcanic Center, Southern Andes, 40ºS. MSc Thesis, University of Chile, Santiago, Chile.

González-Ferrán, O. (1995) *Volcanes de Chile*. Instituto Geográfico Militar, Santiago, Chile.

Harper, J. & Bradford, J. (2003) Snow stratigraphy over a uniform depositional surface: spatial variability and measurement tools. *Cold Regions Sci. Technol.* **37**, 289–298.

Heucke, E. (1999) A light portable steam-driven ice drill suitable for drilling holes in ice and firn. *Geografiska Ann.* **81A**(4), 603–609.

Johannesson, T. (2002) Propagation of subglacial flood wave during the initiation of a jökulhlaup. *Hydrol. Sci. J.* **47**(3), 417–434.

Maclennan, J., Jull, M., McKenzie, D., Slater, L. & Grönvold, K. (2002) The link between volcanism and deglaciation in Iceland. *Geochem., Geophys., Geosystems* **3**(11), 1062, DOI 10.1029/2001GC00282.

Matthews, W. & Clague, J. (1993) The record of jökulhlaups from Summit Lake, northwestern British Columbia. *Can. J. Earth Sci.* **30**, 499–508.

Moreno, H. (1993) Villarrica Volcano: geology and volcanic risk, IX and X regions, 39º25 S. Geologic and volcanic hazard maps 1:50.000 scale. Fondecyt Report (Chilean Geological Survey), 1–82.

Naranjo, J. A. & Moreno, H. (2004) Laharic debris flows from Villarrica Volcano. In: *Villarrica Volcano (39.5ºS), Southern Andes, Chile* (ed. by L. Lara & J. Clavero). *Chilean Geol. Survey, Bull. 61*, 28–38.

Naruse, R., Aniya, M., Skvarca, P. & Casassa, G. (1995) Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. *Ann. Glaciol.* **21**, 297–303.

Østrem, G. & Brugman, M. (1991) *Glacier Mass Balance Measurements: A Manual for Field and Office Work.* Norwegian Water Resources and Energy Administration, and Environment Canada, National Hydrology Research Institute Science Report no. 4, Saskatchewan, Canada.

Paterson, W. S. B. (1994) *The Physics of Glaciers*. Pergamon Press, London, UK.

Paul, F., Kääb, A., Maisch, M., Kellenberger T. & Haeberli, W. (2002) The new remote sensing derived Swiss glacier inventory I: Methods. *Ann. Glaciol.* **34**, 355–362.

Rivera, A., Acuña, C., Casassa, G. & Bown, F. (2002) Use of remotely-sensed and field data to estimate the contribution of Chilean glaciers to eustatic sea-level rise. *Ann. Glaciol.* **34**, 367–372.

Rodríguez, C., Pérez, Y., Moreno, H., Clayton, J., Antinao, J., Duhart, P. & Martin, M. (1999) Geologic map of the Panguipulli-Riñihue area, Lake region, 1:100 000 scale. Geologic Maps Series no. 10, Chilean Geological Survey.

Rosenblüth, B., Fuenzalida, H. & Aceituno, P. (1997) Recent temperature variations in Southern South America. *Int. J. Climatol.* **17**, 67–85.

Shiraiwa, T., Muravyev, Y. D., Kameda, T., Nishio, F., Toyama, Y., Takahashi, A., Ovsyannikov, A. A., Salamatin, A. & Yamagata, K. (2001) Characteristics of a crater glacier at Ushkovsky Volcano, Kamchatka, Russia, as revealed by the physical properties of ice cores and borehole thermometry. *J. Glaciol.* **47**(158), 423–432.

Sigmundsson, F. (1991) Post-glacial rebound and astenosphere viscosity in Iceland. *Geophys. Res. Lett.* **18**, 1131–1134.

Sigvaldason, G. (2000) Volcanic and tectonic processes coinciding with glaciation and crustal rebound: and early Holocene rhyolitic eruption in the Dyngjurfjöll volcanic centre and the formation of the Askja Caldera, north Iceland. *Bull. Volcanol.* **64**, 192–205.

Simkin, T. & Siebert, L. (1994) *Volcanoes of the World*. Smithsonian Institution, New York, USA.

Williams, R., Hall, D., Sigurosson, O. & Chien, Y. (1997) Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973–92. *Ann. Glaciol.* **24**, 72–80.

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