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Recent evolution and mass balance of Cordón Martial glaciers, Cordillera Fueguina Oriental

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Abstract

Past and present glacier changes have been studied at Cordón Martial, Cordillera Fueguina Oriental, Tierra del Fuego, providing novel data for the Holocene deglaciation history of southern South America and extrapolating as well its future behavior based on predicted climatic changes. Regional geomorphologic and stratigraphic correlations indicate that the last glacier advance deposited the ice-proximal (“internal”) moraines of Cordón Martial, around 330 ¹⁴C yr BP, during the Late Little Ice Age (LLIA). Since then glaciers have receded slowly, until 60 years ago, when major glacier retreat started. There is a good correspondence for the past 100 years between the surface area variation of four small cirque glaciers at Cordón Martial and the annual temperature and precipitation data of Ushuaia. Between 1984 and 1998, Martial Este Glacier lost $0.64 \pm 0.02 \times 10^6$ m³ of ice mass ($0.59 \pm 0.02 \times 10^6$ m³ w.e.), corresponding to an average ice thinning of 7.0 ± 0.2 m (6.4 ± 0.2 m w.e), according to repeated topographic mapping. More detailed climatic data have been obtained since 1998 at the Martial Este Glacier, including air temperature, humidity and solar radiation. These records, together with the monthly mass balance measured since March 2000, document the annual response of the Martial Este Glacier to the climate variation. Mass balances during hydrological years were positive in 2000, negative in 2001 and near equilibrium in 2002. Finally, using these data and the regional temperature trend projections, modeled for different future scenarios by the Atmosphere-Ocean Model (GISS-NASA/GSFC), potential climatic-change effects on this mountain glacier were extrapolated. The analysis shows that only the Martial Este Glacier may survive this century.

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1. Introduction

Unlike the Northern Hemisphere, the Southern Hemisphere lacks studies of Late-Holocene deglaciation, including synchronicity of changes (Luckman and

Villalba, 2001), present status of glaciers, and also future projections of glacier behavior. The current deglaciation started at the end of the Late Little Ice Age (LLIA) (*sensu* Clapperton and Sugden, 1988), which corresponds to the last Holocene glacier advance in southern South America, also recently recognized in Cordillera Fueguina (Strelin et al., 2001). Geomorphologic, stratigraphic and different proxy data (Rabassa et al., 1989; Bonisegna et al., 1990; Kuylenstierna et al., 1996; Obelic et al., 1998; Pendall et al., 2001) provide

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only a rough picture of the regional deglaciation since this last Holocene glacier advance.

Considering that glaciers are important factors in the morphologic, hydrologic and bio-ecologic development of mountain areas, it is attempted to quantify the latest Holocene deglaciation of Cordillera Fueguina, trying to find out its adjustment to regional climatic variables.

Because of their location, close to the city of Ushuaia, the Cordón Martial glaciers were selected as a convenient field laboratory. Glaciological studies began here in 1984, however variations in glacier extent over the last 100 years can be followed through historical, mostly photographic documentation. Also, long-term temperature and precipitation data covering this entire time period are available. These data and more recent detailed field work allow to establish an interpretation of the last deglaciation history of this mountain region, which is presented here.

2. Physical settings

Ice-covered massifs nourishing outlet glaciers that terminate in fjords extend up to 2000 m a.s.l. on the western, Chilean side of Cordillera Fueguina. The highest

altitude is reached at Mount Darwin, Cordillera Darwin, with 2440 m a.s.l. To the east, on the Argentinean side, the mountain ranges are ~ 1000 m lower. These lower altitudes, together with a decreased eastward precipitation, induce a reduction of the glaciated area. The eastern part of Cordillera Fueguina, herein named Cordillera Fueguina Oriental, is characterized by many EW-stretching mountain ranges with eastward-decreasing mean altitudes from ~ 1000 to 500 m a.s.l.

Cordón Martial, one of these mountain ranges, located immediately north of Ushuaia (Fig. 1), comprises strongly folded metasedimentary rocks originally accumulated in a Cretaceous marginal basin (Olivero and Martinioni, 2001). The highest peak, Monte Martial, reaches 1319 m a.s.l. The foothills and lower to middle slopes of this mountain range were markedly shaped during the Last Glaciation (Rabassa et al., 1992). They are presently covered by a dense deciduous forest (*Nothofagus pumilio* and *Nothofagus antarctica*) with some evergreen forest (*Nothofagus betuloides*) and wetland (peat bogs) patches. Andean tundra develops on the upper slopes and hanging tributary valleys, above timberline (500–700 m a.s.l.). The tributary valley-floors, mantled by recent outwash deposits and moraines, are

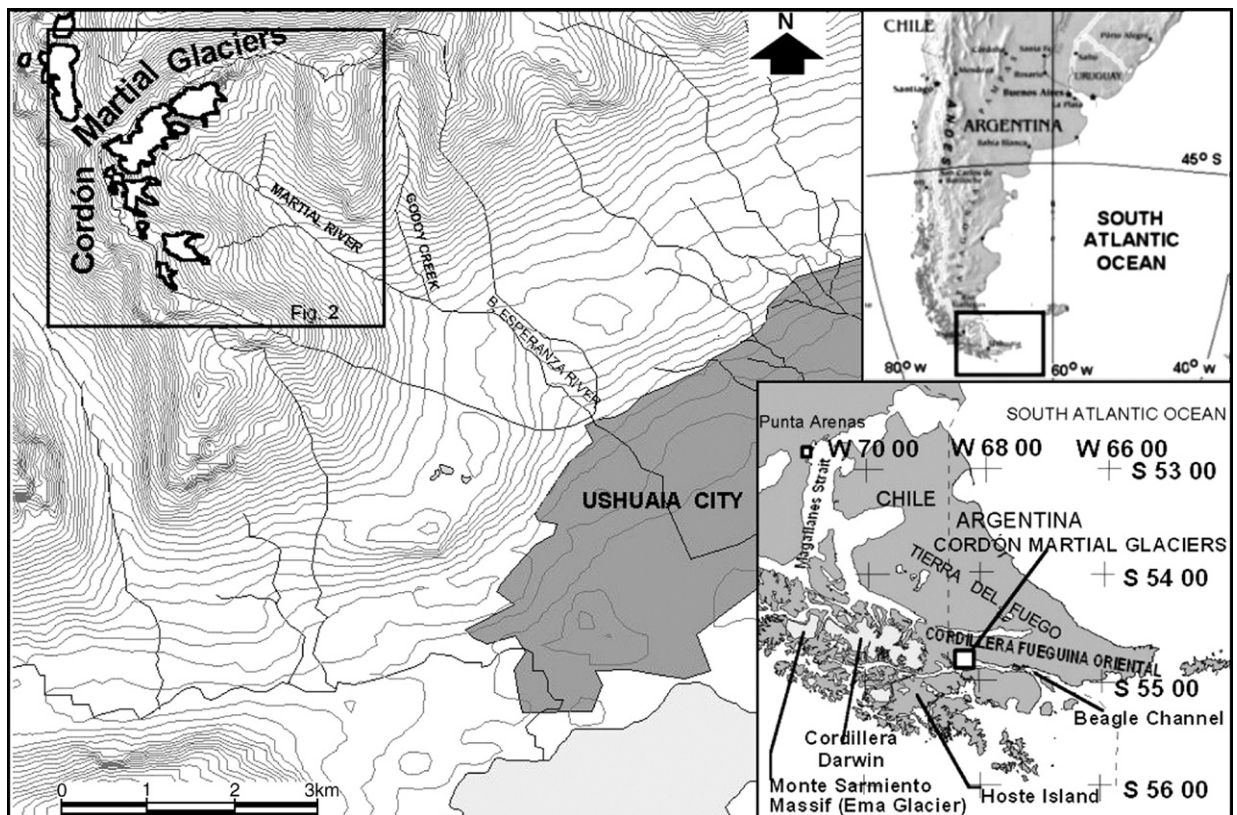


Fig. 1. Field work location. Posgar 94 planar coordinates.

flanked by gentle slopes covered by solifluction lobes (turf-banked terraces and turf-banked lobes). At higher levels (>700 m a.s.l.) talus cones and scree prevail as an effect of frost-shattering and mass wasting on the upper rock faces. Under corresponding conditions and above 900 m a.s.l., small glaciers surrounded by recent moraine deposits, perennial snow patches, and rock glaciers of different types are observed.

There are four small cirque glaciers in the Cordón Martial mountain range, extending from 900 to 1250 m a.s.l. These are (from SW to NE): Martial Sur (MSG), Martial Central-Oeste (MCOG), Martial Central-Este (MCEG), and Martial Este (MEG) glaciers (Fig. 2). At the end of the summer season melt from these glaciers provide the main runoff in the Martial River. After joining the Godoy Creek, Martial River continues as the Buena Esperanza River which runs through Ushuaia and discharges into the Beagle Channel. The Buena Esperanza River is one of the main water resources of Ushuaia.

The climatic conditions of the Cordillera Fueguina Oriental are determined by predominant eastward cyclonic circulation generated at the polar front of the Pacific Ocean. When the mostly occluded cyclones

reach the southern Tierra del Fuego mountain area, they produce a maritime, cold, humid and windy climate with a mean annual (sea level-corrected) air temperature of ~ 5.5 °C. The saturated adiabatic lapse rate is ~ 6 °C/1000 m, producing a cold polar climate over 900 m a.s.l. (Puigdefábregas et al., 1988). Although Cordillera Fueguina Oriental is part of the main Andean mountain chain, it is protected from the prevailing SW winds by the Cordillera Darwin and the mountains of Hoste Island (Fig. 1). This leads to a moderate lee-side orographic situation, with more continental characteristics such as relatively lower precipitation (500 mm in Ushuaia for the last decade), reduced cloudiness and humidity. Nevertheless, higher orographic precipitation is recorded in the mountain range close to Ushuaia (Iturraspe et al., 1989).

3. The last Holocene regional deglaciation

Radiocarbon dating of recent moraines located around the Monte Sarmiento Massif (Fig. 1), SW of Isla Grande de Tierra del Fuego (Strelin et al., 2001), and paleotemperature of Beagle Channel water (Obelich et al., 1998), indicate that the last Neoglacial advance in

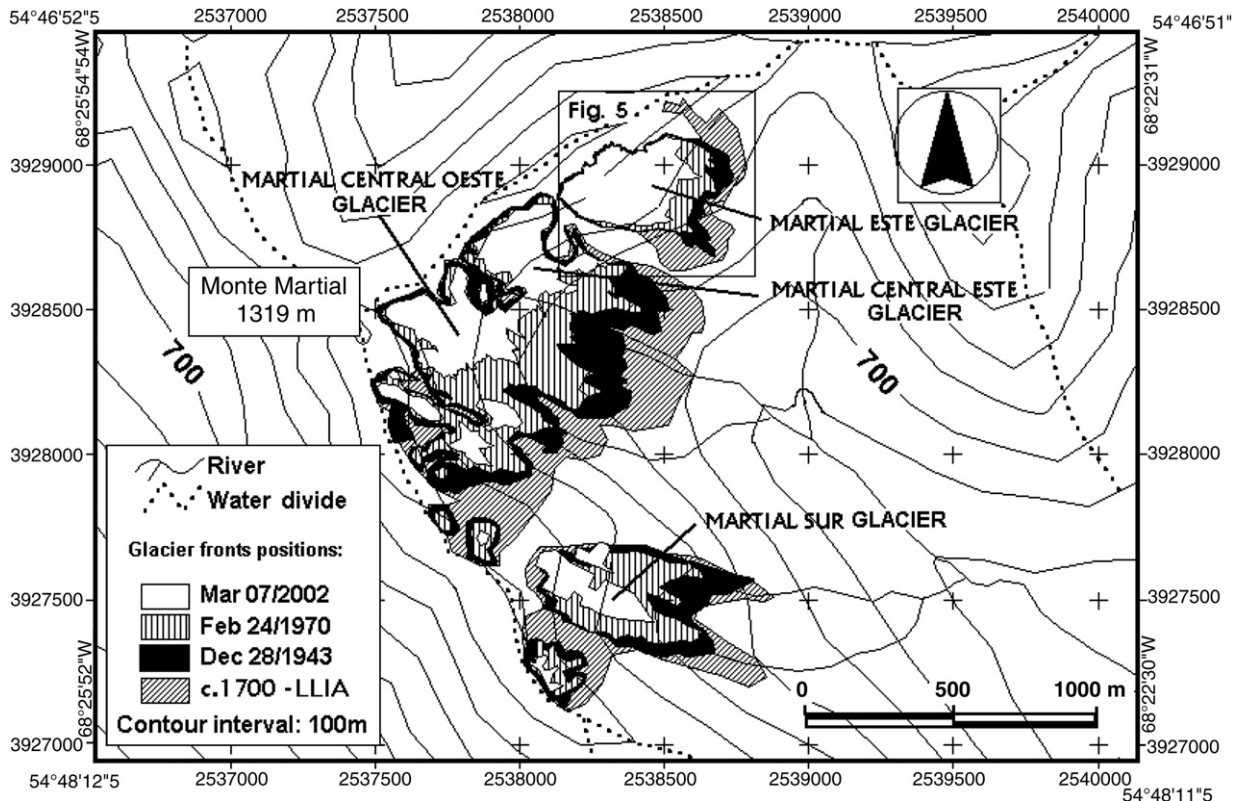


Fig. 2. Evolution of the surface area of Cordón Martial glaciers. X , Y are Gauss Krüger.

Table 1

Glacier advances during the Late Little Ice Age (LLIA) in the Ema Glacier Valley, Monte Sarmiento Massif. Moraine I was deposited during the LLIA glacier advance (Strelin et al., 2001). Moraines II to IV were deposited during successive recessional glacier advances

Monte Sarmiento Massif, Glaciär Ema moraines	Dates of moraine deposits
I	ca. 335 ^a
II	ca. 315 ^a
III	315 ^a –140 ^b
IV-a	140 ^b –110/90 ^b
IV-b	110/90 ^b –90/60 ^b
IV-c	90/60 ^b –60 ^b

^a ¹⁴C yr BP.

^b Calendar years measured on tree rings.

southern Tierra del Fuego occurred around an uncalibrated radiocarbon age of 330 years BP (330 ¹⁴C yr BP or ~1670 AD as assumed in Table 2). Subsequently, minor glacier advances occurred in the Ema glacier Valley at Monte Sarmiento Massif (Table 1), and judging from the tree-trunk diameter-growth and old air-photos, the last recessional moraine ridge (a moraine formed as a retreating glacier paused) was abandoned at most 60 years ago (Strelin et al., 2001).

Boniseгна et al. (1990) provide dendrochronological reconstruction of summer temperatures since 1750 for the area around Ushuaia. Starting from cold summer temperatures around 250 yr BP, a warmer period occurred between 1790 and 1830 (~210–170 yr BP), followed by three colder periods around 140, 110 and 90 yr BP. These data match the last glacier fluctuations

observed for the Ema Glacier Valley at the Monte Sarmiento Massif region (Table 1).

Air-photos and field observations show that glaciers in the Darwin Cordillera receded markedly on the northern slopes since 1943 while they reached equilibrium or even readvanced on the southern slopes (Holmlund and Fuenzalida, 1995). These authors consider higher SW wind activity and consequent precipitation increase on the southern slopes of Darwin Cordillera as the possible explanation for this different glacier behavior. Marked and generalized glacier recession, without the simultaneous advance observed on the southern slopes by Holmlund and Fuenzalida (1995) in Cordillera Darwin, was noticed around the Monte Sarmiento Massif by Strelin et al. (2001). No additional information is available on the Fuegian glaciers behavior since the LLIA, including the Cordón Martial glaciers. However, because of the material available in the historical photographic archive it has been possible to reconstruct their surface fluctuations during the last 100 years.

4. Fluctuation since LLIA of Cordón Martial glaciers

4.1. Methodology and data accuracy

Fluctuations since the LLIA of Cordón Martial glaciers were reconstructed using 1:40,000 air-photographs acquired by the Armada Argentina (Dec., 1943, and Feb.–Mar., 1970), SPOT satellite scenes (15 m resolution, 1995), LANDSAT TM images (28.5 m



Fig. 3. Left: the glaciers of Cordón Martial at the end of the 19th Century (Photo belonging to Santos Caballero Collection, year 1898, Museo del Fin del Mundo, Ushuaia). Right: the same view in March 2002.

resolution, 1986–2003), 20th century panoramic photos provided by the *Museo del Fin del Mundo* and field work by the authors including topographic measurements (1984, 1998 and 2003). Geomorphologic analysis based on air-photo interpretation, several field controls, and the correlation with glaciated valleys of Cordillera Fueguina Occidental, allowed identification and mapping of possible LLIA glacier expansion of the Cordón Martial glaciers.

As the Cordón Martial glaciers usually appear in the background of photographs from Ushuaia, six accurately-dated panoramic photos taken from very similar view points provide a good basis for mapping glacier area variations during the 20th Century. The first half of this

century has a poor time resolution involving only 3 photos. Fig. 3 shows the oldest (1898) and latest (2002) ground photographs. The oblique areas measured on these photos were restituted to the horizontal plane using available air-photos and satellite scenes. The regression function used for this transformation shows a good adjustment ($R^2=0.9$). The area was measured using Arc View Gis 3.1 with an estimated error of $<\pm 0.1$ ha.

The correlation between the measured area fluctuations of the Cordón Martial glaciers with the temperature and precipitation data series of Ushuaia was inspected (Fig. 4). Additional morphometric parameters were obtained using local topographic data and a 20 m-contour interval topographic map (Hoja 5569-17-1

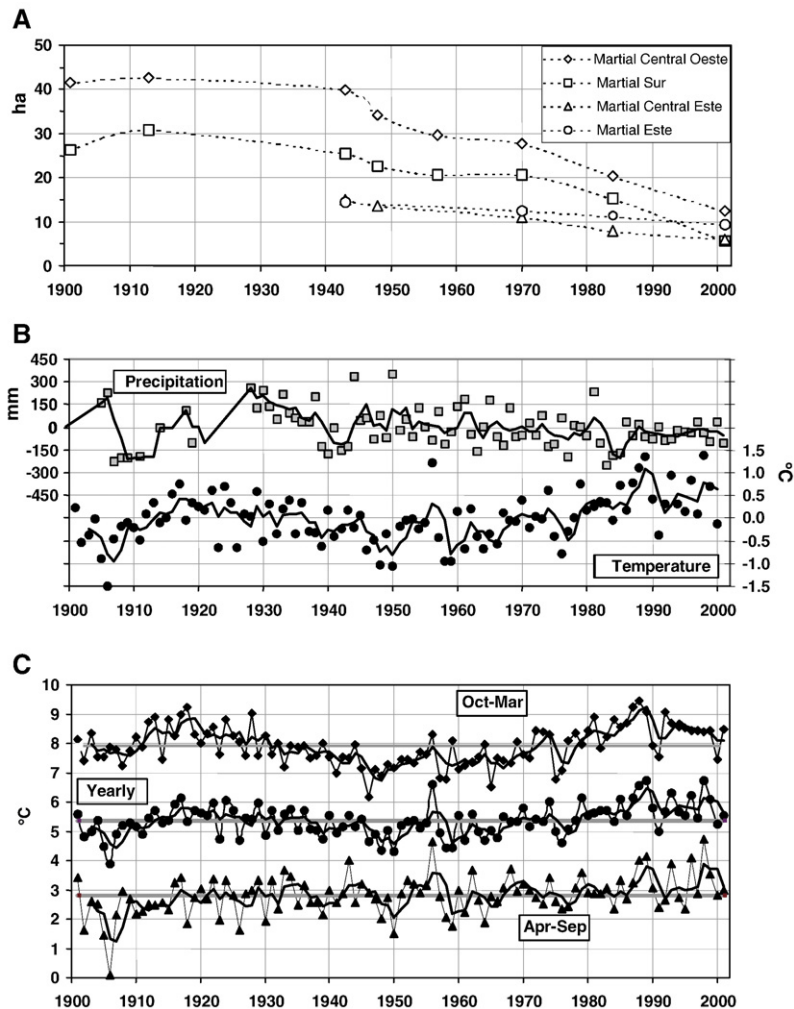


Fig. 4. Graphs showing (A) the area evolution (in ha) of the Cordón Martial glaciers, (B) annual pluviometric and air temperature fluctuation in Ushuaia between 1901 and 2002, referred to the historical means of 535 mm and 5.4 °C respectively, and (C) air temperature trend in Ushuaia between 1901 and 2002, separating seasonal components: winter (April to September) and summer (October to March) data. The thick curves of Fig. 4B and C are 4-year mean values.

Ushuaia, Dirección de Información Geográfica de Tierra del Fuego).

The Martial Este Glacier (MEG) monitoring started in March, 1984. Three fixed points were installed around the glacier and a topographic map of the ice surface was compiled. The studies were interrupted in 1987 and restarted in March 1998, when a new ice surface topographic map – referred to the 1984 fixed points – was compiled. The difference between the 1984–1998 glacier surfaces elevations and ice volume loss was digitally calculated with an error of about ± 0.2 m for ice elevations and $\pm 0.02 \times 10^6$ m³ for the ice volume. Ice-flow velocity was determined in 1998 by measuring the displacement of three of the iron stakes installed in 1984. The approximate ice thickness (h in meters) at the stakes' locations was calculated applying Lliboutry's (1965) simplified formula for glaciers with no basal sliding:

$$h = k \times (u_o / \sin^3 \alpha)^{1/4} \quad (1)$$

where the glacier surface slope α and flow velocity u_o (in m/yr) were measured in the field. Following Potter (1972) a value of $k = 13.8 \text{ m}^{3/4} \times \text{yr}^{1/4}$ was adopted.

Mass balance studies on the MEG, using the stratigraphic system and Kaser et al.'s (2003) recom-

mendations for the glaciological method, were initiated at the beginning of the hydrological year in March 2000 by establishing twelve 3 m-long bamboo stakes evenly distributed over the glacier surface (Fig. 5), 5 in the accumulation zone, and 7 in the ablation zone. Changes in vertical glacier surface altitude, including ice, firn, or snow density values, were measured monthly with an accuracy of about ± 20 mm w.e. When necessary, the bamboos were supplemented or replaced. The net accumulation (nc) and net ablation balances (na) follow the integration of the 12 specific budgets measured at each stake. The net annual balances (nb) were calculated as:

$$\text{nb} = \text{nc} + \text{na} \quad (2)$$

with an error of ± 50 mm w.e.

A meteorological station located at 980 m a.s.l., very close to the glacier front, collected air temperature, humidity and solar radiation data every hour.

4.2. Morphometry of Cordón Martial glaciers

Fig. 2 shows the different positions of the Cordón Martial glaciers fronts since the LLIA. Surface area

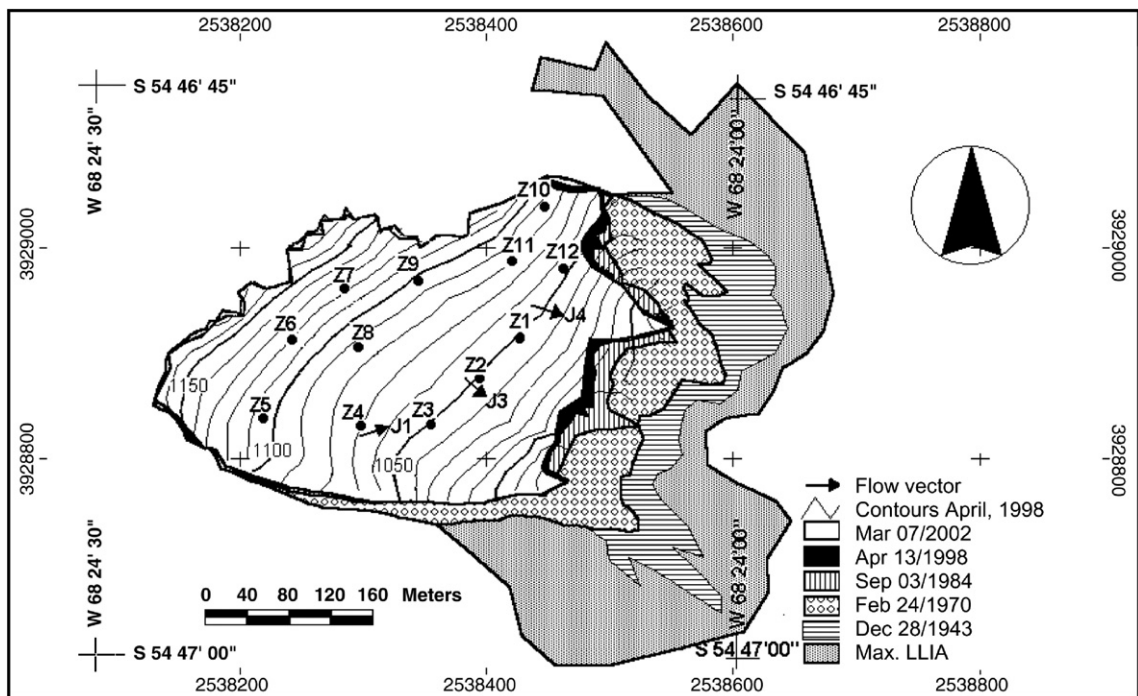


Fig. 5. Topographic map and area fluctuation of MEG since the LLIA. The points marked in the map with "Z" correspond to bamboo stake locations, for mass balance measurements. The three vectors show the 1984–1998 stake displacement direction on the glacier surface. See Table 3 for flow velocity magnitudes. See Fig. 3 for location of MEG in the main Martial valley. X, Y are Gauss Krüger Posgar 94 planar coordinates.

Table 2

Variation of the surface area of Cordón Martial glaciers (in ha) through time. MEG: Martial Este Glacier, MCEG: Martial Central-Este Glacier, MCOG: Martial Central-Oeste Glacier, MSG: Martial Sur Glacier

Year	MEG	MCEG	MCOG	MSG	Total
c.1670	20.6	20.8	61.0	30.9	133.3
1898			41.6	26.3	
1913			42.7	30.7	
1943	14.4	15.1	39.9	25.5	94.9
1948		13.6	34.1	22.5	
1957			29.8	20.5	
1970	12.5	11.1	27.7	20.6	71.9
1984	10.0	8.0	20.4	15.2	53.6
2002	9.3	5.8	12.4	5.6	33.1

variations (Fig. 4A and Table 2) indicate that the glaciers have lost 75% of their total area since the LLIA. Judging from a mean annual temperature of -1.0 °C in the period 2000–2002 at an elevation of 990 m a.s.l. at the meteorological station (Table 5), the glaciers can most probably be classified as temperate.

Martial Sur Glacier's (MSG) position during the LLIA is defined by a V shaped moraine belt at ~ 750 m a.s.l., located 900 m (horizontal distance) from the upper cirque wall (1300 m a.s.l.). During this advance the MSG had a surface area of 31 ha. The current surface slope is 29° to the ESE and it is the most exposed to solar radiation of all of the glaciers in this valley. Between 1898 and 1913, this glacier increased slightly in surface area ($+0.3$ ha/yr); followed by a decrease (-0.2 ha/yr) between 1913 and 1943 when it reached its previous size. The glacier decreased more strongly at a rate of -0.6 ha/yr between 1943 and 1948, and then stabilized during the period 1948–1970. Since 1970 the glacier has shrunk markedly at a rate of -0.7 ha/yr, reaching its present stagnant ice condition with a surface area of ~ 5 ha (Fig. 4A and Table 2).

Martial Central-Oeste Glacier (MCOG), the largest of the four cirque glaciers (12.4 ha), extends between 900 and 1200 m a.s.l., with a surface slope of $\sim 30^\circ$ to the SE. It is connected to the MCEG through a stagnant ice body. During the LLIA, MCOG and MCEG were joined at their terminus but separated by a central moraine. The LLIA glacier front was defined by a moraine belt (~ 700 m a.s.l.) located 1000 m from the upper cirque head (1300 m a.s.l.). Due to the ESE exposure it experienced a similar deglaciation trend to that of MSG. The surface area remained close to constant between 1898 and 1943 (~ 40 ha), decreasing rapidly until 1948 (-1.2 ha/yr), slowly between 1948 and 1970 (-0.3 ha/yr), resuming a rapid decline up to the present (-0.5 ha/yr), as is the case for MSG.

Martial Central-Este Glacier (MCEG) is more protected from solar radiation than the former two through the water divide that separates this glacier from MEG. The glacier is located between 900 and 1200 m a.s.l. with a surface slope of 33° to the SE. The surface area fluctuation can only be reconstructed since 1943 because MCEG is partially hidden behind Monte Godoy in the earlier panoramic photos, which in this case were not acquired at exactly the same location. This glacier shows a slow but steady decline between 1943 and 1970 (-0.1 ha/yr) followed by a relative more rapid decline (-0.2 ha/yr) between 1970 and 2002 (Fig. 4A and Table 2).

Martial Este Glacier (MEG) is located very close to the NE corner of the Martial Valley head, which makes it the least exposed to solar radiation of the four glaciers. The lower and upper ice limits are at higher altitudes, between ~ 1000 and ~ 1180 m a.s.l., respectively, and the wider than longer ice surface is inclined 29° to the SE. This glacier was also located above the others during the last advance, with frontal LLIA moraines at 850 m a.s.l. and less than 500 m horizontal distance from the upper cirque wall. Since 1943, the deglaciation trend of MEG shows a weaker decline, at a mean rate lower than -0.1 ha/yr until 2002, so that its surface area is presently larger than that of MCEG and MSG, and will probably be larger than the surface area of MCOG as well in the near future if the present trends continue. This is notable, since the surface area of MCOG was nearly three times the MEG area in 1943 (Fig. 4A and Table 2).

4.3. Martial Este Glacier monitoring

From 1984 to 1998 Martial Este Glacier experienced a mean vertical thinning of 7.0 ± 0.2 m (0.45 ± 0.01 m w.e./yr), which corresponds to $0.64 \pm 0.02 \times 10^6$ m³ of ice volume loss ($0.59 \pm 0.02 \times 10^6$ m³ w.e.). During the same period the glacier experienced around 12 m of frontal retreat, with flow rates of 2.3 to 3.5 m/yr (all data in horizontal component). Glacier ice thickness was obtained using Eq. (1) and the results are presented

Table 3

Calculated ice thickness (E) of Martial Este Glacier based on Eq. (1) (see text), considering a glacier surface slope α (degrees) and a horizontal flow velocity u_0 , calculated from the 1984 and 1998 horizontal stake displacements (X). Stake positions are shown in Fig. 2

Stake	X (m)	u_0 (m/y)	α	E (m)
j1	31.5	2.3	20	37
j3	45	3.2	21	40
j4	35	2.5	21	37

Table 4

Mass balance data of Martial Este Glacier during the hydrological years 2000, 2001, and 2002. *h*: stake elevation a.s.l.; *nc*: net accumulation; *na*: net ablation; and *nb*: net balance of the glacier in mm water equivalent. "Mean" is the average of *nc*, *na*, and *nb* considering all the zones

Zone	<i>h</i> (m a.s.l.)	Hydrological year 2000			Hydrological year 2001			Hydrological year 2002		
		<i>nc</i> (mm)	<i>na</i> (mm)	<i>nb</i> (mm)	<i>nc</i> (mm)	<i>na</i> (mm)	<i>nb</i> (mm)	<i>nc</i> (mm)	<i>na</i> (mm)	<i>nb</i> (mm)
Zone 1	1048	874	−309	565	508	−1386	−878	658	−804	−146
Zone 2	1049	1042	−619	423	274	−1438	−1164	486	−996	−510
Zone 3	1050	923	−537	386	325	−1267	−942	513	−977	−464
Zone 4	1072	1046	−469	577	545	−1377	−832	563	−917	−354
Zone 5	1105	1163	−202	961	648	−1234	−586	993	−1001	−8
Zone 6	1120	1388	−306	1081	691	−1298	−607	781	−928	−147
Zone 7	1122	1388	−306	1081	691	−1198	−507	964	−847	117
Zone 8	1088	1558	0	1558	787	−966	−178	956	−821	135
Zone 9	1084	1132	−362	770	736	−1118	−382	741	−739	1
Zone 10	1082	1006	−362	644	736	−1481	−745	494	−1082	−588
Zone 11	1074	1075	−288	787	728	−1321	−594	618	−917	−299
Zone 12	1053	972	−387	584	672	−1686	−1014	557	−1144	−587
Mean		1131	−346	785	612	−1314	−702	694	−931	−237

in Table 3. Considering these possible ice thickness values and the 1998 topographic data of MEG, a total ice volume of $2.9 \times 10^6 \pm 0.5$ m³ was obtained.

Mass balance measurements by means of the stratigraphic (stake) method were initiated at Martial Este Glacier in March of 2000, at the start of the hydrological year. The mass balance of the hydrological year 2000 was markedly positive, with high winter snow accumulation followed by a cold and humid summer season. The net balance of the glacier was positive along the entire glacier surface, reaching 785 ± 50 mm w.e. (Table 4). The equilibrium line altitude (ELA) was 1040 m a.s.l. During the hydrological year 2001, winter snow accumulation was scarce, followed by a warm and dry summer (Table 5), determining a negative net balance of -702 ± 50 mm w.e. The ELA was located at 1120 m a.s.l., close to the upper edge of the glacier. For the 2002 hydrological year the glacier net balance was slightly negative (-237 ± 50 mm w.e.). The ELA was located at 1090 m a.s.l., the same altitude as the mean ELA corresponding to the entire 3-year period. The mass balance for the period 2000–2002 was slightly negative, with a mean of -51 ± 50 mm w.e.

4.4. 1901 to 2002 glacier response to climate change

During the 20th Century, the ELA of Cordón Martial glaciers fluctuated markedly (photographic documentation and field works 1984–2002), indicating that some years the accumulation area, and other years the ablation area, extended over the whole glacier. This allows us to expect a rapid response of the glaciers to a change in climate. Although only 8 data points on glacier area fluctuations (MSG and MCWG) are available (Table 2 and Fig. 4A), their trend shows, as can be expected, a rapid adjustment to the change and variability recorded in last 100 years of precipitation and temperature data from Ushuaia (Fig. 4B and C). In this analysis we assume that warm and dry climate produce glacier ice mass decay and that cold and wet conditions favour glacier expansion. Cold and dry climate produce roughly equilibrium conditions, and the same is valid for warm and wet periods.

Although the three historical glacier surface data (1898–1943) are similar, determining a near-constant trend, De Agostini (1929) pointed out that, during the 1923 austral summer, the Martial glaciers, like others in

Table 5

Summer mean annual temperature, lapse rate, and seasonal thermal amplitude during the hydrological years 2000, 2001, and 2002 obtained at the meteorological stations CADIC (Ushuaia) and Martial Este Glacier (MEG)

Cycle	Temperature — Annual average °C			Cycle	Temperature — October–March average °C			Cycle	Seasonal amplitude °C	
	Ushuaia 20 m a.s.l.	MEG 990 m a.s.l.	Lapse rate °C/1000 m		Ushuaia 20 m a.s.l.	MEG 990 m a.s.l.	Lapse rate °C/1000 m		Ushuaia 20 m a.s.l.	MEG 990 m a.s.l.
2000	4.9	−1.5	6.3	2000	7.6	0.9	6.6	2000	4.8	4.2
2001	5.5	−0.6	6.0	2001	8.1	1.5	6.5	2001	5.1	4.0
2002	5.3	−0.9	6.1	2002	8.1	1.1	6.9	2002	5.4	4.0

the region, showed a marked recession compared to observations during his first visit to Ushuaia in 1910. Two important precipitation minima and a marked temperature increase between 1910 and 1925, especially during the summer, are probably related to De Agostini's (1929) statement (Fig. 4B and C). In the period 1925–1939 the temperatures and precipitation remained relatively high with a maximum decadal mean precipitation value of 661 mm occurring between 1928 and 1938. Nevertheless, considering the local lapse rate of ~ 6.2 °C/1000 m (Table 5), a significant amount of solid precipitation probably occurred above 800 m a.s.l., which can explain the near-constant glacier surface area during this decade (Fig. 4A). The marked annual precipitation decrease between 1939 and 1943 probably promoted the 1943 to 1948 glacier recession. From 1948 until 1970 we can explain the glacier stabilization principally as a result of temperature drop. Finally, the glacier retreat since 1970 can be related with the significant reduction in precipitation and increase in temperature (0.8 °C). The decade 1981–1990 was the driest of the century, with a mean annual value of only 473 mm. During the following 10 years, precipitation increased reaching a decadal mean of 505 mm, but still remaining below the secular mean of 535 mm. The climate change of the last 32 years was clearly reflected in the glacier behaviour, through an average surface reduction for the 4 glaciers at a rate of 1.21 ha/year (Table 2).

4.5. Past, present and future of the Cordón Martial glaciers

The reconstructed LLIA ice surfaces of Cordón Martial glaciers yield a ~ 900 m a.s.l. ELA. Considering the measured saturated adiabatic lapse rate (Table 5) and the present ELA position of ~ 1090 m a.s.l., this corresponds to a 1 °C decrease of the mean annual air temperature. This agrees with the ~ 1 °C lower than present seawater temperature around Ushuaia during the LLIA (500–200 ^{14}C yr BP) (Obelic et al., 1998). Tree-ring studies around Ushuaia (Bonisegna et al., 1990) indicate that shortened summer seasons occurred after the LLIA during two periods, 1855–1865 and 1885–1895, with an air temperature decrease of up to 1 °C relative to the 20th Century secular mean. During the last 100 years, the air temperature in Ushuaia has decreased by 1 °C below the secular mean for a few years (Fig. 4B), but no glacier advances have occurred in any of the post LLIA cold periods. Assuming uniform precipitation conditions, it follows that in this area a longer-lasting (> 10 years) temperature drop of 1.0 °C is necessary to trigger a glacier advance resulting in moraine deposition.

In the western Cordillera Fueguina, around the Monte Sarmiento Massif, the same post LLIA cold periods match with glacier advances and recessional moraine deposition. Between 1898 (Fig. 2) and 1943 Cordón Martial glacier fronts remained stable, close to the LLIA moraines. Cold periods were not significant enough to promote an advance but caused the retreat to halt temporarily. An important period of glacier retreat occurred between 1943 and 1948, but was immediately followed by ~ 25 years of no change in glacier surface area. The last 30 years of the 20th Century were characterized by warm and dry climate conditions, which induced a marked glacier recession. This was also the case on the northern slope of Cordillera Darwin in western Tierra del Fuego (Holmlund and Fuenzalida, 1995), including the particularly strong retreat of Marinelli Glacier (Porter and Santana, 2003). Despite uncertainties in predictions in future global warming rates due to changing atmospheric greenhouse gases and aerosol concentrations, as well as to other anthropogenic and natural variables that affect the ocean and atmospheric circulation (Stott and Kettleborough, 2002), most models, such as those used by the Intergovernmental Panel on Climate Change (IPCC), including the GISS-NASA/GSFC model, (Lucarini and Russell, 2002 and url <http://aom.giss.nasa.gov/>) indicate a positive global mean-surface temperature trend during the 21st Century, mainly in response to an enhanced anthropogenic greenhouse effect. The Atmosphere-Ocean Model (GISS-NASA/GSFC) was applied in Tierra del Fuego, at a local grid of 52° to 56° S and 70° to 65° W, yielding a positive mean annual air temperature trend. Assuming that the temperature trend for the last 30 years continues, we linearly extrapolated the curves of the simultaneously declining glaciated area shown in Fig. 4A. This simplified projection suggests that only one of the four cirque glaciers studied, the Martial Este Glacier, will survive the 21st Century. The Martial Sur Glacier would disappear in 2011 and Martial Centro Oeste and Martial Centro Este glaciers would disappear around the mid-21st century.

5. Conclusions

Following the absolute glacier chronology established in Monte Sarmiento Massif, the last moraine ridges of Cordón Martial were deposited ~ 330 ^{14}C yr BP, during the LLIA glaciation (*sensu* Clapperton and Sugden, 1988). No recessional glacier advances, such as those observed in the Monte Sarmiento Massif, were detected among the Cordón Martial glaciers after the LLIA advance. The Cordón Martial glaciers area fluctuations adhere well to

the 20th Century 4-year mean temperature and precipitation curves of Ushuaia. After a relative stability until 1943, the Cordón Martial glaciers retreated markedly for a short period until 1957, stabilized again until 1970, and have retreated continuously since then. The measured mean specific net balance of -0.45 m w.e./yr in the period 2000–2002 for Martial Este Glacier is similar to the value obtained for 11 mountain glaciers in the world: -0.44 m w.e./yr for the 5-year period of 1990–1995 and -0.37 m w.e./yr for the 1980–1990 decade (IAHS (ICSJ)/UNEP/UNESCO, 1996). This value represents a confirmation of a worldwide trend.

Despite their short time range, the 3-year period of net balance for Martial Este Glacier shows significant results. Moderate humid and cool years such as 2000, especially during the summer season, cause a significant positive net balance. Conversely, a moderately dry and warm year like 2001 determines a marked negative net balance. The year 2002 represents a year with near-balance conditions. Small glaciers, like Cordón Martial glaciers of Cordillera Fuegoina Oriental, react fast to 20th Century climate change, so that their behavior is an important indicator of the climate variability. The climate trend projection for the next 100 years predicts the vanishing of most of these glaciers.

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