Inventory of glaciers in isla Riesco, Patagonia, Chile, based on aerial photography and satellite imagery

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ABSTRACT. A glacier inventory for península Córdova, isla Riesco, Chilean Patagonia (53°14′ S, 73°00′ W), has been compiled based on stereoscopic interpretation of aerial photographs of March and December 1984 and 1 : l00 000 topographic maps. Three small icefields comprising 33 glacier outlets, in addition to 12 small separate glaciers, have been identified, with a total area of 57 km². Glaciers are located on mountain peaks with a maximum altitude of 1183 m and a lowermost elevation of 100 m. All glaciers terminate on land, except for three glaciers calving into small fresh-water lakes. A Landsat Thematic Mapper (TM) image of 6 October 1986 has been rectified and analyzed using a supervised classification to estimate snow- and glacier-covered surfaces. Glacier-area data derived from satellite-image analyses have been adjusted at península Córdova using photo-interpreted data, and extrapolated to estimate a glacier area of 215 ± 40 km² for all of isla Riesco. The presence of trimlines and moraines beyond the present position of the glaciers indicates a generalized retreat from a maximum neoglacial position at península Córdova, most probably as a result of regional warming and precipitation decrease observed during the last century.

INTRODUCTION

The glacier inventory of Chile covers the Andean region from Arica (18° S) in the north to the lake district (41° S) in the south, including 1675 individual glaciers with a total area of 6606 km² (Casassa, 1995; Rivera and others, 2000). These glacier inventories have been compiled largely by the Dirección General de Aguas (DGA; National Water Cadastre of Chile). The inventories and the study of glacier variations are especially important in basins close to populated areas in central-south Chile for estimating water resources and predicting future availability. This information is also important for studying climatic changes and for basic glaciological research.

In Patagonia, south of 41° S, detailed glacier inventories and variations have been compiled only for Hielo Patagónico Norte and Sur (HPN and HPS; northern and southern Patagonia icefields), which include a total glacierized area of 17 200 km² and are by far the largest ice bodies in South America (Aniya, l988; Aniya and others, 1996, 1997). HPN lies entirely in Chile, while approximately 81–92% of the area of HPS lies in Chile.

Two smaller icefields located south of HPS in Patagonia are currently being studied by multidisciplinary teams: Gran Campo Nevado in the southern part of península Muñoz Gamero (Kilian and others, 2000), with an approximate area of 200 km²; and isla Santa Inés to the south of the Strait of Magellan (personal communication from K. Bennet and V. Pojhola, 200l), with an estimated area of 100 km². In Tierra del Fuego, recent variations of a few outlet glaciers of Cordillera Darwin (area approximately 2000 km²) have

been determined (Holmlund and Fuenzalida, 1995). Glaciological measurements are being performed by C. Porter (personal communication, 200l) at a few outlet glaciers of Cordillera Darwin and the small ice cap of isla Hoste located south of the Beagle Channel, with an estimated area of 150 km² (Casassa, 1995).

Large glacierized areas in southernmost Chile are virtually unstudied, with neither a glacier inventory nor an assessment of ice variations. The total uninventoried glacier area in Chile between 41° and 55° S is estimated as 5200 km² (Rivera and others, 2002). This paper describes the first glacier inventory for península Córdova, isla Riesco, based on aerial photographs. The inventory is extended to all of isla Riesco using a Landsat TM image and a simple lineal algorithm to correct for enhanced snow cover at the time of image acquisition.

SITE DESCRIPTION

Isla Riesco is a large island oriented approximately east–west, stretching from 52°40′ to 53°30′ S and 73°30′ to 71°20′ W, about l30 km long and 50 km wide (Fig. 1). It is bounded to the north by Skyring sound, to the south by Otway sound, to the east by Fitz Roy channel, to the west by Gajardo channel, to the southwest by the Strait of Magellan and to the southeast by Jerónimo channel. Large Pleistocene glaciers occupied each of these waterways during the Last Glacial Maximum (Clapperton, l993). Península Córdova is located at the southwestern end of isla Riesco, along the northern flank of the Strait of Magellan (Fig. l).
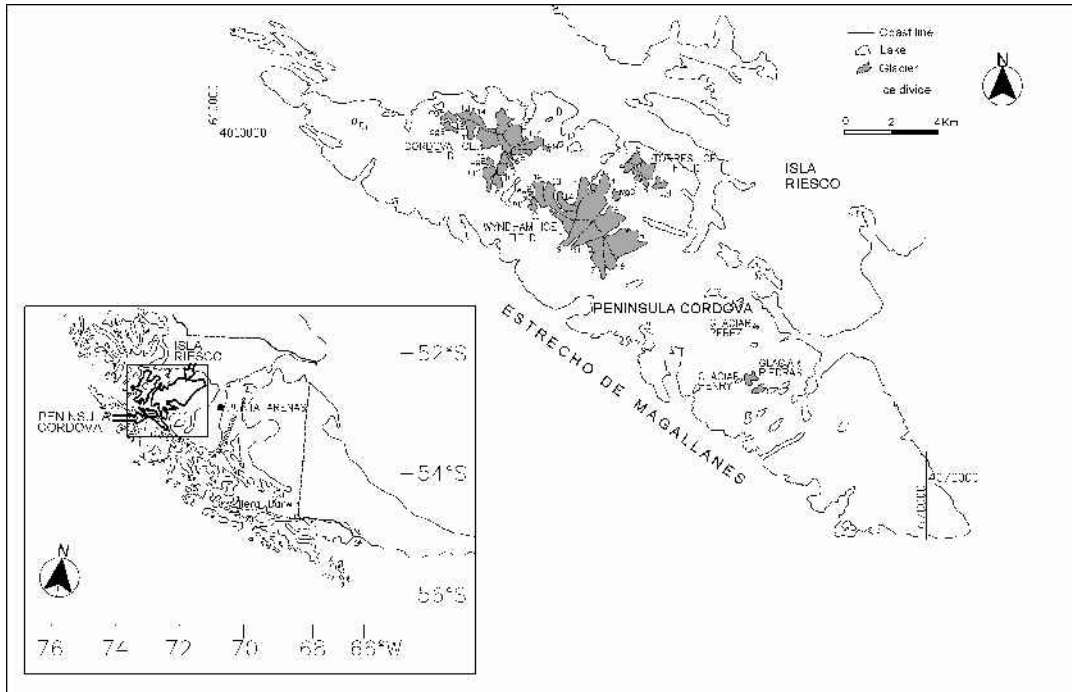
373

Fig. 1. Glaciers of península Córdova, isla Riesco. Numbers and names correspond to the list in Table 1. Gridlines are expressed as Universal Transverse Mercator (UTM) coordinates. The inset shows the coastline of isla Riesco drawn with a thick line, where Península Córdova appears on the lower left of the island. G is Gran Campo Nevado icefield, located on península Muñoz Gamero.

The eastern part of the island is relatively flat and has moderate precipitation ($<1000\,\mathrm{mm\,a}^{-1}$; DGA, 1987) because it is located leeward of the Andes mountains. A few farms exist in this part of the island, mainly involved in cattle raising. The island has two gravel roads, each with a maximum length of about 50 km, located along the shores of Skyring and Otway sounds. The western part of isla Riesco is located within the main belt of the Andean cordillera, with high precipitation rates ($>1000\,\mathrm{mm\,a}^{-1}$) driven by the strong westerly circulation. In this western sector, which is virtually uninhabited, the highest mountain peaks have an elevation of 1830 m, including several small ice caps and mountain glaciers.

Sixty kilometres northwest of península Córdova lies Gran Campo Nevado, an ice cap of about $200\,\mathrm{km}^2$ (Casassa and others, 1998), which is presently being studied by a multidisciplinary German group (Kilian and others, 2000). Preliminary meteorological measurements show an annual precipitation of about $9\,\mathrm{m\,a}^{-1}$ at canal Gajardo on the coast (personal communication from C. Schneider, 2001), which is probably also representative for the westernmost part of isla Riesco.

METHODS AND DATA

Aerial photographs

Vertical aerial photographs for península Córdova of March and December 1984 provide complete coverage during a period with relatively small snow accumulation. These photographs were acquired by Servicio Aerofotogramétrico of the Chilean Air Force with a 23×23 cm format and a nominal scale of 1:60 000. The only other aerial photographs available for the area are the Trimetrogon vertical and oblique photographs acquired by the U.S. Air Force in 1944/45. Glacier boundaries, which generally appear quite distinct on the 1984 photographs, were plotted stereoscopically. Glacier margins were then drawn on 1:100 000 maps of Instituto Geográfico Militar (IGM) sheets "Golfo Xaultegua" and "Estuario Wick-

ham", using a monoscopic Zoom Transfer Scope of Bausch and Lomb. Three icefields and 12 small glaciers were detected on península Córdova (Fig. 1). For the icefields, individual catchment areas were identified for each glacier tongue, based on estimated ice divides according to the 1:100 000 IGM maps.

The glacier margins and ice divides for península Córdova were digitized and imported as vector files to Auto-CAD digital cartographic software. Polygons were defined semi-automatically using a topological scheme, calculating areas, lengths and mean glacier coordinates digitally. Glacier aspect, elevations and relief were estimated directly on the 1:100 000 maps.

Satellite imagery

One Landsat TM image acquired on 6 October 1986 was available for isla Riesco (Fig. 2). The image has a nominal pixel resolution of 28.5 m, and is almost entirely cloud-free, except for a small section southeast of península Córdova, near Jerónimo channel. Snow cover is unfortunately very extensive in the image, due to the early-spring acquisition period, making it difficult to distinguish glaciers from snow cover.

The image was geometrically rectified using a second-order polynomial based on 38 points identified from the 1:100 000 maps, evenly distributed along isla Riesco. The mean registration error is 1.3 pixels (36 m), although maximum errors as large as 3 pixels (86 m) were detected at some locations relatively far from control points.

A supervised maximum-likelihood classification according to Engman and Gurney (1991) was carried out for isla Riesco for the classes sea water, shadow, clouds, glacier, snow and inland lake using Erdas Imagine 8.4 image-processing software. This semi-automatic technique did not perform adequately because glacier and snow were not clearly distinguished in the image. Instead, an on-screen digitizing of polygons of glaciated areas was carried out using a combination of bands 4, 5 and 7 which provided a satisfactory visual-
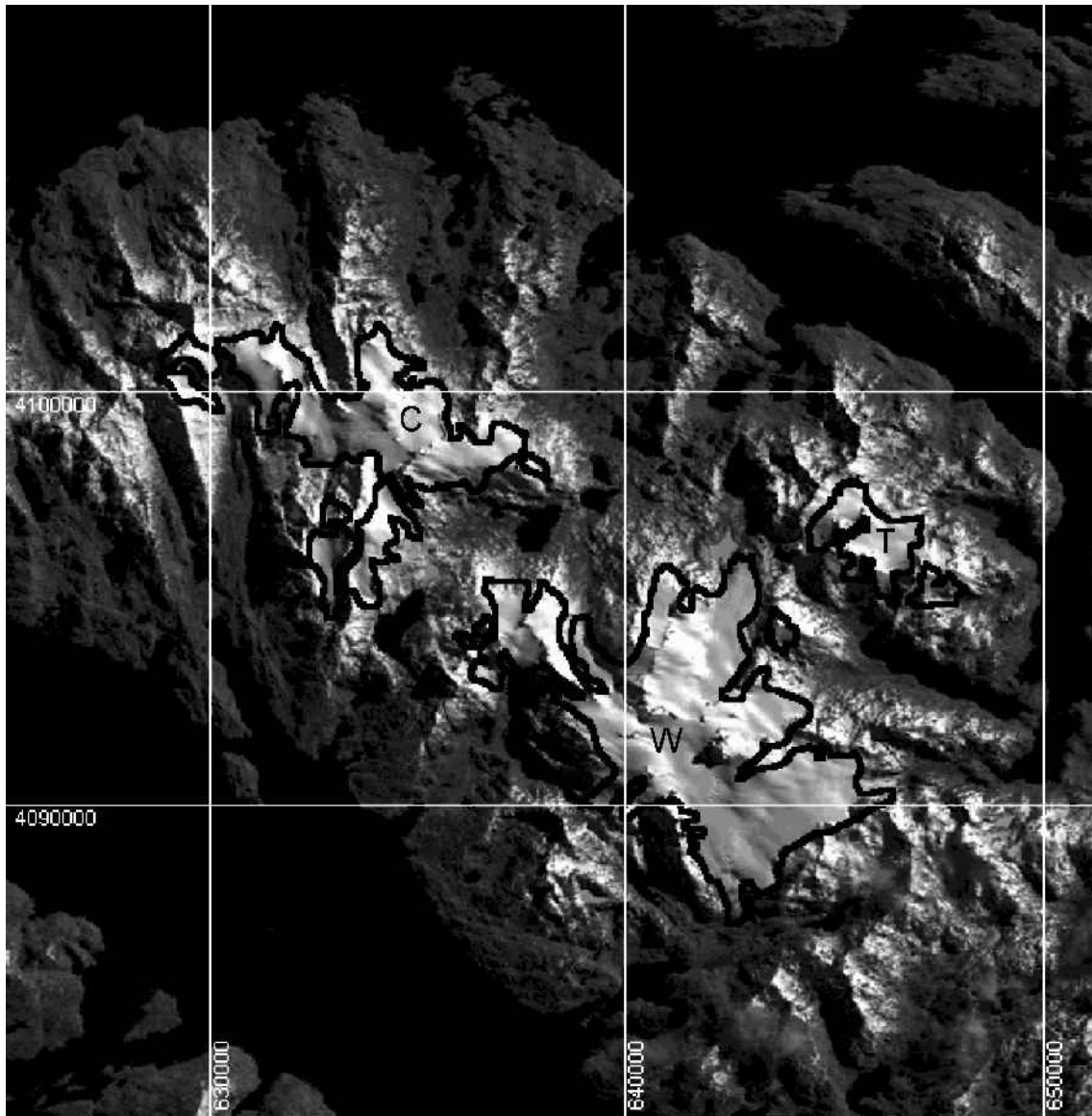
374

Fig. 2. Band 4 data (near-infrared) of a Landsat TM image of Córdova icefield (C),Wyndham icefield (W) and Torres icefield (T) at península Córdova, acquired on 6 October 1986. The thick black line shows the glacier perimeter interpreted from the aerial photographs. Glaciers appear larger in the image due to extensive snow cover at the time of image acquisition. Gridlines correspond to UTM coordinates.

ization. Combinations such as Landsat TM band 4/band 5 (near-infrared), which are typically used to distinguish snow from glacier ice (Engman and Gurney, 1991), did not perform adequately either, which is not surprising considering that probably fresh snow covered all of the glacier and some of the rock area at the time of image acquisition.

By using the on-screen digitizing scheme in combination with the unsupervised classification, an improved glacier area estimate was obtained for isla Riesco. Glacier areas were calculated digitally on the image using Idrisi 32 image-processing software, and are shown in Figure 3.

GLACIER INVENTORY

Inventory of península Córdova derived from aerial photographs

Three small icefields were identified at península Córdova from the aerial photographs: Córdova,Wyndham and Torres icefields (Fig. 1), with an area of 15.4, 32.0 and 3.8 km^2, respectively. These icefields can be divided into 33 smaller

catchment areas, each corresponding to a different glacier tongue that could be identified on the photographs. In addition, 12 separate small glaciers were found, with a total area of 5.6 km^2. Considering both icefields and glaciers, the glacierized area for península Córdova is 56.8 km^2.

The glacier inventory is shown in Table 1, including mean latitude, longitude, length, area, aspect, nature of terminus, elevation and relief. Only three glaciers calve into small fresh-water lakes, the rest terminate on land, and none of the glaciers reaches sea level. No predominant glacier aspect can be found, and glaciers radiate in all directions. Accumulation and ablation areas could not be identified, because the local equilibrium-line altitude (ELA) is unknown (see next section).

The maximum elevation of península Córdova is 1183 m at Mount Wyndham, the highest point of Wyndham icefield, whereas the minimum elevation of glaciers on the peninsula is 100 m, corresponding to the elevation of the proglacial lake of glacier 7 of Wyndham icefield. The second lowest glacier-front elevation is 300 m. The mean highest elevation for all glaciers is 867 m, while the mean elevation of the glacier fronts is 497 m, yielding an overall average elevation of 682 m for the
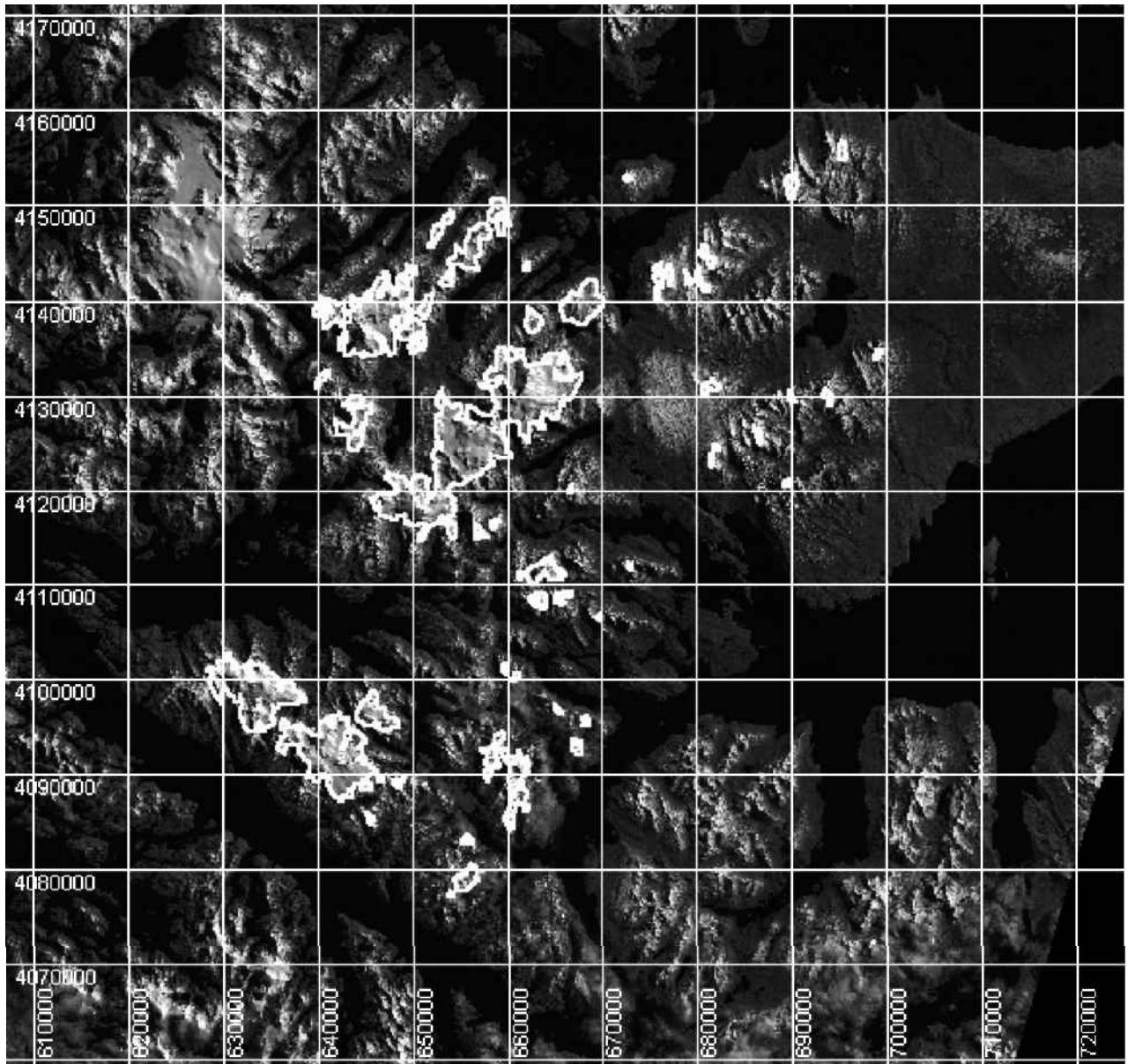
375

Fig. 3. Band 4 data (near-infrared) of the 6 October 1986 Landsat TM image for the central-western part of isla Riesco. The thick white lines show the glacier perimeter interpreted using a supervised classification as described in the text. Gridlines correspond to UTM coordinates.

glaciers. Maximum elevations for some glaciers such as CG3 and CG5 (Table 1; Fig. 1) are probably underestimated because of the low resolution of the 1:100 000 scale maps.

The above information indicates that glaciers at península Riesco are clearly confined to the mountain slopes, with small accumulation areas and with ablation areas that do not extend much beyond the mountain slopes. The only exception is glacier 7 of Wyndham icefield, which has a higher and larger accumulation area, with ice draining down to an elevation of 100 m in the ablation area.

Inventory of isla Riesco derived from the Landsat image

The Landsat image can be used to assess the glacier area for the rest of isla Riesco. This is done in the following way. Firstly, we can compare the glacier areas obtained for península Córdova by aerial-photograph interpretation, calculated as $56.8 \, \text{km}^2$, and by Landsat image analysis, which results in $98.7 \, \text{km}^2$. The areal overestimation of 74% using the Landsat image is clearly a consequence of

interpreting seasonal snow present at the time of acquisition (early spring) as glacier ice. Assuming that the rest of isla Riesco has a similar snow cover at the time of image acquisition, we could simply estimate the glacier area from the analysis of the Landsat imagery, and reduce this area by the reciprocal of the overestimation factor (i.e. 1.74) calculated for península Córdova, that is 57%.

A more accurate procedure to assess glacier coverage from the Landsat image was found by comparing the area of individual ice bodies estimated from the Landsat image with the area derived from the aerial photographs at península Córdova (Table 2; Fig. 4). The ratio (R) of the glacier area obtained by aerial photographs (A_P) and the area obtained by the Landsat image (A_L), calculated as the ratio $R = A_P A_L^{-1}$, was found to be linearly dependent on A_L, as a first-order approximation, for A_L values of $1-47 \, \text{km}^2$. This means that the glacier-area overestimation associated with the Landsat image interpretation is larger for smaller glacier areas. The largest ice mass in península Córdova is the Wyndham glaciers, with $A_L = 47 \, \text{km}^2$ and $R = 0.63$. For areas exceeding $47 \, \text{km}^2$ a constant ratio of 0.63 was adopted

376

Table 1. Glacier inventory for península Córdova. Calving column: N, non-calving glaciers; L, glaciers calving into freshwater lakes

	Mean location	Length of glacier	Area	Aspect	Cal-ving	Max. elev.	Min. elev.	Relief
		km	km²			m	m	m
Córdova icefield								
CIF 1	53°13′ S, 72°59′ W	2.2	1.9	N	N	900	500	400
CIF 2	53°14′ S, 72°58′ W	1.7	2.3	N	N	905	300	605
CIF 3	53°14′ S, 72°57′ W	1.5	0.4	N	N	905	700	205
CIF 4	53°14′ S, 72°57′ W	2.7	1.4	NE	N	905	400	505
CIF 5	53°15′ S, 72°58′ W	1.6	0.8	S	N	905	600	305
CIF 6	53°14′ S, 72°58′ W	1.4	0.5	SE	N	905	640	265
CIF 7	53°15′ S, 72°59′ W	3.2	1.4	SE	L	800	350	550
CIF 8	53°15′ S, 72°59′ W	1.1	0.8	E	N	900	420	480
CIF 9	53°16′ S, 72°59′ W	1.4	0.7	S	N	900	500	400
CIF 10	53°14′ S, 73°00′ W	1.7	2.2	S	N	800	400	400
CIF 11	53°13′ S, 73°01′ W	1.8	1.0	S	N	828	550	278
CIF 12	53°13′ S, 73°02′ W	0.4	0.1	N	N	750	700	50
CIF 13	53°13′ S, 73°02′ W	1.4	0.6	N	N	700	500	200
CIF 14	53°13′ S, 73°01′ W	2..4	1.3	N	N	800	400	400
			15.4					
Córdova glaciers								
CG1	53°16′ S, 73°00′ W	2.2	1.3	S	N	1124	420	704
CG2	53°15′ S, 73°00′ W	0.7	0.3	NW	N	1124	700	424
CG3	53°13′ S, 73°03′ W	1.8	0.6	SE	N	500	400	100
CG4	53°13′ S, 73°03′ W	1.4	0.7	N	N	970	600	370
CG5	53°15′ S, 72°56′ W	0.8	0.2	SE	N	500	400	100
			3.1					
Wyndham icefield								
WIF 1	53°17′ S, 72°53′ W	3.1	1.8	N	N	1000	400	600
WIF 2	53°16′ S, 72°52′ W	0.5	0.2	N	N	700	500	200
WIF 3	53°17′ S, 72°52′ W	4.9	5.8	N	L	1152	300	852
WIF 4	53°17′ S, 72°51′ W	2.6	3.2	N	N	1183	400	783
WIF 5	53°18′ S, 72°50′ W	3.6	5.2	E	N	1000	700	300
WIF 6	53°19′ S, 72°51′ W	2.8	1.7	SE	N	1000	100	900
WIF 7	53°19′ S, 72°51′ W	3.5	3.0	S	L	1000	100	900
WIF 8	53°18′ S, 72°52′ W	2.7	2.6	SW	N	1183	800	383
WIF 9	53°18′ S, 72°53′ W	3.4	2.3	SW	N	1152	500	652
WIF 10	53°18′ S, 72°54′ W	2.3	0.1	NW	N	1000	600	400
WIF 11	53°17′ S, 72°56′ W	0.9	0.6	S	N	973	400	573
WIF 12	53°16′ S, 72°56′ W	2.2	1.6	N	N	973	500	473
WIF 13	53°16′ S, 72°55′ W	4.3	2.7	N	N	900	500	400
WIF 14	53°17′ S, 72°54′ W	2.1	1.2	N	N	900	500	400
			32.0					
Wyndham glaciers								
WG1	53°17′ S, 72°57′ W	0.5	0.1	N	N	800	650	250
WG2	53°16′ S, 72°57′ W	0.5	0.1	N	N	973	850	123
WG3	53°16′ S, 72°50′ W	1.1	0.4	N	N	874	520	354
			0.6					
Torres icefield								
TIF1	53°15′ S, 72°48′ W	1.7	1.6	NE	N	720	500	220
TIF2	53°16′ S, 72°48′ W	1.1	0.3	SE	N	800	500	300
TIF3	53°15′ S, 72°49′ W	1.0	0.5	S	N	800	500	300
TIF4	53°15′ S, 72°49′ W	1.3	0.6	S	N	800	600	200
TIF5	53°15′ S, 72°49′ W	1.0	0.8	N	N	750	500	250
			3.8					
Torres glacier								
TG	53°16′ S, 72°47′ W	1.3	0.8	N	N	948	400	548
Perez glacier								
PG	53°22′ S, 72°39′ W	0.49	0.1	NE	N	700	500	200
Henry glacier								
HG	53°25′ S, 72°40′ W	0.66	0.1	SW	N	700	600	100
Piedras glacier								
PG	53°10′ S, 72°40′ W	0.95	0.9	E	N	802	470	332
TOTAL			**56.8**					

Table 2. Estimated glacier areas for isla Riesco

Polygon name	Polygon No.	A_L km²	R	R^*	Glacier area km²
Córdova icefield and glaciers	10	38.1	0.56	0.56	21.3
Wyndham icefield and glaciers	11	54.2	0.68	0.63	34.0
Torres icefield and glaciers	12	6.5	0.32	0.32	2.1
	13	17.7	0.40	0.40	7.2
	14	20.8	0.43	0.43	8.9
	15	134.3	1.29	0.63	84.3
	16	48.9	0.63	0.63	31.3
	17	37.4	0.55	0.55	20.7
	18	9.9	0.34	0.34	3.4
	19	5.2	0.31	0.31	1.6
		373.0			**214.8**

Notes: Polygon No. refers to a group of polygons of glacier areas interpreted from the Landsat image. For península Córdova, polygon names have been added for Córdova, Wyndham and Torres icefields and glaciers. The smaller glaciers in península Córdova (Perez, Henry and Piedras) are not included since they could not be detected on the Landsat image. Polygon numbers $\geq$13 are located on isla Riesco outside of península Córdova. A_L is the glacier area interpreted using the Landsat image. R is the ratio of area determined by aerial photos (A_P), divided by the area determined by Landsat imagery (A_L), according to the linear regression of Figure 3. R^* is the corrected ratio adopted for estimating glacier areas. Where $A_L \geq 48.9 \, km^2$, a constant ratio $R^* = 0.63$ was adopted (see text).

to avoid obtaining unrealistically large values of R. In fact, glacier areas of $> 47 \, km^2$ on the Landsat image are also largely covered by fresh snow, thus overestimating the real glacier extension.
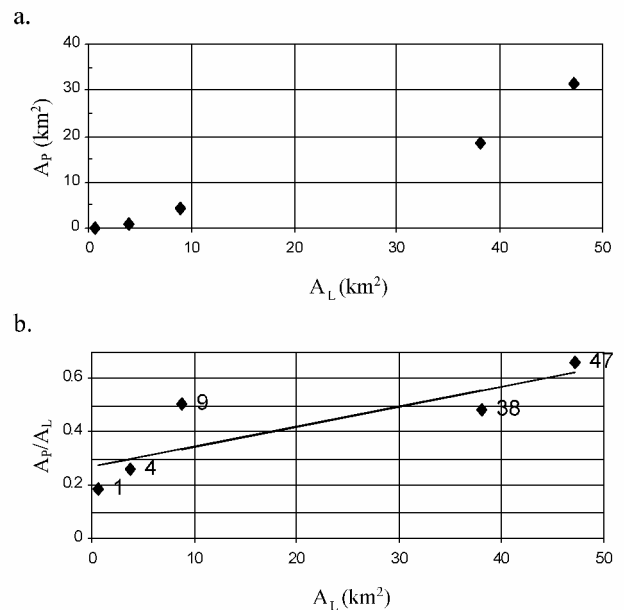

Fig. 4. (a) Plot of glacier areas interpreted from a supervised classification of the 6 October 1986 Landsat image (A_L: x axis) vs the area interpreted from aerial photographs of 1984 (A_P: y axis). (b) Plot of A_L (x axis) vs ratio of $A_P A_L^{-1}$ (y axis). Numbers attached to data points represent areas obtained from the Landsat image, in km^2 (A_L). Data points correspond to the following glaciers: 1. Perez glacier; 4. Piedras and Henry glaciers; 9. Torres icefield and Torres glacier; 38. Córdova icefield and CG1–CG5; 47. Wyndham icefield and WG1–WG3. The line represents a best linear fit with $y = 0.0076x + 0.269$, and $r = 0.84$, valid for $1 \leq A_L \leq 47 \, km^2$. For $A_L > 47 \, km^2$ a constant value of $A_P/A_L = 0.63$ is assumed (see text).

The total glacier area for the rest of isla Riesco, corresponding to polygons 13–19 in Table 2, is $157 \pm 40 \, km^2$. Adding this area to the glacier-covered area of península Córdova obtained by aerial photographs ($56.8 \, km^2$) yields a total glacier area of $215 \pm 40 \, km^2$ for isla Riesco, neglecting errors in the area calculation using the aerial photos. The value of $215 \, km^2$ is more than double the previous estimate of $100 \, km^2$ (Casassa, 1995), which was calculated based on 1:250 000 maps. This shows the need for an improved inventory based on new observations. Considering the high cost of acquiring dedicated aerial photographs, particularly suitable is satellite coverage obtained in a more convenient season (minimized fresh snow cover) with unsaturated pixels over snow and ice and increased resolution compared to Landsat TM. Landsat 7 and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) offer possibilities for such coverage.

GLACIER VARIATIONS AND SENSITIVITY TO REGIONAL CLIMATIC CHANGE

No field data exist for the ELA on isla Riesco. Likewise, the ELA could not be estimated based on 1984 aerial photography or using the 1986 Landsat image, because of image saturation and lack of contrast between snow and ice. Although glaciers show some signs of retreat (see below), it is reasonable to estimate that they have a meaningful accumulation area to replenish at least part of the ablated ice. Therefore, the equilibrium line should be located below 900 m, where nearly all glaciers are located, but above 500 m, the average elevation of glacier fronts, which are located on relatively steep mountain slopes. Any changes in ELA should affect small areas of the glaciers, so the glaciers of isla Riesco should be rather insensitive to climate change (Furbish and Andrews, 1984; Tangborn and others, 1990).

The presence of trimlines above present ice surfaces, and moraines beyond the present position of the glaciers as observed on aerial photographs, indicates that the glaciers of isla Riesco are in a general state of retreat from a Holocene neoglacial, as is evident in other glaciers of southern South America (Clapperton, 1993; Aniya and others, 1997; Rivera and others, 2002). The glacier retreat can probably be correlated with the regional warming of $1.3–2.0°C \, (100 \, years)^{-1}$ observed in Chile during the last 60 years (Rosenblüth and others, 1995), a trend which is also observed in Argentine Patagonia (Ibarzabal and others, 1996). Another factor which should contribute to glacier recession is the precipitation decrease of 25–33% detected at faro Evangelista and bahía Félix stations during the periods 1899–1988 and 1915–85, respectively (Rosenblüth and others, 1995). In the last 15 years, however, a few regional stations show a precipitation increase, as well as an apparent reduction in climate warming (personal communication from J. Carrasco, 2000]), which may result in a future glacier stabilization or readvance.

CONCLUSIONS

Analyses of aerial photographs acquired during mid- and late summer, in combination with 1:100 000 topographic maps, proved adequate for compiling a glacier inventory for península Córdova, isla Riesco. The inventory was extended to all of the western part of isla Riesco using a Landsat TM image acquired in early spring, which shows abundant snow coverage, including glacier-free areas. Although the image does not clearly distinguish between seasonal snow areas and glacier areas, a supervised classification method, in combination with an on-screen image interpretation scheme, was adjusted for the glacier area of península Córdova and allowed to extrapolate the glacier inventory for all the western part of isla Riesco, yielding an approximate total glacier area of $215 \pm 40 \, km^2$ for the island.

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