

Volume changes on Pio XI glacier, Patagonia: 1975–1995

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Abstract

Pio XI glacier, with an area of 1263 km² and a length of 65.7 km, is the largest of the Southern Patagonia Icefield (SPI). During the period 1945–1995 it experienced a net advance of ca. 10 km., a unique behavior considering that virtually all neighboring glaciers are retreating. Two maps at 1:50,000 scale, produced from 1975 and 1995 aerial photography, are used to compute volume changes for this glacier. This is done by digitizing the maps and creating digital terrain models at 200-m resolution. Volume changes for a reduced sample area, in combination with the hypsometric curve of the glacier, are analyzed in terms of the recent advance experienced by the glacier. The sample area (4.5% of the glacier area) for the volume change analysis shows an average thickening on the glacier for the period 1975–1995 of 44.1 m. which represents 2.2 m a⁻¹. The corresponding volume change was 2.52 km³, with a larger thickening in the lower part of the ablation area. The hypsometric curve of the glacier shows a low sensitivity of the glacier to ELA variations. Nevertheless, the increase in temperature has shifted the ELA upwards, reaching close to a threshold, from where the glacier would begin to retreat in the future if the ELA elevation trend continues. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The glaciers of South America have shown a generalized tendency for retreat during this century. In Perú, the retreat has been well documented (Portocarrero, 1995; Hastenrath and Ames, 1995; Kaser et al., 1996). In the Andes of Central Chile, early glaciological studies (Lliboutry, 1956) showed a general retreat with a few exceptions of advancing glaciers in the 1950s. This retreat has accelerated in

recent decades (Rivera and Acuña, 1997). In the central Andes of Argentina, Cobos and Boninsegna (1983), and Llorens and Leiva (1995), also show that a strong retreat is occurring, but with a few exceptions of advances due to surges (Bruce et al. 1987; Leiva et al. 1989). In Cordillera Darwin, in the southernmost Andes, Holmlund and Fuenzalida (1995) describe a clear tendency for retreat of the north-facing glaciers, in contrast to the more stable situation of the south-facing glaciers.

In the Andes of Patagonia, the Southern Patagonia Icefield (SPI), with an area of 13,000 km² is the largest ice body of the Southern hemisphere outside of Antarctica (Aniya et al., 1996). The frontal varia-

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tions of the 48 main outlet glaciers show a generalized retreat. However, several glaciers are stable and one (Pio XI Glacier) has advanced significantly (Aniya et al., 1997).

At a latitude of 49°S in the SPI, which corresponds to the average position of the axis of the westerlies (Caviedes, 1990), the glaciers show a strongly contrasted behavior. At this latitude, on the eastern margin is located O'Higgins Glacier (Fig. 1),

which has experienced a retreat of 11 km in the last 50 years, the largest of all in Patagonia (Casassa et al., 1997), while immediately to the west lies Pio XI Glacier, the largest of the SPI, which has experienced a net advance of 10 km since 1945.

Pio XI Glacier, which was advancing in 1994 over mature 400-year-old trees (Rivera et al., 1997a), is believed to be located at its neoglacial maximum (Warren and Rivera, 1994). The only velocity mea-

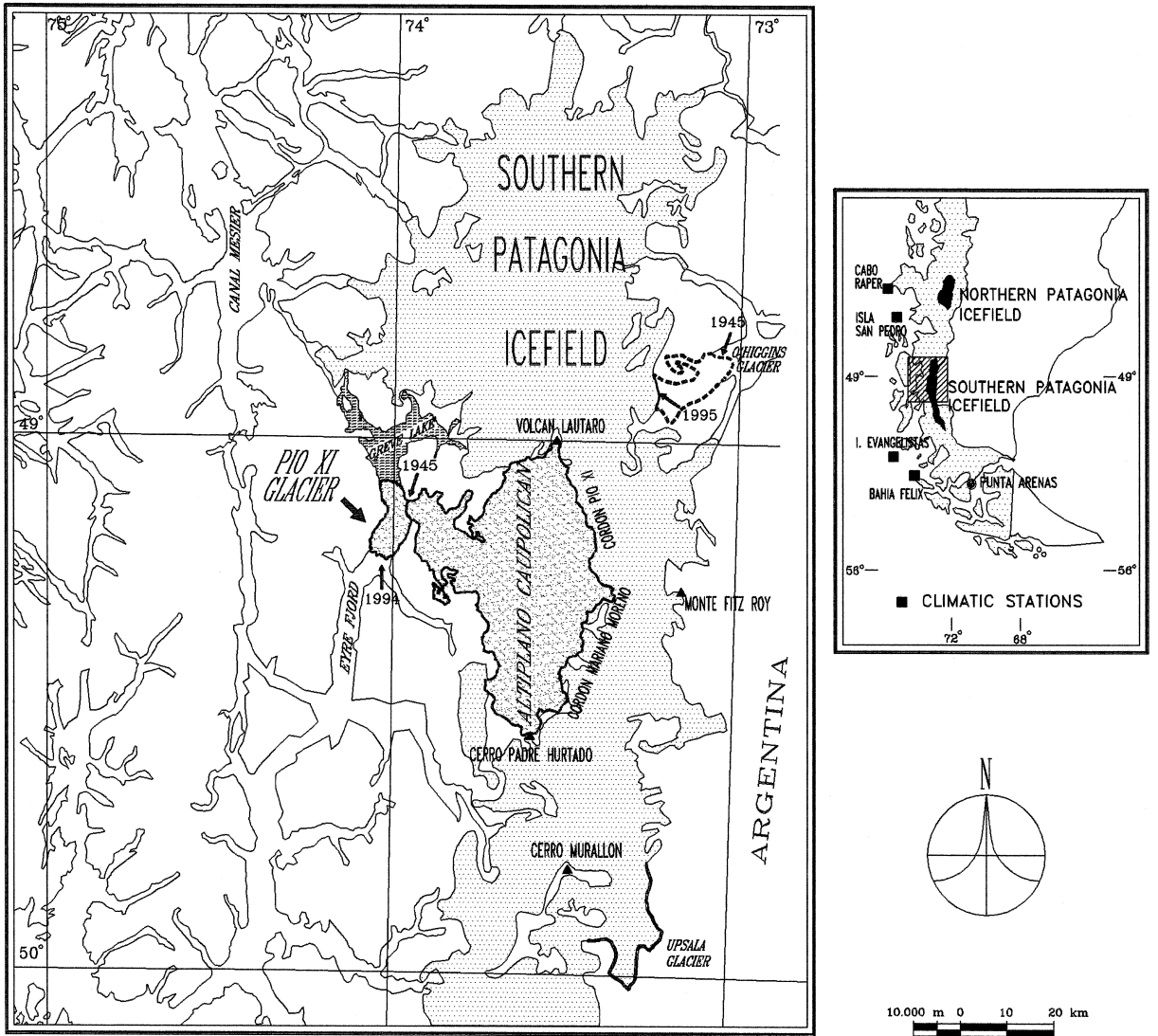


Fig. 1. Location of Pio XI in the SPI and the climatic stations used in this paper.

surements that exist for this glacier are so large (up to 50 m d^{-1}) that they have been interpreted as surging velocities (Rivera et al., 1997b). Different models have been proposed to explain the tendency for advance of Pio XI Glacier (Warren et al., 1997), but there is still no definitive explanation.

The lack of cartography in the SPI has been a serious limitation for defining precisely the topographic characteristics of the glacier tongues and their accumulation areas. In fact, only two hypsometric curves are known to date, which correspond to Moreno and Upsala Glaciers in Argentina (Aniya and Skvarca, 1992). In the case of Pio XI Glacier, the hypsometric curve together with the equilibrium line altitude (ELA) at different periods during this century could shed light to some of the causes for the anomalous advance.

The regional temperature tendency shows a progressive warming during this century (Ibarzabal et al., 1996), which has accelerated in recent years (Rosenblüth et al., 1997). This warming, together with a rainfall decrease indicated at two coastal stations located southwest of SPI (Rosenblüth et al., 1995), suggest a larger retreat of the glaciers in the future.

This paper presents new data regarding volumetric changes of the glacier for the period 1975–1995, which are interpreted in relation to frontal changes. The hypsometric curve of the glacier and ELA altitudes for different periods are analyzed as well.

2. Methods

2.1. Cartography

Two maps of the area of Pio XI Glacier, produced by Instituto Geográfico Militar of Chile (IGM), at 1:50,000 scale were digitized and compared. The first map was generated in the 1980s, using aerial photographs taken during March of 1975, at a scale of 1:45,000. The coordinates are expressed as Universal Transverse Mercator (UTM) units using the South American Datum (SAD 69) of 1969. The altitudes are referred to mean sea level.

The second sheet was generated in 1996, using aerial photographs taken in May of 1995 by the

Servicio Aéreo Fotogramétrico of the Chilean Air Force, at a scale of 1:100,000. This map also has UTM coordinates, but with a WGS 84 datum. The altitudes are referred as well to mean sea level. The 1995 cartography was constructed by IGM based on the accurate GPS position of several control points, which were established on the ground.

Since both maps are referred to mean sea level, they can be compared directly for altimetric purposes. In fact, detailed comparison of heights over rock outcrops showed differences smaller than 10 m.

Contour lines for both maps were digitized, rasterized, interpolated and filtered using the Windows version of IDRISI, a geographic information system (GIS), for generating a digital terrain model (DTM) with a pixel resolution of 200 m. The position error involved by comparing both maps is estimated to be smaller than the pixel size. Ice and rock areas were calculated digitally using IDRISI.

For 1995, the DTM includes all of the accumulation area and a large part of the ablation area as well, down to an elevation of 450 m. The glacier front and the area below 450 m were not covered in the 1995 aerial photographs.

The position of the tidewater front in 1994, was derived from a SIR-C/X-SAR image of April, which was processed by Richard Forster in The Ohio State University (R. Forster, personal communication).

Because the map of 1995 does not cover the lower part of the glacier, and also due to lack of availability of the 1975 cartography for the upper accumulation area, only a limited part of the ablation area of the glacier has been analyzed for volume changes, which is shown in Figs. 2 and 3.

Several altimetric profiles were generated for each map using the software AUTOCAD v. 12 (Figs. 4 and 5). The hypsometric curve of the glacier for 1995 was reconstructed based on the analysis of the DTM, according to the height classification as a function of area (Fig. 6).

2.2. ELA (*equilibrium line altitude*)

For estimating the ELA position, we assume that in Patagonia the snow line at the end of the summer (end of February/beginning of March) corresponds to the ELA. The ELA at different periods was deter-

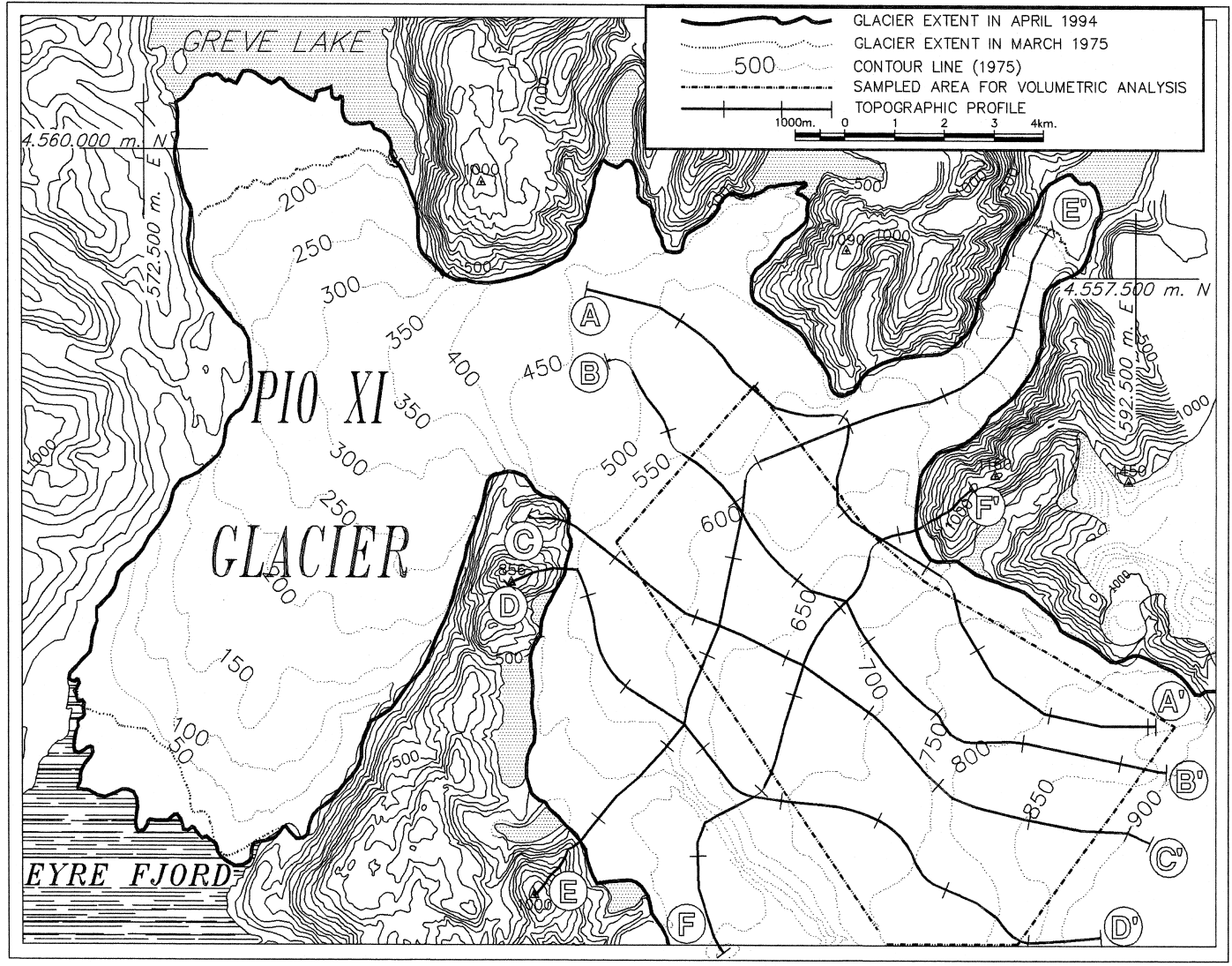


Fig. 2. Sample area for volumetric analyses. Location of the topographic profiles on glacier Pio XI and the glacier fronts in 1975 and 1994.

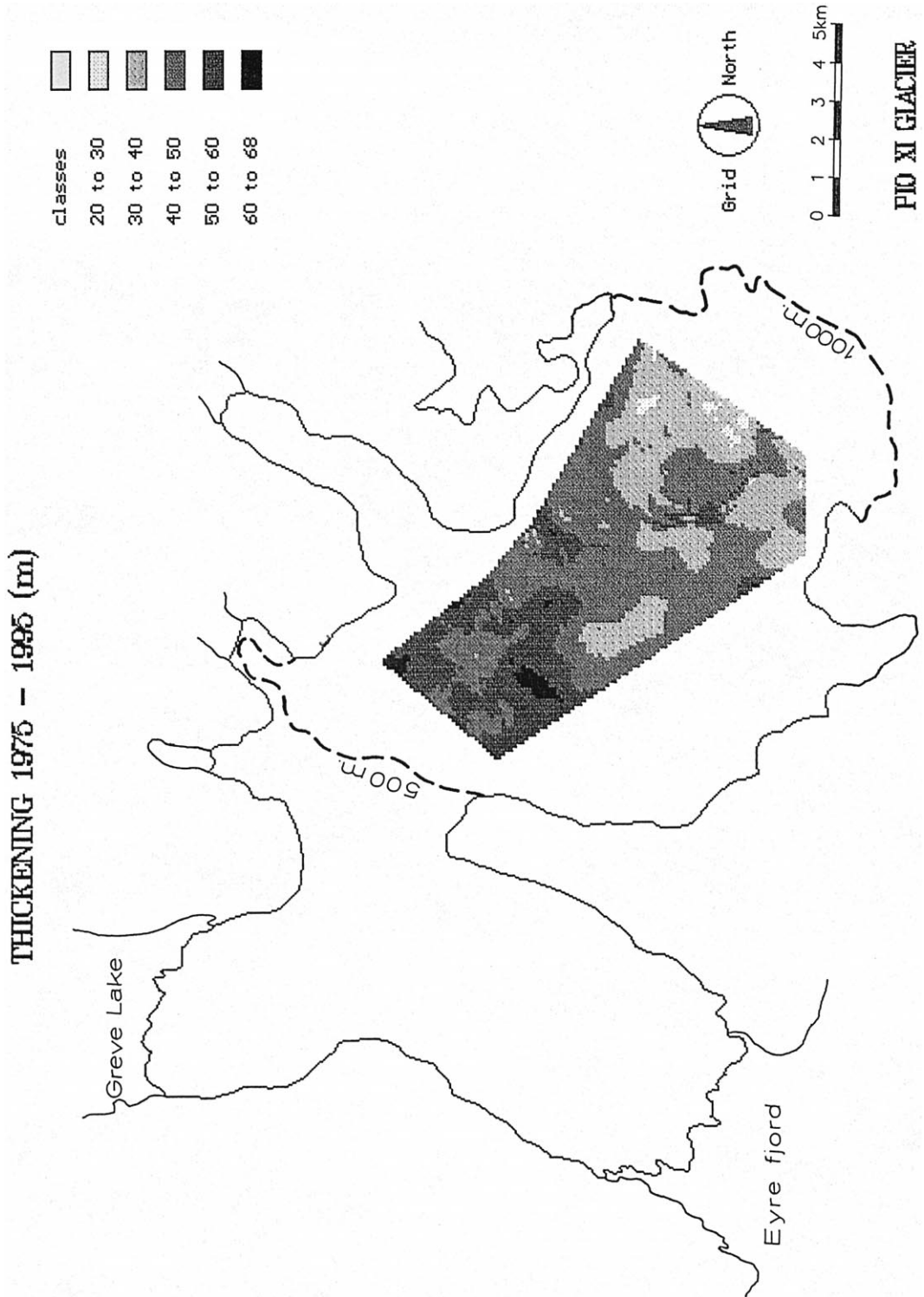


Fig. 3. Ice thickening 1975–1995.

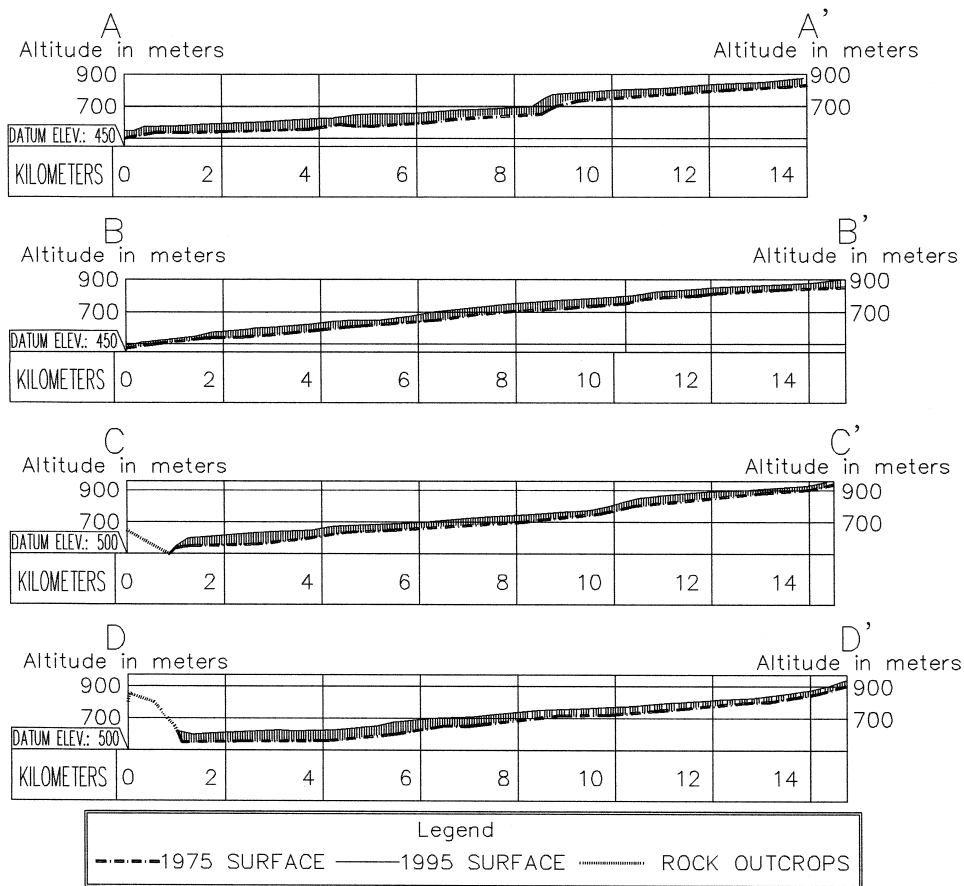


Fig. 4. Longitudinal topographic profiles on Pio XI glacier (1975–1995). The hatched area represents the thickening of the glacier.

mined using field data published earlier, aerial photographs and satellite imagery. Because neither field observations, aerial photographs nor the imagery were acquired exactly at the end of summer, the position derived for the ELA is somewhat speculative, but provide the best data available.

For the years 1945 and 1962, the ELA was defined based on the study of Marangunic (1964), who used Trimetrogon aerial photographs of 1944–1945 and visited the area in 1962. For 1981 and 1985 the ELA was estimated using the results of Rivera (1992), who used aerial photographs for both years. For 1995, the ELA was derived using the SAF aerial photographs of May of that year, using a Bausch and Lomb Zoom Transfer Scope for plotting the ELA to the map.

Finally, the ELA of the glacier at different periods was compared with the present hypsometric curve and the regional temperature and rainfall variations (Figs. 7 and 8).

3. Results

3.1. Calculation of areas

Areas were determined based on 1995 aerial photographs, and the 1:50,000 cartography. The total glacier area in 1995 is 1263 km². This area does not include small rock outcrops, which are associated to

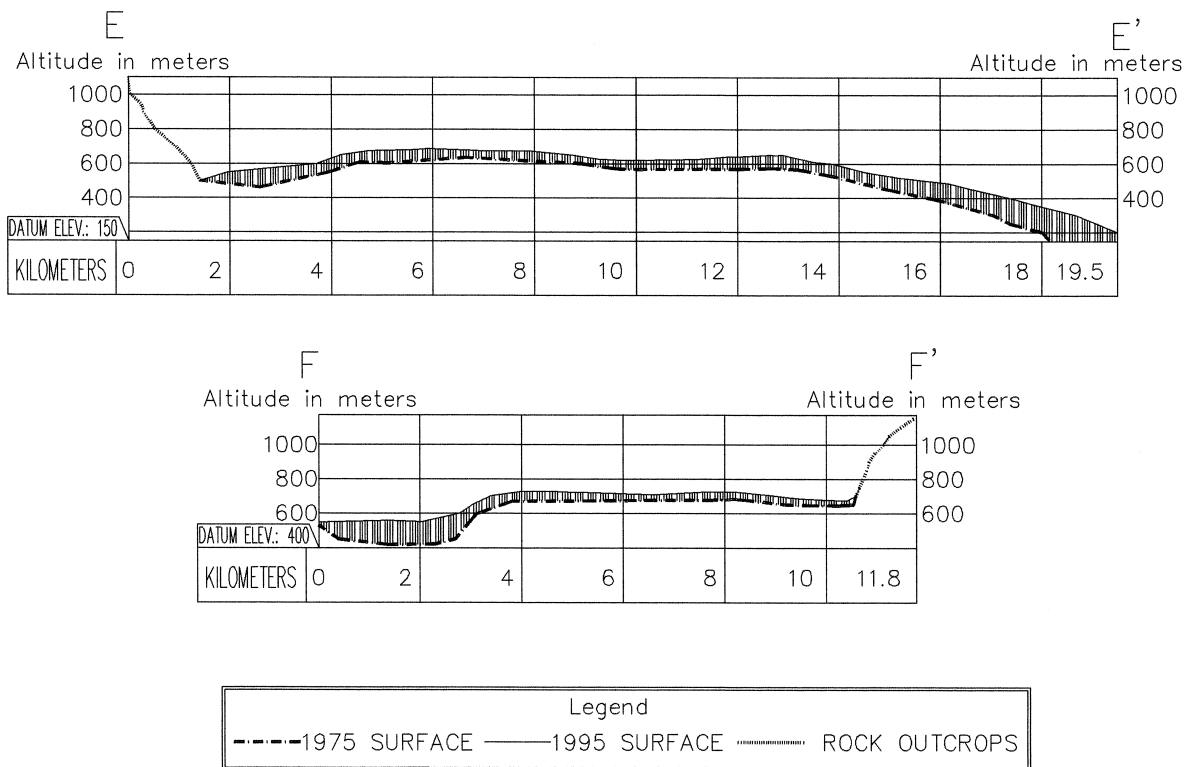


Fig. 5. Transverse topographic profiles on Pio XI glacier (1975–1995). The hatched area represents the thickening of the glacier.

prominent slope changes generally associated with snow and ice avalanches, which comprise a total of 48 km².

The position of the snow line in May of 1995 was located at an elevation of 1050 m. However, several frozen lakes could be observed at 1100 m, so that the ELA during the summer of 1994–1995 was estimated to be at an elevation of 1100 m.

According to this ELA position, the accumulation area in 1995 was 949 km², with an ablation area of 314 km², resulting in an accumulation-area ratio (AAR) of 0.75.

It is interesting to compare these results with those of Aniya et al. (1996), who compiled an inventory covering all the SPI. The study of Aniya et al. was carried out using a Landsat-TM image of January of 1986, georeferenced upon the 1:250,000 preliminary charts of Chile, which have limited accuracy compared with the 1:50,000 charts used in our study.

It can be observed that while the total area obtained by our study is not significantly different from that of Aniya et al., there is a clear change in the extent of the accumulation and ablation areas, as shown in Table 1. As for the larger ablation area derived in this study, it is believed to be mainly due to the advance of the glacier front during the period 1986–1995.

3.2. Volumetric change 1975–1995

An area of 57.1 km² was selected to calculate volume changes in the period 1975–1995. This sample area is located in the ablation area, between an elevation of 500 m and 1000 m (Fig. 2).

In order to compare the surface elevations, the DTMs of 1975 and 1995 were superimposed within this sample area. Both models were adjusted in the areas of rock outcrops, where elevation differences were smaller than 10 m. Small glacier tongues that

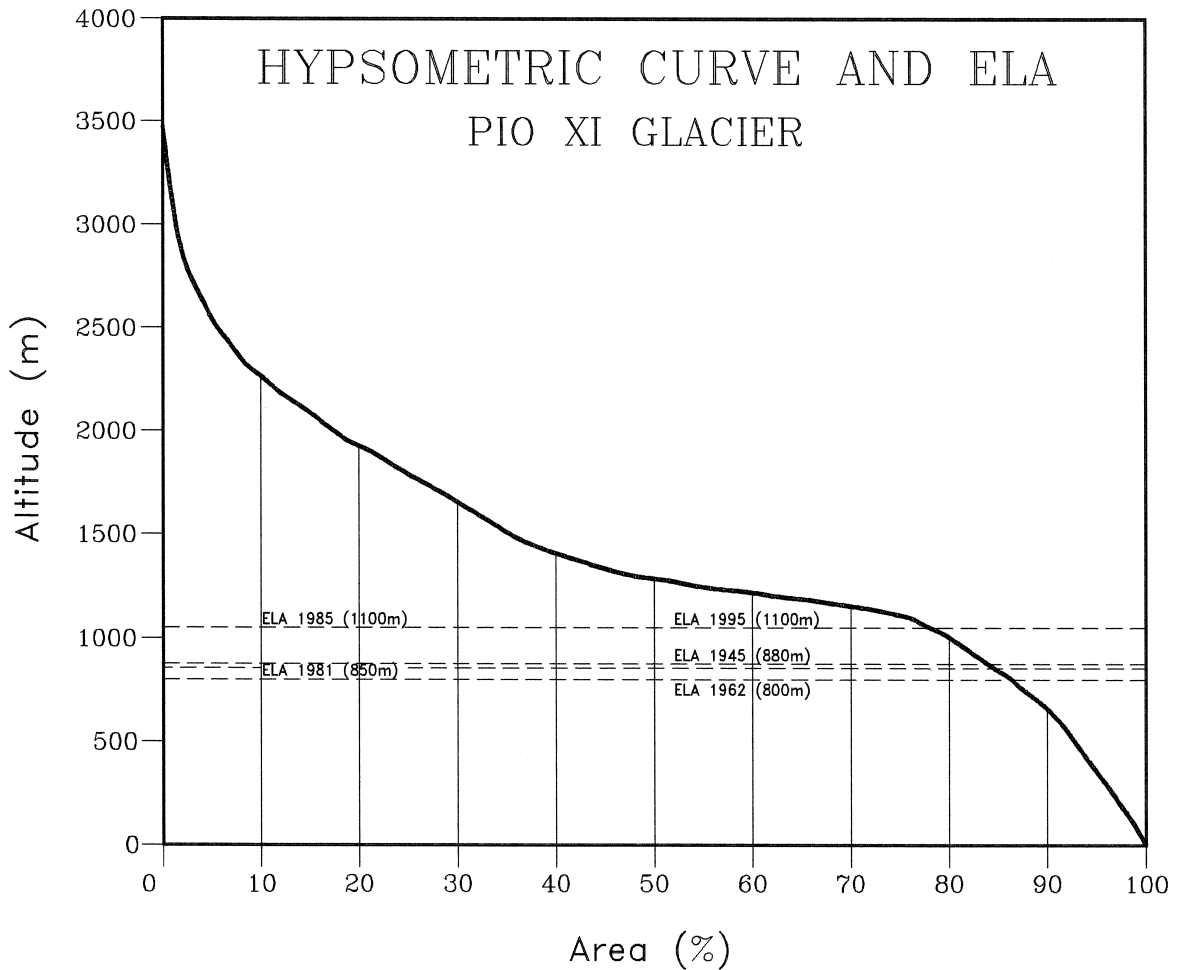


Fig. 6. Hypsometric curve of Pio XI glacier based on the 1995 cartography and ELA.

flow to the north and south were excluded from the sample area so as to eliminate local variations.

The sample area represents an 18% of the ablation area, and a 4.5% of the total glacier area.

Comparison of the DTMs between 1975 and 1995 shows an average thickening of 44.1 m, which represents an average value of 2.2 m a^{-1} for the 20-year period. The largest thickening occurred near the front, with a maximum value of 68 m, and a minimum value of 25 m in the upper area (Fig. 3).

The total ice volume gained within the sample area in the 20-year period is 2.52 km^3 , which repre-

sents a unique case of glacial thickening in Patagonia.

3.3. Topographic change

Several longitudinal and transverse profiles were compiled within the sample area, in order to characterize better the thickening pattern during the period 1975–1995.

The longitudinal profiles (Fig. 4) extend from 900 m to 500 m, in the ablation area of the glacier. Most profiles show a thickening in the lower parts, in particular profiles AA', CC' and DD'. Profile BB',

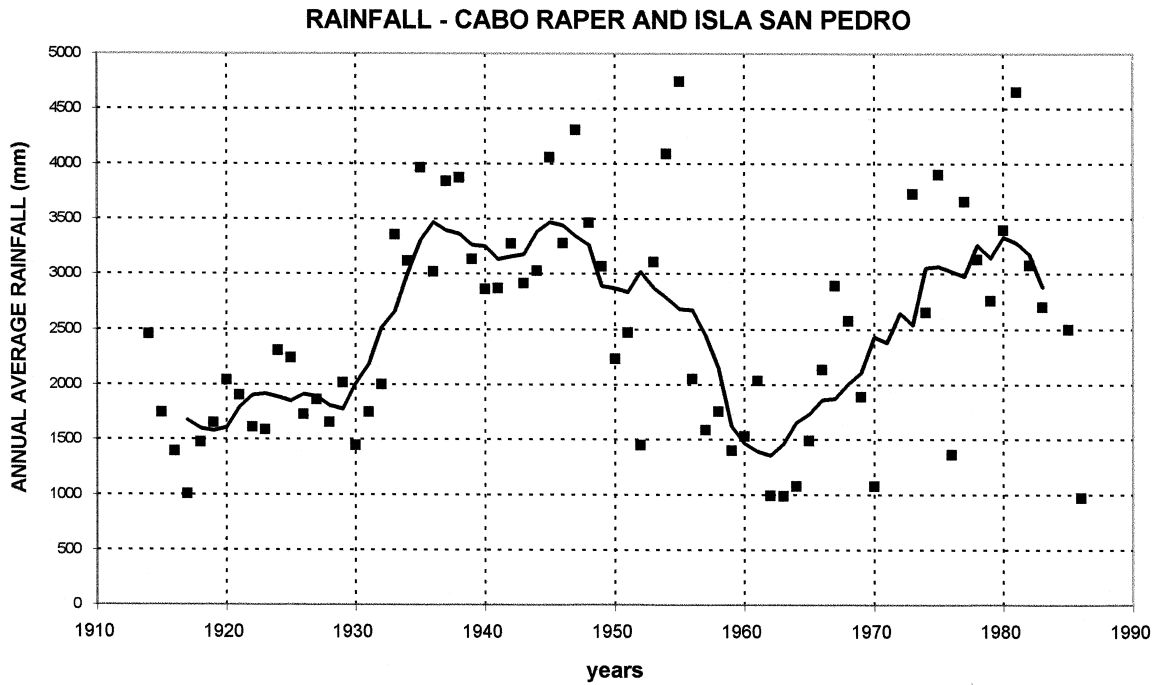


Fig. 7. Annual average rainfall variations calculated with Isla San Pedro (47.4°S/74.6°W) and Cabo Raper (46.5°S/75.4°W) records. The thick curve represents a 4-year moving average.

located in the center of the glacier tongue, presents a larger thickening in the central region.

Transverse profile EE' (Fig. 5) extends from the margins located south of the main tongue, to a

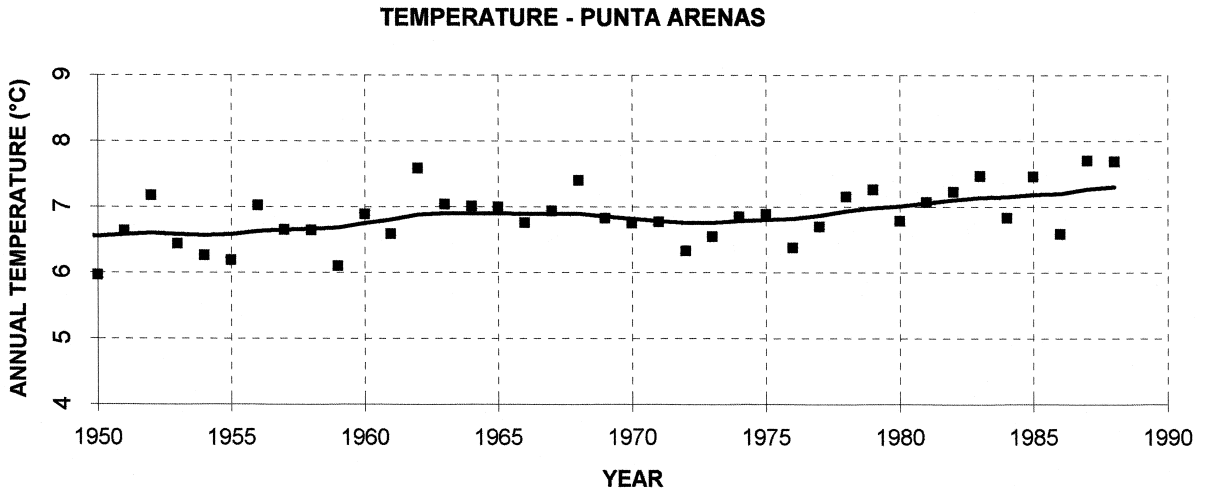


Fig. 8. Mean annual temperature variations in Punta Arenas (53°S/70.9°W). The thick curve represents an exponential smoothing.

Table 1

	Total area (km ²)	Ablation area (km ²)	Accumulation area (km ²)	Bedrock exposures (km ²)	Maximum length (km)
This study	1263	314	949	48	65 ^a , 65.7 ^b
Aniya et al., 1996	1265	251	1014	10	64

^aFrom Vn. Lautaro to 1994's tidewater front.

^bFrom Co. Padre Hurtado to 1994's tidewater front.

secondary tongue oriented to the north through a lateral valley, which ends in a calving front in one of the numerous fjords of Greve Lake. This secondary tongue showed a net advance of 1300 m between, 1975 and 1995, which is equivalent to a mean rate of 65 m a⁻¹. The thickening is larger in both ends of the profile, being smaller in the center.

The second transverse profile, FF' (Fig. 5) presents a very local condition, with a thickening greater than 130 m on the left side, where the glacier advanced over a lateral valley which was not covered by ice in 1975.

Analysis of the spatial pattern of thickening evident in Figs. 3–5 shows a clear maximum in the lower sector of the ablation area, with a bulge at an elevation of 550 m, 19 km from the 1994 tidewater front. This suggests that a large amount of ice mass is being transferred as a kinematic wave from the accumulation area to the ablation area, which might result in a near future in a further advance, depending upon the local calving conditions of the glacier front. Considering an average velocity of 20 m d⁻¹ for the lower ablation area of Pio XI glacier (Rivera et al., 1997b), the excess mass would take 2.6 years to reach the tidewater front, from the time epoch of the May 1995 photographs, that is, at the end of 1997 or beginning of 1998.

3.4. Hypsometric analysis

The hypsometric curve of the drainage area of Pio XI Glacier was calculated based on the 1995 DTM, using 50 m contour intervals which have been interpolated and filtered. This curve is very important in relation to the long term stability of the front, be-

cause it indicates the sensitivity of the AAR to changes of the ELA position for the specific hypsometric geometry of a glacier (Furbish and Andrews, 1984).

As can be appreciated in Fig. 6, Pio XI Glacier shows a hypsometric curve with a steep slope under 1000 m and over 2200 m elevation, whereas between 1100 and 2200 m, and especially between 1100 and 1300 m, the hypsometric curve is much flatter. This is confirmed by the values of glacier area according to altitudinal classes at 500 m intervals (Table 2).

In Table 2 it is observed that 45% of the surface of the glacier is located between 1000 m and 1500 m. This altimetric class corresponds to Altiplano Caupolicán (Fig. 1), also named Meseta del Comandante by Lliboutry (1956), which is characterized by a relatively flat area located at the base of the north–south mountain range composed of Cordón Mariano Moreno and Cordón Pio XI. Thus, Altiplano Caupolicán is a natural glacier basin that receives large amounts of snow that accumulates on the west facing slopes immediately to the west.

3.5. ELA related to temperature and rainfall variations

During the last three decades, Patagonia has undergone an atmospheric warming. For example, Punta Arenas, located 450 km south of Pio XI Glacier, shows a warming for the summer-mean minimum temperature of 1.5°C for the 33-year period of 1960–92 (Rosenblüth et al., 1997). Based on the analysis of temperature data for Argentine stations, Hoffman, (1990) and Ibarzabal et al. (1996) conclude that

Table 2

Altitudinal classes (m)	Surface (km ²)	Surface (%)	Accumulated surface (%)
3000 and more	22	1.7	1.7
2500–3000	49	3.9	5.6
2000–2500	159	12.6	18.2
1500–2000	211	16.7	34.9
1000–1500	571	45.2	80.1
500–1000	155	12.3	92.4
0–500	96	7.6	100
Total	1263		

warming has also occurred over south-eastern Patagonia.

If the ELAs for 1945, 1962, 1981 and 1995 are plotted over the hypsometric curve of Pio XI Glacier (Fig. 6), we can observe a general tendency of elevation increase from 1962 to 1995. However, within this period the ELA has been still located in a region where the hypsometric curve is steep, not resulting therefore in a significant AAR change for the glacier, with a consequent minimal impact on a possible frontal retreat.

On the contrary, in the last 50 years the glacier has shown a strong advance. Considering the warming trend observed in Patagonia, this indicates that the glacier is rather insensitive to changes in temperature. Instead we can speculate that the glacier is responding to the positive precipitation anomaly cycles showed by Cabo Raper and Isla San Pedro climatic stations (Fig. 7) with a delay time between 10 to 25 years. Both stations, while they show a general tendency for rainfall decrease during this century, they exhibit positive precipitation cycles, as occurred between 1935–1955 and 1973–1983 (Rivera et al., 1997b).

3.6. Discussion and conclusions

One of the hypotheses that has been formulated for explaining the asymmetric behavior of the western and eastern glaciers, postulates that the maritime glaciers on the west are more sensitive to the variations in precipitation, whereas the eastern glaciers, of a predominant continental nature, are more sensitive to changes in temperature (Warren and Sudgen, 1993). If this is true, then eastern glaciers would be retreating at a larger rate, according to the regional warming (Fig. 8), whereas the western glaciers would be more stable due to the positive precipitation events observed during some interannual cycles in Patagonia (Fig. 7).

The anomalous case of Pio XI Glacier shows in general terms that this relation is correct. However, the behavior of a glacier depends on the hypsometric geometry of each glacier and the magnitude of the climatic changes observed in the region.

Based on the hypsometric curve for Pio XI Glacier, we postulate that in the last 50 years the glacier has not retreated because the elevation in-

crease of the ELA has resulted in a minimal change in AAR. However, the regional warming has raised the present position of the ELA to a critical elevation in terms of the hypsometric curve (Fig. 6). If the present warming continues in the future, the ELA would rise to a location within the Altiplano Caupolicán, resulting in a significant change in the AAR, which probably would determine a retreat of the glacier. In this scenario, we can assume that the present high sensitivity of the glacier to positive pluviometric cycles will change instead to a high sensitivity to regional warming.

This situation can be presently observed in the contrasting behaviors of Upsala and Moreno Glaciers. In fact, for Upsala Glacier, which has experienced a remarkable retreat in recent decades, the ELA is located in a flat region of the hypsometric curve, with a consequent large impact on the AAR as the ELA rises due to warming (Naruse et al., 1995). On the contrary, Moreno Glacier, which has experienced only small variations during most of this century, shows a relatively steep hypsometric curve with a resulting insensitive response to a rise in ELA (Naruse et al., 1995).

Independent evidence based on large ice velocities measured (Rivera et al., 1997b), and on the looped pattern of medial moraines (Rivera et al., 1997a), shows that Pio XI Glacier might have experienced surging periods since 1945, especially in 1976 and 1992–1994, when the tidewater front advanced significantly. In contrast, the glacier showed a limited retreat in 1985.

The thickening pattern observed in 1975–1995, with a mean value of 2.2 m a^{-1} for the period, does not necessarily indicate a stable trend. In fact, if we assume that Pio XI Glacier experienced surging in 1976 and 1992–1994, then enhanced thickening might have occurred during those years.

However, in a longer time period, when the ELA rises above the critical hypsometric limit as discussed above, the thickening trend would revert to thinning and the front should start to retreat. When this happens, a sudden outburst flood (jökulhlaup) of Greve Lake might occur. This lake was formed in 1962 by damming of the advancing front of Pio XI Glacier. The possible retreat of the glacier and associated jökulhlaup of Greve Lake should be analyzed in future investigations.

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