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A pioneer mass balance estimate for a Patagonian glacier: Glaciar De los Tres, Argentina

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Abstract

Up to now, the database of World Glacier Monitoring Service does not contain mass balance for Patagonian glaciers. The first mass balance data from this region are now presented. In 1995/1996, an investigation including glaciological, meteorological and hydrological monitoring was carried out on Glaciar de los Tres in Mt. FitzRoy Region, Santa Cruz, Argentina. Mass balance calculations were based on direct estimates of its components — winter and summer balances, using the stratigraphic reporting system. Comparison of the glacier meteorology with those in the foothills reveals peculiarities in vertical temperature and precipitation gradients. Correlations with lowland meteorological records were used for correcting raw field data and for final calculation of mass balance parameters. Mass balance was slightly positive (+70 mm w.e.), with accumulation of 2320 mm and ablation of 2250 mm w.e. Three corresponding maps of these parameters are drawn. In spite of a positive 1995/1996 balance, the glacier front retreated 3 m, indicating the past glacier regime. Glacier retreat is the prevalent pattern of the Andes, but the contemporary state of alpine glaciers in the Argentine sector of Patagonia seems to be relatively more favourable. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: glaciers; mass balance; Patagonia

1. Introduction

The Patagonian Andes contain one of the most extensive glacier covers in the world (Fig. 1). Meier (1984) regarded Patagonia as one of the three glacierized regions, whose mass wastage significantly influences the global sea level. It contains ca. 3734 km^3 of ice (Glebova et al., 1984), that is about 96% of the total ice resources of South America. Unfortunately, World Glacier Monitoring Service through its ''Fluctuations of Glaciers'' and ''Glacier Mass-Balance Bulletin'' does not include mass balance (b_n) values calculated for a Patagonian glacier.

For South America as a whole, only recently, mass balance monitoring has been started on Zongo and Chacaltaya Glaciers in Bolivia. Since 1979, yearly b_n values were calculated on four glaciers in Mt. Aconcagua region, ca. 33°S (Echaurren Norte in Chile, Alma Blanca, Piloto and Plomo in Argentina), although direct measurements are discontinuous (Leiva and Cabrera, 1996). Often, results are published only in internal reports (Peña et al., 1984; Lenzano and Leiva, 1989) and are not included into WGMS database.

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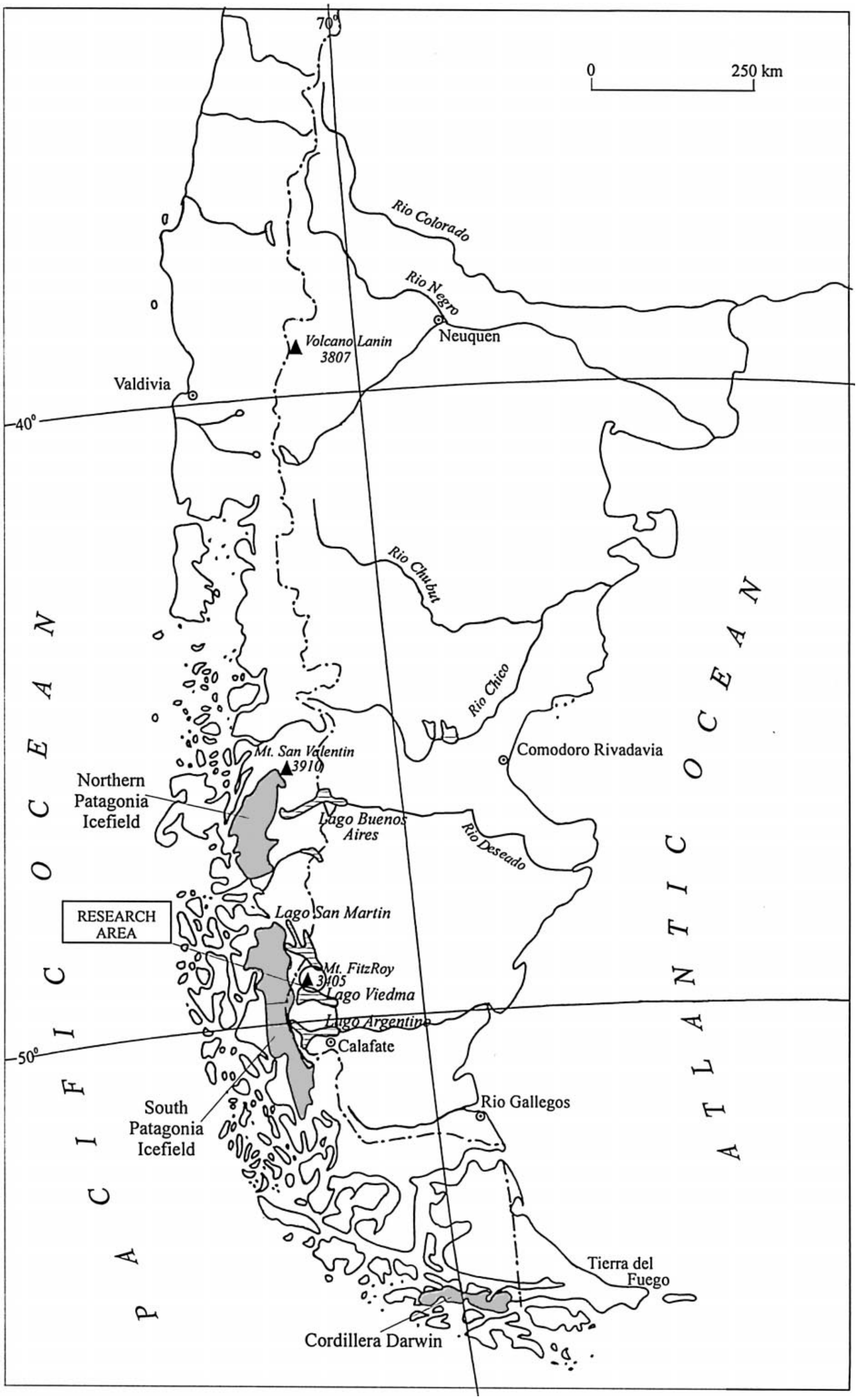

Fig. 1. Current glacier cover of Patagonia.

In Patagonia, episodic estimates of ablation rate for short time spans were obtained in the course of comprehensive multi-year international (Japanese–Argentine–Chilean) research projects in 1980–1990s. Ablation was measured at discrete points within the outlet glaciers of both Northern and Southern Patagonia Icefields (NPI and SPI, respectively) such as San Rafael, Soler in NPI and Upsala, Tyndall and Perito Moreno in SPI system (Ohata et al., 1985; Fukami and Naruse, 1987; Koizumi and Naruse,

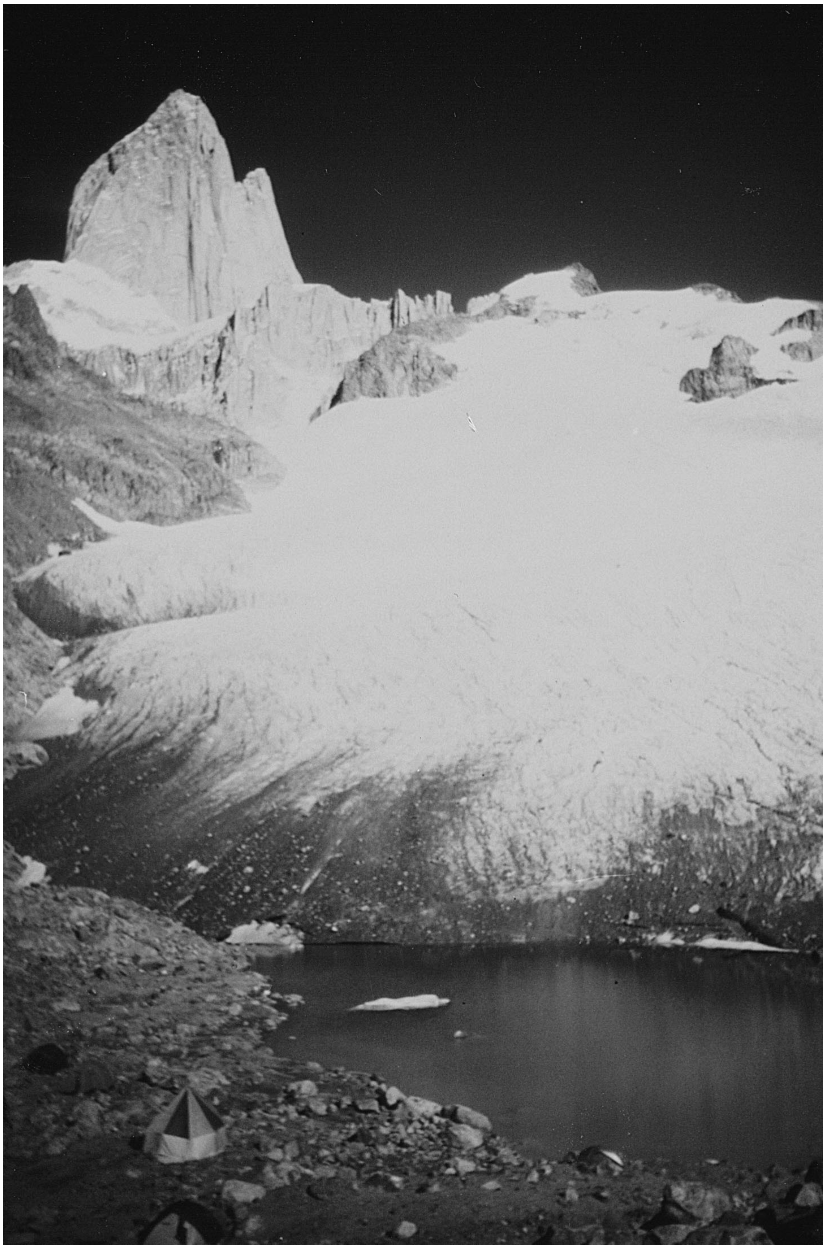

Fig. 2. Glaciar De los Tres, with Laguna Ira in the foreground and Mt. FitzRoy in the background.

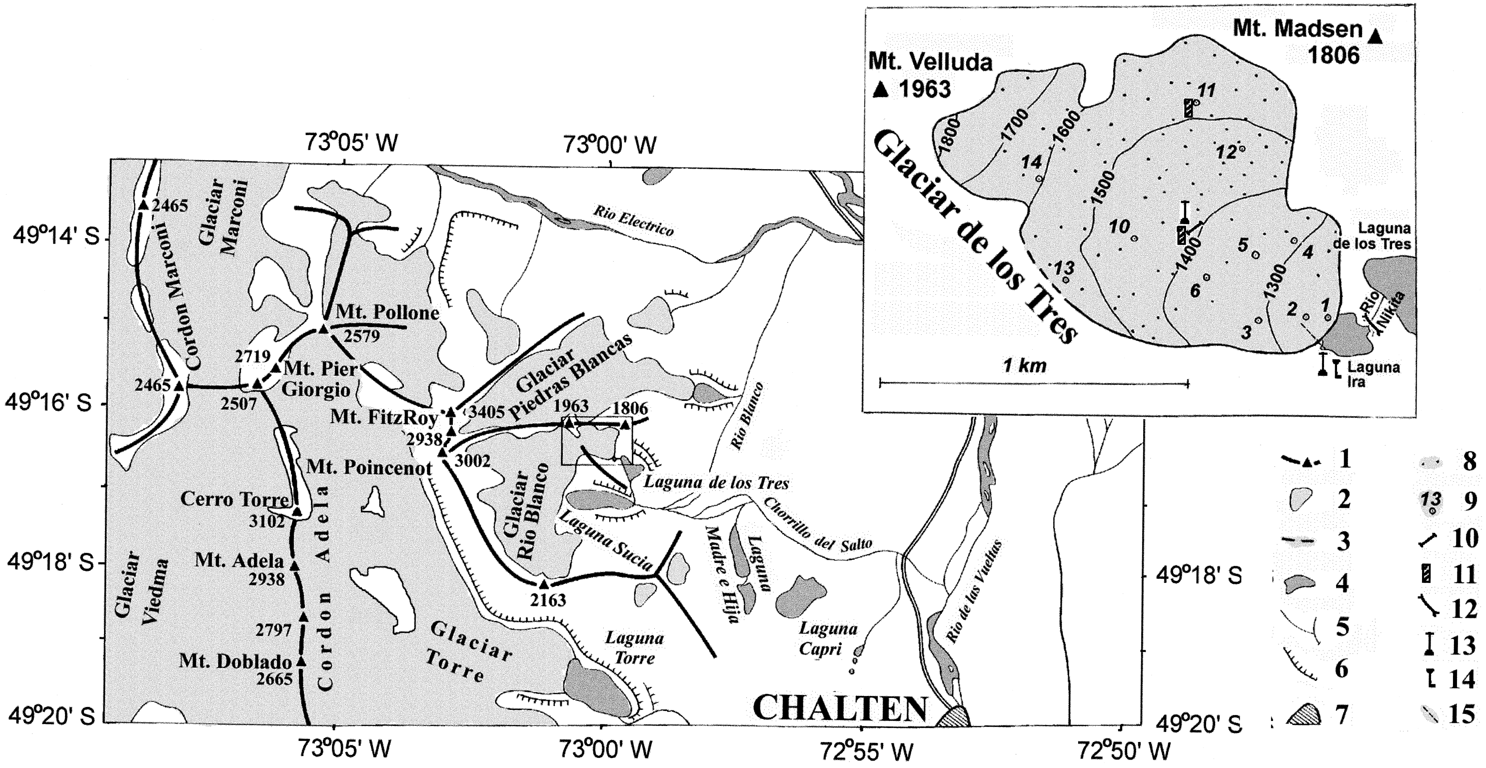

Fig. 3. Research site (with location scheme of the measurement points within the basin of Glaciar De los Tres on the attached inset): 1 — ridges and summits; 2 — glaciers; 3 — ice divides; 4 — lakes; 5 — rivers; 6 — moraine ramparts; 7 — settlement; 8 — points of snow depth survey; 9 — ablation stakes and their numbers; 10 — reference ablation cable; 11 — snow pits; 12 — river gauging site; 13 — temporary weather stations; 14 — precipitation meter; 15 — longitudinal profile for measuring frontal variations of the glacier.

1992; Warren and Sugden, 1993; Takeuchi et al., 1995). A single measurement of accumulation was also made in one point at San Rafael Glacier (Yamada, 1987).

However, direct mass balance monitoring in compliance with the accepted standards (Østrem and Brugman, 1991; Fluctuations of Glaciers, 1993) is hardly possible for such huge glacier formations as NPI and SPI. A more tractable option is to study one of the classic alpine glaciers along the periphery of icefields (Fig. 1).

2. Investigation site and research programme

The first Russian glaciological expedition to Patagonia, under the aegis of EARTHWATCH organization, USA, took place in January–March 1996. The purpose was to observe the regime of the local glaciers to make conclusions about their current trend. We intended to calculate the annual mass balance for an entire glacier — for the first time in Patagonia.

The main criterion determining the choice of a glacier includes accessibility to the glacier and passable terrain over the glacier. Extreme terrain contrast and fast glacier flow (ice flow velocity can reach 3.7 m/day (Naruse et al., 1992) here) characterize most glaciers such that their surfaces are extremely crevassed. Typically, the surface of a glacier looks like a continuous ice-fall and quite impossible for surface travel. To avoid these problems we chose a rather small, to Patagonian scale, Glaciar De los Tres (Fig. 2) for mass balance measurements.

Glaciar De los Tres is situated on the eastern slope of the Andes between lakes Viedma and San Martin (Figs. 1 and 3), in the vicinity of the most outstanding peak of Argentine Patagonia — Mt. FitzRoy (3405 m). The geographical co-ordinates of the central point of the glacier are 49°16′30″ S and 73°00′30″W. Glaciar De los Tres is a valley glacier and it occupies the upper reaches of a short hanging valley (Fig. 4). There is almost no debris cover, and the surface of Glaciar De los Tres remains rather clean down to the terminus. Debris appear only as sporadic boulders and also cause general decrease of surface albedo in the lowermost belts, mainly near the right margin of the snout and near the floating front. The highest point of the glacier lies at 1830 m a.s.l. and its lowermost point (1220 m) coincides with the water level of the tiny lake Laguna Ira.[1] Meltwater run-off from the glacier flows to Laguna Ira which empties, eventually, to the Rio Blanco River.

Fig. 4. Aerial photo of the research area. The arrow indicates Glacier De los Tres.

The catchment of Glaciar De los Tres has clear hydrologic boundaries, and only small section of its side boundary consists on an ice divide with the neighbouring Rio Blanco Glacier. The area of Glaciar De los Tres is 0.976 km^2. The mean slope is 26.9°, the steepness rising gradually with the height (Table 1) with the extremes of 10° and 42° over different parts of the glacier. The glacier is accessible on foot on more than 90% of its area.

Daily observations were conducted on Glaciar De los Tres from 26 January to 4 March 1996, embracing the period of the most intensive ablation of 1995/1996 season. They included: snow survey over all accessible glacier area; snow density, stratigraphic studies and snow/firn temperature in snow pits; daily ablation measurements using the cable method (Djankuat Glacier, 1978); stake measurements of ablation; and periodic mapping of the

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[1] A geographical name of ‘Laguna Ira’ is not conventional: it is given to formerly nameless object by the participants of Russian expedition.

Table 1
Main topographic characteristics of Glaciar De los Tres (by altitudinal spans)

Altitudinal span, m a.s.l.	Surface slope, degree	Area, km^2
>1700	33.7	0.075
1600–1700	32.0	0.100
1500–1600	29.4	0.278
1400–1500	23.7	0.269
1300–1400	22.4	0.176
<1300	20.2	0.078
1220–1830	26.9	0.976

snow-line position. We also made water discharge and conductivity measurements at a gauging site, computed daily water run-off with the help of level vs. discharge rating curve, made continuous water temperature measurements in Laguna Ira and determined lake bathymetry in Laguna Ira and Laguna de los Tres. Continuous air temperatures were also recorded just below the terminus. Occasionally, air temperatures were also recorded at various altitudes on the glacier to calculate vertical gradients. Precipitation was measured and snowfall depth on the glacier was observed.

3. Mass balance measurements on Glaciar De los Tres

The mass balance method was the stratigraphical reporting system (Østrem and Brugman, 1991; Fluctuations of Glaciers, 1993) regarding the net mass balance b_n as the algebraic sum of winter and summer balances, b_w and b_s. This approach does not require measuring summer snow accumulation, and greatly simplifies the field measurements.

In order to calculate the glacier mass balance, a field program, based on that at Djankuat Glacier in the Caucasus (Djankuat Glacier, 1978) and supplemented with the subsequent glaciological mapping, was used. First, direct raw field data on mass balance components were obtained discretely (points of snow depth sounding by metallic rods for measuring accumulation and stakes for measuring ablation). Second, these data served as a basis for drawing b_w and b_s maps, covering the entire glacier area. Third, the maps were digitized using 377 points in a rigid rectangular network (50×50 m on terrain) for estimating overall b_w, b_s and b_a values and their averages by altitudinal spans.

For accumulation, snow depth was measured at 98 points (Fig. 3). Snow density was measured in two pits at altitudes of 1410 m, in the upper part of the snout, and 1525 m, in the firn basin. In both pits, total density, measured on 3–5 February, was the same — 0.54 g cm^{-3}, with very small variation from one layer to another (Fig. 5). Snow cover at Glaciar De los Tres is marked by uniform characteristics: coarse-grained texture devoid of pronounced ice layers or dirt horizons. The lower boundary of snow with the firn layer of the previous year is rather difficult to identify, because no distinctive loose layer exists at the bottom of the snow, the icy layer on snow/firn contact is thin, and the dust concentration and cryoconite formation on the former summer surface is minimal. Also difference in resistance were difficult (but, nevertheless, possible — after some training in the vicinity of a snow pit) to detect using a probe rod. Density, too, differed little between the snow and that of firn (Fig. 5).

For seasonal ablation measurements, a network of 11 stakes (six on the snout and five in the firn basin) was established. Daily measurements were made along a cable stretched between two stakes on a flat and gentle slope (8°) in the upper part of the snout (1410 m), (Fig. 3). The stakes in the firn basin and the upper snow pit used to be visited less regularly, 2–6 times per season. The density of measurement points was about 11 km^{-2}, answering the standards of first-class observations (Schytt, 1962).

Snow pit studies showed that regime of Glaciar De los Tres is the temperate type. By 5 February, the entire seasonal snow pack in the accumulation area reached 0°C. Negative temperatures, -0.2°C, were still preserved within the upper firn at the levels of 3.7 m and 4.4 m below the surface (Fig. 5), but by 27 February, all temperatures were 0°C. Density values in the upper snow pit remained nearly constant throughout the ablation period, decreasing from 0.54 to 0.53 g$\cdot$cm^{-3}. The snow on the snout has vanished completely by 3 March and the underlying superimposed ice has appeared. The zone of superimposed ice surrounds the lower limits of the firn basin by a narrow belt of variable width (0–20 m,

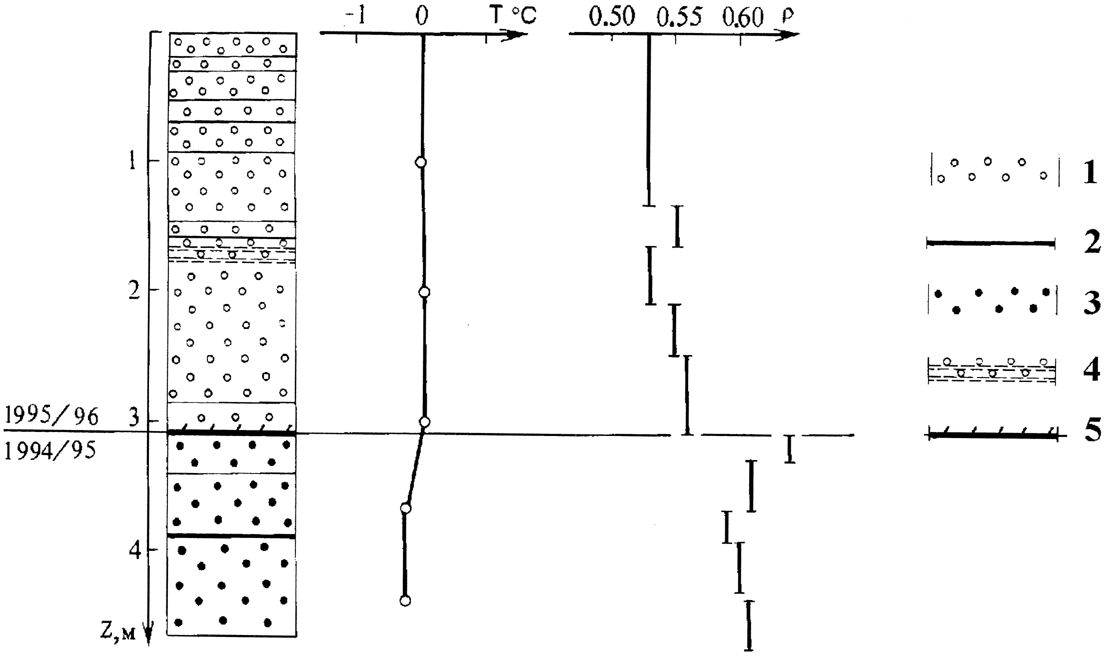

Fig. 5. Snow pit in the accumulation area of Glaciar De los Tres (5 February 1996): stratigraphy, temperature T (°C) and density, ρ (g/cm^3): 1 — coarse-grained snow; 2 — ice layer; 3 — firn; 4 — traces of wind foliation; 5 — dirt horizon.

depending on slope). Its location and width seems to vary from year to year.

4. Glacio/meteorological correlations and insert of amendments

In order to determine and to map the seasonal mass balance constituents adequately, the exact dates of the beginning and the end of the ablation season must be ascertained.

The end of 1995/1996 balance year on Glaciar De los Tres is dated at 7 March. On 6 March, an intensive rain began, and it turned into heavy snowfall by the evening of 7 March when the air temperature fell. A thick layer of the new snow on the glacier most probably did not melt afterwards, by virtue of low air temperature. However, the beginning date of the ablation period was unknown. The first reconnaissance visit to Glaciar De los Tres on 13 January showed that ablation has been already underway. The snow depth survey started on 4 February, when about 15% of the glacier area was already devoid of winter snow. For the same reason, stake measurements from 2 February to 4 March also partially characterized b_s. Thus, indirect estimation of ablation prior to 2 February and during 4–7 March was required to restore true b_w and b_s values.

The only source of information was weather observations in the headquarters of Los Glaciares National Park in Chalten. They were correlated with the data measured at the two stations at the glacier. Ablation could then be estimated using its relationship with air temperature. Unfortunately, meteorological observations in Chalten are not satisfactory enough: e.g., daily temperature is measured here once per day around 9 a.m. ± 1 h, with occasional gaps of a day or even several days.

A relatively good correlation, however, exists between morning air temperature in Chalten t_c and mean daily air temperature at our station Laguna t_L, at 1220 m (Fig. 6):

$$t_L = 0.48 t_c + 0.2 \qquad (1)$$

with a correlation coefficient of $r = 0.79$. Comparison of temperature records reveals the vertical gradient between Chalten and Glaciar De los Tres: -0.73°C/100 m. It becomes much more unstable

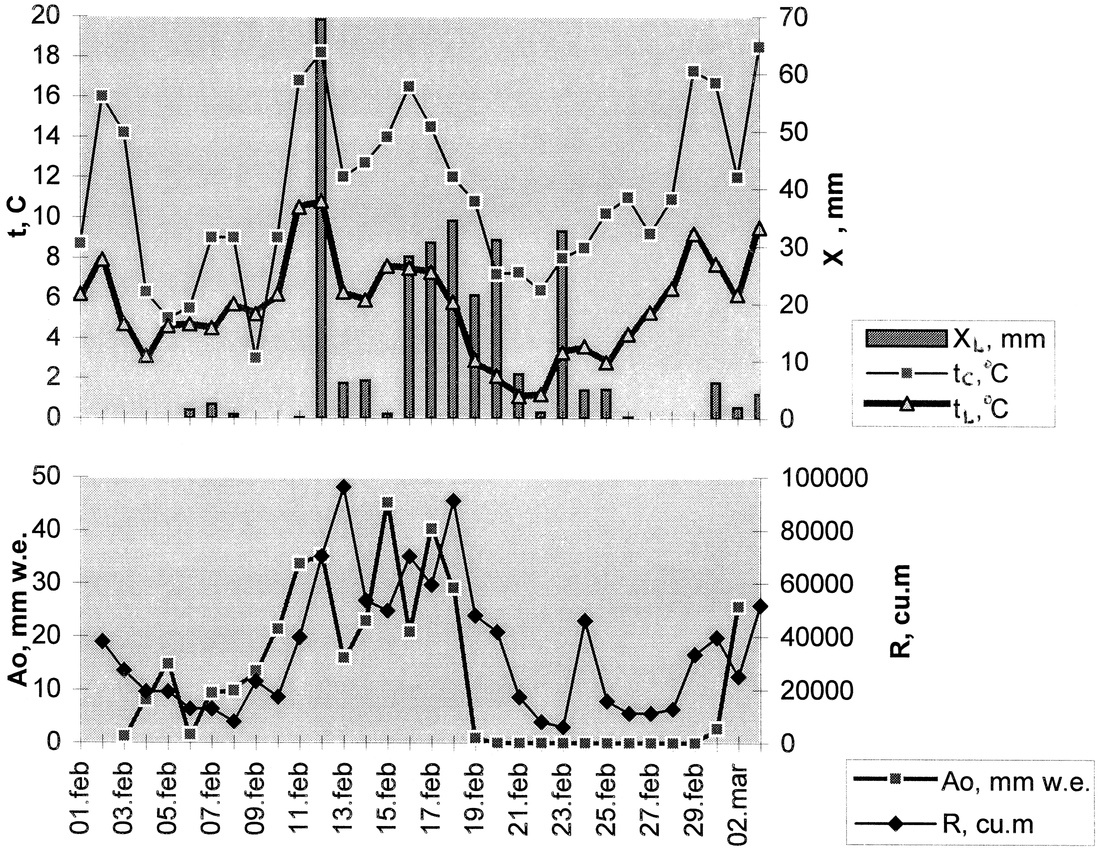

Fig. 6. Mean daily air temperature in Chalten t_c and Laguna t_L (°C), daily sums of precipitation at Laguna X_L (mm), daily bulk liquid run-off at Rio Nikita gauging site R (m^3) and daily melting rate at the reference ablation cable on Glaciar De los Tres A_0 (mm of water equivalent) during February–March 1996.

over the glacier surface. The gradient over the snout is ca. $-1.5°C/100$ m in average, though thermal inversion are observed often here. Higher the gradient reduces to $-0.17°C/100$ m at the altitude $>$ 1400 m and remains nearly constant to the uppermost glacier.

Although a good correlation between t_L and air temperature over the glacier surface was lacking, daily ablation in the reference point at 1410 m a.s.l., A_0 (in mm of water equivalent), turned out to be linearly correlated with t_L values averaged over 24 h:

$$A_0 = 4.86 t_L - 10, \quad r = 0.77, \qquad (2)$$

especially well for the days without precipitation (see also Fig. 6). Melting coefficient, or degree-day factor, averages 0.9 cm/°C · day, decreasing during warm periods. This value, as well as that of 1.18 cm/°C · day, obtained (Koizumi and Naruse, 1992) for nearby Tyndall Glacier, is much higher than registered for the majority of the Earth's non-polar glaciers (Krenke and Khodakov, 1966).

Table 2 contains monthly mean morning air temperature in Chalten for 1995/1996 balance year as well as averaged for the whole regular observation period of this weather station. Snow starts to accumulate early in May and melts away by the first half of August. November usually is warmer than March and only 1.3–2.2° cooler than summer months, so that November snowfall above 500 m a.s.l. seldom compared to March.

Judging by Chalten observations in 1995, cold weather prevailed until late October. Calculations

Table 2
Monthly mean air temperature in Chalten (t_c)

Month	Air temperature, °C	
	In 1995/1996	Multi-year mean (1991–1996)
April	+7.8	+7.5
May	+5.0	+4.0
June	−1.1	+0.5
July	−0.6	+0.4
August	−0.4	+2.7
September	+5.9	+5.9
October	+8.7	+8.1
November	+10.2	+9.7
December	+12.9	+11.3
January	+10.2	+11.9
February	+11.2	+11.0
March	+9.3	+9.5
Annual average	+6.6	+6.9

based on Eqs. (1) and (2) indicate that glacier melt could hardly start prior to the last week of October. Taking into account a time lag necessary for the heating of the snow-firn pack to 0°C, runoff from the glacier may begin around 1 November.

The main source of error when estimating ablation prior to 2 February with the help of (1) and (2) are snowfall in the first part of the summer. This serious problem could be addressed if we could determine vertical precipitation gradient. However, our measurements reveal that daily precipitation in Chalten and on the glacier do not correlate. Topographic contrasts are so large that, being only 11 km distant from the glacier, Chalten has a different climate-precipitation regime of an arid basin that belongs to the semi-desert pampa zone. At the glacier, 22 days of precipitation were recorded from 1 February to 4 March (Fig. 6), bringing a total of 296.7 mm, mainly as rainfalls. The daily maximum, 69.4 mm, fell on 12 February. During the same February–March period only 47 mm of rain was recorded in Chalten. This amount is greater than the 45 mm of precipitation which fall in Chalten during the three previous months (November–January). Most of these 45 mm fell in December, a month of a strongly pronounced positive air temperature anomaly (Table 2). Examination of the Chalten records shows that nearly all precipitation episodes of November–January period were accompanied by high air temperatures. These temperatures were high enough to exclude the possibility of snow even in the uppermost zones of the glacier, judging by the estimated vertical gradients. These arguments support the assumption about the negligible role of summer snowfalls in the 1995/1996 glacier regime prior to the beginning of the field campaign. Our inquiries among climbers and local citizens also testified to the fact that neither in November nor in December 1995 were there episodes of considerable new snow cover formation below 1800 m a.s.l. Consequently, combination of Formulae (1)–(2) seems to be sufficient for estimating A_0 prior to and after our fieldwork.

Extrapolation of reference point ablation data to the whole glacier surface was based on the spatial pattern revealed during the observation period. For some key points, which were important for drawing ablation isolines but inaccessible for direct measurements, ablation was derived indirectly, using reference point data A_0 and methods of factor analysis. Elevation, slope aspect and surface albedo were regarded as three main factors determining changes of ablation from one point to another. For numerical parameterization, a modification of Dyurgerov–Freydlin’s formula (Djankuat Glacier, 1978) was used.

Meltwater refreezing in the firn was determined for each altitudinal span of the glacier according to G. Golubev’s calculation scheme (Djankuat Glacier, 1978). Its magnitude is 120 mm w.e. for the entire glacier, not greatly different from the majority of studied temperature glaciers (Golubev, 1976).

Finally, all ablation values were increased by a factor of 1.03 making up for the systematic ablation underrating owing to sub- and intraglacial melting processes (Djankuat Glacier, 1978) and calving (not very intensive at Glacier De los Tres, ca. 1% of b_s).

5. Spatial pattern of glacier mass balance parameters in 1995/1996

Maps of mass balance, b_n, were made by overlaying maps of b_w and b_s over each other. A series of three maps (Fig. 7) was created.

In places, accumulation values exceed 4000 mm w.e. (snowpack is 9 m thick), including cirques of the firn basin and marginal hollows of the snout, by

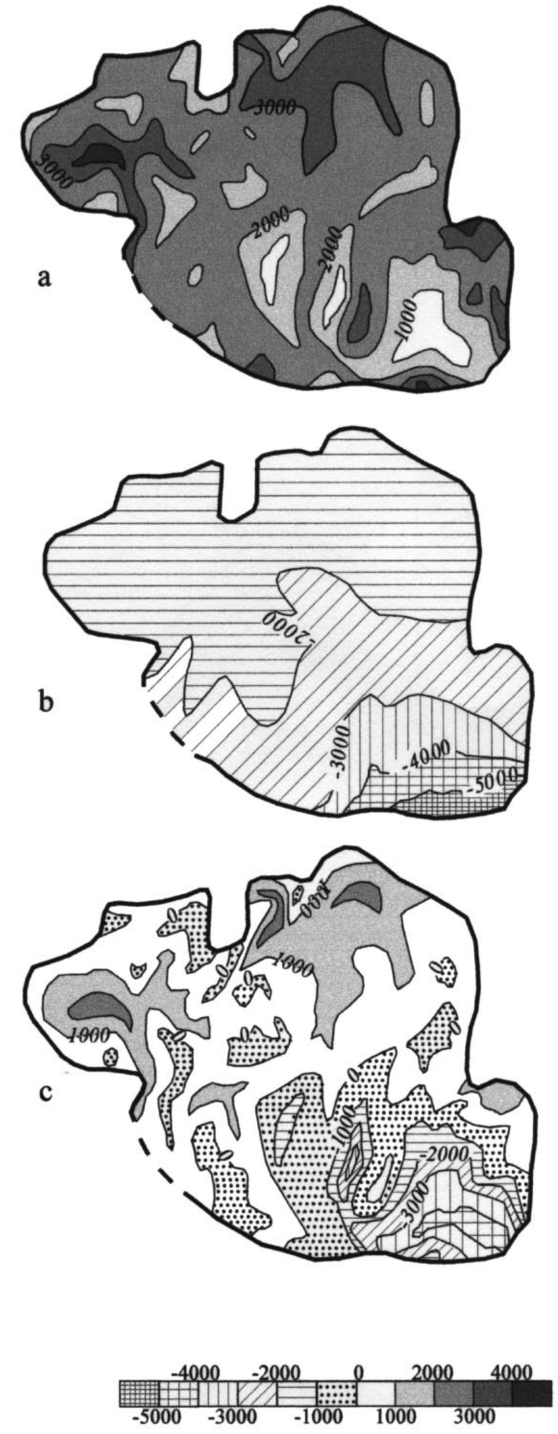

Fig. 7. Maps of accumulation b_w (a), ablation b_s (b) and mass balance b_n (c) of Glaciar De los Tres in 1995/1996. Contours are drawn in 1000 mm w.e. intervals.

snow drifting and avalanches. The b_s pattern is much more uniform in comparison to b_w. Typical ablation values vary within 1500–2000 mm w.e., while the minimum is 1320 mm w.e. high on the glacier and the maximum reaches 5500 mm w.e. at the terminus. Direct ablation measurements on Glaciar De los Tres show that mean daily average of melt is not less than 5–6 cm of ice in the higher zones and even when the sky is completely overcast all day long. Water equivalent of the residual firn can be as high as 2500 mm in some points.

Distribution of mass balance components with height is presented in Fig. 8 and Table 3. Ablation curve has a rather standard shape decreasing with elevation. However, accumulation b_w is nearly constant with height. This can be explained by the exceptional influence of wind drift. The shape of b_n curve resembles that of b_s. The equilibrium line altitude (ELA) for 1995/1996 deduced from Fig. 8 is 1440 m a.s.l. As for the mass balance of entire Glaciar De los Tres in 1995/1996, it is slightly positive (+70 mm w.e.), winter and summer balances equalling 2320 and -2250 mm w.e., respectively. Accumulation area ratio is $\mathrm{AAR} = 0.66$, being thereby in good compliance with the known Meier's point of view that $\mathrm{AAR} = 0.65$ must be regarded typical for glaciers in equilibrium.

6. Modern state of Patagonian glaciers

Only one field season at Glaciar De los Tres is insufficient for any strong conclusions about the current state of the glacier and its comparison to other glaciers in Patagonia. However, indirect evidence resulting from 1995/1996 field reconnaissance, meteorological archive data and scientific literature sources permits some relevant considerations.

1995/1996 balance year seems to be more favourable for the glacier in comparison to previous years. Evidence includes meteorological records from Chalten (Table 2) for accumulation (April–October) and ablation (November–March) periods indicating that winter air temperature in 1995/1996 was lower than its long-term average (+3.6°C vs. +4.1°C), summer air temperature coincided with its norm (+10.7°C), and winter precipitation exceeded the long-term mean by 40% (531 mm vs. 380 mm).

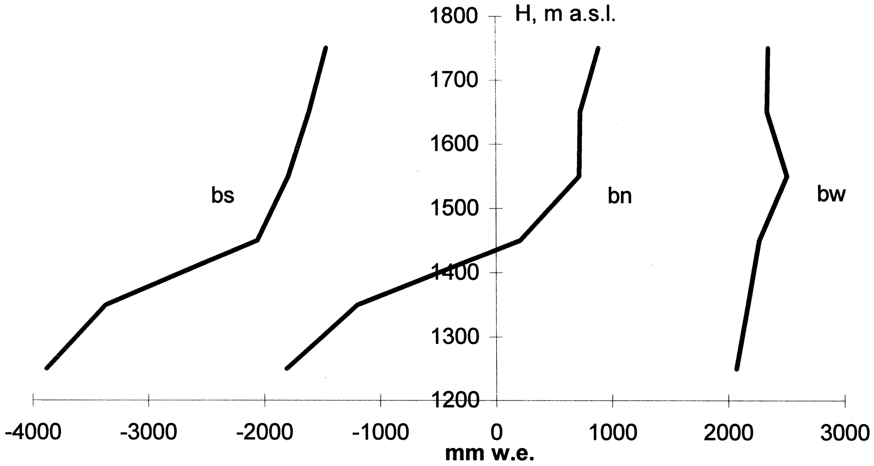

Fig. 8. Accumulation b_w, ablation b_s and mass balance b_n (mm w.e.) of Glaciar De los Tres in 1995/1996 vs. altitude (m a.s.l.).

Also, local dwellers regard cessation of the melting season and arrival of the winter snow cover at the glacier in the beginning of March as unusually early.

The general deglaciation trend prevails in Patagonia today. The climax of the last glaciation, the geochronologic analogue of Little Ice Age, which is locally named Pearson II stage, is dated back to the 18th century (Upsala Glacier — 1800 A.D. (Malagnino and Strelin, 1992), Tyndall Glacier — 1700 A.D. (Aniya and Sato, 1995)). Lateral and terminal moraines of this stage are well manifested in the periglacial zone of Mt. FitzRoy region too — below such glaciers as Rio Blanco, Torre, Piedras Blancas as well as Glaciar De los Tres (Fig. 3). The eastern shore of Laguna de los Tres is a well-preserved 30-m high terminal moraine. Another parallel moraine is lower by about 150–200 m from the crest of the first one. Morphological similarity of both moraines and approximately the same degree of their colonization by pioneer plants indicate that their age doesn't differ greatly. Formation of the two moraines must reflect two glacier activation episodes at the peak of the same glaciation stage. The first one is now ca. 850 m from the terminus of Glaciar De los Tres. Identifying its age with the Pearson II stage means that the velocity of its frontal retreat during last 2–3 centuries was small — 3–4 m/year on the average (5 m/year at most if counting from the crest of the lower moraine). Palaeoglaciological reconstructions of the outlet glaciers (Malagnino and Strelin, 1992), by the way, reveal much more rapid deglaciation — up to 25–35 m/year during the same period.

Table 3
Glaciar De los Tres mass balance and its components vs. height in 1995/1996, mm of water equivalent

Altitudinal span, m a.s.l.	Accumulation (winter balance), b_w	Ablation (summer balance), b_s	Mass balance, b_n
> 1700	+ 2350	− 1460	+ 890
1600–1700	+ 2340	− 1610	+ 730
1500–1600	+ 2510	− 1790	+ 720
1400–1500	+ 2270	− 2060	+ 210
1300–1400	+ 2170	− 3370	− 1200
< 1300	+ 2070	− 3880	− 1810
Glacier entire	+ 2320	− 2250	+ 70

Glaciar De los Tres continues to retreat today. The age of the adjacent Laguna Ira is only few years, judging by many climbers accounts and by the fact that it is absent both on the aerial image (Fig. 4) made in 1991 and on Argentine topographic map 1: 100,000. Consequently, the mean annual retreat of Glaciar De los Tres in early 1990s was about 20 m/year.

In 1996 summer, retreat of 3 m was measured using a tape. Thus, annual retreat of Glaciar De los Tres in 1995/1996 must be less than 3.0 m. This value is similar to the long-term average. It conforms to the stated supposition that mass balance of + 70 mm w.e. registered in 1995/1996 answers natural conditions more favourable for the glacier than its long-term norm.

Maybe, this is the reflection of the relatively positive evolution trend of the last years/decades, revealed for Patagonian glaciers south of 48°S in the compendium of Warren and Sugden (1993) and expressed in considerable deceleration of the general retreat rate since 1970s. Also, the data cited in the most recent compendium (Aniya et al., 1997) lead to the same conclusions: among those 40 snouts of SPI outlet glaciers, where frontal retreat dynamics within the last decades was monitored for a number of partial periods, deceleration of the most recent time spans can not be traced only for 17 glacier fronts (seven on the east side and 10 on the west side). This trend cannot be detected, however, at the glaciers in lower latitudes of the Andes (Aniya, 1992; Casassa et al., 1998).

A rock exposed from under water in the right margin of the glacier front was used as a reference longitudinal alignment (Fig. 3) for estimating terminus change. For the future judgements about terminus variations, a special bench-mark corresponding to the frontal position by 4 March 1996, was covered out on the downglacier side of the rock.

7. Conclusions

The mass balance expedition to Argentine Patagonia has demonstrated clearly the peculiar regime of local glaciers. The measurement system and calculation scheme were adapted to these peculiarities, such as very prolonged ablation season, maybe from 3 up to 5–6 months, the important role of wind regime for accumulation pattern, and local alteration of temperature + precipitation vertical gradients. The peculiarities preclude application of empirical equations of mass balance using meteorological records alone. The latter circumstance is aggravated by the lack of long and precise observational series.

The 1995/1996 balance year on Glaciar De los Tres turned out to correspond closely to a steady state of the glacier. These conditions were obviously more favourable than the preceding years, primarily due to increased accumulation. The observed data, supplemented with information from the few available scientific papers about recent glacier fluctuations in the region, indicate that a possible trend towards a more steady-state glacier budget conditions. For more substantiated conclusions concerning the contemporary tendencies, it would be important to continue mass balance measurements on Glaciar De los Tres.

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