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Article

Glacier variations of Hielo Patagónico Norte, Chile, between 1944/45 and 1995/96

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Abstract

The variation of 22 outlet glaciers of Hielo Patagónico Norte (Northern Patagonia Icefield) between 1993/94 and 1995/96 was elucidated, and together with the results of the previous studies, the variation since 1944/45 was discussed in conjunction with the climate data recorded at two nearest stations. Although the recession has continued at most glaciers, the recession rates have declined since 1990. During the period of 1994–96, the recession rates of most glaciers located on the eastern side of the icefield slowed down, with two glaciers slightly advanced, while those of the glaciers located on the western side slightly increased, compared to the previous study period of 1991–94. It appears that there is a slight difference in response time to climate changes between those glaciers on the western and eastern sides of the icefield. The climatic records show increases in precipitation during the 1970s. The slowing-down of the recession rates of the western glaciers during 1991–94 and that of the eastern glaciers during 1994–96 suggest that they responded to the precipitation increase with a time lag of about 20 and 23 years, respectively. Heavily debris-covered glaciers have continued to waste down before starting to retreat. The snout disintegration in a proglacial lake due to a drastic increase in calving rate, probably a delayed response to the climate change, produced an apparent large recession at a few glaciers. The ice volume lost by the recession in 51 years is estimated at 6.4 to 19.2 km^3, whereas that by thinning to be 212 to 291 km^3.

1. Introduction

This paper is the continuation of a study on the glacier variation of Hielo Patagónico Norte (HPN, or Northern Patagonia Icefield), which started in 1983 (Aniya and Enomoto, 1986a, 1986b ; Aniya, 1988 ; Aniya, 1992a, 1992b ; Wada and Aniya, 1995). It is important to monitor glacier variations, particularly those of temperate glaciers which are supposed to respond quickly to the changing climate.

The Patagonia Icefield comprises Hielo Patagónico Norte and Hielo Patagónico Sur (HPS, or Southern Patagonia Icefield). The HPN is located between latitudes of 46°30'S and 47°30'S along longitude of 73°30'W , with an area of 4200 km^2 (Figs. 1 and 2). It has 28 outlet glaciers with an area larger than 5 km^2 (Aniya, 1988) and the variations of 22 of those glaciers since 1944/45 have been monitored until 1993/94.

We flew over the HPN during the austral summer of 1995/96 to locate the snout position of the outlet glaciers. It is the purpose of this paper to elucidate glacier variations between 1993/94 and 1995/96, and discuss, together with the results of the previous studies, the characteristics of the glacier variations since 1944/45, in conjunction with climate data. We also estimate the volume of ice lost in 51 years due to the recession and thinning.

2. Method

Hand-held, oblique aerial photographs of glacier

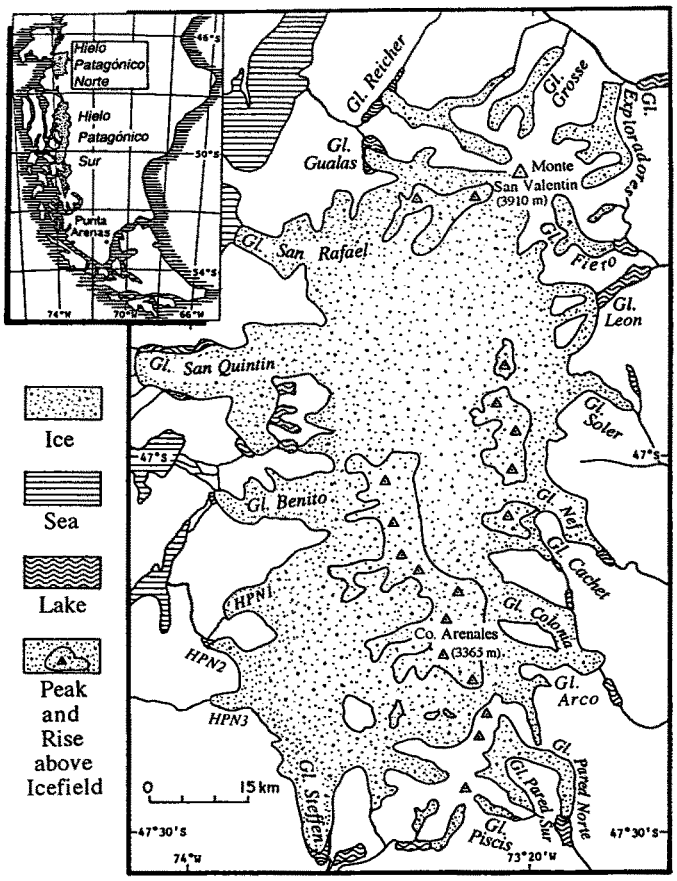

Fig. 1. Outlet glaciers of Hielo Patagónico Norte.

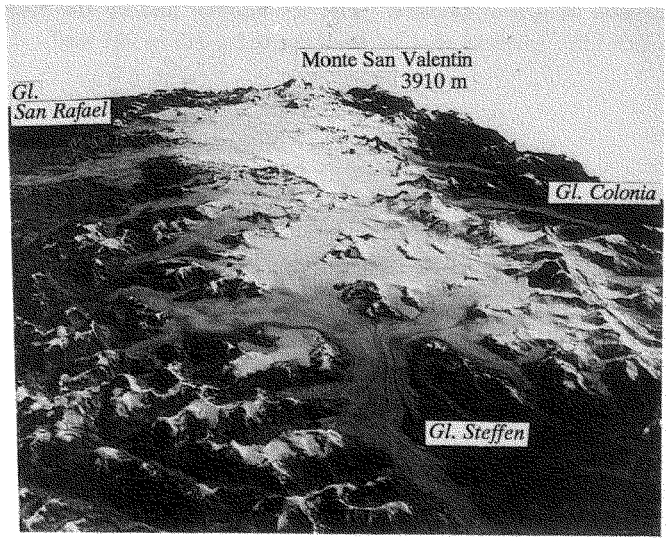

Fig. 2. Bird's-eye view of Hielo Patagónico Norte. Looking from south. Generated by draping the Landsat MSS (Feb. 9, 1987) over the DEM (Digital Elevation Model, 250 m contour interval, of the HPN).

snouts were taken on November 27, 1995, with 35 mm cameras. Photographs of Glaciar HPN3 could not be taken, however, due to local inclement weather condition. These photographs were first compared with vertical aerial photographs taken in 1974/75 at a nominal scale of 1 : 70,000 and the snout position was carefully located on the vertical photographs, which was in turn transferred onto the topographic map at a scale of 1 : 50,000. This map position was then compared with the position plotted for 1993/94 (Wada and Aniya, 1995). Before superimposing these two maps, photographs taken in 1993 and 1995 were carefully compared in detail to determine whether the glacier retreated or advanced. In this process, we found some mistakes or uncertainty in the 1993/94 positions due to image quality for some glaciers and we either located the new position or changed to "no data".

Since hand-held photographs are oblique, usually looking upstream, the delineation of the plan form of the snout edge cannot be precise. In this sense, slight change may not be significant ; however, whether it had retreated or advanced is reasonably certain.

The variation in two quantities was measured : area change and distance. Although the distance change is intuitively easier to comprehend, the discussion is based on the area change for two reasons. Firstly, the position of the snout after the retreat or advance is seldom parallel to the previous position, and secondly, with the area change, we can estimate the volume of ice lost or gained due to the recession or advance.

3. Results and Discussion

The variation in area between 1993/94 and 1995/96 (hereafter referred to as 1994 and 1996, respectively) is listed in Table 1 along with the previous varia-

Table 1. Glacier variations of Hielo Patagónico Norte (area lost in km² with the mean annual rate in paretheses)

Glacier	Period					
	1945-96	1945-75*	1975-86*	1986-91*	1991-94**	1994-96
Northern Side						
Grosse	1.02 (0.020)	0.39 (0.013)	0.22 (0.020)	0	0.13 (0.042)	0.28 (0.140)
Western Side						
Reicher : NE	2.38 (0.047)	0.61 (0.020)	1.18 (0.107)	0.47 (0.094)	0.07 (0.025)	0.05 (0.025)
: SW	3.97 (0.078)	0.36 (0.012)	0.64 (0.058)	0.94 (0.188)	2.02 (0.673)	0.01 (0.004)
Gualas : N	0.88 (0.017)	0.13 (0.0004)	0.19 (0.017)	0.14 (0.003)	0.17 (0.056)	0.25 (0.125)
: S	0.65 (0.013)	0.17 (0.0006)	0.35 (0.032)	0	0.13 (0.043)	# #
San Rafael	12.00 (0.235)	3.56 (0.119)	4.83 (0.439)	3.60 (0.720)	0.0006	0.01 (0.007)
San Quintin	12.45 (0.244)	7.50 (0.250)	1.20 (0.109)	3.30 (0.660)	0.16 (0.052)	0.29 (0.145)
Benito	1.59 (0.031)	0.66 (0.022)	0.07 (0.006)	0.58 (0.116)	0.05 (0.016)	0.23 (0.115)
HPN 1	3.17 (0.062)	1.75 (0.058)	0.37 (0.034)	0.91 (0.182)	0.06 (0.019)	0.08 (0.042)
HPN 2	2.89 (0.057)	1.41 (0.042)	0 ?	1.45 (0.290)	no data	0.03 (0.016)
HPN 3	1.47 (0.032)	0.22 (0.0007)	0.41 (0.037)	0.84 (0.168)	no data	no data
Southern Side						
Steffen	5.06 (0.099)	2.42 (0.081)	0.39 (0.035)	0.88 (0.176)	uncertain # 1	1.37 (0.274)
Eastern Side						
Piscis	0.51 (0.010)	0.49 (0.016)	0.02 (0.002)	0	0.01 (0.003)	a 0.01 (-0.005)
Pared Sur	1.69 (0.033)	1.42 (0.047)	0.27 (0.025)	0	0	0
Pared Norte	1.29 (0.026)	0.97 (0.032)	0.04 (0.004)	0.27 (0.054)	0.007 (0.002)	0.003 (0.001)
Arco	0.48 (0.009)	0 ?	0 ?	0 ?	0 ?	0.48 (0.240)
Colonia	2.01 (0.039)	0.97 (0.032)	0.12 (0.011)	0.70 (0.140)	0.18 (0.061)	0.04 (0.022)
Cachet	4.04 (0.079)	2.68 (0.089)	0.44 (0.040)	0.64 (0.128)	0.23 (0.077)	0.05 (0.023)
Nef	3.66 (0.071)	1.46 (0.049)	1.12 (0.102)	0.56 (0.112)	0.45 (0.149)	0.65 (0.325)
Soler	1.13 (0.022)	0.38 (0.013)	0.16 (0.015)	0.43 (0.086)	0.16 (0.054)	0
León	0.34 (0.007)	0.02 (0.00007)	0.19 (0.017)	0.19 (0.038)	uncertain # 2	a 0.06 (-0.012)
Fiero	0.39 (0.003)	0.15 (0.0005)	0	0.12 (0.024)	uncertain # 3	0.12 (0.024)
Exploradores	0.81 (0.016)	0.16 (0.0005)	0.65 (0.059)	0	0	0
Total	64.46 (0.055)	27.88 (0.040)	12.86 (0.051)	16.02 (0.139)	3.83 (0.071)	3.87 (0.102)

Sources : *Aniya (1992),** Wada and Aniya (1995)
modified in this paper. Old values : #1 (1.30), #2 (0.02), #3 (0.01)
combined to N
a : advance

tions (Aniya, 1992b ; Wada and Aniya, 1995). Fig. 3 depicts these variations for visual assessment.

Those glaciers located on the western side of the HPN had retreated at slightly faster rates than the previous study period of 1991−94. On the other hand, those on the eastern side had varied rates ; retreat rates of some glaciers decelerated while some other accelerated, with two glaciers even advanced. This is also different from the general trend between 1991 and 1994.

Although the recession rates of glaciers on the western side were slightly faster during 1994−96 than 1991−94, these rates are still much slower than the period between 1986−91, indicating that the slowing down of the retreat continued. The eastern side of the HPN found several glaciers whose retreat rates had slowed down. From these characteristic changes of the retreat trends, it may be said that the glaciers on the eastern side responded to some environmental changes later than those on the western side. On the whole, it is evident that until 1991 the retreating rates of the most glaciers had been accelerating ; however, since then, the rates have slowed down.

3.1. Western Side

Glaciar San Rafael, one of the largest outlet glacier of the HPN with an area of 760 km², showed very slight retreat between 1994 and 1996. It had been retreating at the fastest rate in the HPN in the late 1980s ; but virtually stopped retreating since 1991, and around 1992 even a slight advance was reported (Warren, 1993). Wada and Aniya (1995) found that between 1991 and 1994, a small part slightly retreated while an other small part advanced slightly ; however, these changes might be due to the timing of photographing and calving activities. It may be said that Glaciar San Rafael has been fairly stable since 1991 (Fig. 4). This stability could be due to a decrease in calving rate, as the present snout position appears to be close to the bedrock-water interface, inferring from the change in the surface gradient.

Glaciar San Quintin, another largest glacier in the HPN, has been loosing mass of ice through down -wasting in recent years as well as the snout retreat. The accelerated retreat rate during 1994−96 was caused by the retreat at the southern side in a proglacial lake. Winchester and Harrison (1996) reported an advance of 150 m between 1991 and 1993 from the

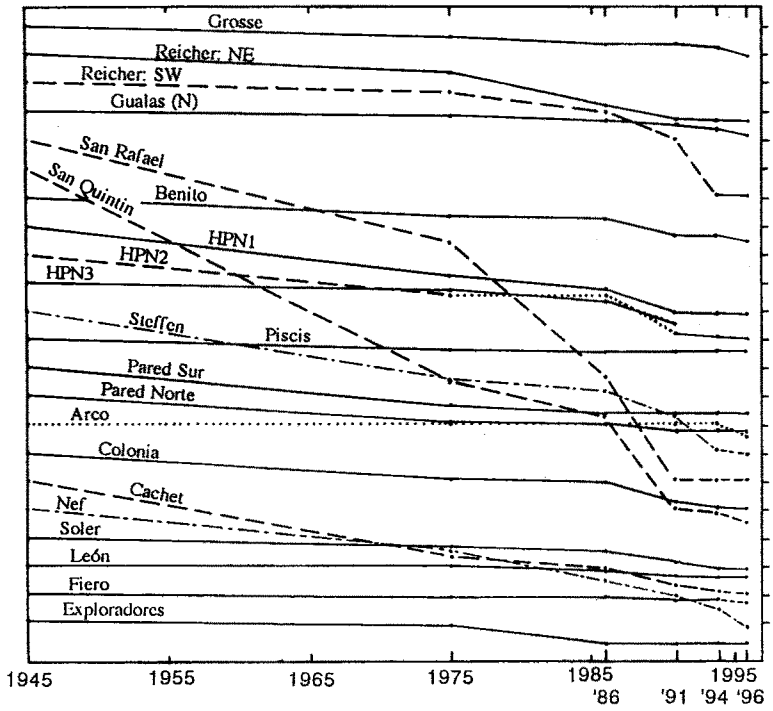

Fig. 3. Glacier variations since 1944/45. The distance between two ticks on the right abscissa indicates an area change of 1 km².

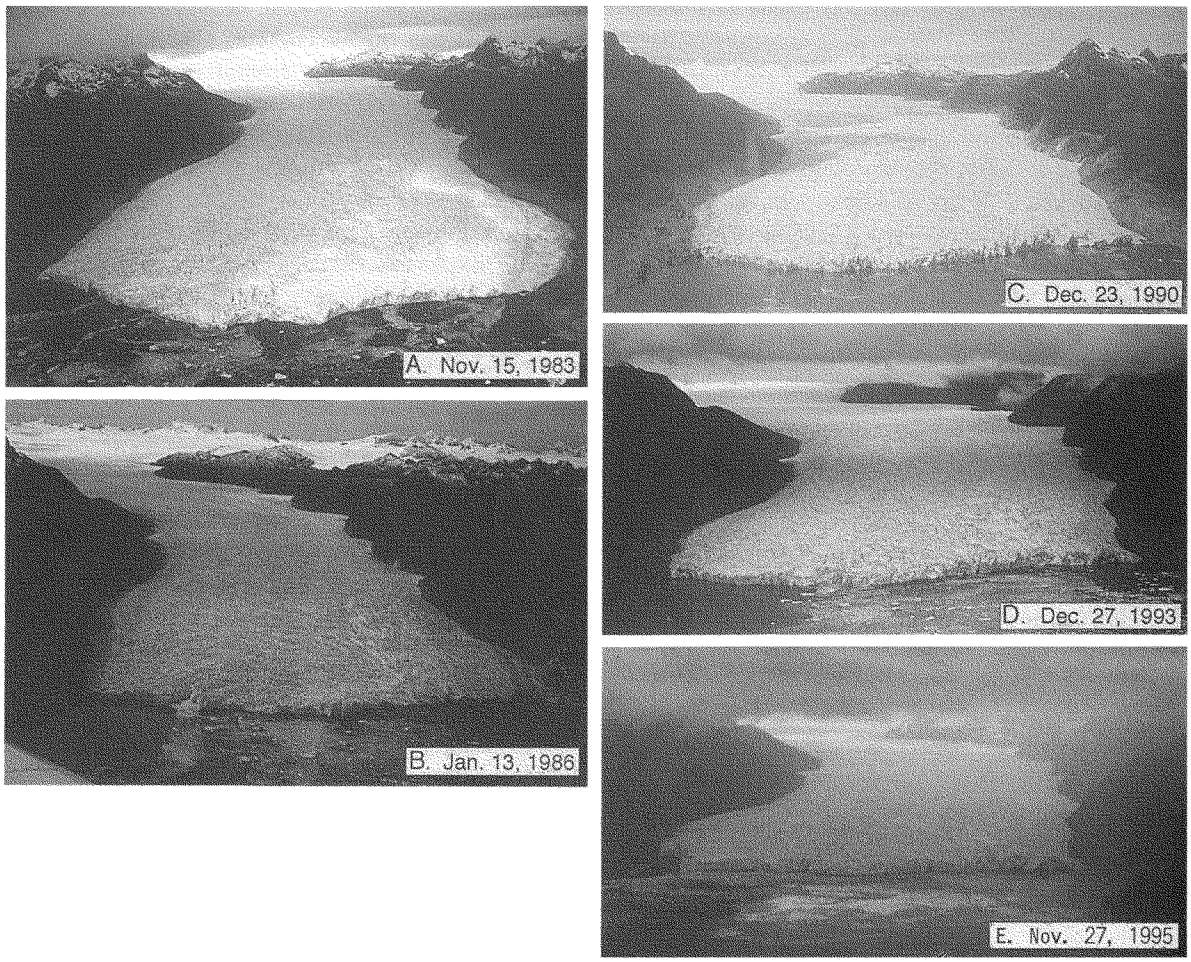

Fig. 4. Variation of San Rafael Glacier since 1983. Between 1983/84 and 1990/91, the glacier retreated very rapidly ; however, since 1990/91, the glacier snout changed very little. Note the left front for comparison (All photographs were taken by Aniya).

ground observation at the westernmost front. The variation trends of Glaciar San Quintin and Glaciar San Rafael since 1986 are similar.

Glaciar Gualas calves into a proglacial lake. Up to 1991, it calved into two lakes ; however, by 1996 the glacier area separating the two proglacial lakes had retreated, forming a channel between them. So, in the statistics of 1996, the snout was treated as a single terminus. With the aid of 1995 and 1990 photographs, the snout position in 1994 was modified. The retreat rate during 1994−96 was 0.125 km^2/y as compared to 0.1 km^2/y between 1991 and 1994. These rates are by far larger than the rates before 1991. The accelerated retreat continued.

The southwestern terminus of Glaciar Reicher disintegrated in a proglacial lake during 1991−94, and in 1996, the snout could be almost regarded as a single terminus. Since the retreat rate of the southwestern snout was only 0.004 km^2/y after 1994, and the rate of the northeastern snout was 0.025 km^2/y, the glacier seems to have reached a new equilibrium after the snout disintegration.

Glaciar Steffen experienced rapid calving retreat in a proglacial lake between 1991 and 1994. However, the snout position in 1994 in the previous study (Wada and Aniya, 1995) was judged to be uncertain in this study and the statistics were taken for a period of 1991−96. In five years, an area of 1.37 km^2 was lost

; however, about 95 % of this was probably lost by 1994.

3.2. Eastern Side

Glaciar Nef showed a large retreat between 1994 and 1996 due to snout disintegration in a proglacial lake, after years of snout narrowing rather than retreating. A similar pattern of disintegration occurred at the southwestern snout of Glaciar Reicher between 1991 and 1994 and at Glaciar Steffen (Wada and Aniya, 1995). They are seemingly against the recent trend ; but these are probably a delayed response to climate changes. The fact that the snouts of these glaciers had been narrowing rather than retreating strongly implies that the snout had been pinned down by the subaqueous topography, most likely moraines. With the continued narrowing and thinning, the glacier finally reached flotation point and then disintegrated rapidly soon after.

The apparent snout position of Glaciar Soler shows no particular change, but from the field work in December 1995, it was found that the area within 1 km from the apparent snout is dead ice and the border between active ice could be clearly recognized. These changes were not taken in the statistics, however, because at other glaciers in a similar state ground checks could not be done.

Glaciar Colonia has a few lines of thrust moraines in front of the snout, as well as on the glacier surface near the snout, indicating the continued recession. Thrust moraines are commonly formed at the border between the dead ice in front and the active ice behind, indicating a feature associated with the retreating glacier (Aniya, 1987).

Glaciar Piscis and Glaciar Leon showed a slight advance during 1994−96. These glaciers had been retreating, although little, during the recent years.

3.3. Debris-Covered glaciers

The snout of Glaciar Arco seemingly remained almost the same since 1945 until 1994 ; however, the debris-covered area at the snout had steadily enlarged during that period. In 1996, it was judged that much of the debris-covered area was dead ice (if ice exists underneath) and the glacier was considered to have retreated. Fig. 3 gives the impression that the retreat was sudden ; but it is a matter of judgment, without close field work. The glacier must have been slowly wasting down, and until 1995 it was difficult to recognize from the air.

Glaciar Grosse is another heavily debris-covered glacier. It has been recognized that down-wasting was very prominent, but frontal recession was not apparent until 1996, when formation of a large proglacial lake by coalescing supraglacial pools was recognized. This also caused an apparent large recession rate.

In the snout area of Glaciar Pared Sur and Glaciar Exploradores, the active glacier front cannot be located due to the heavy debris-cover. The apparent snout positions remain the same for years at these glaciers. Because down-wasting has been dominant, it is anticipated that what happened to Glaciar Grosse during 1995−96 will happen at Glaciar Exploradores in the near future, *i.e.*, the formation of a large proglacial lake and a large retreat.

3.4. Loss of Ice

The total glacier area lost since 1945 amounts to about 64 km^2. The ice thickness near the snout in the Patagonia Icefield was estimated at several glaciers (Aniya *et al.*, 1997). From these data, the average thickness of 100 m to 300 m may be taken for the HPN. This estimation yields 6.4 km^3 to 19.2 km^3 for the total ice volume lost due to the recession

The thinning rate near the snout ranged from less than 1 m a^{-1} to about 4 m a^{-1} between 1945 and 1975 for 16 outlet glaciers of the HPN (Aniya, 1988). Assuming an average rate of 1 to 2 m a^{-1} for the ablation area (1550 km^2) of the HPN, the total volume lost by thinning of the ablation area is about 79 km^3 to 158 km^3 for the period of 51 years.

As for the accumulation area, there is no direct measurement or estimated data for thinning ; however, at Glaciar Soler there is an evidence for thinning. A large icefall of 700 m high is located just below the equilibrium line (1350 m). Comparisons of the photographs taken from the air in 1944 and 1984 (Aniya and Enomoto, 1986a), and those taken on the ground in 1985 and 1995 reveal that the bedrock exposure in the icefall has progressively increased, particularly in December 1995 there was a huge bedrock exposure in the middle of the icefall (Fig. 5). These changes have clearly been caused by the diminished ice supply from the icefield, which is in turn effected by the decrease in the ice surface level. If we conservatively assume a thinning rate of about 1 m a^{-1} for the accumulation area (2600 km^2), the volume lost for the 51 year period would be about 133 km^3.

Consequently, the estimated total ice volume lost

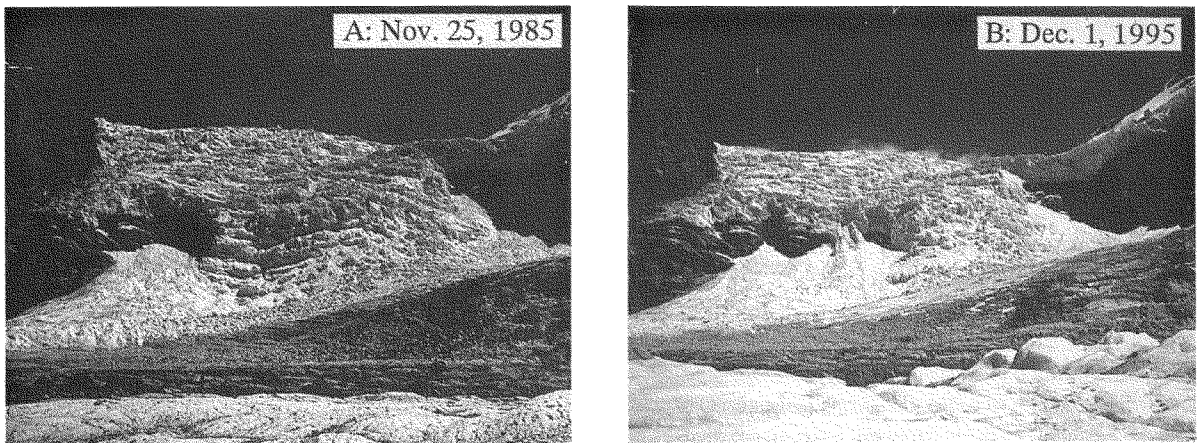

Fig. 5. Conspicuously diminishing supply of ice from the icefield at Glaciar Soler, between 1985 and 1995 (photos taken by Aniya). The icefall is about 700 m high, with its elevations ranging from 750 to 1450 m. The width at the base is about 1.1 km. The ELA is estimated at 1350 m.

by the recession and thinning from 1945 to 1996 ranges from a minimum of about 218 km^3 to a maximum of about 310 km^3 for the HPN.

3.5. Climate Data

There are two climate stations around the HPN. Cabo Raper is located 200 km almost due west of the icefield ; hence it is located in the same Westerlies belt and climatic regime. Another station, Puerto Aisen, is located 200 km north of the HPN, which suggests that the station is probably less affected by the Westerlies than the HPN. Temperature data at Puerto Aisen does not show any specific trends since the start of the record in the 1930s (Aniya and Enomoto, 1986a). On the other hand, precipitation data indicate an increase between 1955 and 1960, and during the 1970s, particularly in winter precipitation (July) of 1971.

Precipitation data from Cabo Raper (Warren, 1993, Fig. 6) show a striking increase in precipitation

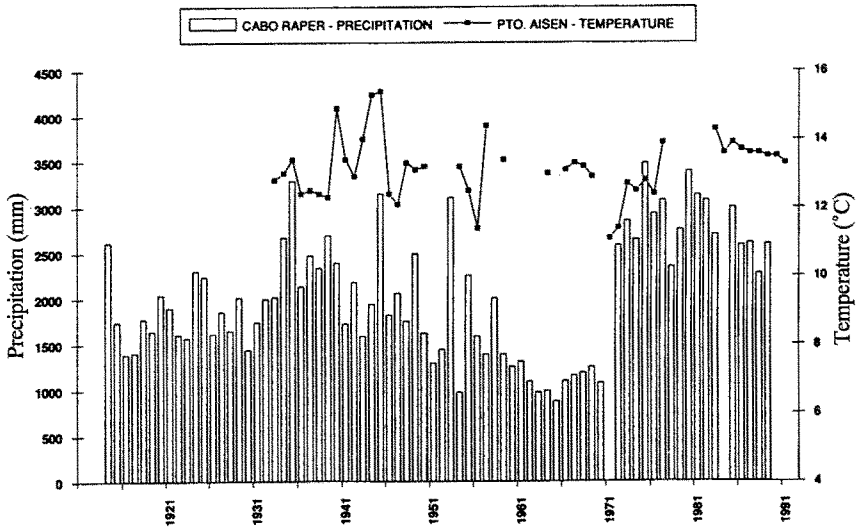

Fig. 6. Precipitation data at Cabo Raper and temperature data at Puerto Aisen (taken from Warren, 1993)

during the 1970s, almost double the value of the 1960s. It has been argued that the precipitation has more influence on the glacier variation, in particular, on those on the western side where climate is maritime (Warren and Sugden, 1993). Therefore, it seems reasonable to suppose that the precipitation increase during the 1970s has caused the slowing down of the retreat (Aniya and Sato, 1996). If so, the time lag for the glacier response is probably on the order of 20 years in the HPN. Winchester and Harrison (1996) reached the same conclusion on the time lag after studying detailed variations of San Rafael and San Quintin glaciers. At Glaciar Pío XI of the HPS, the largest glacier in South America with an area of 1260 km^2, the response time was estimated at 10 to 15 years (Rivera *et al.*, in press).

The slower retreat rates between 1975 and 1986 than between 1986 and 1991 may be due to a precipitation increase between 1955 and 1960. The reason that the effect of the precipitation increase has become apparent sooner at the western glaciers than at the eastern glaciers is not certain, because the drainage area of the western glaciers is generally larger and the available data on ice-flow velocity, although meager, indicate that except for Glaciar San Rafael, the western glaciers (San Quintin, Gualas and Reicher) are not particularly faster (Rignot *et al.*, 1996) than Glaciar Soler (Naruse, 1985, 1987) on the east, which relates to the residence time of ice.

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