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Glacier variations of Hielo Patagónico Norte, Chilean Patagonia, since 1944/45, with special reference to variations between 1995/96 and 1999/2000

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Abstract

Comparison of hand-held oblique photographs taken in the austral summers of 1998 and 1999 over 21 outlet glaciers of Hielo Patagónico Norte (Northern Patagonia Icefield) with those taken in the austral summer of 1995 revealed variations of these glaciers for a period between 1995/96 and 1999/2000. The characteristics and trend of these variations were discussed in the context of variations since 1944/45. Glaciar San Rafael made a strong advance during the period of 1996-99, gaining an area of 0.86 km^2; however, it lost as much due to retreat during the subsequent period of 1999-2000. The average retreat rate per one glacier during the period of 1996-99 was slow (0.037 km^2 y^{-1}), whereas it was very fast during the period of 1999-2000 (0.221 km^2 y^{-1}). Glaciar San Quintin lost an area of 7.55 km^2 between 1996 and 2000, which is by far the largest in any period since 1945. The glacier appears to have started a large scale snout disintegration. The recent global warming appears to have begun taking the real effect on those glaciers in Patagonia. The general slow retreat during the period of 1996-99 may be attributed to the precipitation increase observed in the 1970s. The strong advance and subsequent retreat of Glaciar San Rafael is interpreted to be controlled by fjord topography as well as climatic influence.

1. Introduction

This paper is the continuation of the previous studies by the author in which the variation of 21 outlet glaciers of the Hielo Patagónico Norte (HPN, or Northern Patagonia Icefield) since 1944/45 has been elucidated using trimetrogon, vertical and hand-held oblique aerial photographs (Aniya and Enomoto, 1986a, 1986b; Aniya, 1988; Aniya, 1992; Wada and Aniya, 1995; Aniya and Wakao, 1997).

The HPN is one of the two large icefields located in Patagonia, South America, the other being the HPS (Hielo Patagónico Sur). Together they comprise the largest temperate icebody in the Southern Hemisphere, with a combined area of 17,200 km^2 (HPN, 4200 km^2, Aniya, 1988; HPS, 17,000 km^2, Aniya *et al.*, 1992). The HPN is located between latitudes of 46°30′S and 47°30′S along longitude of 73°30, with icefield elevations ranging from 1000 m to 1500 m, from which 28 glaciers are flowing out in all directions (Fig. 1, Aniya, 1988). Monte San Valentin (3910 m), the highest mountain in Patagonia, is located at the northeast corner of the icefield. A large amount of precipitation, nearly 10,000 mm (Escobar *et al.*, 1992), sustains this icefield, despite its location at relatively low latitude and low elevations. These locational characteristics make the icefields to be a vital area for understanding the global pattern of glacier variations in response to the recent global warming.

Hand-held oblique photographs of the glacier snouts were taken in the austral summers of 1998 and 1999 by the author, and these photographs were compared with those taken in the austral summer of 1995 (Aniya and Wakao, 1997) for variations. Those of 1998 were rather poor in quality due to inclement weather conditions and only 15 out of 21 outlet glaciers could be studied. On the other hand, those of 1999 came out excellent because of good weather and skillful flight. Consequently, all but one (Glaciar Pared Norte) snout positions could be located fairly accurately.

It is the purpose of this paper to report the variation between 1995/96 (hereafter referred to as 1996) and 1999/2000 (likewise, 2000), with the additional data of 1998/99 (likewise, 1999), and to discuss the characteristics and trends of the variation, together with the previous records.

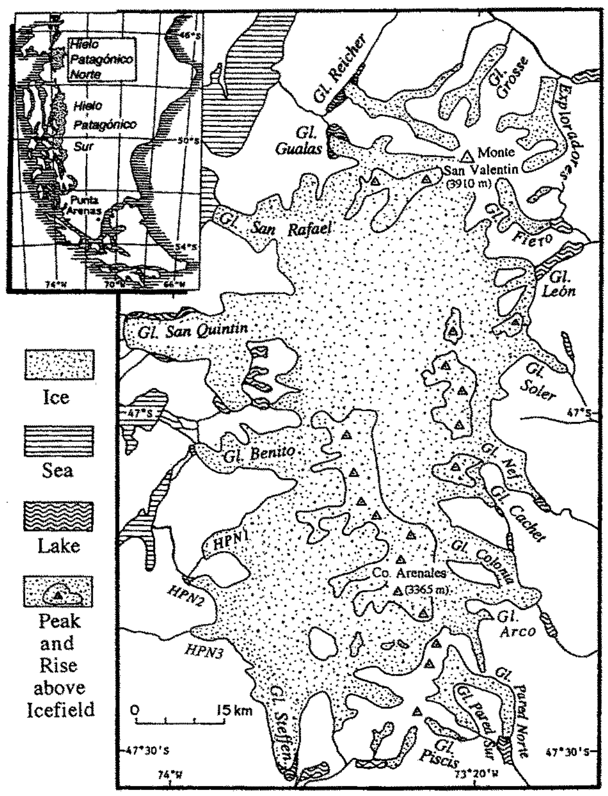


Fig. 1. Study area: Hielo Patagónico Norte and its outlet glaciers.

2. Data and method

The hand-held oblique photographs covering the glacier snout were taken with a 35 mm camera equipped with a zoom lens (28-200 mm) in November 30, 1998 and November 30, 1999 using ASA 400 films. We flew a Beechcraft Baron twin engine over the peripheral of the icefield. In these flights, the author sat on the same side with the pilot, thereby both of us had a similar look toward glaciers, which facilitated easy maneuvering of the aircraft for desired view points. This resulted, together with good weather, in excellent photographs of 1999, although it did not in 1998 because of fog/rain with the low cloud ceiling.

For Glaciar San Quintin, the snout positions of 1944/45 (hereafter referred to as 1945), 1974/75 (likewise 1975), 1985/86 (likewise 1986), 1990/91 (likewise 1991), 1993/94 (likewise 1994) and 1996 were newly redefined on the 1:50,000 topographic map published by the Instituto Geográfico Militar (IGM) of Chile. Previously they were plotted on a map enlarged to 1:100,000 from 1:250,000 Carta Preliminar, also published by the IGM using trimetrogon photographs taken in 1944-47, which was known to contain some errors in positions and outlines. Subsequently, the area and distance changes were measured again and the new statistics are listed in Tables 1 and 2. Although the differences are substantial for 1945-75 (old, 7.50 km^2; new, 8.07 km^2) and 1975-86 (old, 1.20 km^2; new, 1.68 km^2), they do not alter the previous discussion which has been made based on the old statistics (e.g. Wada and Aniya, 1995; Aniya and Wakao, 1997; Aniya, 1999).

For Glaciar Colonia, snout positions of 1986, 1991, 1994 and 1996 were reinterpreted with an aid of Radarsat images of 1995, and the statistics are modified accordingly. Likewise, the statistic for Glaciar Cachet 1991-94 was slightly modified.

For HPN1, the statistics for 1986-91, 1991-94, and 1994-96 were also changed, when defining the snout position of 2000. While the area lost between 1986 and 1991 is substantially different (old, 0.91 km^2; new 0.67 km^2), those for the two other periods are very small. Oblique photographs of HPN3 were successfully taken in November 1999 for the first time since 1991. Using this photography, data for 1986-91 was substantially modified from 0.84 km^2 to 0.21 km^2, when defining the snout position of 2000. This valley is very narrow and liable to dense fog even when other area is clear/fair, which makes it very difficult and dangerous to photo-

Table 1. Glacier Variation of the Northern Patagonia Icefield, 1945-2000 (retreat in distance (m) and an annual average in parentheses)

Glacier	Period			
	1945-2000*	1945-75	1975-86	1986-91
Northern Side				
Grosse	1500 (27)	500 (17)	250 (23)	No substantial change, but thinning
Western Side				
Reicher: NE	2700 (49)	0	2150 (195)	300-500 (60-100)
: SW	4650 (85)	a400 (-13), but narrowed by 200 (7)	280 (25)	850 (170), and snout narrowed by 300 (60)
Gualas: N	1230 (22)	100 (3)	250 (23)	100-150 (20-30)
: S	570 (10)	250 (8)	350 (32)	no substantial change
San Rafael	*ca.* 4200 (76)	400-900 (13-30)	2200 (200)	900-1500 (190-300)
San Quintin: front	600-1400 (11-25)	200 (7)	200-500 (18-45) and considerable thinning	*ca.* 200 (40), and considerable thinning
: N side	*ca.* 500 (9)	200 (7)	0	200 (40)
: S side	1000-2000 (18-36)	1200 (40)	no substantial change	250 (50)
Benito	1000-1500 (18-27)	550 (17) left; 0 right	0, left; 200 (18) right	450 (90)
HPN1	2250 (41)	1400 (47)	300 (27)	450 (90)
HPN2	2800 (51)	1000 (33)	slight retreat	1250 (250)
HPN3	1600 (29)	600 (20) left; 0 right	100 (9) left; 850 (27) right	*ca.* 1000 (200)
Southern Side				
Steffen: front	3500 (64)	900 (30)	250 (23)	350 (70)
:E side	1250 (23)	500 (17)	300 (27)	400 (80)
Eastern Side				
Piscis	950 (17)	760 (25)	100 (9)	no substantial change
Pared Sur	1250 (23)	1000 (33)	250 (23)	no substantial change
Pared Norte	1800 (33, for 45-99)	1300 (43)	slight retreat	400 (80)
Arco	1630 (30)	no substantial change	no substantial change	no substantial change
Colonia	1000 (18)	500 (17)	200 (18)	330 (66)
Cachet	3500 (64)	2000 (67)	250-750 (27-83)	400-950 (80-190)
Nef	3360 (61)	0, but narrowed by 400-700 (13-23)	350 (32), and narrowed by 300-600 (27-55)	no substantial frontal change, but narrowed by *ca.* 600 (120) and calving front is breaking away
Soler	*ca.* 600 (11)	80-300 (3-10)	60-160 (5-15)	130-240 (26-48)
Leon	*ca.* 300 (5)	100 (3)	200 (18)	120-200 (24-40)
Fiero	820 (15)	300 (10)	0	200 (40)
Exploradores	*ca.* 550 (10)	200 (7) apparent, part	350 (32) apparent	no substantial frontal change, but considerable thinning
active front?	800-1600 (15-30)	*ca.* 50	50-150 (5-14)	0

Source: Aniya and Wakao (1997) for 1945-96. San Quintin "front" modified for 1975-86 and 1986-91, "N side" for 1945-75, and "S side" for 1945-75 Colonia slightly modified for 1986-91 and 1991-94.

*does not neccessarily agree with the sum of each period, because the fluctuated part may be different for different period.

the active front was newly inferred, reflecting the reccession since 1945

a: advance

graph this glacier.

The snout position shown in these oblique photographs was first located on the vertical aerial photographs at a nominal scale of 1:70,000 taken in 1974 or 1975 by the IGM of Chile. The topographic maps at a scale of 1:50,000 have been produced from these vertical aerial photographs by the IGM in the early 1980s, which have been used as the base map for plotting snout positions (except for Glaciar San Quintin). In this process, the topographic detail of the snout area is interpreted in order to correlate oblique photographs to the vertical photographs in addition to the previous position of the snout. Then, the snout position on the vertical photograph is transcribed onto the 1:50,000 topographic map. However, this process is fairly difficult for many glaciers because glaciers have been receding and the fresh ground, which used to be covered by the glacier and hence was not shown on the vertical photographs of 1974 or 1975, has since emerged. Therefore, it is liable to make an error when estimating the location of the snout, especially when the quality of the oblique photographs is poor and/or photographic angle is not optimal for relating features of the oblique photographs to those of the vertical photographs, or comparing with the oblique photographs of the previous periods. This is the reason why some of the past snout positions were modified in this paper.

The variation was measured in both distance change (Table 1) and area change (Table 2). Although the distance change is intuitively easier to comprehend, the discussion is primarily based on the area change, because the amount of retreat or advance can seldom be represented by a single figure. Also with the area change, we can estimate the volume of ice lost or gained if the ice thickness can be known by some methods (Aniya and Wakao, 1997; Aniya, 1999).

3. Results and discussion

3.1. Overall change

Tables 1 and 2 show variation statistics for periods of 1996-99 and 1999-2000, along with the previous records. Figure 2 illustrates these variations in area. Between 1996 and 1999, three glaciers were found to have advanced; one strong and two very weak. Glaciar San Rafael made a very strong advance across the entire length of the front during this period. Although Glaciar San Rafael started advancing around 1992 (Warren, 1993; Wada and Aniya, 1995), it was limited to a part of the front and the net area change was

1991-94	1994-96	1996-99	1999-2000
70 (23)	*ca.* 180 (90)	no substantial change	*ca.* 600
90 (30)	60 (20) part	0	350, right side
3550 (1183), due to	no substantial change	320 (107), right side	250
snout disintegration			
200 (67)	*ca.* 100 (50)	280 (73) (uncertain)	150
100 (33)	*ca.* 70 (35) part	a310 (-103) part (uncertain)	700
60 (20), left (small part)	no substantial change	a320 (-107)	*ca.* 500, center part
a50 (-17), right (small part)			
no substantial change,	no substantial change,?	no data for frontal change	*ca.* 1000 (250)right side for 96-00
but considerable thinning	but considerable thinning	(probably no change but thinning)	considerable thinning
retreat?	slight retreat?	no data (probably slight retreat?)	*ca.* 300 (75) for 96-00
190 (63) small part	*ca.* 300 (15) small part	slight retreat	100-250
160 (53) tip of snout	105 (53)	no data	550 (138) for 96-00
no substantial change	40 (20)	no data	*ca.* 150 (38) for 96-00
no data	60 (12) tip of snout for 91-96	no data	*ca.* 400 (100) for 96-00
no data	no data	no data	*ca.* 500 (56) for 91-00
no data	*ca.* 1000 (200) for 91-96	320 (107)	*ca.* 100
180 (60)	no substantial change	no substantial change	*ca.* 250
40 (13)	a30 (-15) right side	30 (10) right side	100
no substantial change	no substantial change	no substantial change	no substantial change
20 (7)	35 (17) left side	50 (17) left side	no data
no substantial change	1430#	no substantial change	200
no substantial change	no substantial change	70 (23)	no substantial change
90-350 (30-117)	70 (35) tip of snout	*ca.* 220 (73) debris-free part	no substantial change
30 (10), and	2570 (1285), due to	460 (153)	*ca.* 100
narrowed by 40-350 (13-117)	snout disintegration		
20-180 (7-60)	no substantial change	*ca.* 50 (17)	no substantial change
no data	a140 (-28) part for 91-96	a ca. 35 (-11), right side	*ca.* 100
no data	*ca.* 180 (36) for 91-96	50 (17) tip of snout	150
no substantial change,	no substantial change,	no substantial change,	no substantial change
but thinning	but thinning	but thinning	
?	?	?	750-1350 (83-150) for 91-00

and 1986-91; HPN1 for 1986-91 and 1991-94; HPN3 for 1986-91;

Table 2. Glacier Variation of the Northern Patagonia Icefield (area lost in km² with the mean annual rate/glacier)

Glacier	Period							
	1945-2000	1945-75	1975-86	1986-91	1991-94	1994-96	1996-99	1999-2000
Northern Side								
Grosse	1.78 (0.032)	0.39 (0.013)	0.22 (0.020)	0	0.13 (0.042)	0.28 (0.140)	0.02 (0.007)	0.74
Western Side								
Reicher: NE	2.60 (0.047)	0.61 (0.020)	1.18 (0.107)	0.47 (0.094)	0.07 (0.025)	0.05 (0.025)	0.01 (0.003)	0.21
: SW	4.35 (0.079)	0.36 (0.012)	0.64 (0.058)	0.94 (0.188)	2.02 (0.673)	0.01 (0.005)	0.18 (0.060)	0.20
Gualas: N	1.25 (0.023)	0.13 (0.0004)	0.19 (0.017)	0.14 (0.003)	0.17 (0.056)	0.25 (0.125)	0.31 (0.103)	0.06
: S	0.98 (0.018)	0.17 (0.0006)	0.35 (0.032)	0	0.13 (0.043)	#	a0.07 (-0.023)	0.40
San Rafacl	12.03 (0.219)	3.56 (0.119)	4.83 (0.439)	3.60 (0.720)	0.0006	0.01 (0.007)	a0.86 (-0.287)	0.89
San Quintin	21.11 (0.384)	8.07 (0.269)	1.68 (0.153)	3.37 (0.674)	0.17 (0.058)	0.27 (0.136)	no data	7.55 (1.888)***
Bcnito	2.05 (0.037)	0.66 (0.022)	0.07 (0.006)	0.58 (0.116)	0.05 (0.016)	0.23 (0.115)	no data	0.46 (0.115)***
HPN1	3.43 (0.062)	1.75 (0.058)	0.37 (0.034)	0.67 (0.134)	0.03 (0.010)	0.10 (0.050)	no data	0.51 (0.128)***
HPN2	3.47 (0.063)	1.41 (0.042)	0?	1.45 (0.290)	no data	0.03 (0.016)**	no data	0.58 (0.145)***
HPN3	1.84 (0.033)	0.22 (0.0007)	0.41 (0.037)	0.21 (0.042)	no data	no data	no data	1.00 (0.111)****
Southern Side								
Steffen	6.66 (0.121)	2.42 (0.081)	0.39 (0.035)	0.88 (0.176)	uncertain	1.37 (0.274)**	1.13 (0.377)	0.47
Eastern Side								
Piscis	0.58 (0.011)	0.49 (0.016)	0.02 (0.002)	0	0.01 (0.003)	a0.01 (-0.005)	0.01 (0.003)	0.06
Pared Sur	1.69 (0.031)	1.42 (0.047)	0.27 (0.025)	0	0	0	0	0?
Pared Norte	1.32 (0.024)*	0.97 (0.032)	0.04 (0.004)	0.27 (0.054)	0.007 (0.002)	0.003 (0.001)	0.03 (0.01)	no data
Arco	0.64 (0.012)	0?	0?	0?	0?	0.48 (0.240)##	0	0.16
Colonia	1.81 (0.033)	0.97 (0.032)	0.12 (0.011)	0.39 (0.078)	0.09 (0.030)	0.08 (0.040)	0.16 (0.503)	0
Cachet	4.29 (0.078)	2.68 (0.089)	0.44 (0.040)	0.64 (0.128)	0.20 (0.066)	0.05 (0.023)	0.24 (0.08)	0.04
Nef	4.81 (0.087)	1.46 (0.049)	1.12 (0.102)	0.56 (0.112)	0.45 (0.149)	0.71 (0.355)	0.42 (0.14)	0.09
Soler	1.62 (0.029)	0.38 (0.013)	0.16 (0.015)	0.43 (0.086)	0.16 (0.054)	0	0.37 (0.123)	0.12
Leon	0.46 (0.008)	0.02 (0.00007)	0.19 (0.017)	0.19 (0.038)	uncertain	a0.06 (-0.012)**	a0.03 (-0.01)	0.15
Fiero	0.57 (0.010)	0.15 (0.0005)	0	0.12 (0.024)	uncertain	0.12 (0.024)**	0.02 (0.007)	0.16
Exploradores	0.81 (0.015)	0.16 (0.0005)	0.65 (0.059)	0 (apparent)	0 (apparent)	0 (apparent)	0 (apparent)	0 (apparent)
real?	3.32 (0.060)	0.09 (0.0003)	0.38 (0.034)	0	?	?	?	2.85 (0.317)****
Total###	78.83 (0.065)	28.45 (0.041)	13.34 (0.053)	14.91 (0.130)	3.69 (0.068)	2.51 (0.074)	1.98 (0.037)	3.75 (0.221)

Source: Aniya and Wakao (1997) for 1945-96. San Quinting modified for 1945-75, 1975-86, 1986-91, 1991-94 and 1994-96; HPN1 for 1986-91, 1991-94 and 1994-96; HPN3 for 1986-91; Colonia slightly modified for 1986-91 and 1991-94; Cachet for 1991-94; and Nef for 1994-96.
#: combined
##: the active front was newly inferred, reflecting the recession since 1945.
###: cxcluding glacicrs with asterisk (s) and Exploradores (real?).
*: for 1945-99
**: for 1991-96
***: for 1996-2000
****: for 1991-2000
a: advance

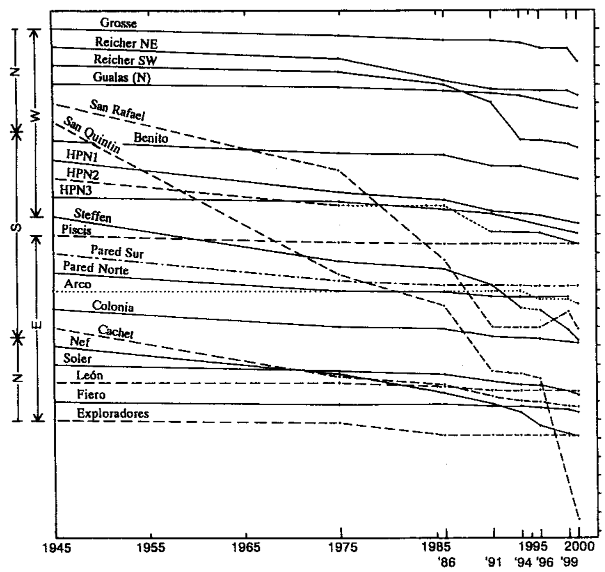


Fig. 2. Variations in area of outlet glaciers of the HPN between 1944/45 and 1999/2000. The distance between two ticks on the right abscissa indicates an area change of 1 km². Dotted line indicates uncertainty. Other kinds of lines are used only for easy reading.

loss until 1996. Between 1999 and 2000, this glacier made a substantial retreat, however, losing as much area as it gained during the advance of 1996-99.

The recession rate of 1999-2000 is very large compared with the previous periods (Table 2 and Fig. 2); indeed it is by far the largest since 1945. In contrast, the recession rate between 1996 and 1999 is the smallest. For 1996-99, even if excluding Glacial San Rafael which made a strong advance, the recession rate is 0.056 $km^2\ y^{-1}$ as compared to 0.221 $km^2\ y^{-1}$ for 1999-2000. The slack in the retreating rate of 1996-99 might be attributed to the precipitation increase during the early 1970s (Warren, 1993).

Glaciar San Quintin retreated very fast between 1996 and 2000 at an average recession rate of 1.89 $km^2\ y^{-1}$, which is by far the largest of all glaciers since 1945. This rate surpasses even the unusually fast retreat during 1986-91, when Glaciar San Quintin and San Rafael receded with then -an-unprecedented speed of around 0.7 $km^2\ y^{-1}$

From these characteristics of the variation trends, it may be interpreted that the recent global warming have begun to take real effects on behavior of the Patagonian glaciers.

3.2. Western side

There are a few glaciers on this side, with interesting variations since 1996. Those include Glaciar San Rafael, San Quintin, Gualas, Reicher and Steffen.

Glaciar San Rafael

This is one of the two largest glaciers of the HPN with an area of ca. 760 km^2 (Aniya, 1988), and it is noted for the large, fast retreat during the 1980s. Between 1999 and 2000, this glacier retreated ca. 500 m near the center. Since the front is wide, about 3 km long, the total area lost amounted in one year to 0.89 km^2. This is probably the most important finding about variations of the HPN glaciers between 1999 and 2000. This glacier started advancing in part around 1992 and between 1996 and 1999, it gained an area of 0.86 km^2.

The advance of this glacier during the early 1990s was attributed to the possible precipitation increase in the early 1970s which was recorded at the nearest meteorological station, Cabo Raper, located about 200 km west of the icefield (Warren, 1993; Aniya and Sato, 1996; Winchester and Harrison, 1996). On this assumption, the response delay time was taken as about 20 years in the HPN. Recently, Aniya *et al.* (1999) suggested topographic constraint of the fjord plan shape as another possible cause for this anomalous behavior. Upon finding the continuing recession of other glaciers between 1996 and 1999, Aniya *et al.* (2000) argued for the topographic control of fjord for the Glaciar San Rafael variations, because the glacier continued to advance where the width of the fjord widened, and then started to retreat. If the precipitation increase in the early 1970s solely had caused an advance of Glaciar San Rafael, it should have affected more or less some other glaciers. It is true that some other glaciers, Glaciar León and Piscis, advanced between 1994 and 1996, however slight, and between 1996 and 1999 Glaciar León and Gualas' south snout advanced when Glaciar San Rafael made a strong advance. Harrison and Winchester (1998) reported advance of Guals' north snout (which they called Gualas West) in 1994, from the ground observation. However, since the advance of Glaciar León and Piscis was very slight, and the advance of Gualas' south snout is just apparent due to stretching out of the (probably floating) tongue, it seems logical to look for another cause for San Rafael's strong advance, as well as climatic forcing.

Glaciar San Quintin

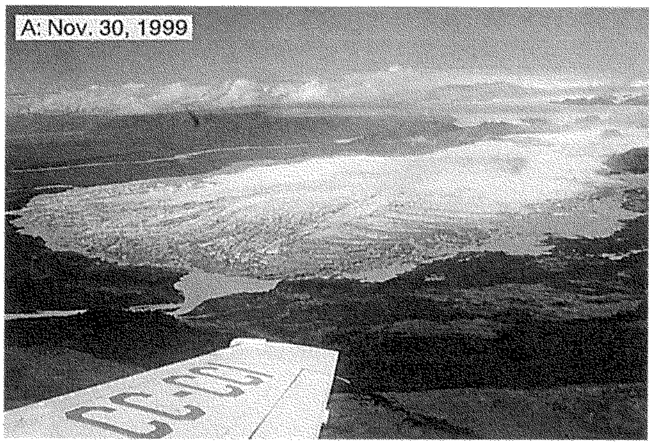
The photography of 1998 was very poor in quality due to heavy fog, and the snout position could not be located. However, those of 1999 came out excellent for interpreting the surface condition and locating the front position (Fig. 3).

As we had predicted a rapid, drastic retreat of the glacier due to prolonged thinning of ice (Aniya and Wakao, 1997), the surface condition observed in November 1999 suggests that large-scale disintegration of the ice in the proglacial lake has begun. By 1999, those proglacial lakes located on the northern, western and southern margins all joined together and the snout is circumscribed by a huge proglacial lake, which is drained by several streams. The area lost between 1996 and 2000 is 7.55 km^2, by far the largest in the HPN (see Fig. 2). We can recognize splaying pattern of crevasses at the front, along many of which lake water invaded (see Fig. 3B), suggesting that accelerating, rapid melting/calving has been in progress. In Fig. 3, a lot of large tabular icebergs or breaking away of large tabular pieces of ice can be seen, suggesting possible flotation of a large part of the snout. A large-scale breaking down of the snout area, which occurred at Glaciar Reicher, Steffen and Nef in the early 1990s, looks imminent at Glaciar San Quintin.

Other glaciers

Glaciar Reicher has two snouts, NE and SW. At the both snouts, the recession was small between 1996 and 1999, particularly at the SW which underwent a large scale snout disintegration between 1991 and 1994. On this ground it was interpreted that the glacier was approaching a new equilibrium. However, the both snouts resumed strong recession after 1999; NE snout losing an area of 0.20 km^2, while SW snout an area of 0.21 km^2 in just one year.

It was interpreted that the south snout of Glaciar Gualas made an apparent advance between 1996 and 1999, which was probably caused by snout stretching due to crevasse widening. The flotation of the snout was inferred from large, tabular shape of icebergs. Stretching was inferred from many, wide crevasses filled with lake water. By 2000, the stretched-out part was gone, resulting in a 700 m retreat and



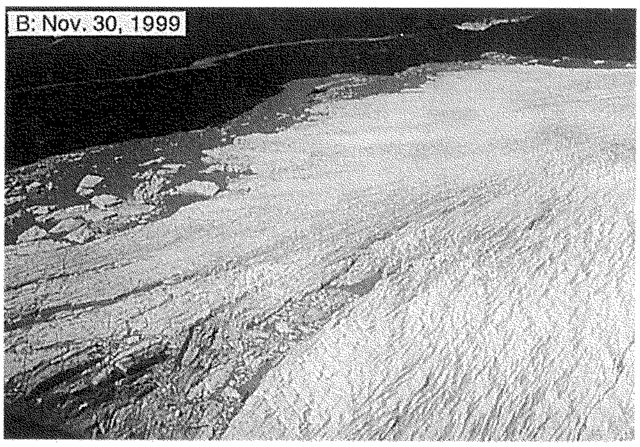


Fig. 3. Glacier San Quintin, 1999. This is one of the two largest glaciers (area; ca. 760 km^2) of the HPN. It has been thinning whose effect has recently resulted in the front retreat. Photo A indicates that the glacier snout is now circumscribed by a single, large proglacial lake. B: a close up photo of the right front where lake water invaded into splaying crevasses, suggesting that a large scale break-up of the floating front is imminent.

a loss of 0.40 km^2, confirming the above interpretation of the snout condition in 1999. According to Harrison and Winchester (1998), Gualas' north snout was in a state of advance in 1994 when they visited, with the relatively flat, crevasse-free surface. However, it lost an area of 0.25 km^2 for 1994-96 and 0.31 km^2 for 1996-99. Photographs I took in 1995 shows a splaying pattern of crevasses, with tabular blocks of ice breaking up. So the deterioration of the surface condition must have been very rapid.

Glaciar Steffen continued a large retreat with the accelerated speed, which has started around 1991-1992 when the disintegration of the snout commenced. The 1999 photographs revealed that a large part of the front was barely attaching to the main body of ice, which was crisscrossed by crevasses filled with lake water. This part will be surely detached in a couple of years at most under the present conditions. From these facts, a large part of the snout is considered to be floating, and another large-scale snout disintegration seems imminent.

3.3. *Eastern side*

On this side two glaciers, Glaciar Piscis and León, made a small advance in the mid 1990s. All other glaciers retreated more or less between 1996 and 2000.

At Glaciar Nef, the recession due to the snout disintegration which had started in 1993 continued; however, the rate slowed down considerably for 1999-2000. Since the gradient of the glacier surface at the left margin changes conspicuously at around 200 m upstream of the present snout (Fig. 4B), it appears that the snout is getting closer to the upper end of the proglacial lake, and this is probably why the retreat has slowed down.

Glaciar Soler made a relatively large retreat between 1996 and 1999, because of the diminished ice supply from the icefield (Fig. 5), coupled with active calving in proglacial lakes (Fig. 6C), which started around 1992. At this glacier, glaciological, meteorological and hydrological observations and measurements have been made in the austral summers of 1983 (Aniya and Naruse, 1985, 1986; Kobayashi and Saito, 1985a, 1985b; Kobayashi and Naruse, 1987; Naruse, 1985; Saito and Kobayashi, 1985), 1985 (Aniya and Naruse, 1987; Aniya *et al.*, 1988; Casassa, 1987; Fukami *et al.*, 1987; Fukami and Naruse, 1987; Fukami and Escobar, 1987; Naruse, 1987; Naruse *et al.*, 1992), and 1998 (Naruse *et al.*, 2000) in order to elucidate the characteristics of the glacier. Thus, we have temperature, precipitation, surface ablation (melting), heat

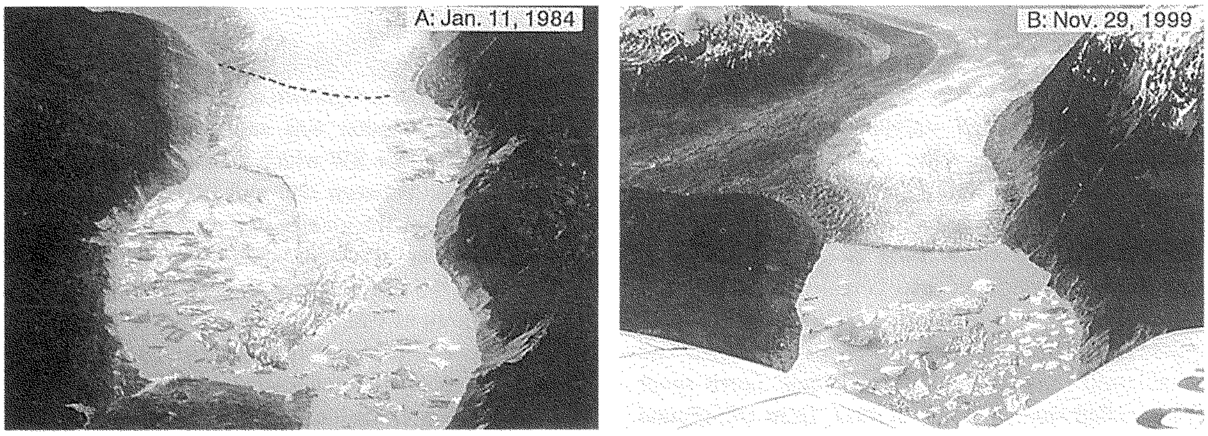


Fig. 4. Glaciar Nef, 1984 and 1999. About 3100 m retreat in 26 years. A: abundant tabular icebergs on the right side of the elongated snout in the proglacial lake suggest that a large scale calving had occurred. Dotted line is the position of snout in 1999. B: the elongated snout broke up in 1993 and it retreated very fast until Nov. 1998. Since then the retreat has slowed down.

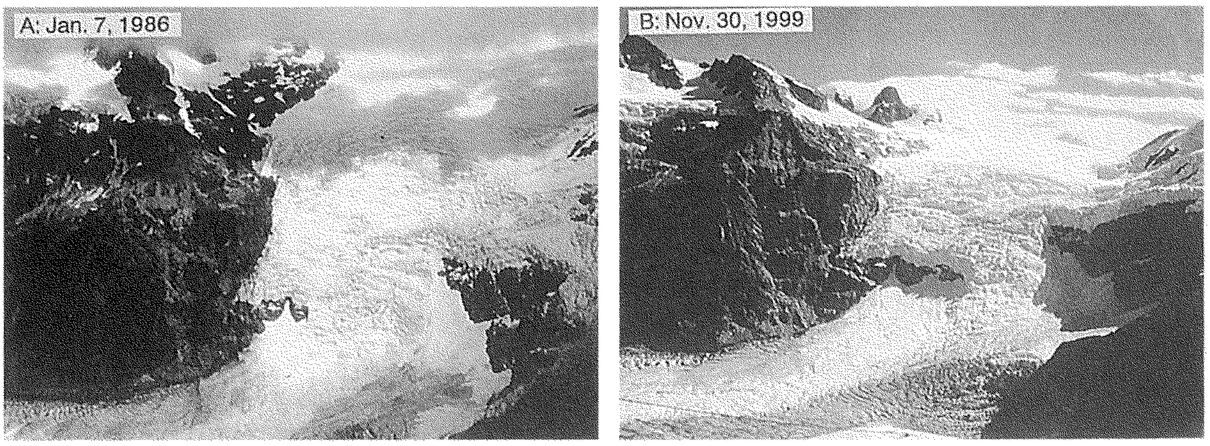


Fig. 5. Icefall of Glaciar Soler, 1986 and 1999. The relief is about 750 m. The ELA (elev. about 1350 m) is located just above the upper end of the icefall (see B). The rock exposure in the middle of the icefall clearly indicates that ice supply from the icefield has considerably diminished.

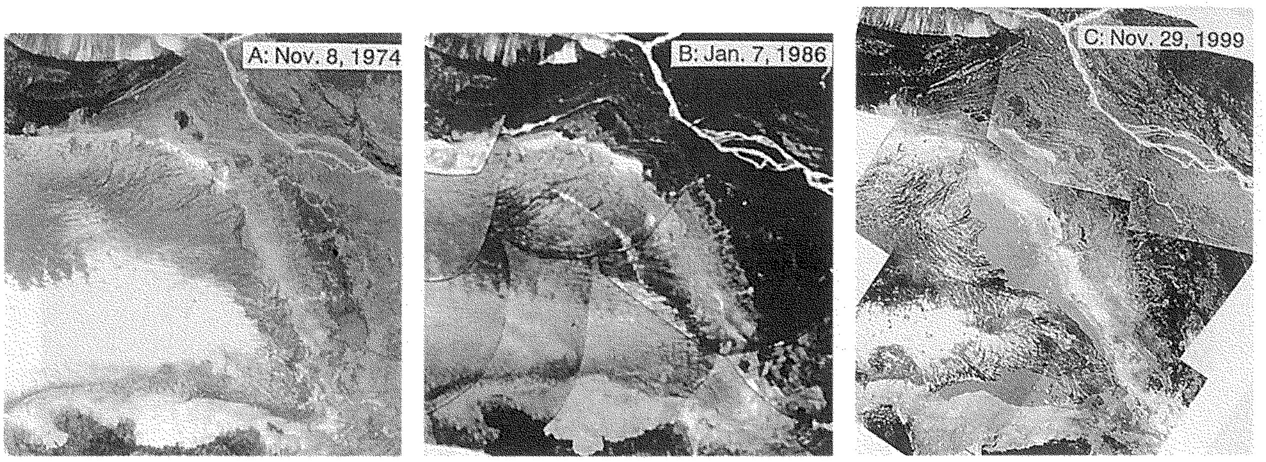


Fig. 6. Snout area of Glaciar Soler, 1974, 1986 and 1999. The photo of 1974 is the vertical one taken by the IGM of Chile, while those of 1986 and 1999 were taken with a 6x6 camera and a mosaic was assembled by the author. Between 1974 and 1986, the snout retreated slightly, whereas between 1986 and 1999, the snout retreated considerably, forming proglacial lakes. The rapid recession may be attributed to the diminished accumulation (see Fig. 5), coupled with calving in newly-formed proglacial lakes.

balance and river run off data for a short period in 1983, 1985 and 1998; it is difficult, however, to discern any specific trend or change which might account for this rapid retreat of the glacier, because the measurement periods were different and not long enough to represent the whole summer. Naruse *et al.* (2000) reported the surface lowering of 42 ± 5 m between 1985 and 1998 (3.2 ± 0.5 m y^{-1}), as compared to 9.9 ± 3 m for 1983-85 (5.2 ± 1.5 m y^{-1}) near the snout (near the left edge of Fig. 6).

Glaciar León advanced between 1994 and 1999, although very slight. However, it retreated about 100 m at the entire length of the glacier front between 1999 and 2000. Glaciar Fiero seems to have started a strong recession. Although the absolute amount of the recession between 1999 and 2000 is 150 m, which is not particularly large in the HPN, it is by far the largest retreat rate for this glacier since 1945.

3.4. Debris-covered glacier

The snouts of Glaciar Exploradores, Grosse, Pared Sur and Arco are heavily covered by thick debris, thereby insulating the glacier surface. Consequently, melting is very slow and the debris-covered part becomes slowly pitted by the formation of supraglacial ponds. This condition makes it very difficult or impossible to determine the ice front to define the snout position. For this reason, the apparent position of the snout is taken as having not changed, while the real or active ice front whose surface is not pitted may have been steadily receding. With some good photographs, the active front could be inferred from the surface topography. This is why the variation of Glaciar Arco was not measured until 1996. In the austral summer of 1999/2000, some changes could clearly be recognized at Glaciar Exploradores, Grosse and Arco.

Glaciar Exploradores

The surface lowering has been prominent since 1986 when the first hand-held oblique photographs were taken and the pitted surface has been steadily enlarging since. In good photographs of 1986 and 1991, the boundary between the pitted and the smooth surface areas could be located, which was taken as the real (active) front. With the good photographs of 1999 such boundary could be located again. In front of the active front is the pitted topography with scattered supraglacial lakes and some of them have coalesced to become larger ones. Although the location of the apparent front do not appear to have changed, the real front receded considerably since 1991, with distances of 750 to 1350 m, losing an area of 2.85 km^2 in nine years.

Glaciar Grosse

Almost the entire surface of the ablation area is heavily covered by thick debris and the surface lowering has been more pronounced than the front retreat. However, during the 1990s, the formation of supraglacial lakes has become very active; subsequently, they are coalesced to form larger lakes. In November 1999, it was found that these lakes had coalesced and become one large lake, circumscribing the snout (Fig. 7B). In one year from 1999 to 2000, it receded ca. 600 m and lost an area of 0.74 km^2, which is considerably large in the HPN. The protruding area of the snout is heavily pitted and it is a matter of short time before losing this part. On the 1999 photographs, I could locate the boundary between the pitted ice surface and intact ice surface, and if we take the margin of the intact ice surface as the real (active) ice front, the recession would be *ca.* 1600 m and an area loss is 1.42 km^2.

3.5. Precipitation data at Cabo Raper

The estimation of the volume of ice loss was discussed in Aniya and Wakao (1997) and Aniya (1999), and the relationship between climatic data and the glacier variation was also discussed in Aniya and Wakao (1997), using the precipitation record at Cabo Raper, located some 200 km west of the HPN (Warren, 1993). Other papers also used this data to discuss the relationship between glacier variations and climate (*e.g.,* Winchester and Harrison, 1996; Harrison and Winchester, 1998). The climatic records Warren provided show a drastic increase in precipitation beginning in 1971. During the 1960s, it was about 1000-1200 mm y^{-1}. In 1971, it jumped to about 2500 mm, and stayed 2500-3500 mm y^{-1} until

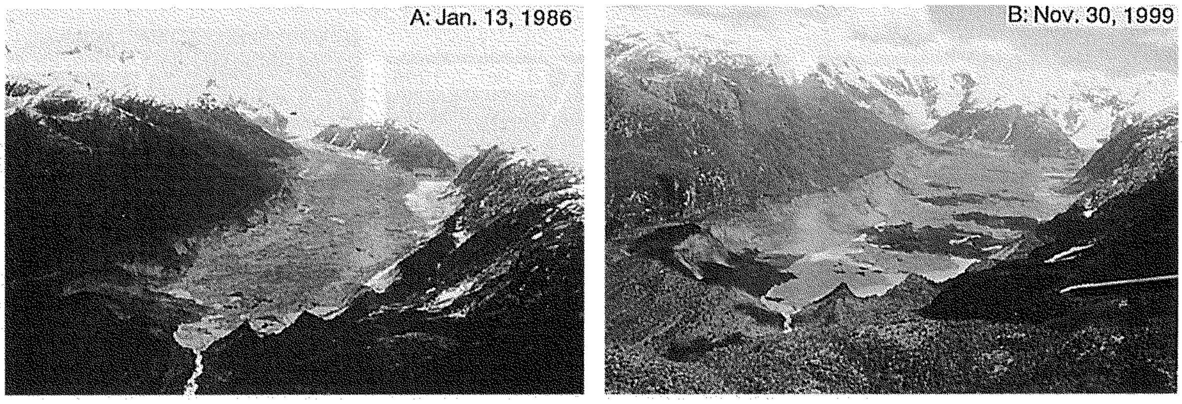


Fig. 7. Glaciar Grosse, 1986 and 1999. The entire surface is heavily covered by debris, which comes from the north face of Monte San Valentin (3910 m), the highest mountain in Patagonia. The mountain is located to the upper left corner of the photos. The surface lowering and the formation of a large proglacial lake is apparent in 14 years.

1989, the last of the record. This is by far the large amount compared to the record of 1913-1960. There are a couple of years when the amount of precipitation doubled over the previous year, but it usually lasted only a year or so, and never lasted for almost two decades.

Dr. Patricio Aceituno, professor of Geophysics, University of Chile, Santiago, Chile, recently questioned the validity of this data (personal comm., Nov. 1999, in Santiago, Chile), because of sudden and sustained increase. The sudden doubling in precipitation for such a long period of time seems very unusual from the past record. Also if this sudden and sustained increase solely had caused the advance of Glaciar San Rafael during the 1990s, why the other, neighboring glaciers such as Glaciar San Quintin, Reicher and Gualas which are located on the same side of the icefield and have the accumulation areas in a similar topographic situation did not make a good advance. It is true that Glaciar San Quintin made a small advance around 1993 (Winchester and Harrison, 1996) and Gualas' north snout also made a small advance at the same time (Harrison and Winchester, 1998); however, these advances seem to be ephemeral, because the glaciers have been retreating since then.

4. Concluding remarks

With the hand-held oblique photography taken in the austral summers of 1998 and 1999, the variation of 21 outlet glaciers of the HPN since 1996 was elucidated, in which it was found out that retreats from 1996 to 1999 were slow at most glaciers, while retreats between 1999 and 2000 were very strong. Glaciar San Quintin, which has been retreating at the fastest rate in the HPN since 1945, appears to have plunged into another phase of rapid retreat, a snout disintegration.

In a rapidly changing glacier area such as the Patagonia Icefield, the fine temporal resolution of remote sensing images proved invaluable. For example, Glaciar San Rafael made a strong advance between 1996 and 1999; yet it had retreated between 1999 and 2000. If we did not have the photographs for the 1999 snout position, we could not have caught such a strong advance and the record would have been a slight retreat between 1996 and 2000. Glaciar Gualas' south snout also made an advance between 1996 and 1999, which was interpreted to be ephemeral and apparent due probably to glacier stretching by crevasse widening. Subsequently, this interpretation was proved right with the 1999 photos which showed that the stretching part was disintegrated and gone, and the glacier lost large area. The detailed monitoring of the glacier variation discussed in this study also indicated that we must be very cautious about interpretation of climatic data in relation to the glacier variation, as there are many other factors such as topographic controls and glacier dynamics.

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