Glacier variations of Hielo Patagónico Norte, Chile, for 1944/45–2004/05

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Abstract

Variations of 21 outlet glaciers of Hielo Patagónico Norte was elucidated for 1944/45–2004/2005, using various sources of remote sensing data including aerial surveys. Of 21, 17 glaciers are found to be calving more or less including one tidewater glacier, San Rafael. These calving glaciers were classified into three types, according to iceberg production; those with (1) many large icebergs, (2) many small icebergs, and (3) no or few icebergs. These three types appear to indicate the stages in retreating in some calving glaciers. The type (1) indicates a rapid retreating stage, often accompanied with snout disintegration, which is preceded or followed by the stage (2) or (3). The largest glacier of the HPN, Glaciar San Quintin has lost area ca. 29 km^2 over the last 60 years, while Glaciar Reicher retreated ca. 6 km. Among debris-covered glaciers, Glaciar Grosse started retreating actively since the mid-1980s, after forming a proglacial lake, while the neighbor glacier, Glaciar Exploradores has been more or less stagnant. Although the general trend in the past 60 years is retreat, there were some episodes of small advances. Glaciar San Rafael made advance between 1996 and 1999, which was probably caused by topographic control of fjord width along with the influence of depth as well.

1. Introduction

In light of the recent global warming, monitoring glacier variation is important because existence and variation of a glacier depend chiefly upon the climatic factors such as temperature and precipitation. In order to understand the world-wide trend and pattern of the glacier variation, monitoring the variation of the Patagonian glaciers is very important because the Hielos Patagonicos (Patagonia Icefield) are located in the Southern Hemisphere where land is scarce. Located at the southern tip of South America from latitude 46°30′ to 53°30′S along longitude 73°–74°W, Hielos Patagonicos comprise two separate icefields now, Hielo Patagónico Norte (HPN, or Northern Patagonia Icefield, 4200 km^2) and Hielo Patagónico Sur (HPS, or Southern Patagonia Icefield, 13000 km^2). The combined area of 17200 km^2 makes the Patagonia Icefield the largest temperate glacier body in the Southern Hemisphere and one of the largest in the world.

Using various sources of remote sensing data, I have been monitoring the variation of the Patagonian glaciers, in particular, of the HPN since 1944/45 (*e. g.*, Aniya and Enomoto, 1986; Aniya, 1988, 1992, 2001; Wada and Aniya, 1995; Aniya and Wakao, 1997).

After updating the variation to 2000 (Aniya, 2001), I have made an aerial survey of the HPN glaciers in November 2001, December 2003, July 2004, December 2004, and August 2005. Using survey photos from 2001, 2003 and 2004 (Dec.), I have updated the glacier variation to 2004/2005, which I report here together with the analysis of variation characteristics and trends over the last 60 years.

2. Study area

HPN is located between 46°30′ and 47°35′S and 73°10′ and 74°05′W and is about 100 km long north-south and 40–60 km wide with an area of 4200 km^2 (Aniya, 1988, Fig. 1). It has the highest mountain in Patagonia, Monte San Valentin (3910 m) on the northeast corner of the icefield. Also in the middle of the icefield, Cerro (Co.) Arenales (3365 m) looms above the icefield whose elevations range 1000–1500 m. To the south of Co. Arenales on the eastern peripheral of the icefield, there are a few mountains higher than 3000 m. From the icefield 28 outlet glaciers flow out in all directions, and 21 of them have been monitored by using various sources of remote sensing data by Aniya as mentioned above. Of the 21 monitored glaciers, 17 are now calving glaciers including Glaciar San Rafael, a tidewater glacier located at the lowest latitude in the world. Glaciares San Quintin and San Rafael are the two largest ones with the nearly equal area of about 760 km^2, which makes them the 5th and

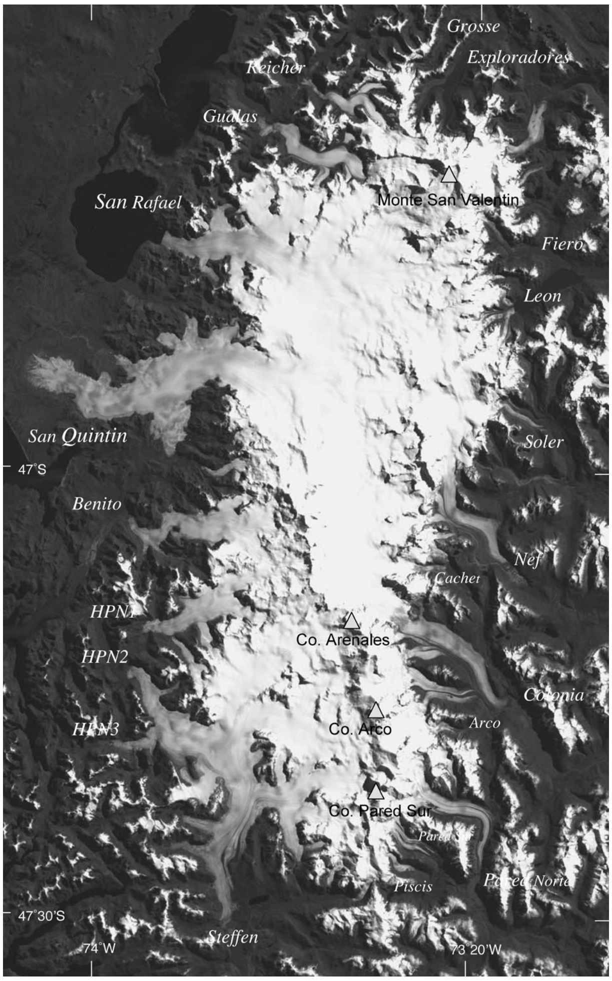

Fig. 1. Landsat image of Hielo Patagónico Norte (Northern Patagonia Icefield) and 21 monitored outlet glaciers (March 11, 2001).

6th largest glacier in South America.

3. Data and method

The first coverage of the remote sensing data of the HPN was the Trimetrogon aerial photographs taken by the USA in 1944/45. Next, from 1974 to 1975, the Chilean Instituto Geográfico Militar (IGM) took vertical aerial photographs at a nominal scale of 1: 60000 for topographic mapping at 1: 50000 with a contour interval of 50 m. On the 1: 50000 topographic map, the glacier margin is indicated; however, it was found out that at some glaciers, the margin/terminus position was wrongly delineated, which was often the result of misinterpretation of the debris-covered area and bare rocks, or water surface.

Since 1984, Aniya has been making aerial surveys of the outlet glaciers of the HPN and the glacier variation of 21 outlet glaciers has been monitored. In these works, oblique aerial photographs were interpreted and correlated with the 1974/75 vertical aerial photographs, from which the terminus position was transferred onto the 1: 50000 topographic map. However, due to the recent rapid recession, locating the terminus position on the oblique photographs onto the vertical photographs has become very difficult, because the recently exposed rock and/or water area was covered with ice in the 1974/75 photographs. In February of 1997 and 1998, the Chilean Servício Aerofotogramétrico (SAF) took another vertical aerial photographs over the HPN at a nominal scale of 1: 70000. With these photographs, the correlation of oblique photographs could be done much more easily and accurately than with the 1974/75 photographs. Consequently, the terminus positions at 1986, 1991, 1995, 1996, 1999, and 2000 of some glaciers were interpreted again and modified. Accordingly, for many glaciers at many periods, I measured again the distance retreated and the area lost for each period. Therefore, the previous statistics were revised along with updating to 2004/05, and the new statistics in this paper supersedes those of the previous publications (*i.e.,* Aniya, 1992; Wada and Aniya, 1995; Aniya and Wakao, 1997; Aniya, 2001). Although the many numbers changed, the general and overall trends of variations were not significantly affected and the previous discussions are still mostly valid.

Because it was easier and more accurate to compare the terminus position of oblique aerial photographs with the vertical remote sensing data of a close date, I used Landsat ETM+ image taken in March 2000 (for Glaciar San Quintin, ASTER data of May 2000) to locate the terminus position of November 2001 (hereafter referred to as 2001/02), and the Landsat ETM+ image taken in April 2003 for December 2003 (hereafter referred to as 2003/04) and December 2004 (hereafter referred to as 2004/05) positions.

4. Results and discussion

The revised and updated glacier variations are listed in two types of measurements; (1) distance retreated (Table 1), and (2) area lost (Table 2). For Glaciares Reicher and Gualas, formerly separated two terminuses have become one due to large retreat and they are listed as one after 2002, while the terminus of Glaciar Cachet separated into two, north snout and west snout, due to large retreat. Figure 2 indicates the variation in area of the 21 monitored glaciers for 1944/45– 2004/05. Although the general trend of the HPN glacier variations over the past 60 years is retreat, there were a few periods of advances at some glaciers, notably Glaciar San Rafael, during and after the 1990s. Some of these advances were so small and were probably episodic rather than sustained, which were probably detected only coincidentally by timing of the aerial surveys, such as those of Glaciares Piscis, HPN3 and León. Other advances such as Glacier Nef 1991–94 and Glaciar Gualas 1996–99 and 2000–02 were ephemeral before large-scale retreat, which was pro-

Table 1. Glacier Variation of the Northern Patagonia Icefield, 1944/45–20004/05 (Retreat in Distance (m), and the mean annual rate in parentheses)

Glacier Period	Period					
	1945–2005*	1945–75	1975–86	1986–91	1991–94	1994–96
Northern Side						
Grosse	2600 (43)	500 (17)	250 (23)	No substantial change, but thinning	ca. 200 (67)	ca. 200 (100)
Western Side						
Reicher: NE	3800 (63)	0	2350 (214)	150–200 (30–40)	100 (33)	150 (75) part
: SW	6000 (100)	**a 400** (−**13**), but narrowed by 200 (7)	280 (25)	850 (170), and narrowed by 300 (60)	3700 (1233), due to snout disintegration	no substantial change
Gualas: N	2950 (49)	100 (3)	250 (23)	100–150 (20–30)	200 (67)	ca. 100 (50)
: S	2600 (43)	250 (8)	350 (32)	no substantial change	100 (33)	ca. 70 (35) part
San Rafael	ca. 4150 (69)	400–900 (13–30)	2200 (200)	900–1500 (190–300)	60 (20), left (small part) **a 50** (−**17**), right (small part)	no substantial change
San Quintin: front	1500–2900 (25–48)	200 (7) 200 (7)	200–500 (18–45), and considerable thinning	ca. 200 (40), and considerable thinning	no substantial change, but considerable thinning	no substantial change?, but considerable thinning
: N side	ca 400 (7)	1200 (40)	0	200 (40)	retreat?	slight retreat?
: S side	ca. 2450 (41)		no substantial change	250 (50)	190 (63) small part	ca. 300 (15) small part
Benito	1950 (33)	550 (17) left; 0 right	0, left; 200 (18) right	max 350 (70) right front	max 300 (100) right front	60 (30)
HPN1	3100 (52)	1400 (47)	300 (27)	400–1100 (80–220)	ca. 50 (17)	no substantial change
HPN2	3050 (51)	1000 (33)	slight retreat?	1400 (88) for 75–91	ca. 50 (17) tip of snout	60 (12) tip of snout for 91–96
HPN3	2900 (48)	600 (20) left; 0 right	100 (9) left; 850 (27) right	100–200 (20–40)	no data	no data
Southern Side						
Steffen: front	3100 (52)	900 (30)	250 (23)	ca. 400 (80)	350 (117)	ca. 200 (100)
: E side	1500 (25)	500 (17)	300 (27)	ca. 350 (70)	180 (60)	ca. 150 (75)
Eastern Side						
Piscis	1050 (18)	760 (25)	100 (9)	no substantial change	40 (13)	**a 30** (−**15**)
Pared Sur	1150 (19)	1000 (33)	250 (23)	no substantial change	no substantial change	no substantial change
Pared Norte	2050 (34)	1300 (43)	slight retreat	400 (80)	slight retreat	50 (25)
Arco	1300 (22)	no substantial change	no substantial change	ca. 350 (70)	no substantial change	ca. 900 450)
Colonia	1150 (19)	500 (17)	100 (9) center	150 (30)	20 (7) right front	no substantial change
Cachet: N	4850 (81)	2000 (67)	850 (77)	70 (14)	150 (50)	50 (25) tip of snout
: W	3750 (63)					
Nef	3400 (57)	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. 100 (20) and snout is bending and breaking up	**a 300** (−**100**), and snout is bending and breaking up	2800 (1400), due to snout disintegration
Soler	ca. 850 (14)	ca. 250 (8) center	50–150 (5–14)	100–150 (20–30)	150 (50) tip of snout	no substantial change
Leon	ca. 250 (4)	100 (3)	200 (18)	150–400 (20–80)	50 (17) part	no substantial change
Fiero	1050 (18)	300 (10)	0	200 (40)	no data	ca. 180 (36) for 91–96
Exploradores	ca. 550 (9)	150–400 (5–13) apparent, part	max 200 (18) apparent, right front	no substantial frontal change, but considerable thinning	no substantial change?, but thinning	no substantial change?, but thinning
active front?	ca. 1400 (23)	ca. 150? (5) right front	ca. 100 (9)	0	?	?

Glacier Period	Period				
	1996–99	1999–2000	2000–2002	2002–2004	2004–2005
Northern Side					
Grosse	150 (50)	no substantial change, pitted pool	no substantial change, pitted pool enlarged	max. 1400 (700)	no substantial change
Western Side					
Reicher: NE	50 (17)	0#	#	snout detached from blocking wall	
: SW	250 (83), right side	300# center	300–550 (150–275)#	max.1000 (500)#	max 50 m, center part
Gualas: N	280 (73) (uncertain)	150	ca. 550 (275)	max 1400 (700)#	0
: S	**a 310** (−**103**) part	700	**a ca. 450** (−**225**)		
San Rafael	**a 320** (−**107**)	ca. 150–450	max 450 (225) center	**a ca. 150** (−**75**) in the center	no substantial change
San Quintin: front	no data for frontal change (probably no change but thinning)	ca. 1000 (250) right side for 96–00, and considerable thinning	max 1000 (500)	max 2300 (1150) protruding snout on right	max 1200
: N side	no data (probably slight retreat?)	ca. 300 (75) for 96–00	0	no substantial change	no substantial change
: S side	slight retreat	100–250	max 500 (250)	no substantial change	400
Benito	no data	narrowed by 150–250 (38–63) for 96–00	200 (100)	ca. 100 (50)	ca. 200, right half
HPN1	no data	ca. 200 (50) for 96–00	ca. 150 (75) R & L fronts	max. 200 (100)	ca. 50, left & right margins
HPN2	no data	ca. 250 (63) for 96–00	ca. 100 (50)	max 400 (200)	250
HPN3	no data	ca. 750 (83) for 91–00	ca. 1150 (575)	**a max 150** (−**75**)	ca. 150
Southern Side					
Steffen: front	no substantial change	ca. 400 L side of snout #	ca. 350 (175) L side of snout	max 900 (450)	300
: E side	no substantial change	#	max 200 (100) small part	450 (225)	max 200
Eastern Side					
Piscis	30 (10) right side	100	ca. 100 (50)	ca. 100 (59)	0
Pared Sur	no substantial change	no substantial change	ca. 200 (100) R side of snout	no substantial change	no substantial change
Pared Norte	100 (33) left side	no data	50–100 (17–33) for 99–02	100 (50)	0
Arco	no substantial change	0	0	0	0
Colonia	150 (50)	no substantial change	150 (75) L tip of snout	max 250 (125) middle part	350, right edge
Cachet: N	ca. 40 (13) debris-free part	100	max 350 (175) center	max 450 (225) N branch##	0
: W				50–100 (25–50) W branch##	50
Nef	600–1200 (200–400)	ca. 150	no substantial change	**a 200** (−**100**)	50, left & right margins
Soler	ca.200 (67) R & L sides of snout	ca. 50	ca. 50 (25) R & L sides of front	300 (150) tip of snout broke off	0
Leon	no substantial change	no substantial change	100 (50) part	**a ca. 100** (−**50**) left half	0
Fiero	50 (17) tip of snout	150	ca. 150 (75)	ca. 100 (50)	ca. 100, left side
Exploradores	ca. 200 (67) for 86–99, and thinning	no substantial change	no substantial change snout area becoming hummocky	no substantial change snout becoming hummocky	no substantial change snout becoming hummocky
active front?	ca. 300 (100) for 86–99	no substantial change	no substantial change	100 (50)?	0?

Source: Aniya (2001) for 1945–2000: however, for some glaciers, statistics were extensively modified with new vertical aerial photographs (1997/98) and satellite images.
*does not necessarily agree with the sum of each period, because the fluctuated part may be different for different period.
two fronts combined because of large recession.
a: advance
due to retreat joining branches were separated into two snouts

Table 2. Glacier Variation of the Northern Patagonia Icefield, 1944/45–2004/05 (area lost in km^2 with the mean annual rate/glacier).

Glacier	Period										
	1945–2005	1945–75	1975–86	1986–91	1991–94	1994–96	1996–99	1999–2000	2000–2002	2002–2004	2004–2005
Northern Side											
Grosse	2.71 (0.045)	0.39 (0.013)	0.22 (0.020)	0	0.25 (0.083)	0.28 (0.140)	0.19 (0.063)	0.16	0.11 (0.055)	0.63 (0.315)	0
Western Side											
Reicher: NE	8.83 (0.147)#	0.61 (0.020)	1.31 (0.119)	0.15 (0.030)	0.11 (0.037)	0.14 (0.070)	0.06 (0.020)	0.21	0.79 (0.395)#	0.67 (0.335)#	0.04
: SW	#	0.36 (0.012)	0.64 (0.058)	0.94 (0.188)	2.21 (0.737)	0 ?	0.16 (0.053)	0.20	#	#	
Gualas: N	4.91 (0.082)#	0.13 (0.0004)	0.19 (0.017)	0.14 (0.028)	0.17 (0.056)	0.25 (0.125)#	0.31 (0.103)	0.06	0.36 (0.180)	2.00 (1.00)#	0
: S	#	0.17 (0.0006)	0.35 (0.032)	0	0.13 (0.043)	#	**a0.07** (−**0.023**)	0.40	**a0.26** (−**0.130**)	#	
San Rafael	12.64 (0.211)	3.56 (0.119)	4.83 (0.439)	3.60 (0.720)	0.0006	0.01 (0.007)	**a0.86** (−**0.287**)	0.68	0.39 (0.195)	**a0.07** (**0.035**)	~0
San Quintin	28.85 (0.464)	8.18 (0.273)	0.87 (0.079)	4.74 (0.948)	2.36 (0.787)	0.82 (0.410)	3.23 (1.077)	2.21	3.33 (1.665)	0.81 (0.405)	2.30
Benito	2.51 (0.042)	0.66 (0.022)	0.07 (0.006)	0.19 (0.038)	0.12 (0.040)	0.28 (0.140)	no data	0.25 (0.063)*	0.21 (0.105)	0.29 (0.145)	0.08
HPN1	4.39 (0.073)	1.75 (0.058)	0.37 (0.034)	1.20 (0.240)	0.11 (0.037)	0.02 (0.010)	no data	0.20 (0.050)*	0.20 (0.010)	0.09 (0.045)	~0
HPN2	4.05 (0.068)	1.41 (0.042)	0 ?	1.32 (0.083)*	0.02 (0.007)	0.04 (0.020)	no data	0.31 (0.078)*	0.14 (0.070)	0.35 (0.175)	0.44
HPN3	3.38 (0.056)	0.22 (0.0007)	0.41 (0.037)	0.11 (0.022)	no data	no data	no data	1.05 (0.117)*	1.00 (0.500)	**a0.05** (**0.025**)	0.14
Southern Side											
Steffen	8.43 (0.141)	2.42 (0.081)	0.39 (0.035)	1.06 (0.212)	0.71 (0.237)	0.38 (0.190)	0.57 (0.190)	0.58	0.81 (0.405)	0.45 (0.225)	0.64
Eastern Side											
Piscis	0.82 (0.014)	0.49 (0.016)	0.02 (0.002)	0	0.01 (0.003)	**a0.01** (−**0.005**)	0.01 (0.003)	0.06	0.11 (0.055)	0.02 (0.010)	0
Pared Sur	2.04 (0.034)	1.42 (0.047)	0.27 (0.025)	0	0	0	0	0 ?	0.16 (0.080)	0	0
Pared Norte	1.46 (0.024)	0.97 (0.032)	0.04 (0.004)	0.27 (0.054)	0	0.04 (0.020)	0.06 (0.020)	no data	0.06 (0.020)*	0.02 (0.010)	0
Arco	0.46 (0.008)	0 ?	0 ?	0.16 (0.003)*	0 ?	0.25 (0.050)*	0	0	0	0	0
Colonia	2.09 (0.035)	0.97 (0.032)	0.09 (0.008)	0.28 (0.056)	0.06 (0.020)	0	0.15 (0.050)	0	0.04 (0.020)	0.10 (0.050)	0.40
Cachet	5.15 (0.086)	2.68 (0.089)	0.83 (0.075)	0.14 (0.028)	0.20 (0.066)	0.02 (0.010)	0.33 (0.110)	0.1	0.23 (0.115)	0.26 (0.13)	0.01
Nef	5.03 (0.084)	1.46 (0.049)	1.12 (0.102)	0.31 (0.062)	0.08 (0.027)	1.21 (0.605)	0.77 (0.257)	0.15	0.03 (0.015)	**a0.16** (**0.080**)	0.06
Soler	1.72 (0.029)	0.40 (0.013)	0.24 (0.022)	0.20 (0.040)	0.08 (0.027)	0	0.21 (0.070)	0.05	0.05(0.025)	0.35 (0.175)	0
Leon	0.55 (0.009)	0.02 (0.00007)	0.19 (0.017)	0.36 (0.072)	**a0.03** (−**0.010**)	0	0	0	0.06 (0.030)	**a0.05** (**0.025**)	0
Fiero	0.90 (0.015)	0.15 (0.0005)	0	0.12 (0.024)	uncertain	0.12 (0.024)*	0.02 (0.007)	0.16	0.18 (0.090)	0.07 (0.035)	0.08
Exploradores	1.44 (0.024)	0.85 (0.028)	0.13 (0.012)	0 ?	0 ?	0 ?	0.37 (0.028)*	0	0	0	0
real?	2.09 (0.035)	0.14 (0.0005)	0.14 (0.013)	0 ?	?	?	1.39 (0.107)*	0	0	0.22 (0.110)?	0
Total##	**101.36 (0.080)**	**29.27 (0.042)**	**12.58 (0.050)**	**13.81(0.132)**	**6.59 (0.105)**	**3.48 (0.092)**	**5.14 (0.095)**	**5.02 (0.279)**	**7.74 (0.176)**	**6.00 (0.136)**	**4.19 (0.200)**

Source: Aniya (2001) for 1945–2000; however, for some glaciers, statistics are extensively modified with new vertical aerial photographs (1997/98) and satellite images(2000, 2003).
#: combined (NE and SW for Reicher: N and S for Gualas).
##: Total, excluding Exploradores (real?). Also excludes data covering more than one period: therefore the grand total does not agree with the sum of the total of each period.
The total (1945–2005) of each glacier does not necessarily agree with the sum of each period, because lateral retreat was included in 1945–05.
*: includes (a) preceeding period(s) with 0 ?, no data or uncertain.
a: advance.

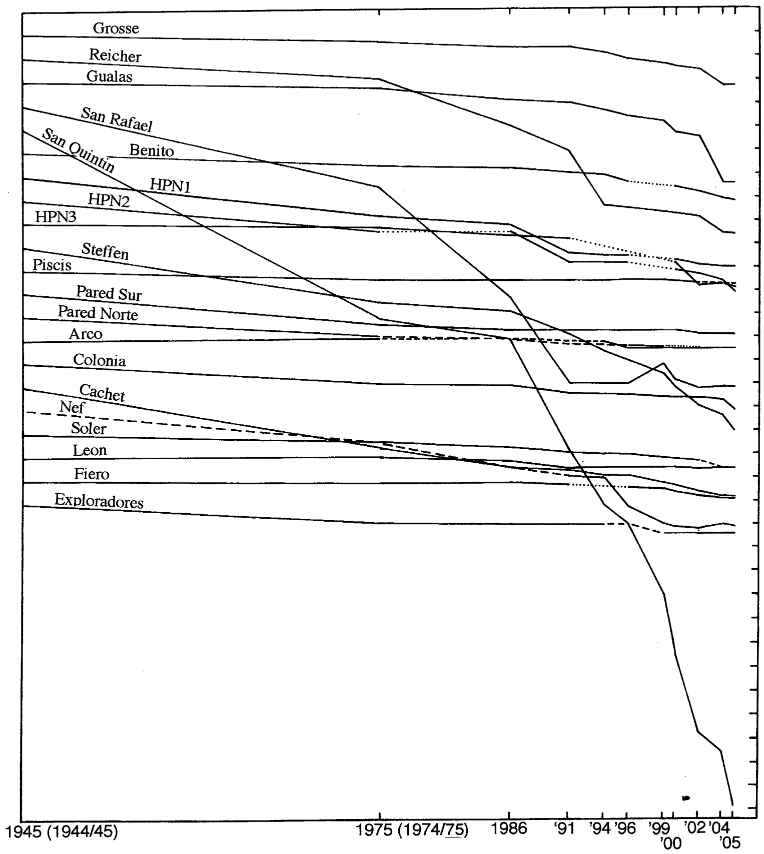

Fig. 2. HPN Glacier variations for 1944/45–2004/05. Glaciers are listed counterclockwise from the north and the spacing between names is arbitrary. One tick on the right ordinate indicates 1 km^2 of change in area (downward, loss; upward, gain).

bably caused by crevasse stretching.

Glaciar San Quintin, the largest glacier of the HPN, lost an area ca. 29 km^2, which is by far the largest loss, while Glaciar Reicher SW made the longest retreat in a proglacial lake, about 6000 m in 60 years. The second longest retreat, close to 5000 m, was found at Glaciar Cachet, causing its snout to split into two, and only the west terminus barely remains in the proglacial lake now. HPN1, which is one of the few land-terminating glaciers, varied a little during the 1990s when many other glaciers made a rapid retreat.

4.1 Calving glaciers

As of 2005, 17 of the 21 monitored outlet glaciers were calving glaciers. It was found out from the 1997/98 aerial photographs, Landsat ETM+ images from 2000, 2001 and 2003, and the aerial surveys by Aniya that the amount of calving and the size of icebergs floating in the proglacial lake are distinctively different among those calving glaciers, particularly during the 1990s and the 2000s. Based on the iceberg characteristics at around 2000, calving glaciers are categorized into three groups (Fig. 3): (1) those glaciers that produce a lot of large (say, longer than 100 m in length), tabular iceberg; (2) those glaciers such as San Rafael that produce many, but normally small icebergs; and (3) those that produce no or very little icebergs. Since the stage (2) or (3) can be recognized before and/or after the stage (1) at some glaciers, these characteristics appear to indicate the stage in the glacier retreat at some glaciers.

4.1.1 Glaciers producing large tabular icebergs and/or went through recent snout disintegration

Snout disintegration in the proglacial lake appears to be characteristic for those of the HPN calving glaciers that produce a lot of large tabular icebergs, particularly since the 1990s. These events are charac terized by many large icebergs that are densely packed in the lake. The first such event was recognized at Glaciar Reicher around 1991–1994 at the SW terminus, retreating 3700 m and losing 2.21 km^2. Since then, this glacier had produced large icebergs, sometimes exceeding 500 m in length, before the terminus has recessed into the confined valley. Then it occurred at Glaciar Nef around 1994–96, retreating 2800 m and losing 1.12 km^2. At Glaciar Steffen, terminus retreated a maximum of 900 m in two years (2002–2004), losing an area of 0.45 km^2. In terms of the area loss, Steffen has been losing a large area since the mid-1980s. HPN3 made small snout disintegration around 2000–2002, retreating 1150 m and losing an area of

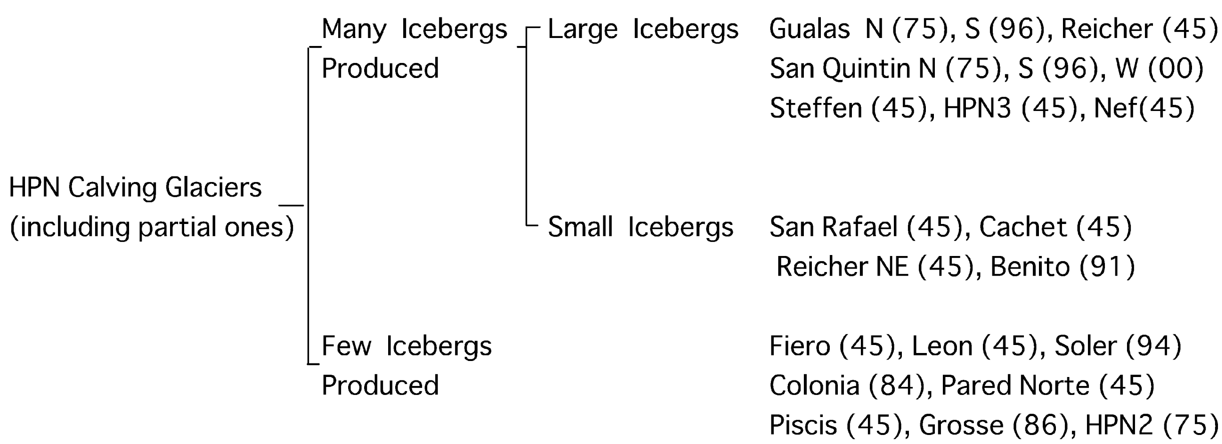

Fig. 3. Classification of calving glaciers of HPN, as of around 2000.
(45) indicates the year when calving was recognized with remote sensing data. In this case, 1945.
* Glaciers whose snout is (was) (near) flotation: Reicher SW, Gualas N&S, San Quintin N & W, HPN3, Steffen, Nef, San Quintin S? Some characteristics of these glaciers (near flotation); (1) producing a lot of large tabular icebergs; (2) irregular terminus fluctuation (such as part advance while other part retreated)-Reicher SW, Gualas N&S, Steffen; (3) apparent advance before extensive calving-San Quintin W, Gualas N & S, Reicher SW?, Nef?; and (4) snout bending in proglacial lake- Nef, Reicher SW.
* Common characteristics of those glaciers producing few icebergs: slow, steady little retreat.
* Since 2000, Glaciar Cachet moved to category 'Few Icebergs produced', Glaciar Benito moved to 'Large Icebergs', and Glaciar Reicher SW was combined with NE to become Reicher in 'Small Icebergs' category.

1 km^2. However, it made a small advance in 2002–2004, extending about 150 m with an area increase of 0.05 km^2.

The largest glacier of the HPN, Glaciar San Quintin has lost by far the largest area ca. 29 km^2; however, the 1997 vertical aerial photographs taken by the Chilean Servício Aerofotogramétrico (SAF) shows a very interesting feature of splaying crevasses near the west front (Fig. 4). A zigzag pattern was formed (Fig. 4A), which can be interpreted as the result of being pushed from behind against the terminal moraine, suggesting that the glacier advanced. The Landsat ETM+ of March 11, 2001 (Fig. 4B), reveals that this part had retreated since, leaving open water between the moraine and the glacier front. This variation suggests that the advance revealed in the 1997 photograph was just ephemeral rather than a robust ad vance, which was probably caused by crevasse stretching, thereby the glacier became thinner with criss-crossed crevasses, facilitating easy breaking up of the terminus. The same phenomena occurred before here. Winchester and Harrison (1996) reported an advance in 1994 from fieldwork, which, however, Aniya and Wakao (1997) interpreted as an ephemeral advance probably caused by crevasse stretching, from the interpretation of the oblique aerial photographs taken before and after 1994. This interpretation was subsequently proved correct (Aniya, 2001). Retreat has been accelerated during the 1990s and the 2000s and large-scale snout disintegration appears to be imminent (Fig. 4C & D).

The similar phenomenon was detected at the north terminus of Glaciar Gualas in 1994. Again, Harrison and Winchester (1998) reported an advance in 1994 in the field. Aniya and Wakao (1997) also reported an advance from the aerial surveys of 1993 and 1995; however, they suspected this was just an ephemeral advance due to crevasse stretching, which was confirmed by the subsequent retreat (Aniya, 2001). The advance of the Gualas' south terminus between 2000–2002 also appears to have been caused by crevasse stretching. The manual interpretation of the Landsat ETM+ of March 8, 2000 suggests that what appeared to be the advanced part could be a tight pack of icebergs, which was the result of the terminus disintegration. Subsequently, Glaciar Gualas' termi nus disintegrated around 2002, although densely packed icebergs remained cramming the lake until 2005 or so. Before the onset of the large-scale disintegration, small advances were observed at the south terminus for 1996–1999 and 2000–2002. Glaciar Gualas also had two calving fronts in a round-shaped proglacial lake, but due to disintegration of terminus in 2002–2004, the snout became one and recessed into the valley now.

At Glaciar Reicher that retreated most, an interesting phenomenon was captured by a series of aerial surveys and satellite images from 1999 to 2004. Figure 5 shows a sequence of a huge iceberg calving, glacier retreat/advance/retreat and drifting of that iceberg. In Figures 5A (Nov. 1999) & B (March 2000), the snout was more or less still intact, although splitting was recognized on the right. In Figure 5C (March 2001) the snout had split into three sections with advance of the left section, producing a medium-sized iceberg (close to 300 m across). Six months later

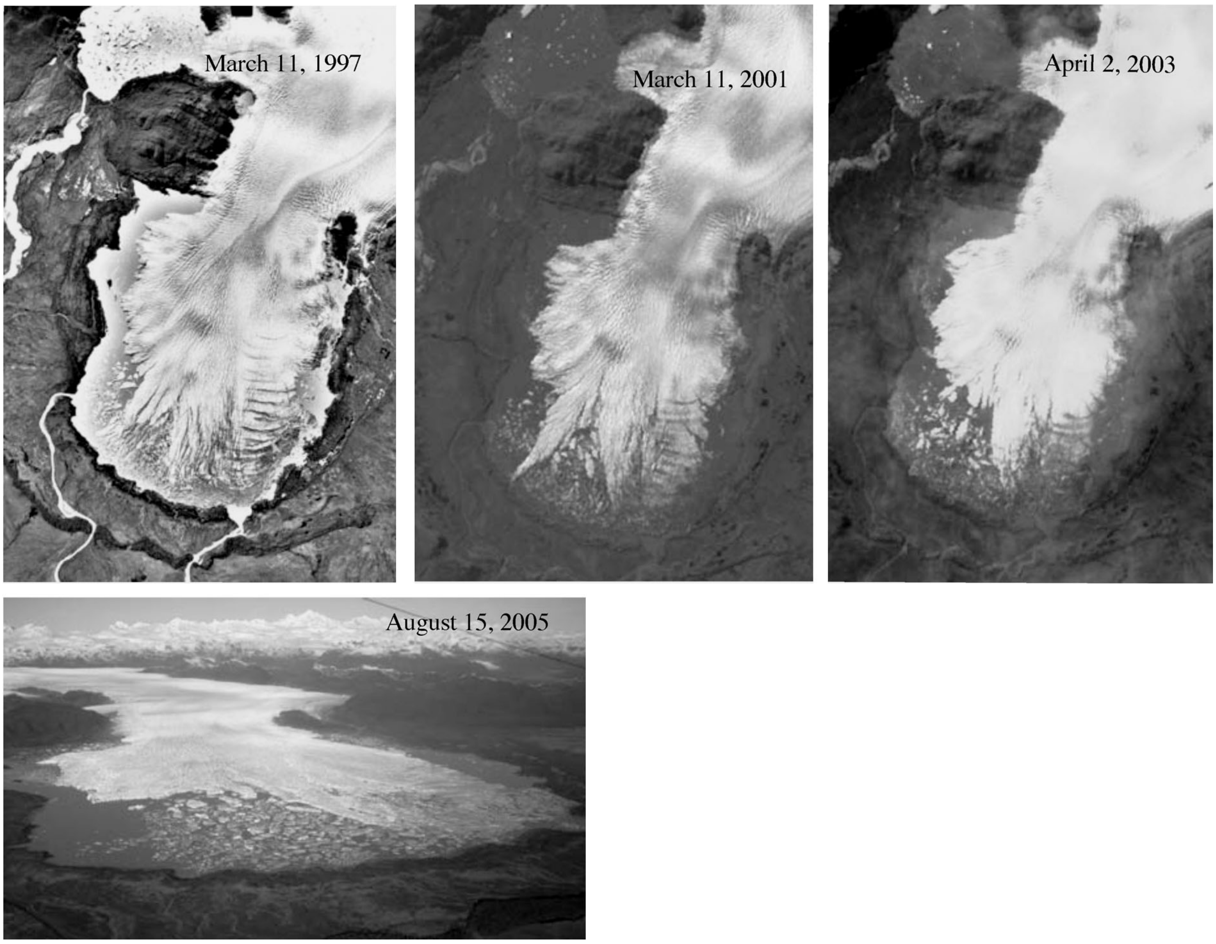

Fig. 4. Rapid recession of Glaciar San Quintin. A: Vertical aerial photograph (February 19, 1997, by SAF, Chile). B: Landsat ETM+ (March 11, 2001). C: Landsat ETM+ (April 2, 2003). D: Oblique aerial photograph (August 15, 2005, by Aniya). For easy comparison with oblique aerial photographs, satellite images were rotated 90 degrees counterclockwise so that the north is to the left.

(Fig. 5D), the left section of the snout broke off, becoming a huge iceberg (about 1100 m×370 m, 0.32 km^2). On this image, darkened glacier surface in the snout area is very conspicuous, which is also weakly recognizable in Figure 5C. Four months later in Figure 5E, the central part of the snout had collapsed, and surprisingly the huge iceberg drifted back to near the snout. Darkened glacier surface is clearly recognizable in this image. Three months later in Figure 5F (Feb. 2002), the right section had advanced and the whole snout area became very dark. In Figure 5G (April 2003), 14 months later, the proglacial lake was choked with icebergs and the huge iceberg drifted down a little toward the southwest (SW) outlet, which surprisingly maintained the size (about 900×300 m) even after 1.5 years since calving. In Figure 5H (Dec. 2003), the iceberg drifted back about 2.3 km to the fjord entrance. In this image, the dark glacier surface of the snout area has almost gone with a vestige at the left front. Seven months later in Figure 5I (July 2004), interestingly the iceberg had been pulled into fjord and rotated clockwise about 150°, indicating very complicated lake current near the snout. Figures 5 J & K (Dec. 2004) show that the iceberg drifted down sideways since, and in Figure 5K, two large icebergs can be seen, of which the one on the upstream side seems a newly calved one.

From this sequence, several interesting features about calving at Glaciar Reicher (or other Patagonian calving glaciers) can be pointed out: (1) the terminus was floating before large calving; (2) glacier made an apparent advance before calving; (3) the huge iceberg remained more or less intact for a long time (nearly four years).

Glaciar Reicher used to have two terminuses, NE and SW, which terminated in respective proglacial lake that has own outlet stream at the damming terminal moraine. Due to rapid recession during the early 1990s, the two terminuses had become almost a single one as can be seen in Figure 5A. After large calving evens described above, the glacier further retreated and the two proglacial lakes coalesced. So the two outlet streams located at the both end of the proglacial lake play a trick on current with strong winds, thereby having caused drifting back and forth of the huge iceberg. In addition, near the terminus,

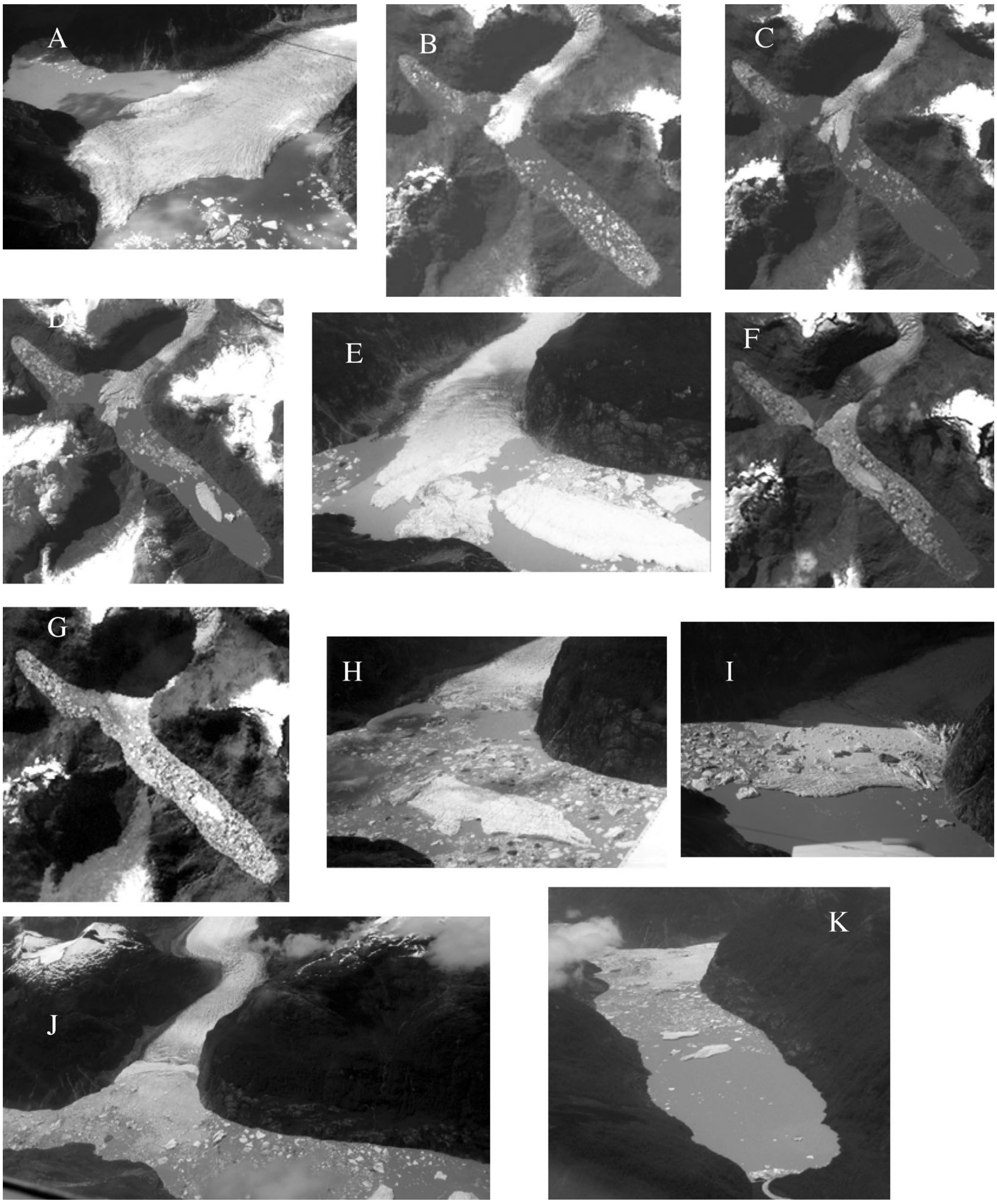

Fig. 5. A sequence of a large calving event at Glaciar Reicher and glacier variations between 1999 and 2004. See text for detailed description of events. A (Oblique by Aniya, Nov. 30, 1999); B (Landsat ETM+, March 8, 2000); C (Landsat ETM+, March 11, 2001); D (ASTER, Sept. 3, 2001); E (Oblique by Aniya, Nov. 29, 2001); F (ASTER, Feb. 10, 2002); G (Landsat ETM+, April 2, 2003); H (Oblique by Aniya, Dec. 18, 2003); I (Oblique by Aniya, July 25, 2004); J & K Oblique by Aniya, (Dec. 25, 2004). For easy comparison with oblique aerial photographs, satellite images were rotated 90 degrees counterclockwise so that the north is to the left.

water discharge from the glacier counteracts with the lake currents, thereby producing very complicated current patters that caused rotation of the iceberg.

Whether or not the ephemeral dark glacier surface in the snout area between 2001 and 2003 was associated with this large calving and the subsequent glacier variation pattern cannot be assessed. The sudden appearance and disappearance of such surface is mysterious, because large dark area in the surface of the ablation part in Patagonia is normally coated with volcanic ash or covered with landslide deposits; however, in this case it does not appear either.

The sequence of this very interesting events that were accidentally captured by a series of remote sensing data strongly indicate the need of close monitoring of Patagonian calving glaciers that dynamically change in a short period of time.

4.1.2 Glaciers producing many small icebergs

Glaciar San Rafael, the second largest glacier of the HPN, has been producing a lot of small icebergs during the 1980s and 1990s (Warren *et al.,* 1995). The section 4.1.4 discusses about this glacier in detail.

Glaciar Cachet used to produce a lot of small icebergs during the 1990s when it was retreating very actively; however, due to large retreat, the snout has now totally separated into two, and only the west terminus terminates in the lake with no icebergs. The north terminus is totally detached from the lake by now. The glacier retreated fairly rapidly during the periods of 1945–75 and 1975–86, compared with the other glaciers of the HPN (Tables 1 & 2). For the period of 1945–75, the retreat was about 2000 m with an annual mean rate of 67 m, and for the period of 1975–86, it was 850 m with an annual mean rate of 77 m.

The situation at Glaciar Reicher NE appears the same as that at Glaciar Cachet. Until around 2001 (before the snout became one) Glaciar Reicher NE produced only small icebergs with slow retreat; however, it retreated 2350 m between 1975 and 1986, with an annual mean rate of 214 m. The other terminus of the glacier, Reicher SW disintegrated between 1991 and 1994, retreating 3700 m (an annual mean rate of 1233 m).

Due to the coarse monitoring interval, we cannot ascertain whether these very rapid retreats of Cachet and Reicher were at a fairly constant, steady rate over the period, or were effected in a short period of time with the disintegration of terminus at (near) flotation. The snout disintegration at Glaciar Nef was accidentally caught by radar images (Wada and Aniya, 1995), showing that it occurred in a short period of time (less than five months). Ground observation at Glaciar Upsala of the HPS tells that snout disintegration occurred in a day or two (Aniya and Skvarca, 1992; Naruse *et al.*, 1997; Skvarca, personal communication in 1991). These records strongly suggest that the large retreat at Cachet and Reicher NE occurred in a short period of time with the snout disintegration rather than at a constant, steady rate over the period.

Glaciar Benito started calving only sometime between 1986 and 1991 due to constant recession since 1945. Presently, it actively produces a fairly large number of medium-sized icebergs and its terminus appears grounded at the moment, with steep surface gradient.

4.1.3 Glaciers with no or few icebergs

Glaciar León, located on the northeast side of the HPN, varied very little since 1945, with the second smallest retreat (0.55 km^2). Within a trend of the general retreat, it even made a small advance, twice in 1991–94 and 2002–2004. It consists of three bodies, León North, León Central and León South, and it is remarkable that none of them has made a substantial retreat over the last 60 years. Glaciar Fiero, located just north of Glaciar León, had been almost stagnant for a long time 1945–1991; however, it started slow retreat after 1991 and the retreat has became steady, although slow after 1999.

Glaciar Colonia has been slowly retreating from 1945 to 2004, but it lost a relatively large area (0.4 km^2) in 2004–2005. This was caused by the land-based part (right half; the left half is in a proglacial lake) and it appears that the continued thinning finally took an effect on retreat. Consequently, the terminus now has become totally surrounded by water, although it appears shallow. During the early 1990s, thrusting near the terminus was very active (Wada and Aniya, 1995), but now it seems no longer thrusting.

Glaciar Pared Norte retreated very little, although the upper glacier area around the bend has sharply decreased. Glaciar Piscis has varied very little, the third smallest variation during the last 60 years and it even made a small advance during 1994–96. Glaciar Soler formed a proglacial lake during the 1990s on the either side of the terminus, and with the continuing steady retreat, the proglacial lake has become encircling the terminus completely by 2000. HPN2 had been retreating slowly, but made a large area loss between 2004 and 2005. The terminus now appears floating or near flotation, with a pocket of open water in the snout area, indicating a large breakdown in the near future.

4.1.4 Contrasting behaviors of Glaciares San Rafael and San Quintin

The contrast in behaviors of the neighboring glaciers, San Rafael and San Quintin, is very interesting. Glaciar San Quintin has lost the largest area (28.85 km^2) since 1945 with by far the fastest rate (see Fig. 2). After a slight slack in the retreating rate between 1975 and 1986, the rate has picked up, producing a lot of icebergs in the proglacial lake.

On the other hand, Glaciar San Rafael, the only tidewater glacier in the HPN, has a unique history of the variation. It retreated very rapidly between 1975 and 1991; however, it become still-stand for 1991–96 and made small advances during 1996–99 and 2002–04, which made the variation contrasts after 1991 very distinctive (Fig. 2). Between 1975 and 86, it retreated 2200 m at an annual mean rate of 200 m, and between 1986 and 1991, a maximum of 1500 m at an annual mean rate of 300 m, which were by far the largest rate in the whole Patagonia. Between 1999 and 2000, it retreated a maximum of 450 m, and for 2000–2002, a maximum of 450 m (225 m/a), at different front sections though. These retreating rates are comparable to those of 1975–86 and 1986–91. Based on these fast retreating rates, Venteris (1999) implied that the terminus of Glaciar San Rafael then was at near flotation. If so, the still-stand and advance during the 1991–99 can be explained by topographic control, as Aniya (2001) pointed out, rather than the precipitation increase at Cabo Raper (Warren, 1993; Winchester and Harrison, 1996; Aniya and Sato, 1996). Around 1991, the retreat stopped where the width of the fjord narrows. While still-standing there, the glacier regained thickness and started advance around 1996. Due to advance into the wider area, the snout spread out thereby getting thinner, which in turn made the snout condition near flotation.

They both are located on the western side of the icefield, next to each other north (San Rafael)—south (San Quintin), and their accumulation areas with the obscure divide between them lie on the windward of the westerlies. Glaciar San Rafael terminates in a fjord now, while Glaciar San Quintin terminates in a large, fresh-water proglacial lake. Since there seems no difference in the condition of the accumulation areas of the two glaciers, fjord topography (chiefly width) appears to have strongly influenced the variation of Glaciar San Rafael since the 1990s.

4.1.5 *"Height-above-buoyancy" model*

Van der Veen (1996) proposed a model called "height-above-buoyancy" to explain a rapid retreat of calving tidewater glacier, in which the position of the calving front is controlled by the local water depth such that, at the terminus, the ice thickness in excess of flotation cannot become less than a certain threshold value (∼50 m for Columbia Glacier (Van der Veen, 1997, p. 164–165; 2002). This model may explain some Patagonian calving glaciers that underwent a rapid retreat during the 1980s and the 1990s.

However, the bathymetry is not available for most glaciers in Patagonia. Glaciar San Rafael is one of the few exceptions, where the bathymetry is available (Nakajima *et al.,* 1987; Warren, 1993). According to them, the water depth of the fjord center part ranges from about 180 m to over 300 m, while the depth of the Laguna section is less than 200 m. Naruse (1985) measured the height of the calving cliff (seracs) to be 50–70 m at Glaciar San Rafael in November 1983. If we compare the terminus position in 1983 (Aniya and Enomoto, 1986) and the bathymetry (Warren, 1993), the water depth near the terminus is about 130–180 m. Assuming that the glacier was grounded in 1983, and if we apply the "height-above-buoyancy", expressed as $h - d\rho_w/\rho_i$, where h is ice thickness (180 + 60 = 240), d water depth, ρ_w water density, and ρ_i ice density (900 kg m^{-1}), the "height-above-buoyancy" is about 40 m. Since the terminus is very jagged because of many seracs due to heavy crevassing, many parts could have been at near-flotation even in 1983. Near the 1992 terminus position, the average depth of the fjord is about 140 m with a maximum of over 300 m near the center (Warren, 1993). With this depth the center part of the glacier could have been floating. The width of the fjord narrows near the 1992 terminus position.

The "height-above-buoyancy" model, in conjunction with change in the fjord width, may explain the rapid retreat during the 1980s and the subsequent still-stand and advance during the 1990s. The fjord

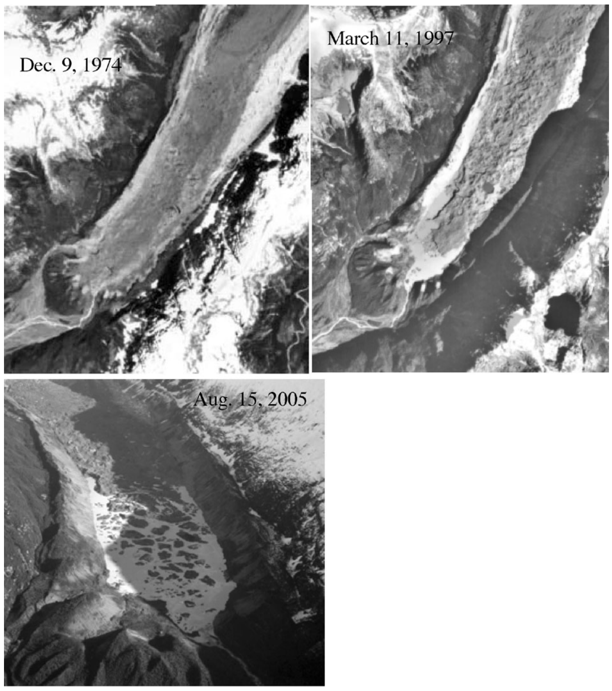

Fig. 6. Glaciar Grosse: completely debris-covered glacier with a recent retreat, forming a proglacial lake. A: Vertical aerial photograph (December 9, 1974, by Chilean IGM). B: Vertical aerial photograph (March 11, 1997, by SAF, Chile). C: Oblique aerial photograph (August 15, 2005, by Aniya). In A and B, the north is down to facilitate an easier comparison with C.

width affects the glacier thickness and the height-above-buoyancy as follows. When the glacier terminus advances into the wider area of fjord, the snout area spreads out, thereby getting thinner, and the height-above-buoyancy decreases. Conversely, when the glacier recedes into the narrower part, glacier gets thicker, and the height-above-buoyancy increases. In addition, fjord depth plays a role. When the glacier terminus retreats further into fjord with increasing water depth, the height-above-buoyancy decreases, causing the terminus to float. Then calving becomes more active and the glacier rapidly recedes until the terminus reaches where the fjord becomes sufficiently narrow and the glacier becomes thick enough to maintain the height-above-buoyancy. When the glacier attains enough thickness while stagnant, it starts advancing into the wider area, where the glacier gets thinner causing more calving and consequent retreat.

4.2 *Debris-covered glaciers*

There are five glaciers whose snouts are heavily covered with debris, Glaciares Grosse and Exploradores on the north side of Monte San Valentin (3910 m), Glaciar Fiero on the east side of Monte San Valentin, and Glaciares Pared Sur and Arco on the southeast side of the icefield. Except for Glaciar Grosse, the terminuses of all debris-covered glaciers are land-based.

Particularly Glaciar Grosse is completely covered with debris so that there is no white part visible. Because of thick debris-cover, the retreat of Glaciar Grosse was slow until 1991. A proglacial lake started to appear around 1986, and after 1991, the terminus in the proglacial lake become pitted topography with many supraglacial ponds (Fig. 6). Subsequently these ponds had coalesced to become larger ponds, which were eventually connected with the steadily growing proglacial lake. In contrast to this behavior, the neighboring Glaciar Exploradores has remained more or less the same since 1975, with a small retreat between 1996 and 1999 (Table 1 and Fig. 7). Although debris has accumulated in the terminus area, the glacier is still actively moving (Aoki and Sawagaki, 2006), and the position of the terminus has remained more or less the same. However, from the field observation during the 2000s, the glacier was found to have been slowly melting. The difference in these behaviors could be attributed to the winter precipitation pattern deduced from Landsat winter images (*e.g.,* July 12, 1999; July 25, 2003 among others) when those glaciers on the east side (*i.e.,* Exploradores) receive more snowfall than those on the west side (*i.e.,* Grosse). Glaciar Fiero had varied very little for 1945–1999; then it commenced a slow, but steady retreat.

Glaciar Pared Sur located on the east side of Co. Pared Sur (∼3000 m) varied very little since 1975, which can probably be attributed to thick debris cover that insulated the underlain ice. Glaciar Arco, coming from the eastern side of Co. Arco (∼3000 m) showed the smallest variation among the 21 outlet glaciers of the HPN, probably due to thick debris cover on the terminus area.

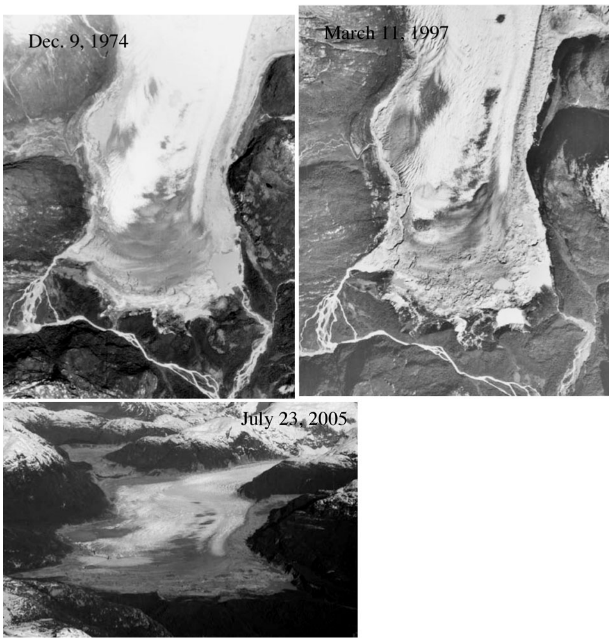

Fig. 7. Glaciar Exploradores: heavily debris-covered glacier, with a little retreat, in contrast to Glaciar Grosse. A: 1974 vertical aerial photograph (December 9, by Chilean IGM) and B: 1997 vertical aerial photograph (March 11, by SAF, Chile). C: Oblique aerial photograph (August 15, 2005, by Aniya). In A and B, the north is down to facilitate an easier comparison with C.

4.3 Cause for variations

The detailed discussion about the relationship between climate data and the glacier variation was provided in Aniya and Wakao (1997) as well as Aniya (2001). The most common factor for the general recession of the HPN glaciers over the last 60 years is climatic, *i.e.,* temperature rising and/or precipitation decrease.

In addition, at some calving glaciers, there is a topographic control. At Glaciar San Rafael, for example, because the width of the fjord changes where recent frequent variations of stagnation/advance/retreat have occurred, the fjord topography seems playing an important role in the variations now.

5. Conclusions

Variations of 21 outlet glaciers over the last 60 years of the HPN indicate that glaciers have been in the trend of general retreat, at some glaciers very strong while at others rather weak. The trend of the retreat has become stronger after the 1990s. Seventeen glaciers out of 21 are now calving, more or less and six of them became a calving glacier due to the retreat over the last 60 years. The frontal area lost due to recession amounted to ca. 100 km^2 in 60 years, close to a third of which was effected at Glaciar San Quintin, the largest glacier of the HPN. The neighboring tidewater glacier, San Rafael retreated at a similar rate with San Quintin until ca. 1990; however, during the 1990s and the 2000s, its terminus position had remained more or less the same with a cycle of stagnation/advance/retreat, This contrasting behavior of Glaciar San Rafael and Glaciar San Quintin during the 1990s and the 2000s may be explained by the topographic control exerted by the fjord width with some influence of depth as well at Glaciar San Rafael.

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