Variations of Patagonian Glaciers, South America, utilizing RADARSAT Images

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Abstract

Combining RADARSAT images (1997) with either Landsat MSS (1987 for NPI) or TM (1986 for SPI), variations of major glaciers of the Northern Patagonia Icefield (NPI, 4200 km^2) and of the Southern Patagonia Icefield (SPI, 13,000 km^2) were studied. Of the five NPI glaciers studied, San Rafael Glacier showed a net advance, while other glaciers, San Quintin, Steffen, Colonia and Nef retreated during the same period. With additional data of JERS-1 images (1994), different patterns of variations for periods of 1986-94 and 1994-97 are recognized. Of the seven SPI glaciers studied, Pio XI Glacier, the largest in South America, showed a net advance, gaining a total area of 5.66 km^2. Two RADARSAT images taken in January and April 1997 revealed a surge-like very rapid glacier advance. O'Higgins Glacier, which retreated more than 13 km during 1945-86, stagnated for 1986-97. Perito Moreno Glacier has the continuing stability. Other glaciers, Viedma, Upsala, Tyndall, and Ameghino, lost area, ranging from 0.52 to 7.16 km^2. Between January and May 1997, Upsala Glacier lost an area of 2.71 km^2.

Introduction

Locate at the southern end of the Andes, the Patagonia Icefield comprises the Northern Patagonia Icefield (NPI, or Hielo Patagonico Norte) and the Southern Patagonia Icefield (SPI, or Hielo Patagonico Sur). In the Southern Hemisphere, the Patagonia Icefield is by far the largest temperate ice body which is supposedly very susceptible to environmental changes. Thus, in light of the recent global warming, it is very important to monitor the variations of the

Patagonian glaciers, in order to elucidate and understand the global pattern of the glacier variation in response to the recent climate changes.

For a study of glacier variation in a remote area such as Patagonia, remotely-sensed data are very useful, often only available data. In this regard, the earth orbiting satellites are expected to provide such much needed data; however, due to the persistent inclement weather condition in Patagonia, the satellites, which are equipped with the conventional optical sensors, cannot often acquire reasonably cloud-free data of the Patagonia Icefield. In fact, for the NPI there is no Landsat TM data to date; only several nearly cloud-free MSS images available, and for the whole SPI, only one almost cloud-free TM data exists. Therefore, the weather-independent SAR images will enhance the opportunity to monitor the glacier variations in Patagonia.

RADARSAT images covering some Patagonian glaciers were acquired between January and May 1997. It is the purpose of this study to elucidate the recent variations of several major glaciers of the Patagonia Icefield between 1986 or 1987 and 1997 by superimposing RADARSAT images on a Landsat MSS image of the NPI (1987), or a Landsat TM image of the SPI (1986). For some glaciers, additional data, JERS-1 SAR images taken in 1994, were also utilized to break the variation period into 1987 (1986)-94 and 1994-97.

Study Area

The NPI is located between 46°30' and 47°30'S along 73°30'W, with the total area of 4200 km^2 and 28 outlet glaciers (Aniya, 1988, Fig. 1).

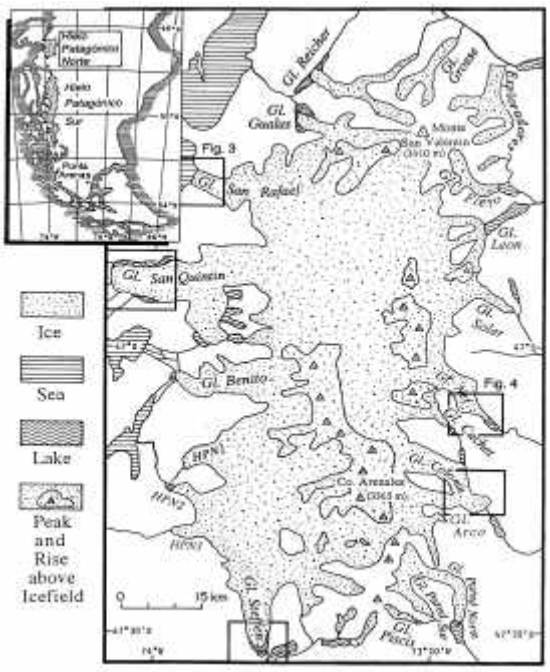

Fig. 1. Northern Patagonia Icefield and the studied glaciers.

The icefield is about 100 km long in the N-S direction, with the width of 40-45 km. Monte San Valentin, with a height of 3910 m, is the highest mountain in Patagonia. San Rafael and San Quintin glaciers are the two largest glaciers with an area of about 760 km^2 each, followed by Steffen Glacier (454 km^2) and Colonia Glacier (437 km^2). At the end of 1995, 13 out of the 20 monitored glaciers were calving into proglacial lakes and a fjord (San Rafael Glacier).

The SPI extends for about 350 km between 48°20' and 51°30'S along 73°30'W (Fig. 2) , with an area of 13,000 km^2 and the general width of 30 to 40 km (Aniya et al., 1992). The main mountain range runs north-south along the middle of the

icefield. Of 48 outlet glaciers, all but two were calving. Pio XI (also called Bruggen) Glacier, with an area of 1275 km^2, is the largest glacier in South America (Aniya et al.,1996). Three glaciers (Viedma, Upsala, O'Higgins) exceed 700 km^2 in area.

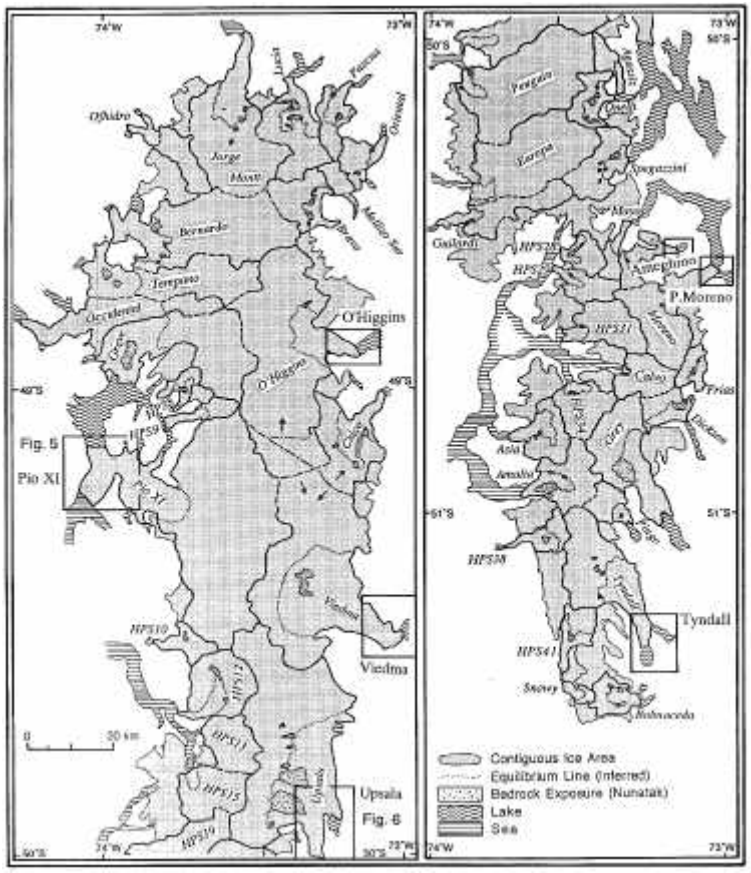

Fig. 2. Southern Patagonia Icefield and the studied glaciers.

Patagonian glaciers are temperate (Aristarain and Delmas,1993), characterized by large amounts of accumulation and ablation. The annual precipitation is estimated at about 6-7000 mm (Escobar et al., 1992).

Previous Studies on Variations

Of 28 outlet glaciers of the NPI, the variations of 20 glaciers have been monitored between 1944/45 and 1995 using various types of remotely-sensed data such as trimetrogon and vertical aerial Photographs, and hand-held oblique aerial photographs (Aniya, 1988, 1992; Wada and Aniya, 1995; Aniya and Wakao, 1997). These studies indicate that the glaciers had retreated fast until 1990; however, since then, the retreating rates have much slowed down, with one exceptional glacier (San Rafael) advancing.

The variations of 48 outlet glaciers of the SPI between 1944/45 or the late 1960s and 1986 were recently studied (Aniya et al., 1997), using various sources of remotely sensed data, including trimetrogon and vertical aerial photographs, Landsat MSS and TM images, and SPOT images. This study revealed that except for two glaciers, Pio XI and Moreno glaciers, all glaciers retreated more or less.

Method

Two consecutive scenes of Landsat MSS (Feb. 9, 1987) covering the NPI were mosaicked and geometrically corrected to an accuracy of within 2

pixels for resampling with a pixel size of 80 x 80 m, using 1: 50,000 topographic maps with a 50 m contour interval. For the whole SPI, two full scenes and a quarter scene of Landsat TM (Jan. 14, 1986), which were only reasonably cloud-free data, were mosaicked and geometrically corrected to an accuracy of within 2 pixels with a pixel size of 30 x 30 m using 1:250, 000 carta prelimanar (Aniya et al. 1992). Subsequently, geometric correction of all RADARSAT images (Jan. 4, 7, 10, 17 and 22, Apr. 7 and 10, and May 3 and 4, 1997; fine mode) was done using these Landsat mosaics as the reference and resampled with a pixel size of 8 x 8 m for the NPI data and 30 x30 m for the SPI data with 10-18 ground control points. For JERS-1 data (Dec. 29, 1993, Feb. 7 and 14 and May 10, 1994), geometric correction was done with a pixel size of 12.5 x 12.5 m (NPI) and 30 x 30 m (SPI). Since the study areas are rough, mountainous terrain, the reasonably-good registration was possible only for the snout area.

Results and Discussion

Northern Patagonia Icefield

Of the 20 outlet glacier of the NPI which has been monitored (Aniya and Wakao, 1997), the five major glaciers, San Rafael, San Quintin, Steffen, Colonia and Nef were chosen for this study.

San Rafael Glacier had retreated between 1944/45 and 1990 (Aniya, 1988, 1992); however, an advance for 1990-93 was reported (Warren, 1993: Wada and Aniya, 1995). The possible cause of this reversal of the glacier behavior is inferred to be a rainfall increase during the early 1970s recorded at Cabo Raper located 200 km due west of the icefield (Warren, 1993; Aniya and Sato, 1995; Winchester and Harrison, 1996). Superimposition of a RADARSAT image (Jan. 7, 1997) on the Landsat MSS (1987) revealed that an apparent advance is 570 m near the middle of snout, gaining an area of 0.61 km^2 (Fig. 3A). With a JERS-1 image (Feb. 14, 1994), an interesting variation pattern emerges. From 1987 to 1994, the northern half of the front advanced by 150 m (gain of 0.14 km^2), while the southern part retreated by 270 m (loss of 0.27 km^2), resulting in a net area loss of 0.13 km^2. From 1994 to 1997, the entire front advanced by 380 m, gaining an area of 0.74 km^2 (Fig. 3B, C).

San Quintin Glacier has been slowly retreating at the front, with considerable down-wasting (Aniya and Wakao, 1997). Winchester and Harrison (1996) reported little advance sometime between 1991 and 1993 from the ground observation, which was too small to detect from the oblique aerial survey (Aniya and Wakao, 1997). Because of its size, it was difficult to accurately map the frontal position with hand-held oblique photographs. The RADARSAT image (Jan. 7, 1997) clearly define the wasting front and the superimposition on the Landsat MSS (1987) revealed an area loss of 1.95 km^2 or a retreat of about 310 m, which occurred primarily at the northern front of more than 6 km long in a proglacial lake. A comparison of the RADARSAT image with a JERS-1 SAR image (Feb. 14, 1994) indicates that the western half

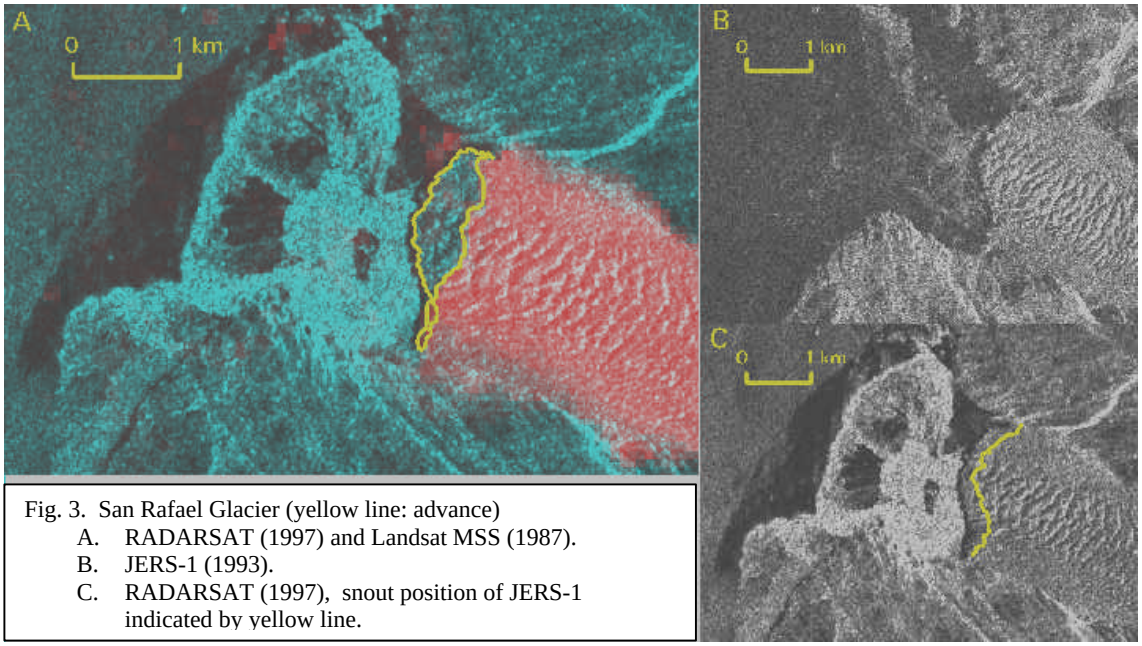

Fig. 3. San Rafael Glacier (yellow line: advance)
A. RADARSAT (1997) and Landsat MSS (1987).
B. JERS-1 (1993).
C. RADARSAT (1997), snout position of JERS-1 indicated by yellow line.

of the northern front had slightly advanced between 1994 and 1997, while the eastern half lost small area. However, proglacial lakes at the southern front have enlarged, in addition to the formation of a few proglacial lakes at the western front, as well as a few supraglacial lakes near the front. These overall changes clearly indicate that the glacier surface near the front has become increasingly slushy with continuing down-wasting and consequent retreat.

Steffen Glacier experienced a large-scale snout disintegration in a proglacial lake at the left part of the front sometime between 1990 and 1993 (Wada and Aniya, 1995), which is still recognizable on a JERS-1 SAR image (Feb. 14, 1994). Superimposition of the RADARSAT image (Jan. 7, 1997) on the Landsat MSS (1987) revealed that the retreat occurred mainly at the left part of the front with an area lost of 1.59 km^2. A comparison of the JERS-1 SAR image (1994) with the RADARSAT image (1997) indicates slight change at the left front (loss of 0.20 km^2), suggesting the glacier has become stable after the large-scale disintegration.

Colonia Glacier started a rapid retreat after 1985 (Aniya, 1992), producing thrust moraines near the front (Aniya and Wakao, 1997). Superimposition of the RADARSAT image (Jan. 7, 1997) on the Landsat MSS (1987) revealed that it retreated ca. 400 m, loosing an area of 0.69 km^2. These results suggest that Aniya (1992) may have overestimated variations for 1986-91 (retreat of 500 m and an area loss of 0.70 km^2), because it did not advance for 1991-1997. Two lumps of debris on Arenales Glacier, a tributary of Colonia Glacier, moved 1560 m (upper one) and 1130 m (lower one), yielding an average annual flow rate of 113-156m/y.

The snout of Nef Glacier (164 km^2) in the proglacial lake had been narrowing since 1944/45, rather than retreating (Aniya, 1992), and sometime between December 1993 and May 1994 the snout disintegrated into pieces of icebergs, which was detected by JERS-1 SAR data (Wada and Aniya, 1995). Superimposition of RADARSAT (Jan. 17, 1997) on the Landsat MSS (1987, Fig. 4A) revealed an area loss of 2.01 km^2. JERS-1 SAR (Dec. 29, 1993, Fig. 4B) shows that the narrow snout in the proglacial lake had drifted south, indicating

floatation of the snout prior to disintegration. A comparison of the RADARSAT image (Fig. 4C) with JERS-1 (May 10, 1994) revealed an area loss of about 0.77 km^2 for 1994-97.

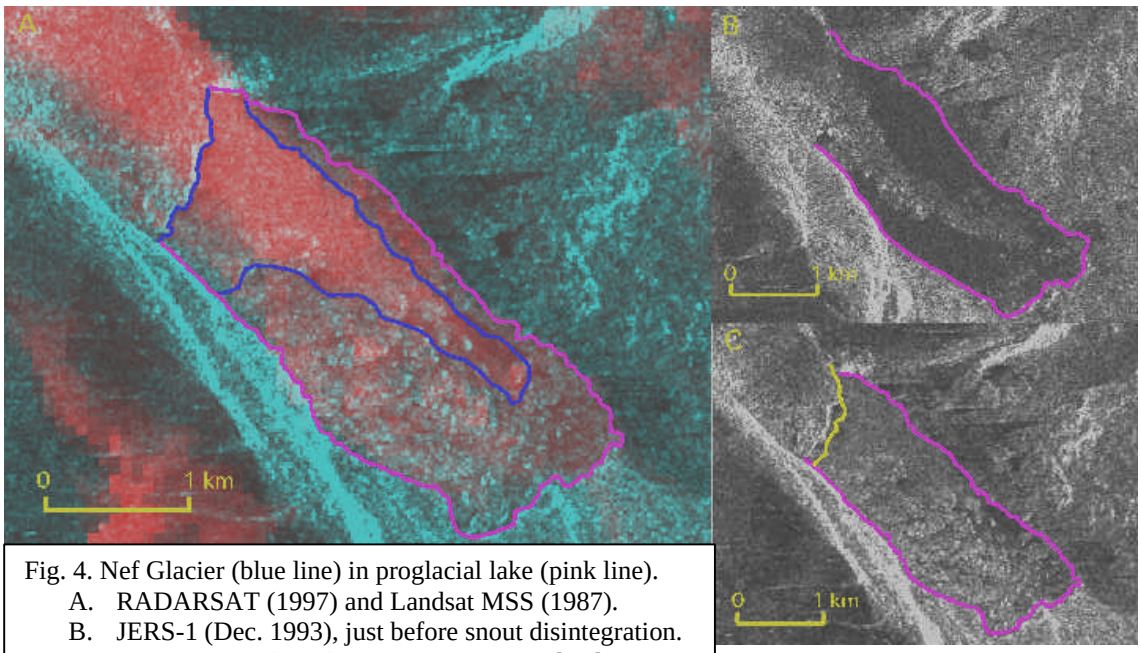

Fig. 4. Nef Glacier (blue line) in proglacial lake (pink line).
A. RADARSAT (1997) and Landsat MSS (1987).
B. JERS-1 (Dec. 1993), just before snout disintegration.
C. RADARSAT (1997), narrow snout completely gone.

Southern Patagonia Icefield

Of 48 outlet glaciers, large glaciers and those glaciers where we have conducted field survey/observation were chosen. They are Pio XI, Viedma, Upsala, O'Higgins, Perito Moreno, Ameghino, and Tyndall glaciers.

The behavior of Pio XI Glacier is enigmatic, with repeated advance and retreat in this century (Mercer, 1964), while other glaciers have been more or less retreating. The advance which started around 1945 resulted in two snouts by 1975 after reaching the opposite bank of the fjord, gaining an area of 60 km^2 (Aniya et al., 1996). While the northern snout continued to advance, the southern snout stopped advancing, and retreated during 1981- 85 (Warren and Rivera, 1994). Recently, Rivera et al. (1997) proposed that Pio XI is a surging-type glacier, from the variation record and the morphology and materials of the contorted medial moraines. Superimposition of RADARSAT image (Jan. 10, 1997) on the Landsat TM (1986) revealed that the northern snout advanced on the average 950 m, gaining an area of 5.06 km^2, while at the southern snout the center part retreated 250 m (area loss of 0.45 km^2), and the right side advanced a maximum of 750m (gain of 1.05 km^2), with a net area gain of 0.60 km^2 (Fig. 5a). A comparison of January 10 and April 7 RADARSAT images shows that the southern front advanced about 520 m (average 6.0 m/day for 87 days), gaining an area of 1.74 km^2 (Fig. 5B), while the northern front remained almost stationary. This rapid advance may support the hypothesis of the surge-type which could probably be detected only by SAR images in Patagonia.

Viedma Glacier, the second largest glacier in South America with an area of 945 km^2 (Aniya et al,1996; Skvarca et al., 1995b), varied only slightly since

1968, and between 1981 and 1991 it retreated about 400 m (Aniya et al., 1997). Skvarca et al. (1995b) reported several hundred meters of retreat between 1986 (Sept.) and 1993 (Jan.), using EERS-l SAR data. Superimposition of the RADARSAT image (Jan. 22, 1997) on the Landsat TM (1986) indicates an area loss of 1.34 km^2, or about 580 m retreat. A visual comparison of the RADARSAT (Jan. 1997) with the ERS-1 SAR (Feb. 1993, Skvarca et al., 1995b) indicates a slight retreat at the left edge of the front. Therefore, the glacier front has not change much since 1993. Two RADARSAT images (Jan. and May 4, 1997) indicate no intra-seasonal fluctuation of the snout.

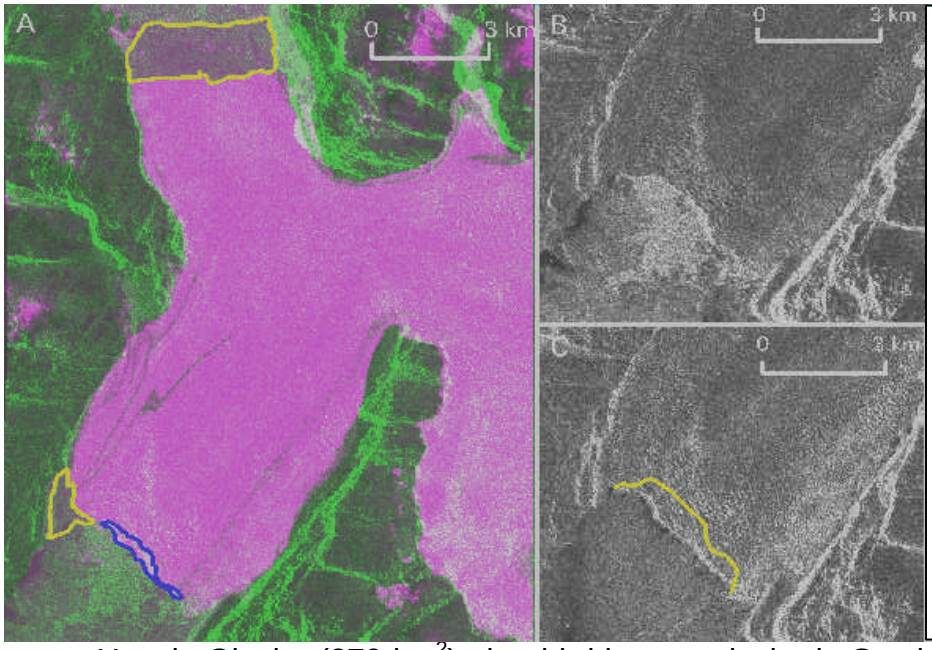

Fig. 5. Pio XI Glacier
A. RADARSAT (Jan. 1997) and Landsat TM (1986)
Yellow line: advance.
Blue line: retreat.
B. RADARSAT (Jan10, 1997)
C. RADARSAT (April 7, 1997)
Yellow line: Position of Jan. 10 snout.

Upsala Glacier (870 km^2), the third largest glacier in South America, had retreated steadily until around the late 1960s; then a little advance occurred between 1968 and 1978 (Aniya and Skvarca, 1992). Since 1978, the glacier has been very rapidly retreating, with a few large-scale calving events in 1981-82 (retreating rate 2100 m/y), 1990-93 (400 m/y), and 1993-95 (700 m/y) (Skvarca et al., 1995a). Two RADARSAT images taken on January 22 and May 4, 1997, revealed another such event, losing an area of 2.71 km^2 with a maximum retreat of 2 km (Fig. 6B,C), filling the Bahia Upsala with icebergs. Detection of such event with remote sensing was only possible with the SAR in Patagonia. Superimposition of the RADARSAT image (Jan. 22, 1997) on the Landsat TM (1986) revealed an area loss of 7.16 km^2 and a maximum retreat of 2.8 km (250 m/y)(Fig. 6A).

O'Higgins Glacier, in contrast to Pio XI Glacier, retreated more than 13 km in 45 years and lost an area of 50 km^2 by 1986 (Aniya et al., 1992). Superimposition of the RADARSAT image (Jan. 10, 1997) on the Landsat TM (1986) disclosed a very interesting fact that the front had remained at the similar position. Casassa et al. (1997) reported the stagnation of the front between 1986 and 1995, although the area loss due to side shrinkage was considerable. On the Jan. 10 RADARSAT image, an arcuate distribution pattern of icebergs is recognized about 8 km from the snout, suggesting the presence of subglacial

moraine(s) located near the 1960 position (Casassa et al., 1997). A comparison of January 10 with April 7 RADARSAT image indicates a slight retreat at the center part of the front.

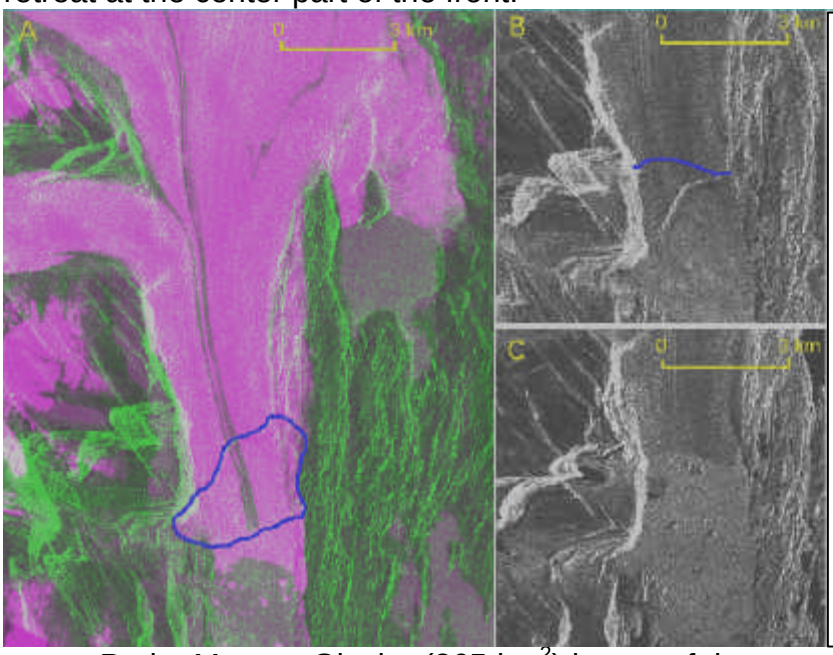

Fig. 6. Upsala Glacier

A. RADARSAT (Jan. 1997) and Landsat TM (1986) Blue line: retreat.
B. RADARSAT (Jan. 22, 1997) Blue line: position of May 4 snout.
C. RADARSAT (May 4, 1997) A large iceberg can be seen.

Perito Moreno Glacier (265 km^2) is one of the two exceptional glaciers of SPI, with more or less stable snout over the last 50 years (Aniya and Skvarca, 1992; Naruse et al., 1995). The net behavior for 1986-97 revealed by the superimposition of RADARSAT (Jan. 4, 1997) on the Landsat TM (1986) is loss of an area of 0.53 km^2 with 170 m retreat at the southern front, while the northern front remained the same, indicating the continuing stability. During the same period, Ameghino Glacier (77 km^2), located 4 km north of Perito Moreno Glacier, retreated 1.0 km, losing an area of 0.52 km^2. Two RADARSAT images (Jan. 4 and April 10) indicates that frontal positions of the both glaciers were about identical.

Tyndall Glacier (337 km^2), located near the southern end of the SPI, has been steadily retreating since 1944/45 (Naruse et al., 1987; Aniya et al., 1992; Aniya et al., 1997). Superimposition of the Landsat TM on a JERS-1 (Feb. 7, 1994) revealed that the glacier retreated a maximum of about 1.6 km. While an area loss at the right of the center is 1.03 km^2, that at the left amounts to 3.44 km^2 including those parts terminating in Lake Tyndall (distance retreat of about 680 m) and the area between these two lakes, totaling 4.47 km^2. A comparison with the RADARSAT (May 3, 1997) indicates that the retreat continued at the both side as well as at the center part until 1997.

Summary and Conclusion

The variations of 12 major glaciers of the NPI and SPI between 1986 or 1987 and 1997 were elucidated using RADARSAT images and Landsat MSS and TM, along with some JERS-1 images taken in 1994. The results indicate

that except four glaciers, San Rafael Glacier of NPI and Pio XI ,O'Higgins and Perito Moreno glaciers of SPI, all studied glaciers had retreated, which are similar to the trends observed in the previous period. San Rafael Glacier had kept advancing which started after 1990. A very rapid advance in a short period of time revealed at Pio XI Glacier may support a hypothesis of the surge-type. O'Higgins Glacier, which had retreated most in Patagonia until 1986, remained stable for 1986-97. Perito Moreno Glacier showed the continuing stability. This study demonstrated that RADARSAT images provided invaluable data for the study of the glacier variation in Patagonia, where perpetual inclement weather conditions usually prohibit the acquisition of images by the conventional optical sensors.

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