MONITORING RECENT GLACIER VARIATIONS IN THE SOUTHERN PATAGONIA ICEFIELD, UTILIZING REMOTE SENSING DATA

Masamu Aniya
Institute of Geoscience, University of Tsukuba, Japan
Renji Naruse
Institute of Low Temperature Science, Hokkaido University, Japan
Masami Shizukuishi
PASCO Corporation, Japan
Pedro Skvarca
Instituto Antártico, Argentina
and
Gino Casassa
Byrd Polar Research Center, Ohio State University, USA

ABSTRACT

Monitoring glacier variations at a world-wide scale is important in light of the recent, apparent global warming trend. Despite the fact that the Southern Patagonia Icefield (SPI) is the largest ice body of temperate glaciers in the southern hemisphere, the recent variation of its outlet glaciers has not been systematically studied. Utilizing Landsat MSS (1976) and TM (1986) digital data, digitized aerial photographs taken in the late 1960s and 1970s, trimetrogon aerial photographs taken in 1944/45, and maps produced from them, we elucidated variations of six major outlet glaciers, Brüggen, Jorge Montt, O'Higgins, Upsala, Moreno and Tyndall glaciers distributed in the SPI, from 1945 to 1986. While most glaciers showed a general recession, up to more than 13 km in the 41 year period, Brüggen glacier advanced about 9 km between 1945 and 1976, and blocked a fjord, with the result of the snout splitting into the northern and southern tongues. The southern tongue of Brüggen Glacier had slightly retreated, however, between 1976 and 1986, while the northern tongue had continued to advance. Breaking the 41 year period into two by the intermediate date of the late 1960s or 1970s, we found for the recent 10-15 years an accelerated recession at Upsala Glacier, slow downs at O'Higgins and Tyndall glaciers, and a relatively steady rate at Jorge Montt Glacier. On the Landsat mosaic of the SPI, the icefield area was measured and found to have diminished by about 500 km^2 to around 13,000 km^2 in 41 years. The surface lowering has been also considerable, more than 100 m, at some glaciers. As a whole, the SPI has been loosing a considerable amount of ice since 1945.

KEYWORDS: Southern Patagonia Icefield, Recent Glacier Variation, Landsat TM and MSS Digital Data

1. INTRODUCTION

In light of an apparent global warming trend in recent years, it is very important to monitor glacier variations at a world-wide scale, as glaciers, particularly the temperate ones, respond to climatic changes in a relatively short period of time. In this line, a world wide inventory of glacier variations has been initiated (Haeberli *et al.*,1989). Notably lacking in this inventory is the data on the Patagonian glaciers, despite the fact that they are the largest bodies of temperate glaciers in the southern hemisphere; hence are very important for the world-wide inventory. Patagonia is located at the southern end of South America, striding across Argentine and Chile. There are two icefields in this area, called Northern Patagonia Icefield (NPI) with an area of about 4,200 km^2 (Aniya, 1988), and Southern Patagonia Icefield (SPI) with an area of about 13,000 km^2. The authors have been studying glaciers in Patagonia since 1983 in the field (Nakajima, 1984, 1987). For the NPI Aniya (1988, 1992) compiled an inventory of 22 outlet glaciers and studied their variations in detail since 1944/45. As for the recent variation of outlet glaciers in the SPI, although Mercer (1962) summarized variations of some outlet glaciers in the SPI from the available literatures and trimetrogon aerial photographs taken in 1944/45, very little studies have been carried out, except for few glaciers such as Moreno (e.g., Nichols and Miller, 1952; Raffo *et al.*, 1953; Mercer, 1962, 1968; Denisov *et al.*, 1987), Upsala (Mercer, 1965), Brüggen (or Pio XI, e. g., Mercer, 1962, 1964; Iwata, 1983), and Tyndall (Naruse *et al.*, 1987).

We have initiated a systematic study of glacier variations in the SPI utilizing Landsat MSS and TM digital data and aerial photographs taken by Chilean and Argentine governments. We also utilized trimetrogon aerial photographs taken in 1944/45 and preliminary maps made from them. It is the purpose of this paper to present variations of the major outlet glaciers in the SPI from 1945 to 1986, with intermediate date of the late 1960s or 1970s, and to discuss their implications.

2. STUDY AREA

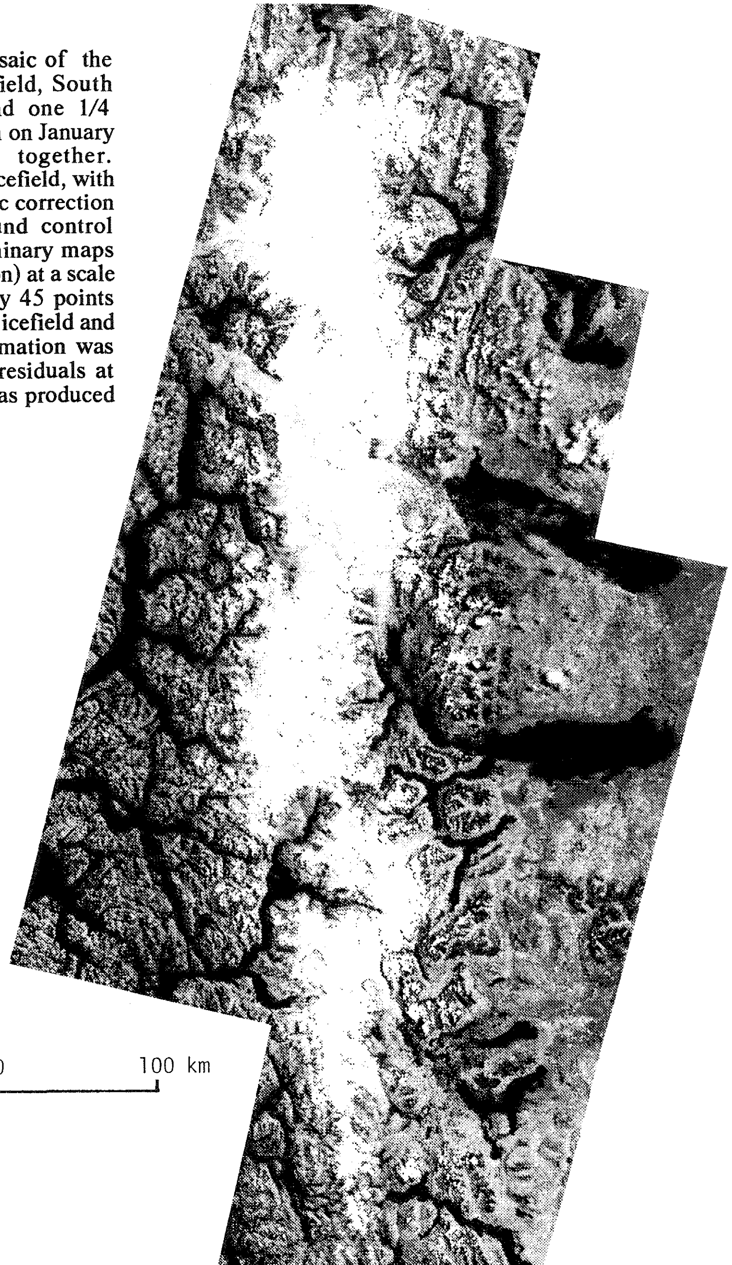
2.1 Southern Patagonia Icefield

It stretches from 48°20'S to 51°30'S along 73°30'W for about 350 km with the width up to 60 km (Figs. 1 and 2). The area was measured to be 13,500 km^2 on the map produced from 1944/45 trimetrogon photographs (Lliboutry, 1956). Utilizing the Landsat TM digital mosaic (Fig. 1) of two full and one quarter scenes, taken in January 1986, to which a geometric correction was applied (Aniya and Naruse, 1992), the area in 1986 was digitally measured to be about 13,000 km^2. Locating on the west coast in the roaring forties zone, the area is characterized by a large amount of precipitation, which is estimated at more than 5000 mm/yr (Dirección General de Aguas, 1987) and also a large amount of ablation due to relatively warm air temperature. Thus the Patagonian glaciers are one of the most typical temperate glaciers in the world, and are supposed to respond very quickly to climatic variations.

2.2 Individual Glaciers

Among many outlet glaciers located in the SPI, we have chosen the following glaciers for this study on the basis of size, location and availability of data (Figs. 1 and 2). Brüggen Glacier is calving in a fjord on the western side at the top one-third of the icefield and is one of the largest in this area with a length of about 53 km measured on the 1986 Landsat mosaic (no area data yet). This glacier is noted for a rapid advance since 1945 (Mercer, 1964; Iwata, 1983), when other glaciers were retreating. The surface pattern of the volcanic ash bands indicates that this is not due to surging. Jorge Montt Glacier is calving in a fjord at the northern end of the icefield and is listed 52 km long (Lliboutry, 1956); however, it was measured to be about 57 km on the 1986 Landsat image. O'Higgins Glacier is located on the upper eastern side of the icefield, almost opposite side of Brüggen Glacier. It terminates in a lake. It's length is estimated to be about 29 km on the 1986 Landsat image. Upsala Glacier is located on the middle eastern side and is the largest glacier in South America, with an area of 870 km^2 and a length of 60 km. Moreno Glacier is located at the lower eastern side with an area of 257 km^2 and a length of 30 km. Since access to this glacier is easy, there are a lot of field observations in this century, indicating that the glacier snout has been oscillating frequently. This glacier is famous for damming up the lake to the south by reaching the opposite bank of the channel. Both Upsala and Moreno glaciers have calving fronts in branches of Lake Argentino. Tyndall Glacier is the southernmost major outlet glacier with an estimated area of 355 km^2 and a length of 39 km. This glacier is probably the largest in the southern half of the SPI. It is calving presently in a small proglacial lake.

Fig. 1. Landsat TM mosaic of the Southern Patagonia Icefield, South America. Two full and one 1/4 consecutive scenes, taken on January 14, 1986, were pieced together. White area indicates the icefield, with ice and snow. Geometric correction was applied using ground control points taken from preliminary maps (Lambert Conic projection) at a scale of 1:250,000. Originally 45 points were selected around the icefield and quadratic affine transformation was applied. Checking the residuals at points, the final image was produced using 11 points.



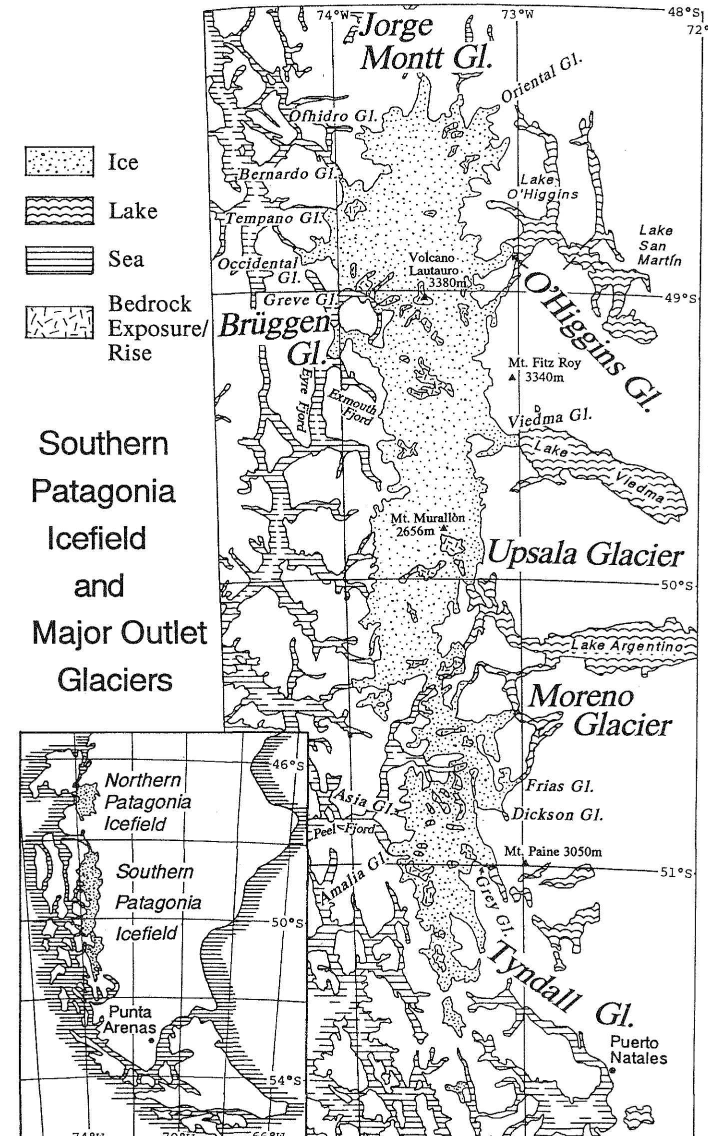


Fig. 2. Generalized map of the Southern Patagonia Icefield, showing the studied glaciers (indicated by large letters). Map based on Lliboutry (1956) and elevations modified after Argentine topographic maps published by Instituto Geográfico Militar.

Glaciers located on the western lower two-thirds were not studied because of the data limitation. Aerial photographs covering this area were taken in December 1984, only one year net-difference from the Landsat TM data. Besides they are generally small and indistinctive except for Asia and Amalia glaciers. Occidental Glacier located north of Brüggen Glacier was not included because the TM data is missing. Viedma Glacier, which is one of the largest in this area, cannot be studied because of cloud cover on the TM data.

3. METHOD

Remote sensing data covering the SPI glaciers are very limited. The oldest one is trimetrogon aerial photographs taken in the austral summer of 1944/45 (hereafter referred to as 1945 photographs) by USA, from which preliminary maps at a scale of 1:250,000 showing spot heights, form lines and the limit of glaciers have been produced by Instituto Geográfico Militar (I.G.M.) of Chile. For most of the icefield, these maps are still the largest scale map available for study. Vertical black and white aerial photographs at scales of about 1:70,000 were taken by I.G.M. of Argentina during the late 1960s and 1970s, covering those glaciers located in Argentina. Photogrammetric Division of the Chilean Air Force (FACH) covered the Chilean side with vertical aerial photographs from the late 1970s to the early 1980s at scales of about 1: 70,000. The national park "Paine" area was covered by vertical aerial photographs at a similar scale in 1975 by I.G.M. of Chile.

In addition to these classical remote sensing data, Landsat MSS and TM data were utilized. In the history of Landsat operation for 20 years, however, there is only one set of TM data covering the whole icefield in a single day or so, which are almost cloud-free and can be utilized for glacier studies. These images were taken on January 14, 1986. For the northern one-third of the icefield, a cloud-free MSS data taken on February 25, 1976 is available for a comparison with the 1986 TM data. However, for the southern two-thirds of the icefield, there is no other Landsat data which can be utilized for glacier studies, because of heavy cloud covers. This fact tells about the state of the general weather condition in this area

For those glaciers covered with both 1976 MSS and 1986 TM data, digital superimposition was done to compare the snout position of the glaciers. The 1976 data was then manually compared with trimetrogon aerial photographs taken in 1944/45 and preliminary maps produced from them. Although the glacier area was digitized on the 1:250,000 preliminary maps, digital superimposition was not attempted, because the maps contain some errors and do not show sufficient detail for digital analysis. The TM data was geometrically corrected using these preliminary maps and the MSS data was superimposed using the common ground points. These are Brüggen, Jorge Montt, and O'Higgins glaciers

For those glaciers covered with only one date of the TM data, vertical aerial photographs were utilized. These photographs were digitized at 300 dpi with a drum scanner. Then they were superimposed on the geometrically-corrected TM data. Since a single photograph contains a large amount of relief displacement due to high relief in the area, the cubic affine transformation was employed for superimposition onto the TM data. Again these photographs were manually compared with trimetrogon aerial photographs and preliminary maps. These are Upsala, Moreno, and Tyndall glaciers. For these glaciers, topographic maps at a scale of 1;100,000 have been recently produced with a contour interval of 50 or 100 m.

4. RESULTS

4.1 Superimposition of Landsat MSS and TM data

4.1.1 Brüggen Glacier Locating on the western side of the icefield, the behavior of this tidewater glacier during the last 41 years is very peculiar among the Patagonian glaciers. While the glaciers in general have shown a retreating trend, Brüggen Glacier showed a net advance of about 9 km (290 m/yr) between

Fig. 3. Variation of Brüggen Glacier, 1945-1976-1986. Landsat MSS (1976) and TM (1986) superimposed. Northern tongue: advance (white). Southern tongue: retreat (dark). Glacier limit of 1945 shown with broken lines. Dark specks on water: calved ice.

behaviors during the subsequent period of 1976-86. Namely, while the northern one advanced further, up to 1200 m (120 m/yr), the southern one showed a maximum retreat of 600 m (60 m/yr)(Fig. 3). We do not know exactly when the advance of the southern snout had stopped and the retreat had started as there are no other remote sensing data or ground observations. Mercer (1964) first documented this rapid advance of Brüggen Glacier.

4.1.2 Jorge Montt Glacier This glacier is located at the northernmost end of the icefield and drains to the north into a fjord. During the last 41 years, the glacier had retreated at a fairly steady rate of 32-40 m per year for a total of about 1400 m (36 m/yr). Notable change between 1945 and 1976 was that the width of the glacier had diminished significantly. Before, the glacier ice had spilt over to the left bank and spread out; however, due to the surface lowering the spilling had ceased and the apparent width of the glacier had become close to one half. Figure 4 indicates the variation between 1976 and 1986. Both sides of the glacier are heavily covered with debris, which made only the debris-free, center area of the glacier distinctively visible on the images. The TM image shows an interesting 1945 and 1976 (Table 1). Due to this advance, a fjord was blocked and the snout has split into the northern and southern ones. As a result, the fjord between the northern snout and Greve Glacier to the north has become an impounded lake with a lot of suspended sediments, which has eventually started draining north along Occidental Glacier. Currently these snouts are terminating in the waters of different nature: the northern one in a fresh or brackish water, and the southern one in a fjord. Although it is not certain, naturally, whether or not the difference in the quality of water would affect the snout behavior, the northern and southern snouts showed different

Table 1. Variations of major outlet glaciers in the Southern Patagonia Icefield, 1945-1986.

	Retreat (m)		
Glacier Name	1945 - 1986 (41yrs)	1945-1976	1976-1986
Brüggen			
northern tongue	-5300 (-129)	-4100 (-132)	-1200 (-120)
southern tongue	-8400 (-205)	-9000 (-290)	Max. 600 (60)
Jorge Montt	1400 (34)	1000 (32)	400 (40)
O'Higgins	13400 (327)	11000 (355)	Max. 2400 (240)
Upsala	2600 (63)	1945 - 69 900 (37)	1969 - 86 2300 (135)*
Moreno	-600	1945 - 70 -250 (max.-500)	1970 - 86 -500
	actually much more frequent oscillation during this period		
Tyndall	3900 (95)	1945 - 75 3200 (107)	1975 - 86 700 (64)

*between 1970 and 1978 an advance of 350 m was revealed by other data.
The number in parentheses indicates an average annual rate.

feature at the snout. It seems that the tip of the snout is off set against the main body along a crack, suggesting a large calving of the glacier. However, checking with the 1979 vertical aerial photographs with stereoscopic inspection, it was found out that the seemingly-single, large calved body of ice (so interpreted on the TM image) was actually a dense pack of small calved ice fragments. They are so tightly packed that it was recognized on the Landsat image as a single, solid body of glacier ice. Only with stereoscopic inspection, ice cliffs at the calving front could be recognized. This episode suggests that we must be very careful when dealing with calving glaciers on satellite data.

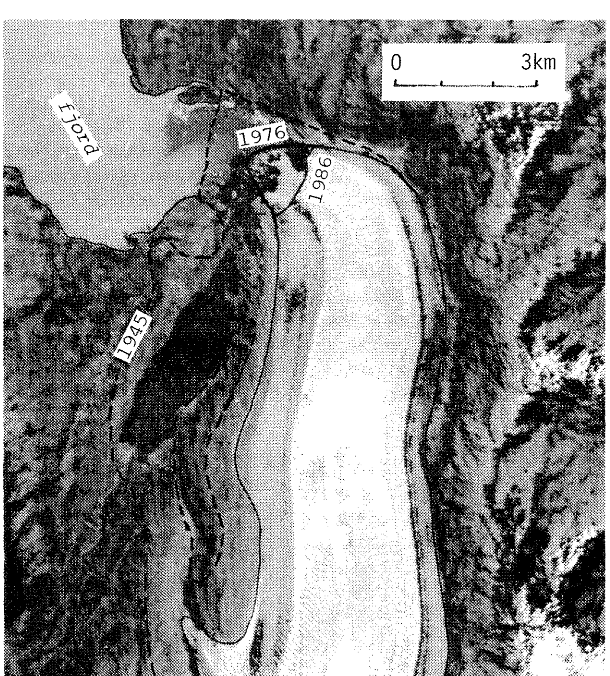


Fig. 4. Variation of Jorge Montt Glacier, 1945-1976-1986. Landsat MSS (1976) and TM (1986) superimposed. Glacier limit of 1945 shown with broken lines.

4.1.3 **O'Higgins Glacier** Locating on the eastern side of the icefield and terminating in Lake O'Higgins (Argentine side, called Lake San Martín), this glacier had shown a very large amount of recession between 1945 and 1986, with a total of 13.4 km (327 m/yr). This value is exceptionally large in Patagonia, even if including glaciers in the Northern Patagonia Icefield, where San Rafael glacier, a glacier which showed by far the largest recession in that region, had retreated 2800 m in the similar period (Aniya, 1988) Figure 5 shows the snout change between 1976 and 1986, in which the northern half appears to have retreated distinctively more than the southern half, as indicated by the dark tone. The snout is also covered with a 1984 (Dec.) photograph, in which there is no such difference in the frontal position between the northern and southern sectors. There are no particular reasons to consider an advance in one year at the southern sector only. A very careful manual examination of the TM data indicates that this area is very smooth and slightly different in texture from the upstream, suggesting that this is a pack of calved ice on the lake. Superimposition of the images also failed to show the debris covered areas on both sides of the glacier. Again this revelation tells us that we must be very cautious on the satellite image and be aware of the limitation of the digital processing. Such an error was indeed made at this glacier by a group of Soviet scientists (Denisov *et al.*, 1987), which was correctly pointed out by Krimmel (1988).

4.2 Superimposition of digitized aerial photographs and Landsat TM data

4.2.1 **Upsala Glacier** For Upsala Glacier, several dates of aerial photographs are available and we chose the photographs taken in November 1968 (hereafter referred to as 1969 photograph) at a nominal scale of 1:71,000 by Argentine I.G.M. to digitize and compare with the Landsat TM data. In 24 years from 1945 to 1969, a maximum retreat of 900 m (57 m/yr) was observed, while between 1969 and 1986 a total retreat of 2300 m (135 m/yr) was measured near the center of the glacier (Fig. 6). These two values indicate that the recent recession has been more intense than that prior to 1969. Manual comparisons of other remote sensing data including a Soviet Salyut-6 satellite photograph and a Landsat RBV have revealed that Upsala Glacier had actually advanced about 350 m at the glacier center between 1970 and 1978, and after 1981 a rapid recession has started (Aniya and Skvarca, 1992). Therefore in effect a total of 2650 m (2300 plus 350) was lost in eight years between 1978 and 1986 (330 m/yr). This is a very fast rate, comparable only to the recession rate of O'Higgins Glacier. The surface lowering of more than 100 m since 1969 was estimated in the field in November 1990 near the present snout.

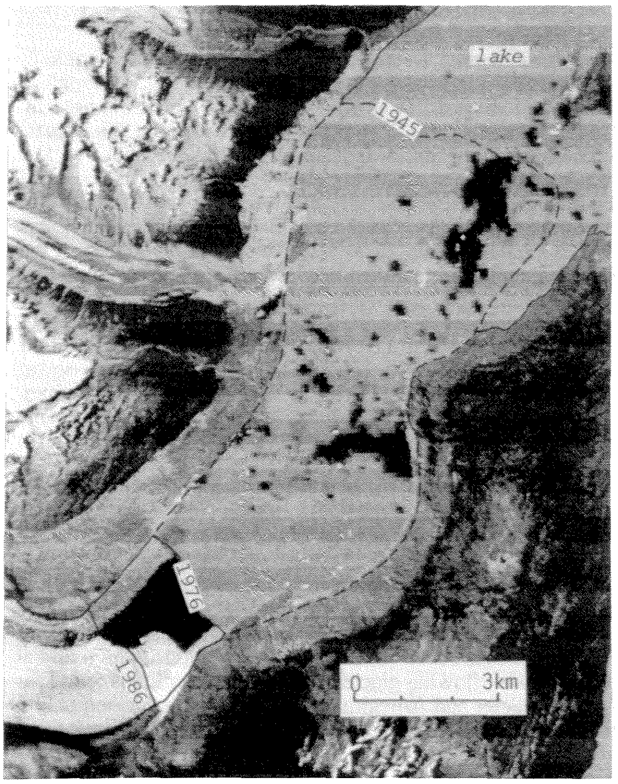


Fig. 5. Variation of O'Higgins Glacier, 1945-1976-1986. Landsat MSS (1976) and TM (1986) superimposed. Glacier limit of 1945 shown with broken lines. Dark spots and areas on the lake: pack of calved ice.

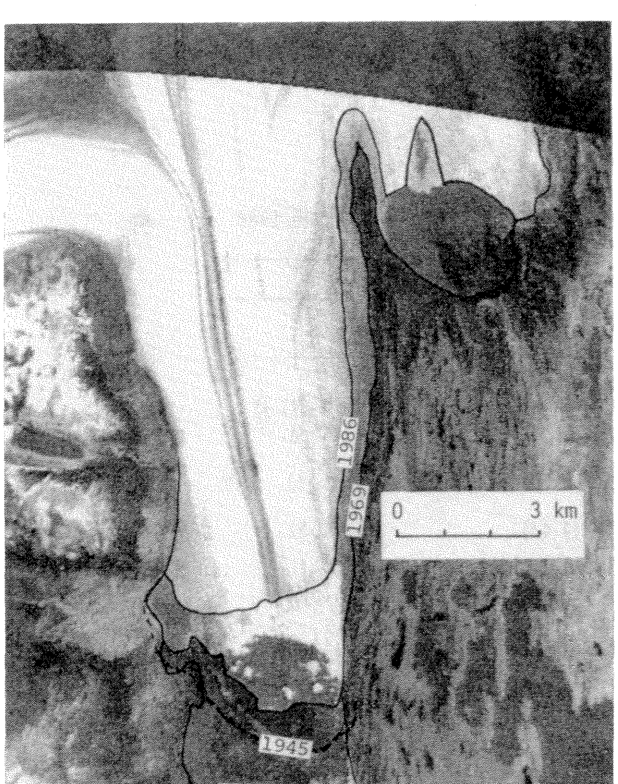


Fig. 6. Variation of Upsala Glacier, 1945-1969-1986. Aerial photograph (1969) and Landsat TM (1986) superimposed. Glacier limit of 1945 shown with broken lines. Dark area at the top is beyond the photographic cover.

4.2.2 **Moreno Glacier** This glacier is well-known for its quick advance and retreat in this century. It had started advancing at the end of the last century and for the first time in 1917 it reached the opposite bank of the lake and impounded a lake to the south (Brazo Rico of Lake Argentino). Since then the glacier dammed up the lake many times (Mercer, 1968). We digitized a 1970 (March) photograph from few dates available to compare with the Landsat TM data (Fig. 7). The snout area can be divided into the northern and southern tongues by the tip of the snout which is close to the opposite bank. The northern tongue had advanced about 500 m, while the southern tongue advanced only few tens of meters between 1970 and 1986. Manual comparisons of the other remote sensing data indicate that the snout position has been frequently oscillating and the 1986 position was the furthest since 1970. The tip was touching the opposite bank in 1990, although the channels to the north and south were connected by a tunnel. Consequently, it seems at this glacier that there is no point to discuss the glacier variation at relatively long intervals. We need almost yearly data to meaningfully discuss the variation of Moreno Glacier. For this type of monitoring, a regular coverage of satellite surveillance is well-suited; however, inclement weather conditions in Patagonia prevent such surveillance, regrettably.

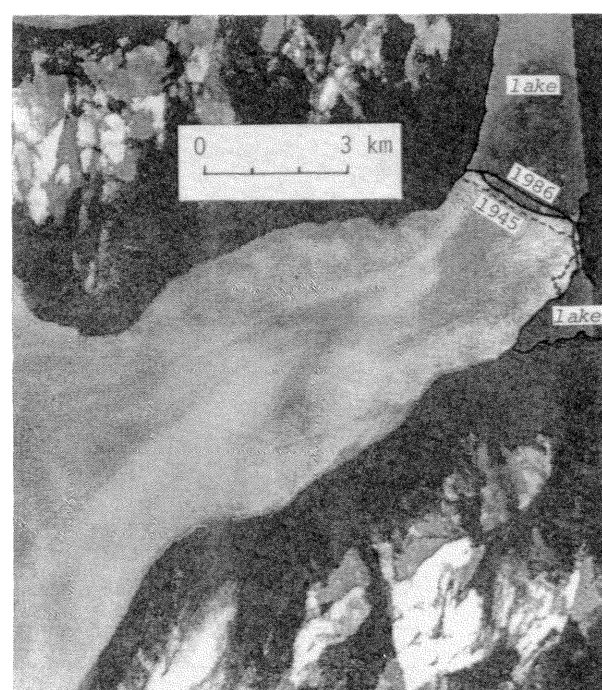


Fig. 7. Variation of Moreno Glacier, 1945-1970-1986. Aerial photograph (1970) and Landsat TM (1986) superimposed, showing an advance (dark). Glacier limit of 1945 shown with broken lines. Straight portion delimiting the eastern part of the lake is the photograph's edge, not lake shoreline.

4.2.3 **Tyndall Glacier** This glacier is located near the southern end of the icefield, right next to the famous mountain "Paine" to the east. The wasting snout of this glacier used to terminate in two proglacial lakes: however, currently in one due to the recent recession. There are two side lobes on the left bank, about 18 km upstream from the snout. For this glacier, a photograph taken in March 1975 was digitized to compare with the Landsat TM data (Fig. 8). In 30 years between 1945 and 1975, a maximum recession of 3200 m (107 m/yr) was measured, while from 1975 to 1986 it retreated 700 m (64 m/yr). Thus the recent retreat rate was much less, nearly one half of the previous rate, which is contrary to the trend found at Upsala Glacier. The surface lowering of about 140 m since 1945 was estimated in the field in December 1990 at the left bank, about 18 km upstream of the present snout.

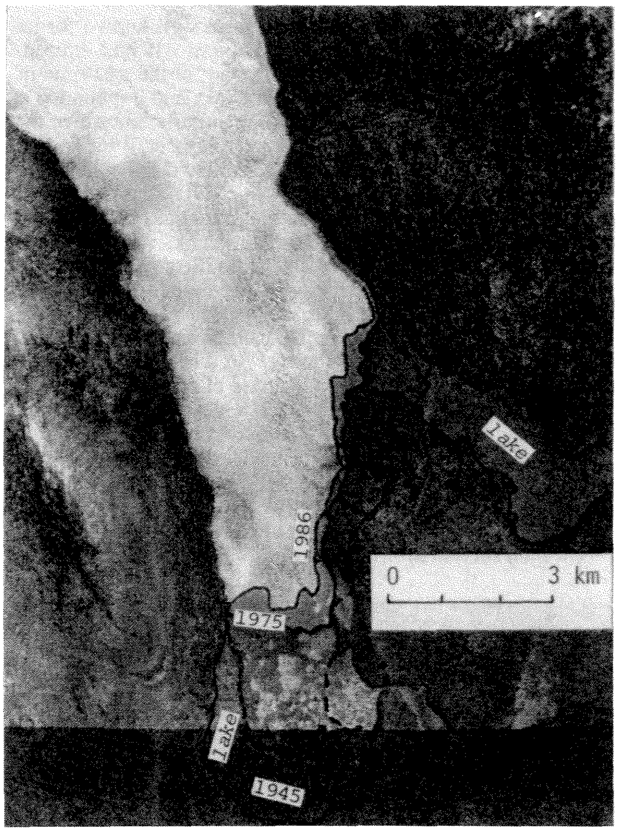


Fig. 8. Variation of Tyndall Glacier, 1945-1975-1986. Aerial photograph (1975) and Landsat TM (1986) superimposed. Glacier limit of 1945 shown with broken lines. Dark area at the bottom is beyond the photographic cover.

5. DISCUSSION AND CONCLUDING REMARKS

Frontal area changes due to retreat/advance are listed in Table 2, which are essential to compute the volume change, although at the moment there is no information on glacier thickness in Patagonia, except for Tyndall Glacier where a maximum thickness of about 600 m is reported at the area about 18 km from the snout (Casassa, 1992). It is evident from Tables 1 and 2 that the glaciers are generally in a trend of retreat since 1945, with one extraordinary exception of Brüggen Glacier which has shown a great advance. However, even at Brüggen Glacier, the southern tongue had retreated between 1976 and 1986, although in terms of the net area change, it still advanced. Upsala and Tyndall glaciers lost comparable front areas. If we break the 41 year period into two, from 1945 to the late 1960s or 1970s and then to 1986, the recession was much faster in the latter period at Upsala Glacier, while it was in the earlier period when O'Higgins and Tyndall glaciers receded faster. Jorge Montt Glacier receded fairly steadily for 41 years.

It should be pointed out that the two glaciers, O'Higgins and Brüggen, showing by far the largest retreat (11 km) and advance (9 km) respectively between 1945 and 1976, are located at the similar latitudes with only several tens of kilometers apart. Since they are located on the opposite side of the icefield divide, mass balance mechanisms are probably different; however, there must be some other factors to account for these contrasting behaviors because such contrasts cannot necessarily be found at other east-west flowing glaciers. A similar situation is found for Moreno Glacier and Ameghino Glacier which is located only 8 km north of Moreno Glacier. Although the variation of Ameghino Glacier has not been studied in detail, the glacier has been known for a rapid retreat in this century (Nichols and Miller, 1952), and recent remote sensing data indicate that the retreat has been continuing. Moreno Glacier, on the other hand, has been alternating advance and retreat frequently in this century. Both glaciers have juxtaposed accumulation areas to the west of the snouts. Although some explanations have been offered to account for this contradictory behaviors of neighboring glaciers (Nichols and Miller, 1952), we do not know the exact mechanism yet.

Table 2. Loss of frontal area due to retreat in the Southern Patagonia Icefield, 1945-1986.

	Area lost (km^2)*		
Glacier Name	1945 - 1986 (41yrs)	1945-1976	1976-1986
Brüggen			
northern tongue	-21.1 (-0.51)	-18.4 (-0.59)	-2.7 (-0.27)
southern tongue	-50.0 (-1.22)	-51.4 (-1.65)	1.4 (0.14)
Jorge Montt	4.9 (0.12)	3.8 (0.12)	1.1 (0.11)
O'Higgins	50.4 (1.23)	44.9 (1.45)	5.5 (0.55)
Upsala	10.7 (0.26)	1945 - 69 3.4 (0.14)	1969 - 86 7.3 (0.43)**
Moreno	-1.1	1945 - 70 -0.7	1970 - 86 - 0.4
	actually much more frequent oscillation during this period		
Tyndall	11.5 (0.28)	1945 - 75 8.9 (0.30)	1975 - 86 2.6 (0.24)

*lateral shrinkage is not included.

**between 1970 and 1978 an advance was revealed by other data.

The number in parentheses indicates an average annual rate.

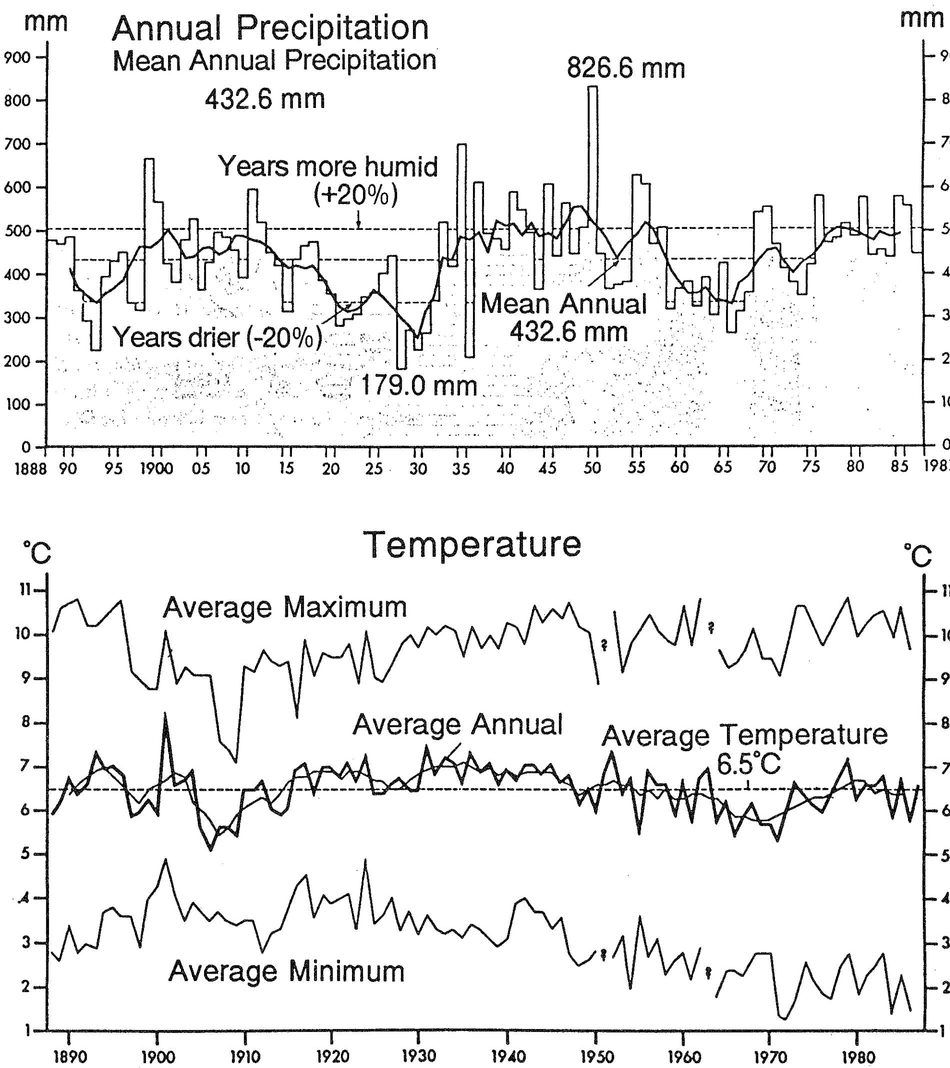


Fig. 9. Climatological data at Punta Arenas (50°08'S, 70°53'W. 6 m a.s.l.), 1888-1987. (after Endlicher and Aguila, 1988)

Although we have elucidated the general trend of the glacier behaviors in the SPI since 1945, there are no climatological data recorded at nearby stations to compare with, as the number of inhabitants in Patagonia is very small and the general interest in this area is minimum. Only climatological data with sufficiently long record come from Punta Arenas (53°08'S, 70°53'W), about 240 km south of the southern end of the SPI. The station is not only far away but also situated in a different climatic zone (dry) from the SPI. Nonetheless we attempted to see trends in precipitation and air temperature from Figure 9 (Endlicher and Aguila, 1988). According to these data, the amount of precipitation had declined between 1948 and 1965, and as for air temperature, a cooling trend can be seen between 1945 and 1970 and a warming trend after 1970. The Patagonian glaciers are supposed to respond quickly to climatic changes, because they are characterized by a large mass balance, that is, large amounts of accumulation and ablation, and since the change in air temperature affects the snout area more quickly, it seems that these climatic trends would explain some glaciers' behaviors; however, naturally, not all of them. Without further detailed studies in the field, it is premature to conclude as such; however, it appears that the recent rapid recession is a response to the recent world-wide warming trend.

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References

Aniya, M. 1988. Glacier inventory for the Northern Patagonia Icefield, Chile, and variations 1944/45 to 1985/86. *Arctic and Alpine Research*, **20**: 179-187.

Aniya, M. 1992. Glacier variation in the Northern Patagonia Icefield, Chile, between 1985/86 and 1990/91. *Bulletin of Glacier Research*, **10**: 83-90.

Aniya, M. and Naruse, R. 1992. Studies on glacier and snow-cover variations in South America utilizing satellite data--Outlet Glaciers in the Southern Patagonia Icefield. In *Better Understanding of Earth Environment via Satellite,* the second symposium in the fiscal year of 1991 held in Tokyo March 2-3, 1992: 250-256 (in Japanese).

Aniya, M. and Skvarca, P. 1992. Characteristics and variations of Upsala and Moreno glaciers, Southern Patagonia. *Bulletin of Glacier Research,* **10**: 39-53.

Casassa, G. 1992. Radio-echo sounding of Tyndall Glacier, southern Patagonia. *Bulletin of Glacier Research,* **10**: 69-74.

Denisov, L. V., Nosenko, G. A., Grechko, G. M., Ivanchenko, A. S., and Kotlyakov, V. M. 1987. Glaciological studies and experiments from the Salyut-6 orbital space station. *Polar Geography and Geology,* **11**: 12-24.

Dirección General de Aguas 1987. *Balance Hídrico* de Chile. Ministerio Obras Públicas, Santiago, Chile, 59p.

Endlicher, W. and Aguila, A. S. 1988. El clima del sur de la Patagonia y sus aspectos ecológicos---Un siglo de mediciones climatológicas en Punta Arenas. *Anales del Instituto de la Patagonia,* Ser. Cs. Nts., Universidad de Magallanes, **18**: 57-86.

Haeberli, W., Bösch, H., Scherler, K.,Østrem, G., and Wallén, C.C. (eds). 1989. *World Glacier inventory, Status 1988.* IAHS (ICSI)-UNEP-UNESCO.

Iwata, S. 1983. Further advance of Pio XI Glacier. In *Glaciological and Meteorological Studies in Patagonia, Chile, by Japanese Research Expeditions in 1967-1982* (Data Center for Glacier Researches, Japanese Society of Snow and Ice), 14-17.

Krimmel, R. M. 1988. Terminus of Glaciar O'Higgins, southern Chile. *Journal of Glaciology,* **34** (116): 142.

Lliboutry, L. 1956. *Nieves y Glaciares de Chile.* Ediciones de la Universidad de Chile, Santiago, Chile, 471p.

Mercer, J. H. 1962 Glacier variations in the Andes. *Glaciological Note,* 12: 9-31.

Mercer, J. H. 1964. Advance of a Patagonian glacier. *Journal of Glaciology,* 5(38): 267-268.

Mercer, J. H. 1965. Glacier variations in southern Patagonia. *The Geographical Review,* 55: 390-413.

Mercer, J. H. 1968. Variations of some Patagonian glaciers since the late-glacial. *American Journal of Science,* **266**: 91-109.

Nakajima, C. (ed.). 1985. *Glaciological Studies in Patagonia Northern Icefield, 1983-1984.* Data Center for Glacier Research, Japanese Society of Snow and Ice, 133.

Nakajima, C. 1987. Outline of the glaciological research project in Patagonia, 1985-1986. *Bulletin of Glacier Research,* **4**: 1-6.

Naruse, R., Peña, H., Aniya, M., and Inoue, J. 1987. Flow and surface structure of Tyndall Glacier, the Southern Patagonia Icefield. *Bulletin of Glacier Research,* **4**: 133-140.

Nichols, R. L. and Miller, M. M. 1952. The Moreno Glacier, Lago Argentino, Patagonia: advancing glaciers and nearby simultaneously retreating glaciers. *Journal of Glaciology,* **2**(11): 41-46.

Raffo, J. M., Colqui, B. S., and Madejski, M. E. 1953. Glaciar Moreno. Dirección General del Servicio Meteorológico Nacional, Buenos Aires, *Serie Hidrometeorológica Publicatión* No. 9: 293-341.