CURRENT KNOWLEDGE OF THE SOUTHERN PATAGONIA ICEFIELD

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1. ABSTRACT

We present here a review of the current glaciological knowledge of the Southern Patagonia Icefield (SPI). With an area of 13,000 km^2 and 48 major glaciers, the SPI is the largest ice mass in the Southern Hemisphere outside of Antarctica. The glacier inventory and recent glacier variations are presented, as well as ice thickness data and its variations, ice velocity, ablation, accumulation, hydrological characteristics, climate changes and implications for sea level rise. Most of the glaciers have been retreating, with a few in a state of equilibrium and advance. Glacier retreat is interpreted primarily as a response to regional atmospheric warming and to a lesser extent, to precipitation decrease observed during the last century in this region. The general retreat of SPI has resulted in an estimated contribution of 6% to the global rise in sea level due to melting of small glaciers and ice caps. Many glaciological characteristics of the SPI, in particular its mass balance, need to be determined more precisely.

2. INTRODUCTION

The Southern Patagonia Icefield (SPI) extends north-south for 370 km, between 48°15' S and 51°35' S, at an average longitude of 73°30' W (Figure 1). Its mean width is 35 km, and the minimum width is 9 km. The first detailed glacier inventory was compiled by Aniya *et al.* (1996), who showed that the SPI is composed of 48 major outlet glaciers and over 100 small cirque and valley glaciers. These glaciers flow from the Patagonian Andes to the east and west, generally terminating with calving fronts in freshwater lakes (east) and Pacific Ocean fjords (west).

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The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies.
Edited by Gino Casassa et al., Kluwer Academic /Plenum Publishers, 2002.

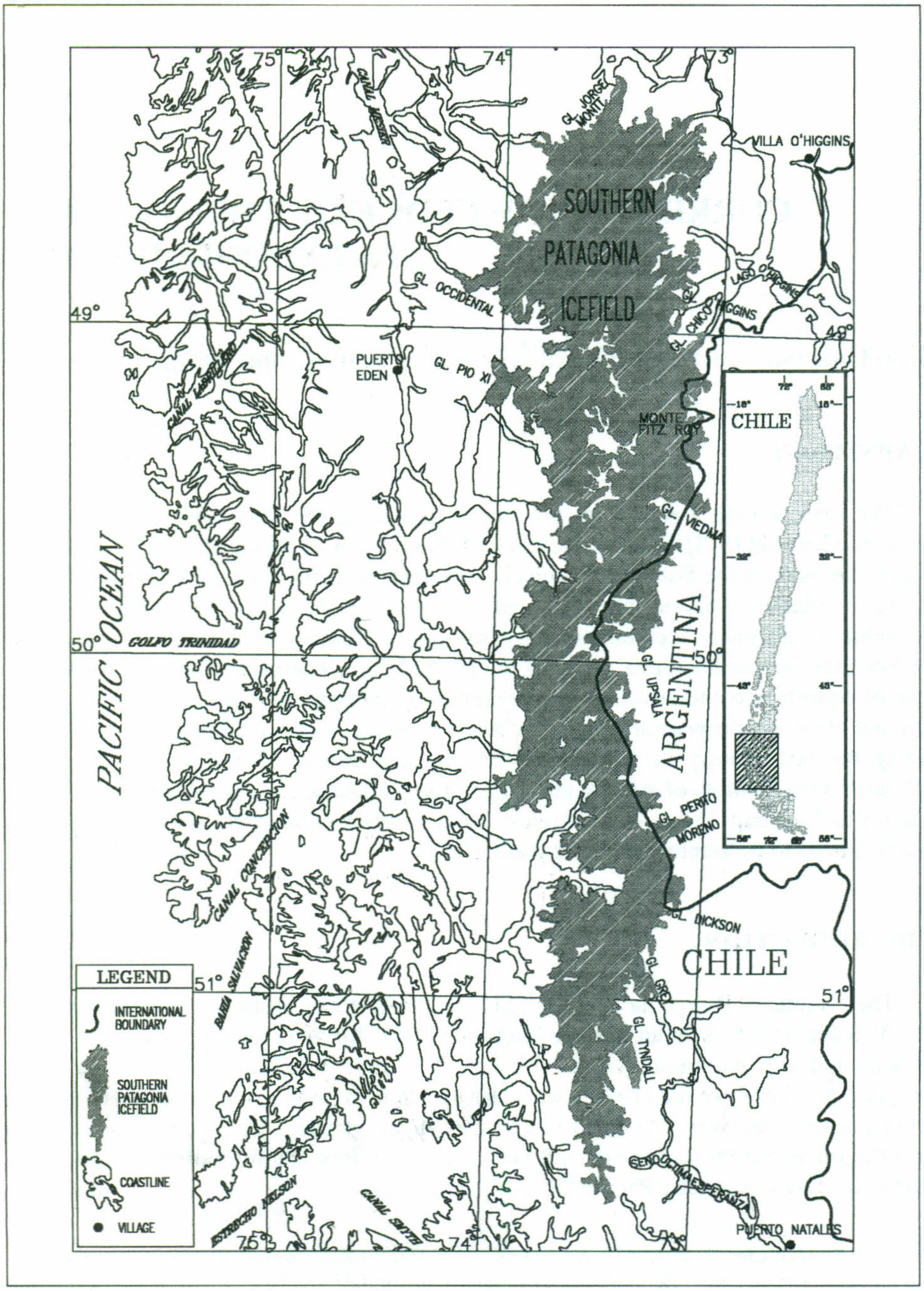

Figure 1. Location map, Southern Patagonia Icefield, Chile-Argentina. Modified from: Características Glaciológicas del Campo de Hielo Patagónico Sur, Casassa, G., Rivera, A., Aniya, M., and Naruse, R., 2000, *Anales del Instituto de la Patagonia, Serie Ciencias Naturales*, **28**:5-22. (a journal of the Universidad de Magallanes, Punta Arenas, Chile).

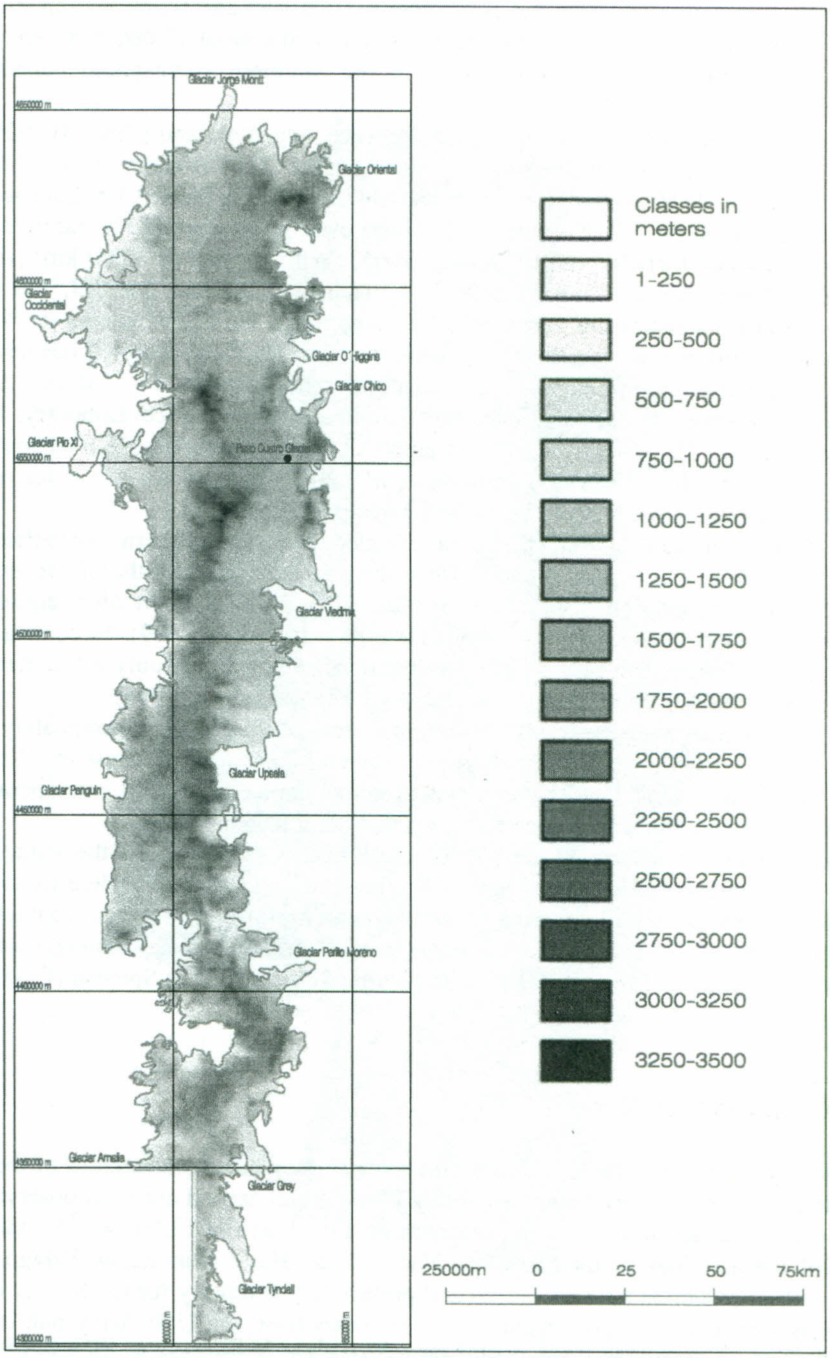

Figure 2. Digital terrain model for Southern Patagonia Icefield. Pixel size is 1 km. Data source are 1:250,000 preliminary maps, 1:100,000 maps from the Instituto Geográfico Militar, Argentina in the eastern SPI, and in the northern sector, 1:50,000 scale maps from the Instituto Geográfico Militar, Chile.

In the accumulation area, the outlet glaciers share a vast and relatively flat plateau with an average altitude of 1600 m (Figure 2). With a total area of 13,000 km^2 (Aniya *et al.,* 1996), the SPI is the largest ice mass in the Southern Hemisphere outside of Antarctica (Casassa *et al.,* 1998a).

According to the latest border agreement between Argentina and Chile, 81~92% of the SPI belongs to Chile and the rest belongs to Argentina. The official name for the SPI in Chile is "Campo de Hielo Sur" (Southern Icefield). The SPI is located 100 km south of the "Campo de Hielo Norte" (Northern Icefield), known in the scientific literature as the "Northern Patagonia Icefield" (NPI; Casassa, 1995). With an area of 4,200 km^2 (Aniya and Wakao, 1997; Aniya, 1988), the NPI is much smaller than the SPI, but their glaciological characteristics are very similar. In Argentina, the SPI is known as "Hielo Continental" (translated as "ice sheet"), a name that is not widely accepted because the SPI does not cover a large portion of a continent, but rather a reduced inland area. Other Spanish authors prefer "Hielo Patagónico Sur" (Southern Patagonia Ice: Lliboutry, 1956; Marangunic, 1964; Martinic, 1982), or "Campo de Hielo Patagónico Sur" (Southern Patagonia Icefield: Horvath, 1997; Casassa *et al.*, 2000). We prefer the latter name, because it preserves both a morphological and a geographical origin.

The SPI is located within the area affected by the southern westerlies. In consequence, due to a strong orographic effect, the western margin of the SPI receives a high amount of precipitation, with an average annual estimate of 10 m water equivalent (w.e.) for the icefield plateau (DGA, 1987; Casassa and Rivera, 1999). In contrast, the eastern margin of the SPI receives little precipitation, amounting to only a few hundred mm annually in the Argentine pampa (Ibarzabal y Donángelo *et al.,* 1996).

The mean annual temperature of the marginal areas of the SPI is approximately 6 °C (Carrasco *et al.,* 1998), which permits the existence of a unique ecosystem of beech forest at the glacier fronts. Due to the climatic regime, the ice in the SPI is temperate, at least in all of the ablation area and part of the accumulation area.

A comprehensive review of the glaciological studies performed at the Patagonian icefields was presented several years ago by Warren and Sugden (1993). Here we present an updated review of the SPI covering glacier inventory, glacier variations, ice thickness and its variations, ice velocity, mass balance, glacial hydrology, climate changes and sea level rise. A large part of this work has been previously published in Spanish (Casassa *et al.,* 2000).

3. GLACIER INVENTORY

Lliboutry (1956) was the first to describe the glaciological characteristics of the SPI. He studied Trimetrogon aerial photographs of 1944/45 and carried out field observations at de Los Tres Glacier, near Fitz Roy, determining a total area of 13,500 km^2 for the SPI. As part of the activities of the "Instituto Nacional del Hielo Continental Patagónico", Bertone (1960) compiled the first partial and preliminary inventory for the SPI, covering the glaciers that drain to lago Argentino. A few years later, the U.S. Army published a preliminary inventory for the whole SPI (Mercer, 1967).

Based on Landsat satellite imagery of 14 January 1986 (Figure 3), together with 1:250,000 "preliminary" topographic maps of the Instituto Geográfico Militar, Chile and stereoscopic analyses of aerial photographs, Aniya *et al.* (1996) compiled the complete inventory for the SPI (Table 1), identifying 48 major outlet glaciers.

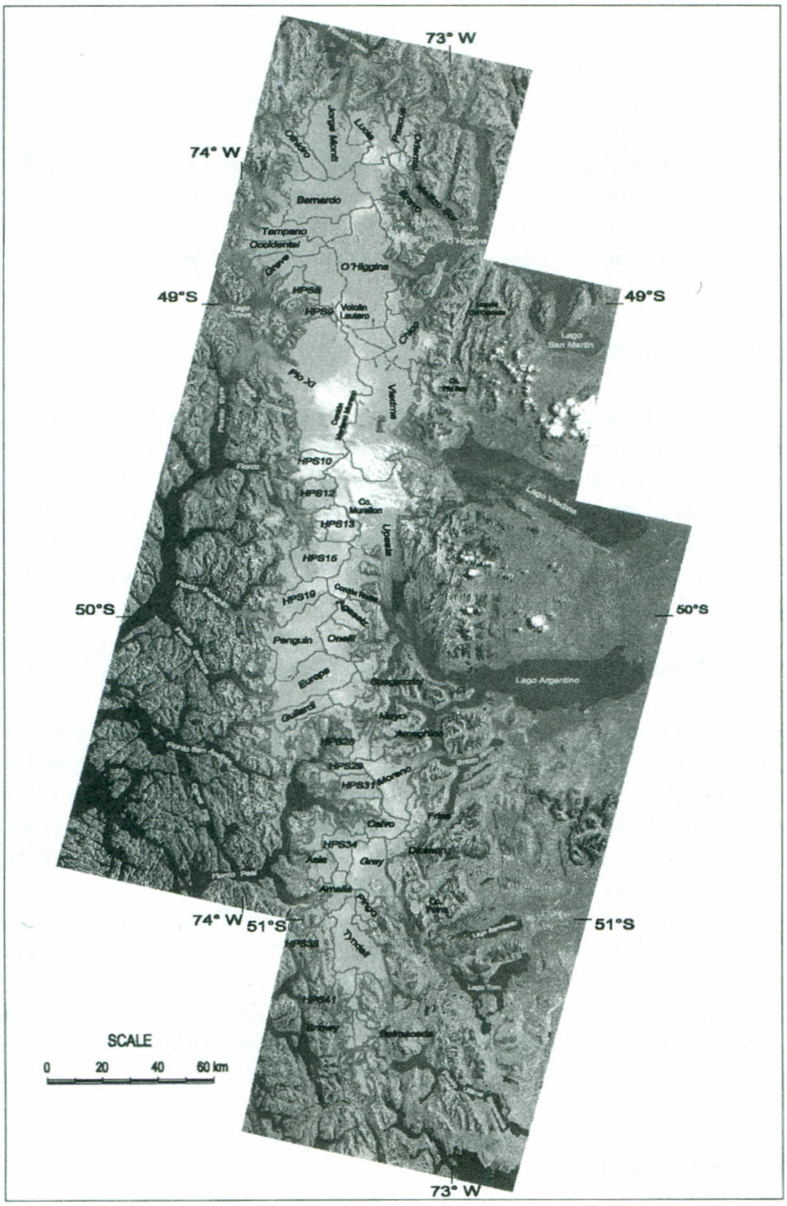

Figure 3. Satellite image mosaic of Southern Patagonia Icefield. The mosaic is a composite of three Landsat TM bands acquired 14 January 1986 (Naruse and Aniya, 1992). The mosaic was geolocated with 1:250,000 Preliminary Maps of Chile. Modified from: Características Glaciológicas del Campo de Hielo Patagónico Sur, Casassa, G., Rivera, A., Aniya, M., and Naruse, R., 2000, *Anales del Instituto de la Patagonia, Serie Ciencias Naturales*, **28**:5-22. (a journal of the Universidad de Magallanes, Punta Arenas, Chile).

Accumulation and ablation areas were estimated based on the snowline position on the Landsat imagery, assumed to coincide with the equilibrium line at the time of image acquisition. Of the 48 glaciers, 46 calve into freshwater lakes and fjords, while 2 terminate on land.

The largest glacier of the SPI is Pío XI, with a total area of 1265 km^2. Next largest glaciers are Viedma (945 km^2), Upsala (902 km^2) and O'Higgins (810 km^2). Areas are calculated by Aniya (personal communication), which are a better estimate of the values published by Aniya *et al.*, 1996.

The area covered by ice and snow within the 48 glaciers of the SPI is 11,259 km^2, with an additional 228 km^2 of exposed rocks in the accumulation area, which makes a total of 11,487 km^2. Adding to this value an area of 1,513 km^2 of small valley, cirque and mountain glaciers results in a total area of 13,000 km^2 for the SPI (Aniya *et al.,* 1996).

4. GLACIER VARIATIONS

Before 1997, information on glacier variations of the SPI existed for only half of the major glaciers (Warren and Sugden, 1993). Aniya *et al.* (1997), determined the area and frontal variations of the 48 major glaciers of the SPI, based on 1:250.000 "preliminary" maps of Chile, aerial photographs and satellite imagery. Other authors have extended the data set using historical data or recent aerial photographs of individual glaciers (Warren *et al.,* 1997; Rivera *et al.,* 2000; Rivera *et al.,* 1997a; Rivera *et al.,* 1997b; Agostini, 1945; Aniya *et al.,* 1999; Skvarca *et al.,* 1995a; 1999). In a few cases, glacier variations can be extended more than one century based on descriptions and maps produced by explorers (e.g. Naruse and Casassa, 1985; Casassa *et al.,* 1997a; Rivera, 1992; Martinic, 1999).

A generalized retreat is observed in 42 glaciers, while four glaciers were in equilibrium between 1944 and 1986 (HPS 13, HPS 15, Calvo and Spegazzini) and two advanced during the same period (Pío XI and Moreno). The largest retreat rate is shown by the O'Higgins Glacier, with a rate of loss in area of 1.21 km^2/a, or 484 m/a of frontal loss, between 1944/45 and 1985/86 (Aniya *et al.,* 1997). In the period 1896-1995, the O'Higgins Glacier retreated 14.6 km (Casassa *et al.,* 1997a).

The maximum advance was detected at the Pío XI Glacier (Mercer, 1964), with a rate of 1.45 km^2/a during the period 1946-1986, which translates into an average frontal advance of 288 m/a (Rivera *et al.,* 1997b). Recent field observations show that the Pío XI Glacier has been retreating since 1997. Perito Moreno Glacier is presently in equilibrium, but underwent frequent oscillations during the period 1947-1986, with a net gain in area of 4.1 km^2.

5. ICE THICKNESS

Casassa (1992) published ice thickness data for the SPI, detecting a maximum of 650 m of ice in the ablation area of Tyndall Glacier in 1990, using a 2.5 MHz analog radio-echo sounding device. In 1993, Casassa and Rivera (1998b) measured slightly smaller ice

Table 1. Glacier inventory for the Southern Patagonia Icefield. Glaciers are numbered counterclockwise from north to south. Adapted from Aniya *et al.* (1996). AAR represents accumulation area ratio divided by total glacier area. ELA is equilibrium line altitude.

Glacier	Latitude (S)	Longitude (W)	Length (km)	Total Area (km^2)	Orientation	Accumul. Area (km^2)	Ablation Area (km^2)	AAR	ELA (m)	Calving Y/N	Max. Elevation (m)	Min. Elevation (m)
1 Jorge Montt	48° 04'	73° 30'	42	464	N	348	116	0.75	950	Y	2640	0
2 Ofhidro	48° 25'	73° 51'	26	116	NW	91	25	0.79	1000	Y	1655	45
3 Bernardo	48° 37'	73° 56'	51	536	W	444	92	0.83	1300	Y	2408	0
4 Témpano	48° 44'	74° 03'	47	332	W	242	90	0.73	900	Y	2408	0
5 Occidental	48° 51'	74° 14'	49	244	W	60	184	0.25	950	Y	---	<100
6 Greve	48° 58'	73° 55'	51	438	NW-W	292	146	0.67	1000	Y	3607	---
7 HPS8	49° 02'	73° 47'	11	38	SE	25	13	0.66	---	Y	---	---
8 HPS9	49° 03'	73° 48'	19	55	W	29	26	0.52	---	Y	3607	---
9 Pío XI	49° 13'	74° 00'	64	1265	W	1014	251	0.80	---	Y	3607	0
10 HPS10	49° 32'	73° 48'	16	61	W	---	---	---	---	Y	---	---
11 HPS12	49° 41'	73° 45'	23	204	S-W	164	40	0.80	---	Y	2257	0
12 HPS13	49° 43'	73° 40'	19	141	W	---	---	---	---	Y	2656	0
13 HPS15	49° 48'	73° 42'	19	174	N-W	164	10	0.94	---	Y	2446	0
14 HPS19	50° 00'	73° 55'	26	176	W	157	19	0.89	---	Y	---	0
15 Penguin	50° 05'	73° 55'	38	527	NW	507	20	0.96	---	Y	3180	0
16 Europa	50° 18'	73° 52'	39	403	W	379	24	0.94	---	Y	---	0
17 Guilardi	50° 23'	73° 57'	36	148	W	125	23	0.85	---	Y	---	0
18 HPS28	50° 25'	73° 35'	12	63	W	47	16	0.75	---	Y	2238	0
19 HPS29	50° 28'	73° 36'	17	82	W	69	13	0.85	1200	Y	2950	0
20 HPS31	50° 36'	73° 33'	23	161	SW	141	20	0.88	900	Y	2950	0
21 Calvo	50° 41'	73° 21'	13	117	W	114	3	0.97	---	Y	---	0
22 HPS34	50° 43'	73° 32'	14	137	NW	122	15	0.89	800	Y	---	0
23 Asia	50° 49'	73° 44'	12	133	W	86	47	0.65	---	Y	2179	0
24 Amalia	50° 57'	73° 45'	21	158	W	126	32	0.80	900	Y	---	0
25 HPS38	51° 03'	73° 45'	16	62	W	27	35	0.44	---	Y	---	---
26 HPS41	51° 18'	73° 34'	17	71	SW	39	32	0.55	---	Y	---	---

Table 1. continues on next page

Table 1 (continued).

Glacier	Latitude (S)	Longitude (W)	Length (km)	Total Area (km^2)	Orient-ation	Accummul. Area (km^2)	Ablation Area (km^2)	AAR	ELA (m)	Calving Y/N	Max. Elevation (m)	Min. Elevation (m)
27 Snowy	51° 22'	73° 34'	9	23	W	11	12	0.48	---	Y	---	---
28 Balmaceda	51° 23'	73° 18'	12	63	E	42	21	0.67	650	Y	---	---
29 Tyndall	51° 15'	73° 15'	32	331	E	213	118	0.64	900	Y	---	50
30 Pingo	51° 02'	73° 21'	11	71	SE	56	15	0.79	---	Y	---	200
31 Grey	51° 01'	73° 12'	28	270	SE	167	103	0.62	---	Y	---	100
32 Dickson	50° 47'	73° 09'	10	71	SE	42	29	0.59	---	Y	---	---
33 Frías	50° 45'	75° 05'	9	48	E	30	18	0.62	---	N	---	---
34 Moreno	50° 30'	73° 00'	30	258	NE	188	70	0.73	1150	Y	2950	175
35 Ameghino	50° 25'	73° 10'	21	76	N	32	44	0.42	1000	Y	2250	201
36 Mayo	50° 22'	73° 20'	15	45	N-S	28	17	0.62	900	Y	2250	200
37 Spegazzini	50° 15'	73° 20'	17	137	E-S	116	21	0.85	---	Y	---	175
38 Onelli	50° 07'	73° 25'	13	84	NE-S	52	32	0.62	---	Y	2940	175
39 Agassiz	50° 06'	73° 22'	17	50	E	37	13	0.74	---	Y	3064	175
40 Upsala	49° 59'	73° 17'	60	902	SE	611	290	0.68	1150	Y	3180	175
41 Viedma	49° 31'	73° 01'	71	945	E-S	564	381	0.60	1250	Y	---	250
42 Chico	49° 00'	73° 04'	25	243	E	194	49	0.80	---	Y	---	285
43 O'Higgins	48° 55'	73° 08'	46	810	N-E-S	701	109	0.87	1300	Y	3607	285
44 Bravo	48° 38'	73° 10'	23	129	E	98	31	0.76	1500	N	3067	300
45 Mellizo Sur	48° 37'	73° 07'	14	37	SE	32	5	0.86	1400	Y	3067	300
46 Oriental	48° 27'	73° 01'	17	74	E	56	18	0.75	1150	Y	3017	285
47 Pascua	48° 22'	73° 09'	23	88	N	58	30	0.66	950	Y	3017	151
48 Lucía	48° 20'	73° 20'	29	200	N	145	55	0.72	1000	Y	3067	27
TOTAL				**11,259**		**8,285**	**2,773**	**0.75**				

Notes: Glacier 23 (Asia according to Lliboutry, 1956) is named "Brujo" in the 1:100,000 map "Peninsula Wilcock" of IGM Chile.
Glacier 24 (Bravo according to the 1:50,000 map "Mellizo Sur" of IGM Chile), is locally known as "Rivera". Lliboutry (1956) also names it "Rivera".
Moreno Glacier is also known as "Perito Moreno" Glacier.

thickness values in the same area of Tyndall Glacier, this time with a digital radio-echo sounding system, concluding that the glacier had thinned in the period 1990-1993.

In 1995 and 1996, Casassa *et al.* (1997b) performed ice thickness measurements with a digital radar system near the front of Grey Glacier. In 1997, Rivera and Casassa (2000) performed ice thickness measurements at Paso de los Cuatro Glaciares by means of a profiling radar system pulled by a snowmobile, measuring ice thicknesses in excess of 750 m, the maximum range of the radar.

Rott *et al.* (1998) measured ice thickness on Moreno Glacier using seismic reflection and explosive charges along a transect on the ablation area. In addition to ice thickness, Rott and co-workers could also detect layers of subglacial sediments. In 1999 and 2000, researchers from the University of Washington, U.S.A., performed ice thickness measurements in the ablation area of Tyndall Glacier by means of a digital radar system, detecting a maximum of 650 m (Raymond *et al.*, 2000). Rivera and Casassa (2002; Chapter 10) present a summary of ice thickness measurements at SPI.

6. ICE THICKNESS CHANGES

Several measurements of ice thickness changes have been carried out at the ablation areas based on repeated ground surveys and a comparison of glacier maps corresponding to different dates. The results indicate that a regional thinning prevails, with one glacier showing no variation (Moreno), and one glacier which thickened (Pío XI). The results are shown in Table 2.

Table 2. Ice thickness changes for SPI.

GLACIER NAME	RATE (m a^{-1}) THINNING (-) THICKENING (+)	PERIOD	REFERENCE
O'Higgins	-3.2	1914 - 1933	Casassa *et al.*, 1997a
	-6.7	1933 - 1960	Casassa *et al.*, 1997a
	-2.5 to -11	1975 - 1995	Casassa *et al.*, 1997a
Pío XI	+2.2	1975 - 1995	Rivera and Casassa, 1999
Upsala	-3.6	1968 - 1990	Aniya *et al.*, 1997
	-9.5 to -14	1991 - 1993	Naruse *et al.*, 1995a, Skvarca *et al.*, 1995b, Naruse *et al.*, 1997
Ameghino	-2.3	1949 - 1993	Aniya 1999
Moreno	No change	1991 - 1993	Skvarca and Naruse, 1997 Naruse *et al.*, 1995b
Dickson	-2.5 to -8.1	1975 - 1998	Rivera *et al.*, 2000
Grey	-2.3	1975 - 1995	Casassa *et al.*, 1997b
Tyndall	-2.0	1945 - 1993	Aniya *et al.*, 1997
	-1.7	1975 - 1985	Kadota *et al.*, 1992
	-4.0	1985 - 1990	Kadota *et al.*, 1992
	-3.1	1990 - 1993	Nishida *et al.*, 1995

Ranges of thickness changes correspond to spatially different observations within the ablation area.

7. ICE VELOCITY

Most of the ice velocity measurements in the SPI have been carried out in the ablation area of the glaciers with traditional surveying methods.

Satellite techniques have been applied more recently for determining ice velocity, including both radar interferometry and phase correlation of radar data (Rott *et al.,* 1998; Michel and Rignot 1999; Forster *et al.,* 1999).

The largest velocity values have been measured in late spring at the calving front of Pío XI Glacier, with a maximum value of 50 m/d and a mean value of 20 m/d for a 3-day period (Rivera *et al.,* 1997b). Velocity data are presented in Table 3.

Table 3. Ice velocity measurements at SPI.

GLACIER NAME	VELOCITY m/d	MEASUREMENT PERIOD	MEASUREMENT METHOD	REFERENCE
Upsala	4.44	21-29 November, 1993	Theodolite	Skvarca *et al.,* 1995b
	3.7	14-18 November, 1990	Theodolite	Naruse *et al.,* 1992
Moreno	1.1 to 2.19	9-10 October, 1994	Interferometry	Michel and Rignot, 1999
	2.1 to 5	14-18 November, 1990	Theodolite	Naruse *et al.,* 1992
	0.5 to 3.5	October, 1994	Interferometry	Rott *et al.,* 1998
	2.64	November, 1993 to December, 1994	Theodolite	Skvarca and Naruse, 1997
Tyndall	0.1 to 1.9	30 November, 1985 to 3 December, 1985	Theodolite	Naruse *et al.,* 1987
	0.07 to 0.51	7-15 December, 1990	Theodolite	Kadota *et al.,* 1992
	0.065 to 0.61	9-18 December, 1993	Theodolite	Nishida *et al.,* 1995
Penguin	0.9 to 2.2	October, 1994	Interferometry	Forster *et al.,* 1999
Pío XI	1 to 50	14-17 November, 1995	Theodolite	Rivera *et al.,* 1997b

Ranges of velocities correspond to observations at different sites on each glacier.

8. MASS BALANCE

Very limited data of ablation and accumulation exists for the SPI. Based on meteorological and hydrological data available for stations located around the SPI, isolines of precipitation have been estimated (DGA, 1987), and general characteristics of glacial hydrology of SPI have been published (Peña and Escobar, 1987; Peña and Gutiérrez, 1992).

Space imagery can provide information about snow and ice surface patterns (Forster *et al.,* 1996), but at SPI it has not yet been possible to quantify ablation and accumulation based on such imagery. Physical models based exclusively on climatic conditions can provide an estimate of mass balance, both during present and past conditions (Hulton and Sugden, 1995), but accuracy of such results can be poor if no calibration with field data is available.

Ablation data have been obtained in the following glaciers by the traditional stake method for periods ranging from a few days to a few months:

- Tyndall Glacier: Takeuchi *et al.,* 1995, Koizumi and Naruse, 1992.
- Moreno Glacier: Skvarca and Naruse, 1997.
- Pío XI Glacier: Casassa and Rivera, 1999.

The only annual ablation-stake measurement has been done at Moreno Glacier, with a magnitude of 10 m/a (Skvarca and Naruse, 1997), a value considered to be representative of the lower ablation area of the SPI. A similar value was calculated based on ablation data for a period of a few months and extrapolated using the degree-day method (Takeuchi *et al.,* 1995).

As for accumulation, only one field measurement using the stake method is available for annual periods, corresponding to a site at 1460 m elevation on Chico Glacier where a mean accumulation of 0.78 m/a water equivalent (w.e.) was measured with a 12 m-high tower in the period 1996-1998 in combination with snow pit data (Casassa and Rivera, 1999). A few accumulation data based on snow pit studies and short-period snow stake heights are available for specific sites on the SPI (Casassa and Rivera, 1999).

Two shallow firn cores have been retrieved at the SPI. The first one corresponds to the ice divide at Moreno Glacier, with a length of 13.2 m (Aristarain and Delmas, 1993), who estimated an annual accumulation of 1.2 m/a w.e. The second core corresponds to the ice divide at Tyndall Glacier, with a length of 45.97 m and an annual precipitation estimate of 13,5 m/a w.e. (Godoi *et al.,* 2002; Chapter 14).

Based on the scarce ablation and accumulation data available, Casassa and Rivera (1999) developed a digital topographic model at a resolution of 1 km for 98% of the total area of SPI, leaving out of the study area the south western portion of SPI, where no topographic information was available. Their results show an annual ablation of 23.8 km^3/a over an ablation area of 4100 km^2 and an annual precipitation of 58.4 km^3/a over an accumulation area of 8700 km^2. A residual value of 34.6 km^3/a results if steady state is assumed. This represents the volume wasted from 98% of the area of SPI, which should calve as icebergs into lakes and fjords.

Two studies have used the hydrometeorological method to compute mass balances for the SPI. In the basin of Serrano river, Marangunic (personal communication) calculated a mass balance by applying algorithms for estimating ablation and accumulation rates at different elevations. Escobar *et al.* (1992) calculated a hydrological balance for the SPI based on the climatic and hydrologic data published by DGA (1987).

9. GLACIAL FLOODS

Several cases of glacial floods, known as *jökulhlaup*, have occurred at the SPI. At Dickson Glacier, a flood associated with the sudden drainage of a proglacial lake was observed in 1982 and 1987. The flood of 1982 at Dickson Glacier was described and modeled by Peña and Escobar (1985). Both floods affected the hydrological system downstream from Dickson Glacier, increasing river and lake levels by several meters. At present, due to the large retreat of Dickson Glacier, the proglacial lake is now permanently joined to Dickson lake, so that a new *jökulhlaup* is not expected in the near future.

The most spectacular case of *jökulhlaup* in the SPI is that of Moreno Glacier, where several flood events have occurred during the last century (Nichols and Miller, 1952; Mercer, 1968; Liss, 1970). The floods are produced by the periodic advance of Moreno Glacier over the Magallanes península, effectively damming the Brazo Sur of Lago Argentino, known as Brazo Rico. A maximum lake level rise exceeding 10 m has been detected, evidenced by old coast lines preserved around Brazo Rico. When the lake level of Brazo Rico compared to the main water body of Lago Argentino reaches a certain critical level, Brazo Rico drains catastrophically, firstly through an englacial tunnel and later by an open-water channel. The last *jökulhlaup* occurred in the mid-1980's. Since then, Moreno Glacier has not dammed Brazo Rico again, and a narrow open water canal exists at the glacier front, continuously draining Brazo Rico.

10. CLIMATE CHANGES IN CHILE

Historical records of air temperature in Chile have been analyzed by Rosenblüth *et al.* (1995) and Rosenblüth *et al.* (1997), detecting a warming rate of 1.3 to 2.0 °C/100 years in the period 1933-1992. This warming has practically doubled at some stations in western Patagonia during the last three decades (Rosenblüth *et al,* 1997). Climate studies of the eastern margin of the SPI indicate that this warming also prevails in Argentine Patagonia (Ibarzabal y Donángelo *et al.,* 1996).

A few Chilean and Argentine stations around the SPI show an important precipitation decrease of approximately 25-33% during the last century (Rosenblüth *et al.,* 1997, Ibarzabal y Donángelo *et al.,* 1996), although other stations show no change (Santana, 1984). Recent data show a precipitation increase at some stations (Carrasco *et al.,* 2002; Chapter 4).

The climatic data suggest that the generalized glacier retreat in the SPI, is due to a regional warming, together with a probable precipitation decrease during the last century in the area.

11. SEA LEVEL RISE

Sea level has been rising in the last 100 years at a rate of 1 to 2 mm/a (Gornitz, 1995). This sea level rise is related to several causes, including thermal expansion due to global warming of the oceans, melting of glaciers and small ice caps, and the contribution of the Antarctic and Greenland ice sheets. Warrick and Oerlemans (1990) estimated that glaciers and small ice caps presently contribute 0.4 mm/a of the total sea level rise.

A few authors have related the glacier variations of the Patagonian glaciers to global sea level change. Meier (1984) calculated that the world-wide contribution of small glaciers and ice caps (excluding Greenland and Antarctica) to sea level between 1900 and 1961, was 0.46 ± 0.26 mm/a. Meier further estimated that the Andes south of 30° S accounted as a whole, for about 12% of this value, that is, 0.06 mm/a, without calculating a separate contribution for the Patagonian icefields due to lack of data. Dyurgerov and

Meier (1997) estimated a world-wide sea-level rise of 0.25 ± 0.10 mm/a due to small glaciers, but excluded data of the Patagonian icefields, so that the calculation of Meier (1984) is considered to be more representative.

Aniya (1999) calculated an ice volume loss of 594 ± 239 km^3 for the SPI in the period 1945-1996, obtaining a water equivalent volume of 505 ± 203 km^3. Rivera *et al.* (in press) calculated a total water equivalent volume loss of 401 ± 174 km^3 for the SPI in 1945-1996. Rivera's estimate is smaller than Aniya's because a smaller glacier area for SPI was used, limited to the area of the outlet glaciers, and a reduced area and volume loss measured at Pio XI Glacier was considered. Dividing the water equivalent value of Rivera and co-workers by the total ocean area of the world, results in a contribution of 1.108 ± 0.481 mm/a in the 51 year-period from 1945 to 1996, that is, 0.022 ± 0.009 mm/a. If this is valid, then the SPI contributes about 6% of the total sea level rise due to small glaciers and ice caps as estimated by Meier (1984), or 10% if all the Chilean glaciers are considered (Rivera *et al.*, in press).

12. CONCLUSIONS

Field data, complemented by information recovered from aerial photography and satellite imagery, have provided a glacier inventory for the SPI and the variations of its major glaciers since 1945. Except for a few cases, the glaciers show a general retreat. The variation record has been extended back to the XIXth century in the case of a few glaciers such as Pío XI and O'Higgins. The retreat is probably caused by a regional warming observed during the last 100 years, together with an apparent precipitation decrease. The advance of Pío XI and Moreno Glaciers could be due to dynamic or topographic causes of a local nature, or simply a non-linear response of calving glaciers to climate (Warren and Rivera, 1994). The general retreat observed at the SPI results in a total estimated contribution of 6% to the global sea level rise due to melting of small glaciers and ice caps.

The use of traditional and modern field techniques together with remote sensing methods have added important glaciological information, such as ice velocity, ice thickness, and ablation/accumulation, for some areas of the SPI. However, lack of spatial distribution of such glaciological information, together with the limited availability of regular maps at a scale of 1:100.000 and 1:50.000, prevents a more detailed characterization of the SPI, particularly of its accumulation area. Specific mass balance and ice flux data are needed, which would permit a more precise contribution to sea-level rise and adequate calibration for modeling the present and future behavior of SPI.

13. ACKNOWLEDGMENTS

Part of this work was funded by Fondecyt project 1980293 and by Grants in Aid for International Scientific Research Program by the Japanese Ministry of Education, Science and Culture (1990: No. 02041004 and 1993: No. 05041049). We thank César Acuña for drafting the maps and María Angélica Godoi, for help with Table 1. We also appreciate valuable comments from Mr. Mateo Martinic and Al Rasmussen. Centro de

Estudios Científicos is a Millennium Science Institute. This article is a modified version of an article originally published in Spanish: Características glaciológicas del Campo de Hielo Patagónico Sur, Casassa *et al.*, 2000, *Anales del Instituto de la Patagonia,* Serie Ciencias Naturales, **28**:5-22 (a journal of the Universidad de Magallanes, Punta Arenas, Chile).

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