

## Glaciological and geomorphological studies at Glaciar Exploradores, Hielo Patagónico Norte, and Glaciar Perito Moreno, Hielo Patagónico Sur, South America, during 2003–2005 (GRPP03–05)

Masamu ANIYA<sup>1</sup>, Hiroyuki ENOMOTO<sup>2</sup>, Tatsuto AOKI<sup>3</sup>, Takane MATSUMOTO<sup>4</sup>,  
Pedro SKVARCA<sup>5</sup>, Gonzalo BARCAZA<sup>1</sup>, Ryohei SUZUKI<sup>6</sup>, Takanobu SAWAGAKI<sup>7</sup>,  
Norifumi SATO<sup>8</sup>, Evgeni ISENKO<sup>9</sup>, Shogo IWASAKI<sup>10</sup>, Hernan SALA<sup>5</sup>, Akira FUKUDA<sup>11</sup>,  
Kazuhide SATO<sup>12</sup> and Renji NARUSE<sup>13</sup>

1 Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305–8572, Japan

2 Department of Civil Engineering Kitami Institute of Technology, Kitami 090–8507, Japan

3 Department of Geography, Kanazawa University, Kanazawa 920–1192, Japan

4 Faculty of Science, Hokkaido University, Sapporo 060–0819, Japan

5 Instituto Antártico Argentino, Serrito 1248, C1010AAZ Buenos Aires, Argentina

6 Graduate School of Environmental Studies, Nagoya University, Nagoya 464–8601, Japan

7 Graduate School of Earth Environmental Sciences, Hokkaido University, Sapporo 060–0810, Japan

8 Kaihatsu Koei Co., Ltd. Kita 4, Nishi 5, Chuo-ku, Sapporo 060–0004, Japan

9 Institute of Low Temperature Science, Hokkaido University, Sapporo 060–0819, Japan

10 National Institute of Polar Research, Itabashi, Tokyo 173–8515, Japan

11 Graduate School of Science and Technology, Shizuoka University, Hamamatsu 432–8561, Japan

12 Nagaoka National College of Technology, Nagaoka 940–8532, Japan

13 NPO, Glacier and Cryospheric Environment Research Laboratory, 2–339 Higashi-cho, Tottori 680–0011, Japan

(Received October 2, 2006; Revised manuscript accepted November 22, 2006)

### Abstract

The major results of the Glaciological Research Project in Patagonia (GRPP) 2003–2005, which targeted Glaciar Exploradores of the Hielo Patagónico Norte (HPN) and Glaciar Perito Moreno of the Hielo Patagónico Sur (HPS), were reported. Studies at Glaciar Exploradores include recent glacial chronology, glacier flow measurements with D-GPS, meteorological measurements with an AWS and hydrological measurements at the outlet stream. Three moraine systems were recognized, and most recent two of them were formed sometime between the 12th and 17th century and the early to mid-19th century. The annual glacier flows in the area within 5 km from the terminus ranged 48 to 138 m in 2003–2004. Strong emergence velocity was observed near the terminus. The annual precipitation near the terminus was close to 3000 mm, the mean annual air temperature was 7.5°C and the annual specific runoff was about 6200 mm in 2005. Also the variations of 21 outlet glaciers of the HPN from 1944/45 to 2004/05 were presented with their notable characteristics. The area loss due to recession in 60 years amounted to ca. 100 km<sup>2</sup>, of which close to 30% was accounted by Glaciar San Quintin, the largest glacier of the HPN.

At Glaciar Perito Moreno, observations and measurements were carried out for flow, strain grid and meteorological measurements, and calving activities. Flow velocity per day in December 2004 ranged 3.95 to 0.53 m, with the average of 1.66 m at the calving front. At the middle reach, the average daily flow velocity was 1.5 m, and the profile survey revealed that the inner zone maintained thicker conditions, but with no significant trend of additional thickening. The annual mean temperature near the EL (ca. 1350 m) was 1.0°C, while that at near the terminus was 6.3°C in 2005.

### 1. Introduction

The glaciological Research Project in Patagonia (GRPP) was initiated in 1983, as a joint project of

Japan and Chile (Nakajima, ed., 1985) and since then, the GRPP has been carried out with Chilean and/or Argentinean partners (Nakajima, ed., 1987; Naruse and Aniya, 1992; Naruse and Aniya, 1995; Aniya and Naruse, 2001a,b). This paper reports some of the major



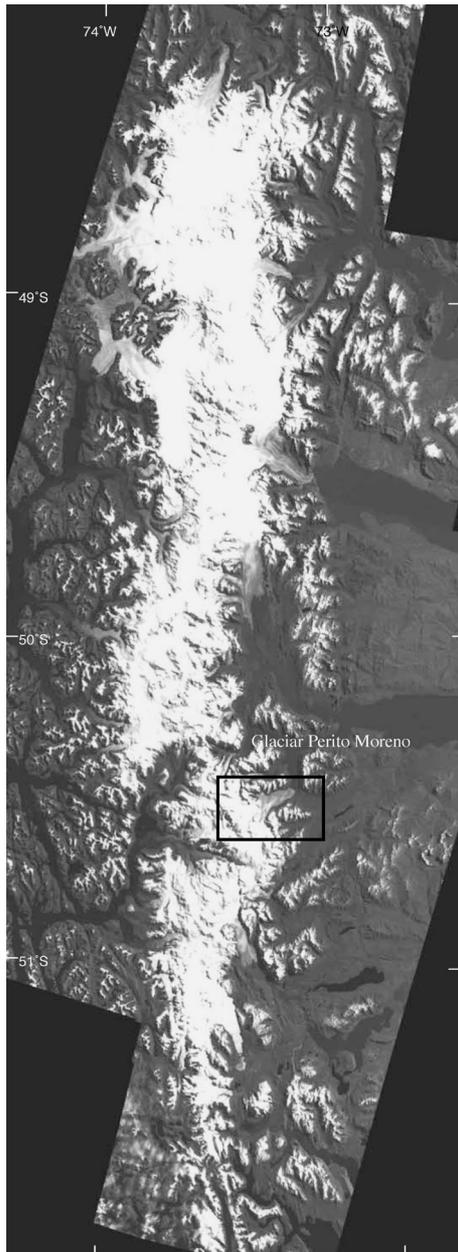


Fig. 3. Hielo Patagónico Sur and Glaciar Perito Moreno. (Landsat ETM+mosait, March 11, 2001)

glacial advances before the LIA advance, although without assigning ages. For the HPS, three (Mercer, 1976) or four (Aniya, 1995) Neoglaciations were identified. However, at the HPN, normally only two (Aniya and Naruse, 1999) or at some glaciers three (Glasser *et al.*, 2005) moraine systems are recognized between the present glacier snout and the Pleistocene moraines.

Glaciar Perito Moreno of the HPS is one of the most studied glaciers in the Patagonia Icefield (*e.g.* Skvarca and Naruse, 1997); yet we do not know the mechanism of its stability at least over the last 60 years when other glaciers in Patagonia have been retreating and thinning (*e.g.*, Rignot *et al.*, 2003). The characteristics of glaciers in Patagonia are large accumulation in upper zone and large ablation in lower zone, which ice transport by glacier flow makes bal-

ance. At Glaciar Perito Moreno, the large ice flow velocity has been observed and the influence of the glacier flow on the glacier change is considered to be great. It is presumed that glacier kinetics that offsets the mass imbalance has strong influences on glacier stability. In order to possibly understand or obtain a clue why the glacier is stable, we need a long-term record of meteorological, glaciological and calving activity observations.

## 2. Study Area

### 2.1 Glaciar Exploradores, HPN

The HPN is located around 47°S and 73°30'W with an area of about 4200 km<sup>2</sup> in 1974 (Aniya, 1988, see Fig. 2). It has the highest mountain in Patagonia, Monte San Valentin (3910 m) at the northeastern corner of the icefield. The icefield has 28 outlet glaciers, of which 21 major glaciers have been studied for their variations since 1944 to 1999 (Aniya, 2001). Glaciar Exploradores is located at the northeast corner of the icefield on the north flank of Monte San Valentin, with an area of about 95 km<sup>2</sup>, a length of 20.3 km and an AAR 0.66 in 1974 (Aniya, 1988). The ablation area of the glacier used to be formed by three glacier bodies, but one branch joining from the east has detached by now due to recession. In front of the present glacier snout, there is a big, continuous terminal moraine, with which prominent lateral moraines on both sides are associated. If we can infer the age of this moraine, we may be able to establish a part of the Holocene glacial chronology of the HPN, because there are similar moraines at other glaciers such as Grosse, Reicher, Gualas, Nef, Colonia to name but a few. Despite its relative stability when other glaciers of the HPN have been rapidly retreating, no glaciological study has been carried out at Glaciar Exploradores yet. Members who worked at this field include; Aniya, Aoki, Matsumoto, Barcaza, Sawagaki, Sato, and Iwasaki.

### 2.2 Glaciar Perito Moreno, HPS

Glaciar Perito Moreno is one of the most well-known glaciers in Patagonia, because it is located in the Glacier National Park of Argentina that has been designated as the World Natural Heritage, attracting many tourists from all over the world. It is located on the eastern side of the HPS at 53°30'S and 73°00'W, with an area of 258 km<sup>2</sup>, a length of 30 km and an AAR of 0.73 in 1986 (Aniya *et al.*, 1996). The GRPPs have been studying this glacier since 1990 and have accumulated a wealth of glaciological and meteorological information (*e.g.*, Naruse and Aniya, 1992; Aniya *et al.*, 1992; Aniya and Skvarca, 1992; Naruse *et al.*, 1992; Naruse and Aniya, 1995; Naruse *et al.*, 1995a; 1995b; Takeuchi *et al.*, 1996; del Valle *et al.*, 1995; Skvarca and Naruse, 1997; Naruse *et al.*, 2001; Iizuka, *et al.*, 2004; Skvarca *et al.*

*al.*, 2004). In addition, because of easy access, there are few studies by others (*e.g.*, Warren, 1994; Rott *et al.*, 1998; Michel and Rignot, 1999). One of the most well-known and notable characteristics of Glaciar Perito Moreno is the repeated advance with consequent damming up of lake “Brazo Rico-Sur” (Mercer, 1962; 1968). The uniqueness of the glacier also includes its stability since the 1940s despite the general trend of glacier recession in Patagonia (Aniya and Skvarca, 1992; Aniya *et al.*, 1997). The most recent advance and damming up occurred in 2003, which was for the first time since 1988. The ice-dam was eventually ruptured on March 13, 2004 (Chinni and Warren, 2004; Skvarca and Naruse, 2006). Members who worked at this glacier include; Enomoto, Skvarca, Suzuki, Isenko, Sala, Fukuda, Satow and Naruse.

### 3. Studies at Glaciar Exploradores

#### 3.1 Geomorphology and recent glacial advances

##### 3.1.1 Moraine distributions and dating

At Glaciar Exploradores, a big, conspicuous terminal moraine has been clearly recognized (Harrison *et al.*, 2004) and it was assumed to be of the LIA from its position. However, when we started the GRPP03 in 2003, we recognized another terminal moraine system inside the big moraine (Aniya *et al.*, 2005). Then in December 2004, we suspected another terminal moraine down below along Río Exploradores from the road, which was subsequently confirmed in the field in August 2005.

Therefore, there are three moraine systems at Glaciar Exploradores, which we denote here as TM1 (oldest), TM2 (main), and TM3 (most recent). We collected dating materials from these moraines; two from the TM1, six from the TM2, and seven from the TM3, in order to establish the recent glacial chronology (Fig. 4).

TM1 is located about 3 km down from the TM2, on the right bank of Río Exploradores by the mountain slope. Its relief from the valley floor is more than 250 m, with a length ca. 1000 m and a width ca 900 m at the base. It consists of a pile of gigantic boulders, whose long axis ranges 5–10 m, and is densely covered with thick vegetation on well-developed soils. However, two dating materials (organic matters) yielded modern ages of ca. 100 BP, which are obviously not indicative of the time period of the moraine formation.

TM2 is the most prominent, conspicuous terminal moraine here. At places, water seeps out from near the base of the moraine, indicating that the moraine is still ice-cored. The relief of the proximal side exceeds 80 m and it is limiting the entire glacier front in an arc, with spilling ways at the both end (one was dry by now though). It used to have two spillways in the middle, which became dry before 1945 and have become a wind gap since. We obtained six dates for

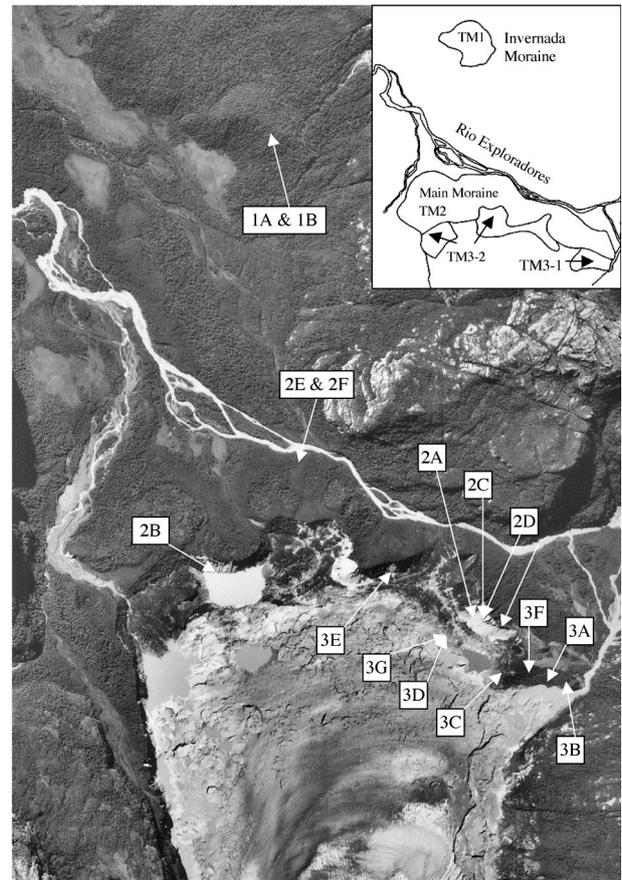


Fig. 4. Sampling points for datings in front of Glaciar Exploradores (Aerial photograph by SAF, Chile, March 11, 1997)

this moraine from wood samples: 2A,  $9250 \pm 50$  BP; 2B,  $1900 \pm 50$  BP; 2C,  $1400 \pm 40$  BP; 2D,  $1050 \pm 54$  BP; 2E,  $870 \pm 50$  BP, and 2F,  $820 \pm 60$  BP. We also counted the number of tree rings of a cut tree by the road with a diameter of 40 cm to be roughly 200 years (5 year/cm). The largest diameter at breast height (DBH) around here is 5–60 cm. With a simple linear extrapolation, we obtain about 300 years since the tree invasion.

The moraine system, TM3, is located between TM 2 and the current glacier snout, and can be divided into two types, TM3-1 and TM3-2, according mainly to the vegetation cover, size and morphology, among others. TM3-1 is located at the eastern edge by the outlet stream, consisting of several ridges more or less parallel to each other and the present snout. It has large *Nothofagus* whose DBH ranges to 40–50 cm, just in front of the snout. The area is scattered with limestone boulders, which cannot be found elsewhere at Exploradores. TM3-2 is still mostly ice-cored with generally flat topography; however, in places the surface has become hummocky partly due to differential melting of the core ice. At many places, vegetation has invaded and we can find *Nothofagus* with the DBH 15–20 cm. Recent acceleration of core-ice melting is evident at many places, with trees falling and/or surface ponds enlarging. The following dates

were obtained for TM3: 3A, ca. 108 BP (plant); 3B, ca. 109 BP (organic matter); 3C, ca. 115 BP (wood); 3D, ca. 121 BP (wood); 3E, ca. 123 BP (organic matter); 3F, ca. 134 BP (plant); 3G, ca. 147 BP (organic matter).

### 3.1.2 Ages of moraines and scenario of the recent glacial advances

From these datings, moraines' topographic relations to each other, and tree ring analysis the following results and conclusions are reached.

(1) Invernada Moraine: the age could not be positively defined as the ages obtained from the samples are obviously too young to be of indicative of the formation age. However, from the date of the Main Moraine, it could be of the Neoglaciation III (ca. 1600–1300 BP, Aniya, 1995).

(2) Main Moraine: from the six dates we obtained for this moraine, the youngest, ca. 820 BC (AD 1180) seems to delimit the moraine formation age. In addition, tree ring analysis suggests that the trees invaded the moraine around ca. 300 years ago. Therefore the moraine formation was probably sometime between the 12th and 17th centuries.

(3) Modern Moraines: Moraine 3-1 is probably formed during the early to mid-19th century, while Moraine 3-2 was formed after 1944/45 from interpretation of the Trimetrogon aerial photographs.

Based on these dates, the following scenario seems most probable. After forming the main moraine sometime between the 12th and 17th century, the glacier retreated. Then the glacier bodies that formed both TM3-1 and TM3-2 advanced at the same time around the early to mid-19th century. The glacier body that formed TM3-1 started retreating earlier than the other part (TM3-2), and during the slow retreat the glacier formed a series of recessional moraines (mid-to late 19th century). Meanwhile, the large part of the glacier that subsequently formed TM3-2 had been stationary for a long time, being blocked by the large main moraine. It was only ca. 1940s when that part

started receding after a prolonged period of surface lowering. Because of long stagnation (about 100 years?), a mantle of thick debris has been developed, which facilitated easy plant invasion under the mild climate.

### 3.2 Glacier flow and its characteristics

In recent years, most of the outlet glaciers from the Hielo Patagónico Norte have been receding quickly. However, the terminus of Glaciar Exploradores has been stable (Aniya, 2001). He attributed its stability to the debris cover in the snout area. During the GRPP03–05, we observed the flow of Glaciar Exploradores with the following two purposes. The first is to check whether or not the terminus is really stagnant, and the second is to consider the reason for the stability if the glacier is really found to be stable.

#### 3.2.1 Measurement procedures

Due to its size and the difficulty to establish control points on either side of lateral moraines for the conventional triangulation survey to fix the position of a stake on the glacier surface, we used in stead the post-processed differential GPS (D-GPS) method to measure the flow velocity of the glacier. We made D-GPS observations three times: December 2003, December 2004 and August 2005, each lasting for 2–3 weeks, during which several measurements were carried out. In December 2003, the initial set-up of points and measurements were undertaken by Aoki and Sawagaki, while other observations in 2004 and 2005 were done by Aoki alone. The instrument we used is a Topcon GP-SX1, which is a L1 single band receiver, and we used the WGS-84 for mapping coordinates.

In December 2003, we established a point in the base camp as the reference point for D-GPS, at which we measured the position six times, each lasting for eight hours. Subsequently, the radius of the error circle was found to be 2.0 m and 5.0 m in the horizontal and vertical component, respectively. Among six

Table 1 D-GPS measurements for the reference point (2003 and 2004 (M08)).

	<b>Latitude</b>	<b>Longitude</b>	<b>Ellipse Height</b>	<b>UTM X coordinate</b>	<b>UTM Y coordinate</b>
<b>301</b>	-46.4940094472	-73.1483717639	143.255	642076.04528325	-5150079.71352369
<b>302</b>	<b>-46.4940022389</b>	<b>-73.1483902028</b>	<b>146.883</b>	<b>642074.64926345</b>	<b>-5150078.87949961</b>
<b>303</b>	-46.4940219361	-73.1484052917	142.601	642073.44019575	-5150081.04073451
<b>304</b>	-46.4939972944	-73.1483672361	147.319	642076.42435573	-5150078.37147986
<b>305</b>	-46.4940022389	-73.1483789722	145.328	642075.51097593	-5150078.89970474
<b>306</b>	-46.4939904222	-73.1483841694	144.518	642075.14298328	-5150077.57750555
<b>M08</b>	<b>-46.4999516900</b>	<b>-73.1613532800</b>	<b>195.970</b>	<b>641064.61457996</b>	<b>-5150716.63055905</b>

302 was employed for subsequent measurements of glacier points for flow.

measurements (Table 1), we chose the one that was nearest to the center of the horizontal error circle as the reference coordinates for the subsequent D-GPS measurements and processing of the points on the glacier. In December 2004, the reference point was moved to M08, because the base camp was moved, and the same procedure was undertaken to obtain the new reference coordinates for the 2004 and 2005 measurements.

In the 5 km stretch of the ablation area from the terminus, we set up six measuring points on big, conspicuous erratics strewn on the glacier surface as the permanent point, on each of which a bolt was embedded for a GPS placement (Fig. 5). Over the periods, some erratics tilted; however, the shift of the bolt was not significant, when considering the amount of the movement. Point G1 was lost in 2004, probably due to the boulder falling into a crevasse, and a point G1B was newly established nearby as a substitute. In addition, some temporary points were also set up on the glacier ice by drilling a hole for a stake during the each observation period. With the D-GPS measurements, we obtained the latitude, longitude and ellipse height, of which the latitude and longitude were translated into the UTM coordinates using GIS (Geographic Information Systems) to calculate the glacier flow with the Euclidean geometry. The vertical measurements were not converted to the orthographic heights, because the geoid height of the limited, small area is safely assumed to be the same.

### 3.2.2 Results and discussion

The results of the measurements are shown in Table 2. The annual flow rates (Dec. 2003-Dec. 2004)

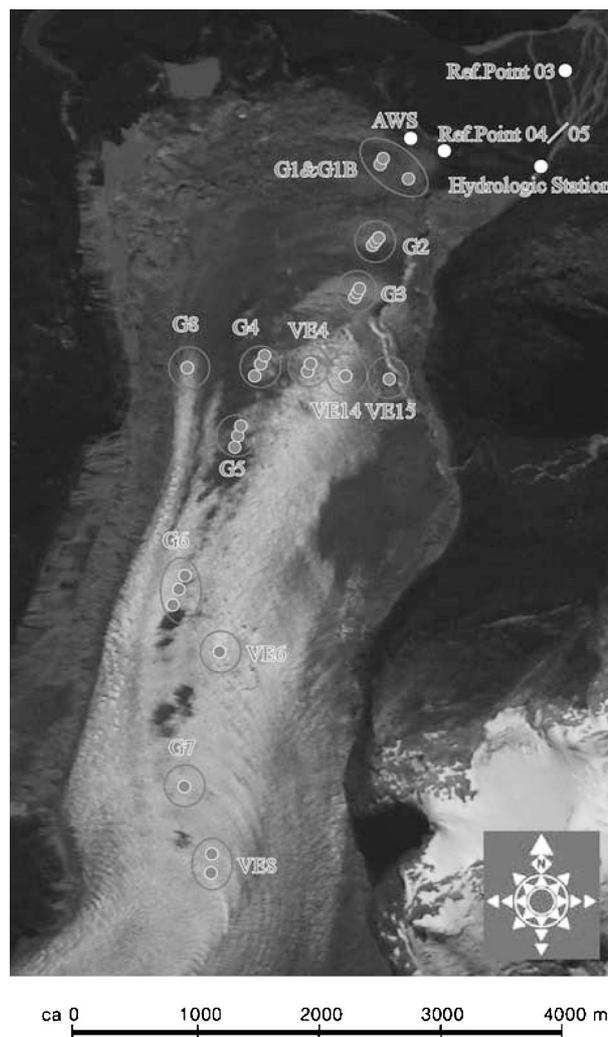


Fig. 5. Flow measurement points and their movements, along with the location of meteorological and hydrological stations.

Table 2 Glacier flow measurements at Glaciar Exploradores, HPN.

	Research Period (days)	Horizontal Flow (m)	Azimuth of Horizontal Flow *	Vertical Displacement (m)	Horizontal Flow Velocity (cm/day)	Vertical Displacement Velocity (cm/day)	
<b>G1</b>	2004/05	216	10.469	55.013	1.521	4.8	0.7
<b>G2</b>	2003/04	364	48.010	40.749	0.597	13.2	0.2
	2004/05	216	29.480	40.762	-3.360	13.6	-1.6
<b>G3</b>	2003/04	364	59.943	33.172	3.150	16.5	0.9
	2004/05	216	36.569	32.841	-1.504	16.9	-0.7
<b>G4</b>	2003/04	363	97.514	19.134	-0.366	26.9	-0.1
	2004/05	218	60.438	14.495	-5.657	27.7	-2.6
<b>G5</b>	2003/04	364	108.184	16.380	0.486	29.7	0.1
	2004/05	222	68.001	15.193	-6.728	30.6	-3.0
<b>G6</b>	2003/04	364	137.519	14.930	-4.883	37.8	-1.3
	2004/05	222	86.927	17.507	-2.086	39.2	-0.9

2003/04- whole year

2004/05 - summer to winter

\* degrees from north to east

of points G2, G3, G4, G5 and G6 range from 48 m to 138 m. In addition, the flow rate between the mid-summer and the mid-winter (Dec. 2004-Aug. 2005) were obtained for those five points and G1B.

#### *Horizontal flow*

The glacier flows were observed at all the measuring points, including even G1 and G1B that were set on the debris-covered snout area, only several tens of meters from a proglacial lake. These measurements clearly indicate that the ice at the terminus area is not stagnant; it is actively moving at a surprising rate. The direction of the ice movement is offset to the east from the centerline of the glacier, probably because the outlet stream is located on the eastern margin.

The relationship between the annual flow velocity and the distance from the terminus indicates that the velocity decreases from the upper reach toward the terminus almost linearly. Upon a close examination, however, there seems a slight gap between points G4 and G3. Points G3, G2, G1 and G1B are located on the debris-covered ice, while points G4, G5 and G6 are located on the debris-free ice. The decreasing rate for points G4-G6 is higher than that for points G3-G1, and trend lines for each group are slightly offset. This implies that there is compression in the glacier flow between point G3 and G4. Indeed the glacier surface around G3 shows a convex form. The glacial dynamics affected the surface morphology.

On 22 December 2004, a heavy rainfall was recorded (120 mm/day) and the day after the flow velocity increased by 120–150%, suggesting that the basal water of the glacier accelerated the glacier flow. From this observation, basal sliding and possibly basal deformation of till are significant components of the flow at Glaciar Exploradores.

#### *Vertical flow*

From December 2003 to December 2004, the change in the surface elevation was not significant at all the points, although the high rate of surface melting was observed, indicating that the upwelling of ice compensated the loss of ice. From our measurements, the emergence velocity and the melting rate in the ablation area are found to be about the same, which is important for maintaining the stability of the terminus position.

In December 2004, the emergence velocities also increased after the hard rainfall, suggesting that the higher compression induced by the higher horizontal flow velocity enhanced the emergence velocity.

#### *3.2.3 Concluding remarks*

From the measurements of horizontal and vertical flows in three periods, it was found out that Glaciar Exploradores is moving very actively, even at the debris-covered terminus. This is why Glaciar Explo-

adores has been relatively stable when other glaciers of the HPN have been receding. However, from the field observation during 2003–2005, it is apparent that Glaciar Exploradores is now in the phase of slow, gradual retreat, because the proglacial lakes and englacial ponds in the debris-covered terminus area are expanding and the glacier surface has become increasingly hummocky.

#### *3.3 Meteorology*

In order to clarify the climatic condition on and around Glaciar Exploradores and to estimate melt rate on the glacier, an automatic weather station (AWS) was installed south of the 2004/05 base camp toward the terminus (182 m a.s.l.), and it has been monitoring meteorological elements such as air temperature, relative humidity, global radiation, wind speed, wind direction, atmospheric pressure and precipitation since then. Observations on spatial distributions of melt rate and air temperature and of surface heat balance characteristics were also carried out on the ablation area of the glacier in December 2004. In addition, observations of air temperature and melt rate distribution were carried out in August and December 2005.

The monthly mean air temperature and the monthly total precipitation at the AWS in 2005 are shown in Fig. 6. At the glacier terminus, air temperature was the highest in February and the lowest in August in 2005. The daily mean air temperature varied between 7 and 16°C in summer and between –1 and 7°C in winter. The annual mean temperature in 2005 was 7.5°C. There was only nine days with a negative value of the daily mean air temperature in 2005, maybe due to low altitude and to the influence of maritime climate condition. In contrast, maritime climate and the cooling effect of glacier may have kept daily air temperature lower than 15°C in almost all days in summer.

It is widely known that the climatic feature of the Pacific coast in Patagonia is characterized by heavy precipitation throughout the year. The sum of measured precipitation at the AWS was 2794 mm, with 29 days of record missing from late November; thus the actual precipitation during 2005 could have been nearly 3000 mm. At the moment we have no other data to compare, with which to discuss whether or not this value is close to the normal in the region. Precipitation intensity at the glacier terminus was usually lower than 5 mm h<sup>-1</sup>, and thus the highest daily precipitation since December 2004 was 120 mm (22 December 2004). On the other hand, the number of days with precipitation in the year was very large, and it is hard to find a clear pattern in the seasonal variation of precipitation from our record. In four days during the winter observation period in August 2005, wet snow fell and accumulated about 3 cm and 10 cm thick on the terminus and the upper part of the ablation

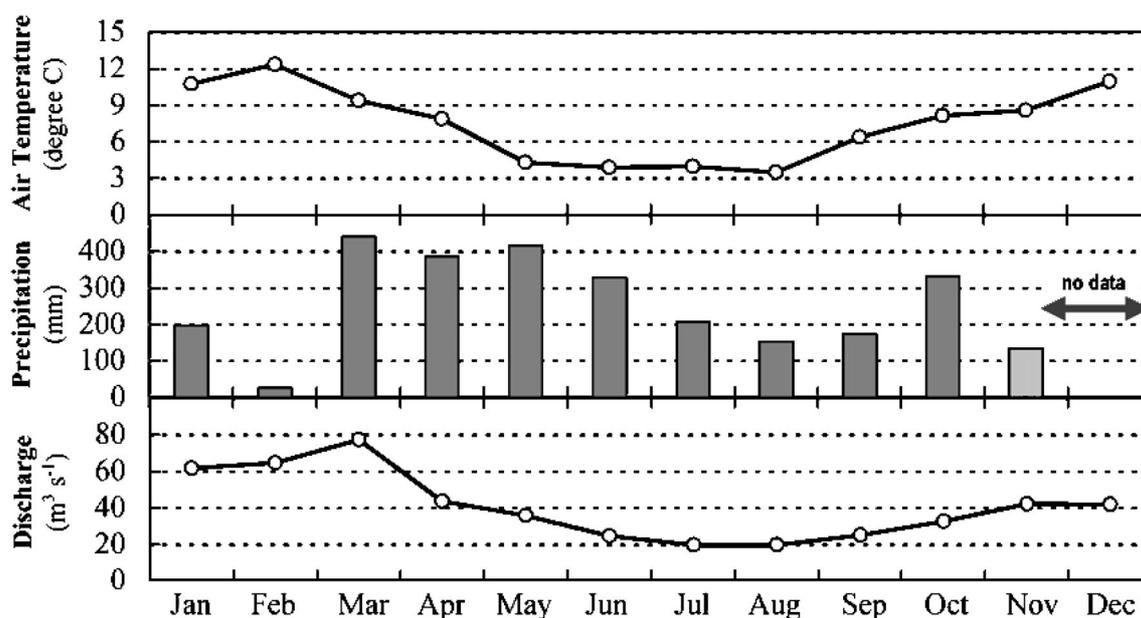


Fig. 6. The monthly mean air temperature, the total precipitation and the mean discharge at the terminus of Glaciar Exploradores in 2005. Because some data are missing for November, the precipitation total of November is probably an underestimate.

area (VE8 in Fig. 5), respectively. However, we suppose that the proportion of snowfall in the total precipitation would be small because air temperature usually stayed higher than 0°C even in wintertime.

Wind blowing in the up-valley direction along Río Exploradores was often observed at the AWS, especially rainy and cloudy days. Thus, the frequency of wind direction between southeast and southwest that would indicate glacier wind was only 20% during the observation period in December 2004, which is in contrast to at the terminus of Glaciar San Rafael where glacier wind occurred 80% to 90% of the time during the summer 1983 (Ohata, 1989).

The daily melt rate in the clean ice part of the ablation area was 60 mm d<sup>-1</sup> on average during the observation period in December 2004, whereas that on the ice covered by thin debris was 76 mm d<sup>-1</sup>. As a result of the observation in December 2005, we found the relationship between the melt rate and the thickness of the debris cover which is quite similar to those reported by many previous studies (e.g., Mattson *et al.*, 1993) as follows: when the debris cover is thinner than around 7 cm, the melt rate tends to be higher than clean ice, whereas if the debris cover exceeds this thickness, the melt rate is retarded. Based on the results of the observations of air temperature and the melt rate in December 2004, the degree-day factor in the clean ice part of the ablation was calculated to be 7.1 mm°C<sup>-1</sup> d<sup>-1</sup> on average.

### 3.4 Hydrology

We installed a hydrological station to measure and record the water level of Río Deshielo (local name), the outlet stream from Glaciar Exploradores,

with the one-hour interval on a site very close to the glacier terminus in December 2004 (see Fig. 5 for location). The area of drainage basin is about 207 km<sup>2</sup>, thus the proportion of glacier-covered area is around 60%. Hourly discharge was calculated from the recorded water level and the stage-discharge curve that was obtained from nine discharge measurements.

In Figure 6, the monthly mean discharge in 2005 is shown. The daily mean discharge usually varied between 40 and 100 m<sup>3</sup> s<sup>-1</sup> in summer and once in March exceeded 200 m<sup>3</sup> s<sup>-1</sup> due to heavy rainfall. Even in mid winter, discharge around 20 m<sup>3</sup> s<sup>-1</sup> was continuously observed due to glacier ablation and rainfall. The annual specific runoff from the drainage basin in 2005 was about 6200 mm. This value is consistent with the estimates of the annual specific runoff (5700–6700 mm) obtained from the water balance computation within the river basins around the HPN by Escobar *et al.* (1992). One of the interesting features found in hydrological regime of Río Deshielo is that the diurnal discharge variation appeared less clear than many other proglacial streams in the world throughout the year, while discharge usually showed a remarkable increase after a severe rainstorm. This may have resulted from frequent rainfalls, that is, contribution of water from the non-glacierized area that occupies about 40% of the whole drainage basin. However, we have no clear explanation on this feature yet.

Due to high sediment supply from the glacier, stream water always contained suspended sediment during the observation period (in contrast, suspended sediment concentration in Río Norte and its tributaries in the area upstream from the terminus of Glaciar

Exploradores during winter was visually observed to be very much low). Suspended sediment concentration measured at the hydrological station varied between 0.1 and 0.7 g L<sup>-1</sup> during the period.

#### 4. Glacier variations of the HPN

During the GRPP03–05, aerial surveys were carried out in December 2003, July 2004, December 2004 and August 2005. The aerial survey of July 2004 was the first such attempt in Patagonia in winter and revealed many interesting and important features, which have been heather to date unknown to the scientific community. For example, despite the middle of winter, ablation areas of many glaciers, particularly those on the west side of the icefield were free of snow, with bare ice and crevasse openings. During this survey, those on the east side were covered with snow, indicating together with winter Landsat images (*e.g.*, July 12, 1999; July 25, 2004) that during winter snow falls much more on the east side than on the west side of the icefield. Subsequent field campaign in July–August 2005, including both ground investigation and two aerial surveys in July and August, revealed that snow on the ablation area melt away quickly, for example 10–20 cm of snow in a day or two with the sun, indicating warm temperature.

Among those five aerial surveys, data of Decembers 2003 and 2004 were used to update the glacier variation to 2004/2005 from the previous work (Aniya, 2001). In this updating work, aerial photographs of

ca. 1: 70,000 taken in 1997/98 were available (see for detail Aniya, 2007), and the previous snout positions of some glaciers were modified and the varied distance and area were measured again to modify the statistics. Figure 7 shows the variation of 21 outlet glaciers from 1944/45 to 2004/05.

During the last 60 years, the general trend has been recession with a wide variety of retreating rates, thereby losing an area of ca. 100 km<sup>2</sup>. There are a few notable characteristics in the variation. First of all, the area loss of Glaciar San Quintin, the largest glacier in the HPN, is outstanding with ca. 29 km<sup>2</sup>, accounting nearly 30% of the total area loss. The neighboring glacier, Glaciar San Rafael, retreated almost as fast as San Quintin until ca. 1990; however, the variation during the 1990s and the 2000s has been quite different from San Quintin. While San Rafael has become more or less stable with repeated stagnation/advance/retreat, San Quintin has continued to recede fast. It seems imminent at San Quintin that snout disintegration will soon occur at any time. The terminus oscillation of San Rafael after 1990 seems to have been strongly controlled by the fjord topography (primarily width, with some influence of depth as well), because the oscillation has occurred where the width of fjord changes. Glaciar León, on the other hand, varied very little over the same period, while the neighboring glaciers, Glaciares Soler (to the south) and Fiero (to the north) have been gradually retreating.

Contrasting behaviors of two neighboring debris-covered glaciers, Grosse and Exploradores are also interesting to note. They both are located on the north side of Monte San Valentin (3910 m), the highest mountain in Patagonia, and hence are not directly connected with the icefield. Glaciar Grosse started forming a proglacial lake during the 1980s and since then the proglacial lake has been steadily growing. Glaciar Exploradores, in contrast, has remained more or less stagnant during the same period, because of the strong emergency flow near the snout. The difference in winter precipitation due to their relative locations in the icefield (Grosse–northwest side; Exploradores–northeast side, of Monte San Valentin) may account for these recent contrasting behaviors.

It would be interesting to compare the summer and winter photographs of the same year to see whether or not there is a seasonal fluctuation.

#### 5. Studies at Glaciar Perito Moreno

##### 5.1 Observation sites

Observations of ice velocity at the terminus, glacier surface height and flow in the middle reach were carried out in November and December 2004, and in December 2005. The observation points are shown in Fig. 8.

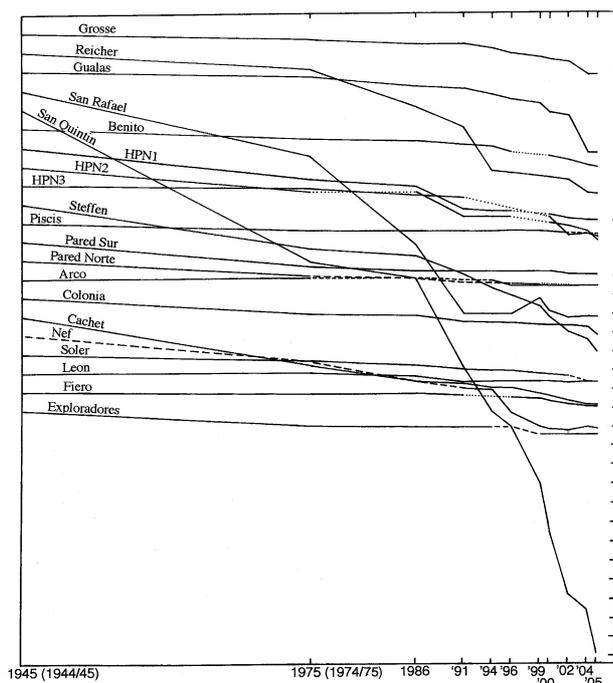


Fig. 7. Area changes of 21 outlet glaciers of the HPN from 1944/45 to 2004/05. One tick on the right ordinate indicates 1 km<sup>2</sup> change (down-decrease; up-increase).

At the glacier terminus, ice movements were measured by tracking ice pinnacles at the calving front, and short-term change of the glacier flow was investigated. The water level of the glacier lake and glacier calving activities were monitored by a water level gauge. Differential GPS (D-GPS) observations were repeated in the middle reach. The air temperature was recorded on the surrounding slope of Glaciar Perito Moreno and on the north slope of Co. (Mt.) Cervantes (2380 m).

### 5.2 Glacier flow velocity at the terminus

At the glacier terminus, the flow velocity of the glacier was measured by triangulation from the opposite shores of a bay in Lago (Lake) Brazo Rico, the same as Naruse *et al.* (2001). In November and December 2004, more than ten targets were observed for a one-month period, with the maximum ice velocity of  $3.95 \text{ m d}^{-1}$ , the minimum of  $0.53 \text{ m d}^{-1}$ , and the average

of  $1.66 \text{ m d}^{-1}$ . During the two-week observation in December 2005, the maximum velocity was  $3.54 \text{ m d}^{-1}$ , the minimum  $0.51 \text{ m d}^{-1}$  and the average  $1.34 \text{ m d}^{-1}$ . The average of the two years yields a large ice velocity of  $1.5 \text{ m d}^{-1}$ .

The daily flow velocity was investigated for one-month long in November and December 2004 (Fig. 9). The increase in flow velocity was observed on December 6. Since this increase was observed at several points, it was not caused by collapse of a local ice block, and some conditions for increasing ice velocity must have existed in this zone. Precipitation was suspected, but unfortunately it was not recorded. Because November and December 2004 had much rain for this area, the precipitation may have influenced the frequency of calving and large-scale collapses.

### 5.3 Calving frequency

With the same method as Iizuka *et al.* (2004), a water gauge was installed at the opposite side of a calving front, which recorded at a 2-second interval, and large waves due to collapse of ice blocks from the calving front were observed. The waves by calving lasted over 10 seconds with the amplitude over 10 cm; thus they can be easily distinguished from waves caused by wind. The calving frequencies in November and December 2004 are shown in Figure 10. Since the gauge was set on a single site and recurring waves were integrated when the amplitude exceeded 10 cm, this data indicate relative values of the scale and frequencies of calving. An amplitude exceeding 20 cm indicates the occurrence of a big calving.

These data show that calving activities increased on particular dates, December 3 and 4. Since the frequency of smaller (*i.e.*, 10 cm) amplitude increased, there could have been a large number of small calving. The increase in the glacier flow velocity was observed during these two days, which may have

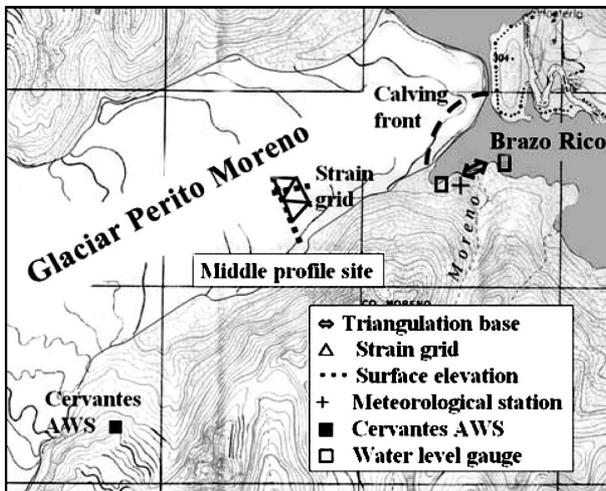


Fig. 8. Observation points for glacier flow and surface elevations at Glaciar Perito Moreno.

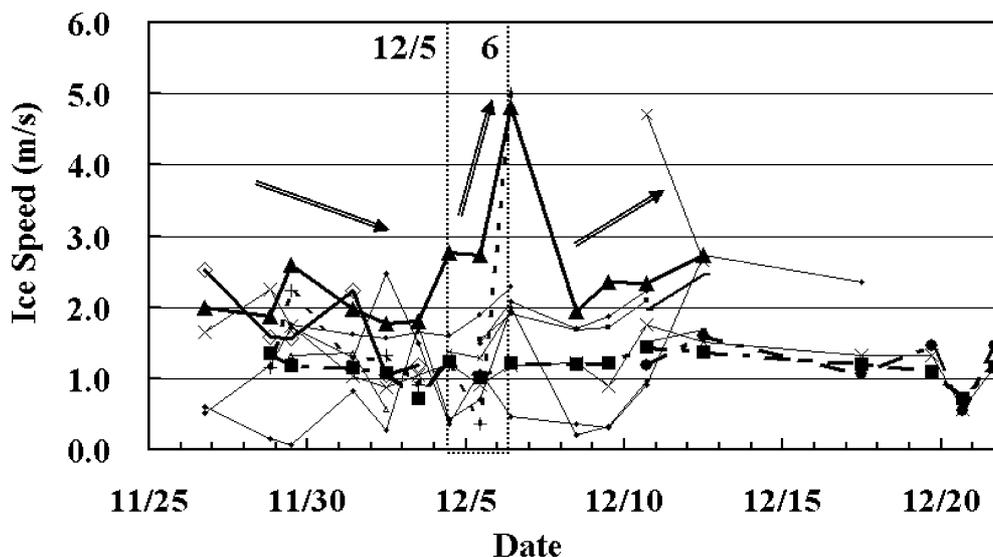


Fig. 9. Daily variation of glacier front velocity at Glaciar Perito Moreno, in November and December 2004.

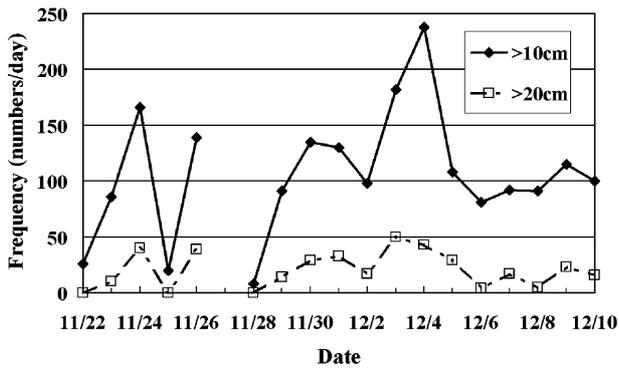


Fig. 10. Frequency of calving from Glaciar Perito Moreno to Lago Brazo Rico, in November and December 2004.

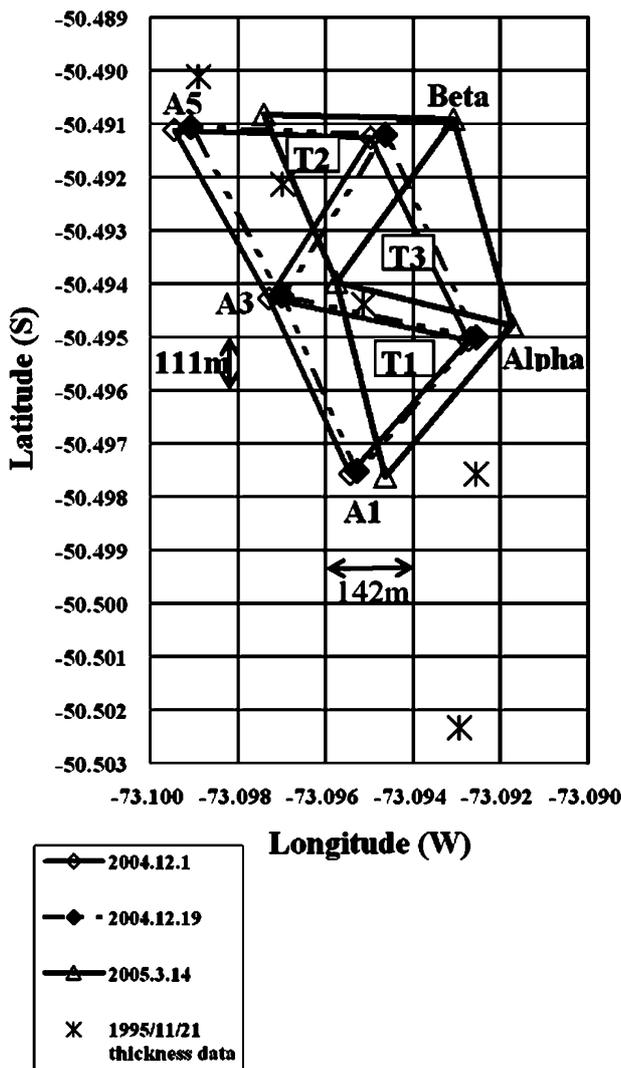


Fig. 11. Observation of glacier deformation by D-GPS set at the middle reach of Glaciar Perito Moreno. Five measuring points and three strain grids were set in December 2004.

been related to the increased calving activities.

#### 5.4 Middle reach profile

In the middle reach shown in Figure 8, the surface

elevation has been monitored since 1990 (Skvarca *et al.*, 2004) and thickening was recognized by the observation in austral summer of 2002/03. While the inner sites showed the continuous thickening trend in 2003, the lateral zone did not. From the observations in 2004 and 2005, the thickening trend was not observed although the elevation remained at a high level.

Since this area is in the ablation zone, surface elevation change can fluctuate due to changes in melting, ice flow and/or dynamic conditions of the glacier. We set five measuring points for D-GPS survey and measured deformation of three strain grids on the ice surface (Fig. 11). By repeating the measurements of displacements of these points, we can calculate ice deformations for divergence/convergence and vertical ice motions, thereby the emergence velocity can be estimated for grids, T1, T2 and T3. The ice thickness data are available from the seismic-wave observation in 1995 (Stuefer, 1999) and was used for this calculation. The D-GPS survey was done in December 2004, and March, July and December 2005. The preliminary result from the first half of the year (2005) shows an ice velocity of  $1.5 \text{ m d}^{-1}$  on average. This is almost the same as the previous measurement (Naruse *et al.*, 1995b).

The grid T1, which is located near the lateral zone, showed a negative emergence velocity (sink or divergence), while grids T2 and T3a that are located in the inner zone showed a positive emergence velocity (rise or convergence). There are strong variations in the vertical motion in place and time.

This uplifting area is the same as the area of a large inter-annual variation in the surface elevation, which has been monitored since 1990. The dynamic behavior will be an important factor for explaining the unique variation of Glaciar Perito Moreno. The data are still being accumulated in 2006 to investigate the effects of ice advection and in-situ dynamics.

#### 5.5 Temperature record

The winter observation reported that the lower part of Glaciar Perito Moreno showed ablation even in winter. On the other hand, in the upper part, snowfall was expected even in summer. The air temperature record around the altitude of the equilibrium line (ca. 1150 m) is useful information with which to infer the occurrence of ablation. The air temperature record was obtained by an AWS that was set-up on the north slope of Co. Cervantes (see Fig. 8). The annual mean temperature for 2004–2005 was ca.  $1.0^\circ\text{C}$ . The temperature frequently became below zero; thus there were many occasions of snowing in this area throughout a year. On the other hand, the annual mean temperature at the glacier terminus area was  $6.3^\circ\text{C}$ , and the winter temperature was positive in the monthly mean. Since the seasonal variations at these stations were small, the difference of  $5^\circ\text{C}$  between

these two stations results in contrast in the ablation and accumulation patterns on this glacier; that is, year-round accumulation in the upper zone possible, while year-around ablation in the lower zone possible. A strong glacier flow would balance the ice masses between the upper accumulation zone and the lower ablation zone including calving area.

### 5.6 Discussion on lake water level change, calving, and ablation

Lago Brazo Rico is located to the south of Glaciar Perito Moreno and connected with Lago Brazo Sur. Their areas together are 117.9 km<sup>2</sup> (Skvarca and Naruse, 2006). The water level of the lake is closely related to a glacial change. Advancing glacier tongue becomes an ice dam when reaching the opposite bank, thereby causing the lake water level to rise, making the glacier front and ice dam instable.

There has been recurring formation and collapse of ice dam and water level changes at an interval of several years to ten years (Skvarca and Naruse, 2006). In a short-time scale, there is a seasonal cycle of the water level, an increase in summer and a decrease in winter, which is related to daily calving and melting variations. The water level gauge is a good indicator for these phenomena.

The variation in the water level after that event indicates that it rose quickly between December 2004 and February 2005 with a speed of 1.3 cm d<sup>-1</sup> and a total of 0.7 m in 55 days (Fig. 12). After reaching a peak on February 14, 2005, it started decreasing toward winter with some irregularities around May. After hitting the minimum on July 23, the lake surface started to rebound quickly. A comparison of the temperature record and the water level change indicates a seasonal change in unison with the winter minimum and a short variation of 2–3 months.

The water level record indicates that fall of the water level stopped in July, and after August, continuous water level rise started. The glacier front becomes unstable with a water level rise, and then calving can be enhanced. There is an interaction of glacier and lake changes.

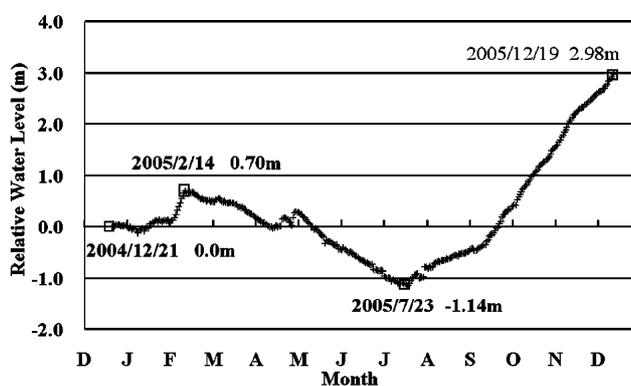


Fig. 12. Water level change of Lago Brazo Rico.

Toward understanding the glacier change in Patagonia, elucidation of influences of melt water and glacier dynamics is fundamental. A large amount of melt water flows out through the inside of a glacier and from the bottom, which is expected to greatly affect glacier dynamics and state. The amount of snow accumulation in the upper icefield and its transport downward by glacier flow, the amount of melt water, and ice dynamics are still unknown parameters for Patagonian glaciers.

### Acknowledgments

This study was supported by a grant in aid for Scientific Research of Japan Society for Promotion of Research (No.15253001, Principal investigator, M. Aniya). We thank Compañía Hielo y Aventura, Prefectura Naval Argentina, Parque Nacional Los Glaciares for field campaign at Glaciar Perito Moreno, and H. Rott, University of Innsbruck, Austria, for collaboration of the meteorological data at Glaciar Perito Moreno.

### References

- Aniya, M. (1988): Glacier inventory for the Northern Patagonia Icefield, Chile, and variations 1944/45 to 1985/86. *Arct. Alp. Res.*, **20**, 179–187.
- Aniya, M. (1995): Holocene glacial chronology in Patagonia: Tyndall and Upsala Glaciers. *Arct. Alpine Res.*, **27**, 311–322.
- Aniya, M. (2001): Glacier variations of Hielo Patagónico Norte, Chilean Patagonia, since 1944/45, with special reference to variations between 1995/96 and 1999/2000. *Bull. Glacier Res.*, **18**, 55–63.
- Aniya, M. (2007): Glacier variations of Hielo Patagónico Norte, Chile, for 1944/45–2004/05. *Bull. Glaciol. Res.*, **24**, 59–70.
- Aniya, M. and Skvarca, P. (1992): Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia. *Bull. Glacier Res.*, **10**, 39–53.
- Aniya, M. and Naruse, R. (1999): Late-Holocene glacial advances at Glaciar Soler, Hielo Patagónico Norte, South America. *Trans. Japanese Geomorph. Union*, **20**, 69–83.
- Aniya, M. and Naruse, R. (2001a): Overview of glaciological research project in Patagonia in 1998 and 1999: Holocene glacier variations and their mechanism. *Bull. Glacier Res.*, **18**, 71–78.
- Aniya, M. and Naruse, R. (eds.) (2001b): *Glaciological and Geomorphological Studies in Patagonia, 1998 and 1999*. Rapid Printing Center, Sapporo. 206 p.
- Aniya, M., Naruse, R., Shizukuishi, M., Skvarca, P. and Casassa, G. (1992): Monitoring recent glacier variations in the Southern Patagonia Icefield, utilizing remote sensing data. *Internat. Archives Photogramm. Remote Sen.* Vol. XXIX, part B7: 87–94.
- Aniya, M., Sato, H., Naruse, R., Skvarca, P. and Casassa, G. (1996): Remote sensing application to inventorying glaciers in a large, remote area — Southern Patagonia Icefield. *Photogramm. Eng. Remote Sensing*, **62**, 1361–1369.
- Aniya, M., Sato, H., Naruse, R., Skvarca, P. and Casassa, G. (1997): Recent glacier variations in the Southern Patagonia Icefield, South America. *Arct. Alp. Res.*, **29**, 1–12.
- Aniya, M., Satow, K., Skvarca, P., Anma, R., Aoki, T., Sawagaki, T., Tanikawa, T., Naruse, R., Glasser, N. and Harrison, S. (2005): Overview of Glaciological Research Project

- in Patagonia 2003. *Bull. Glaciol. Res.*, **22**, 109–119.
- Chinni, G. A. and Warren, C. R. (2004): Correspondence. The 2004 outburst flood at Glaciar Perito Moreno, Argentina. *J. Glaciol.*, **50** (171), 615–616.
- del Valle, R., Skvarca, P., Mancini, M. and Lusky, J. (1995): A preliminary study of sediment cores from Lago Argentino and fluctuations of Moreno Glacier, Patagonia. *Bull. Glacier. Res.*, **13**, 121–126.
- Escobar, F., Vidal, F., Garin, C. and Naruse, R. (1992): Water balance in the Patagonia Icefield. *In* R. Naruse and M. Aniya (eds.), *Glaciological Researches in Patagonia, 1990*, 109–119, Japanese Society of Snow and Ice, Nagoya, Japan.
- Glasser, N., Jansson, K. N., Harrison, S. and Rivera, A. (2005): Geomorphological evidence for variations of the North Patagonian Icefield during the Holocene. *Geomorph.*, **71**, 263–277.
- Harrison, S., Glasser, N. F. and Aniya, M. (2004): Morphostratigraphy of moraines in the Lago Tranquilo areas, Chilean Patagonia. *Bull. Glaciol. Res.*, **21**, 37–43.
- Iizuka, Y., Kobayashi, S. and Naruse, R. (2004): Water surface waves induced by calving events at Perito Moreno Glacier, southern Patagonia. *Bull. Glaciol. Res.*, **21**, 91–96.
- Mattson, L. E., Gardner, J. S. and Young, G. J. (1993): Ablation on debris covered glaciers: an example from the Rikhiot Glacier, Panjab, Himalaya. *IAHS Publication*, **218**, 289–296.
- Mercer, J. H. (1962): Glacier variations in the Andes. *Glaciol. Note*, **12**, 9–31.
- Mercer, J. H. (1968): Variations of some Patagonian glaciers since the Late-glacial. *Amer. J. Sci.*, **266**, 91–109.
- Mercer, J. H. (1976): Glacial history of southernmost South America. *Quarter. Res.*, **6**, 125–166.
- Michel, R. and Rignot, E. (1999): Flow of Glaciar Moreno, Argentina, from repeat-pass Shuttle Imaging Radar images: comparison of the phase correlation method with radar interferometry. *J. Glaciol.*, **45** (149), 93–100.
- Nakajima, C. (ed.) (1985): *Glaciological Studies in Patagonia Northern Icefield, 1983–1984*. Data Center for Glacier Research, Japanese Society of Snow and Ice, 133 p.
- Nakajima, C. (ed.) (1987): *Glaciological Studies in Patagonia 1985–1986*. Data Center for Glacier Research, Japanese Society of Snow and Ice, 175 p.
- Naruse, R. and Aniya, M. (1992): Outline of Glacier Research Project in Patagonia, 1990. *Bull. Glacier Res.*, **10**, 31–38.
- Naruse, R. and Aniya, M. (1995): Synopsis of glacier researches in Patagonia, 1993. *Bull. Glacier Res.*, **13**, 1–10.
- Naruse, R., Skvarca, P., Kadota, T. and Koizumi, K. (1992): Flow of Upsala and Moreno glaciers, southern Patagonia. *Bull. Glacier Res.*, **10**, 55–62.
- Naruse, R., Aniya, M., Skvarca, P. and Casassa, G. (1995a): Recent variations of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. *Ann. Glaciol.*, **21**, 297–303.
- Naruse, R., Skvarca, P., Satow, K., Takeuchi, Y. and Nishida, K. (1995b): Thickness change and short-term flow variation of Moreno Glacier, Patagonia. *Bull. Glacier Res.*, **13**, 21–28.
- Naruse, R., Skvarca, P. and Kobayashi, S. (2001): Measurements of surface height and flow velocity at the calving terminus of Perito Moreno Glacier, southern Patagonia, in December 1999. *In* M. Aniya and R. Naruse (eds.), *Glaciological and Geomorphological Studies in Patagonia 1998 and 1999*, 141–144.
- Ohata, T. (1989): Katabatic wind on melting snow and ice surfaces (I), Stationary glacier wind on large maritime glacier. *J. Meteorol. Soc. Japan*, **67**, 99–112.
- Rignot, E. A., Rivera, A. and Casassa, G. (2003): Contribution of the Patagonian Icefields of South America to sea level rise. *Science*, **302** (5644), 434–437.
- Rott, H., Stuefer, M., Siegel, A., Skvarca, P. and Eckstaller, A. (1998): Mass fluxes and dynamics of Moreno Glacier, Southern Patagonia Icefield. *Geophys. Res. Lett.*, **25** (9), 1407–1410.
- Skvarca, P. and Naruse, R. (1997): Dynamic behavior of Glaciar Perito Moreno, southern Patagonia. *Ann. Glaciol.*, **24**, 268–271.
- Skvarca, P. and Naruse, R. (2006): Correspondence. Overview of the ice-dam formation and collapse of Glaciar Perito Moreno, southern Patagonia. *J. Glaciol.*, **52** (177), 318–320.
- Skvarca, P., Naruse, R. and Angelis, H. (2004): Recent thickening trend of Glaciar Perito Moreno, southern Patagonia. *Bull. Glaciol. Res.*, **21**, 45–48.
- Stuefer, M. (1999): Investigations on mass balance and dynamics of Moreno Glacier based on field measurements and satellite imagery. (unpublished PhD dissertation, Universität Innsbruck), 166 p.
- Takeuchi, Y., Naruse, R. and Skvarca, P. (1996): Annual air-temperature measurement and ablation estimate at Moreno Glacier, Patagonia. *Bull. Glacier Res.*, **14**, 23–28.
- Warren, C. R. (1994): Freshwater calving and anomalous glacier oscillations: recent behaviour of Moreno and Ameghino glaciers, Patagonia. *The Holocene*, **4**, 422–429.