Report 6

Characteristics of ablation at San Rafael Glacier

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Abstract. San Rafael Glacier is a long glacier nearly 40 km long, which is characterized by high annual solid precipitation in the accumulation basin. The snow line in the middle of December, 1983 was approximately 1000 m.

The daily ablation rate in the lower part of the ablation area (site A. 103 m a.s.l.) was 6.8 cm/d in water equivalent, and decreased as altitude increased. The daily ablation rate in the firn area was 1 to 2 cm/d. There is a marked high ablation rate at some sites. This is not due to the difference in albedo but probably due to the locally strong glacier wind.

The result of a heat balance study at site A shows that daytime ablation varied greatly, from 1.6 to 6.0 mm/h, but at nighttime it was almost constant at 1.4 to 2.2 mm/h. The heat balance over a four-day period shows that in the heat source part the contribution of net radiation was 48%. latent heat 15% and sensible heat 37%. The turbulent term and radiation term contributed about evenly to ice melting. Net longwave radiation was positive.

Calving at the glacier terminus was seen very frequently. The glacier flow at the terminus amounted to 14 m per day on the average. From simple calculation of the mass loss by melting of snow and ice at the surface, and the mass from calving at the terminus, these two were estimated to be of the same order.

There was one period when extraordinary water discharge occurred at the terminus of the glacier which lasted for one and a half days. This seemed to be connected to the formation of a supraglacial pond by abnormal melting at the surface.

1. Introduction

San Rafael Glacier is a large, long glacier more than 40 km long in the eastern part of the Patagonia Northern Icefield. It has a large accumulation area around 1500 m a.s.l. Its ablation area is below 1000 m a.s.l. where its width averages about 3 km. The ablation area is small compared to the large accumulation area. The terminus runs down into sea called Lagoon San Rafael. The terminus area is very warm and on the side slopes there exists a jungle.

The aim of our observations was to investigate the ablation processes here. The observation consisted of the measurement of the ablation amount on the glacier which was said to be quite high in this area (NARUSE and ENDO, 1967), estimation of the heat used for melting of ice and survey of the calving process occurring at the terminus as another form of ablation.

2. Observation sites and systems

The following observations were made to investigate the ablation processes.

1) Ablation measurements. This was done by using stakes to estimate surface melting of snow and ice. The stakes were set at 12 sites along the glacier. The position of the stakes are shown by A to K in Map 2 (see front page). The altitude, type of surface and number of stakes at each site is shown in Table 1. The measurements were made at various periods of 1 to 10 days depending on the site. The albedo, that is, the reflectivity of the global radiation of the surface, was measured at a few sites. The measurements were made by automatic camera exposure (OHATA et al., 1980).

2) Heat balance measurements. These measurements were made at site A (Map 2) at the lowest observation point in the ablation area. The details of the measurements are shown in Table 2.

3) Measurement of the glacier flow at the surface. This was done at site PB (Report 4) using the theodolite. The base line was 64 m long. The top of the same seracs seen above the horizon of glacier surface was measured every day. However the accuracy of the measurement were too low to discuss on the daily fluctuation.

3. Ablation along the glacier

Ablation rates were measured along the glacier up to the altitude of 1040 m. The accumulated amount of ablation at each stake is shown in Figure 1. The days of beginning and end of measurements were different for different sites, so only the gradient of the curve can be used for comparison. In Figure 2, the average daily amounts of ablation for each period are shown in relation to the altitude. At the lowest observation site A, it was 6.8 cm per day in water equivalent. The ablation amount above H was small because the surface was snow there. A to K are on a good line except C and G. These two site show enhanced abla-

Table 1. The altitude, number of stakes, and type of surface at each ablation measurement site.

Site	Altitude (m)	Number of stakes	Surface
A	103	5	Ice
B	201	2	”
C	421	2	”
D	594	2	”
E	675	1	”
F	701	1	”
G	731	2	”
H	1008	2	Firn
I	1022	2	”
J	1043	1	”

Table 2. The system of heat balance measurements.

Element	Levels	Sensors	Remarks
Air temperature	3	Thermistor	
Humidity			Humidity at site MS were used
Wind speed	3	Cup type anemometer	
Global radiation	1	Thermocouple type pyranometer	
Net radiation	1	Net radiometer	

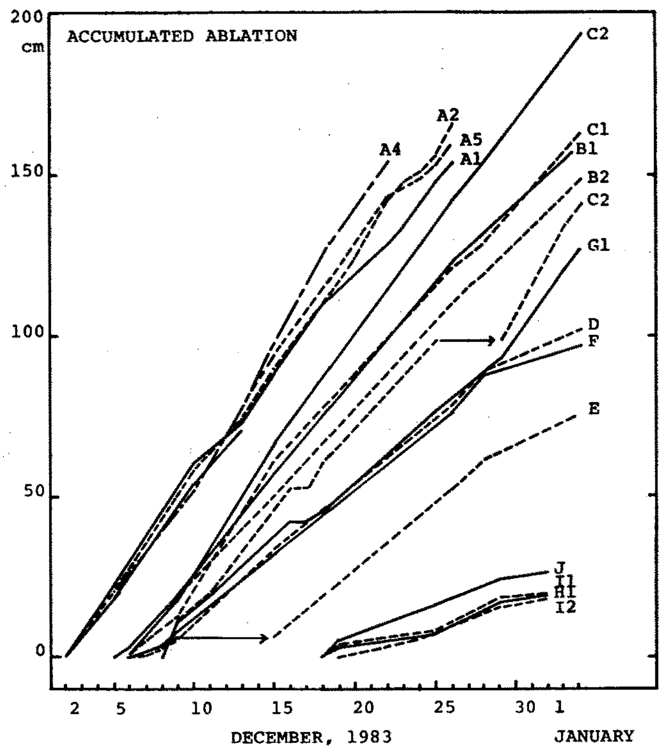

Fig. 1. Accumulated ablation amount for sites A to K.

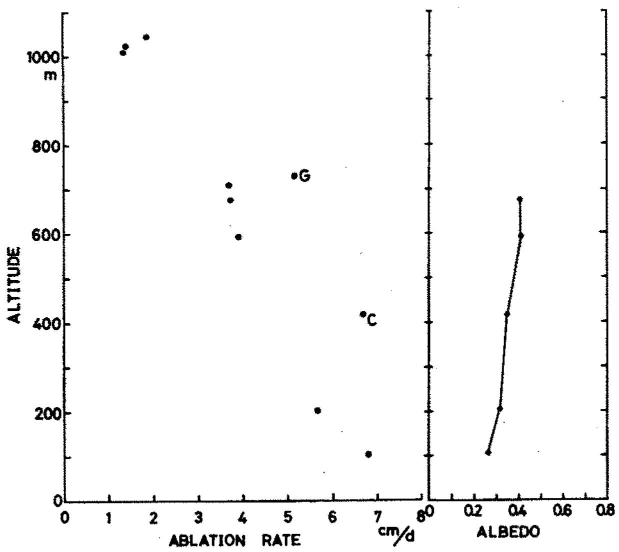

Fig. 2. Mean daily ablation rate and albedo of the surface at each site.

tion. The value of surface albedo at each ablation site is shown. There is no measurement at G but it can be considered to be similar to E. The reason for the gaps in C and G does not seem to be due to the difference in the albedo, but to the strong glacier wind there, which increases the turbulent mixing. No comparison with meteorological elements can be made due to lack of data, but whenever we passed these sites when traversing, the wind was stronger sites. These two sites had similar topographical settings, that is, ridges extended into the glacier slightly upstream of each site.

4. Heat balance at site A

The heat used for melting the glacier surface was calculated from the heat balance observation of the ice surface. Detailed heat balance measurements were made at site A from December 28 to January 1. A photograph of the site is shown in Figure 3. The meteorological condition for this period in comparison with the whole observation period, was slightly lower air temperature, and slightly higher global radiation. The heat balance equation can be written as below

$$Q_{NR}+Q_S+Q_L+Q_C+Q_M = 0$$
$$Q_{NR} = Q_{SW}\,(1-a)+Q_{LW}$$

where

Q_{NR}: Net radiation
Q_{SW}: Downward shortwave radiation
Q_{LW}: Net longwave radiation
Q_S: Sensible heat flux
Q_L: Latent heat flux
Q_C: Heat conduction to sub-surface ice layer

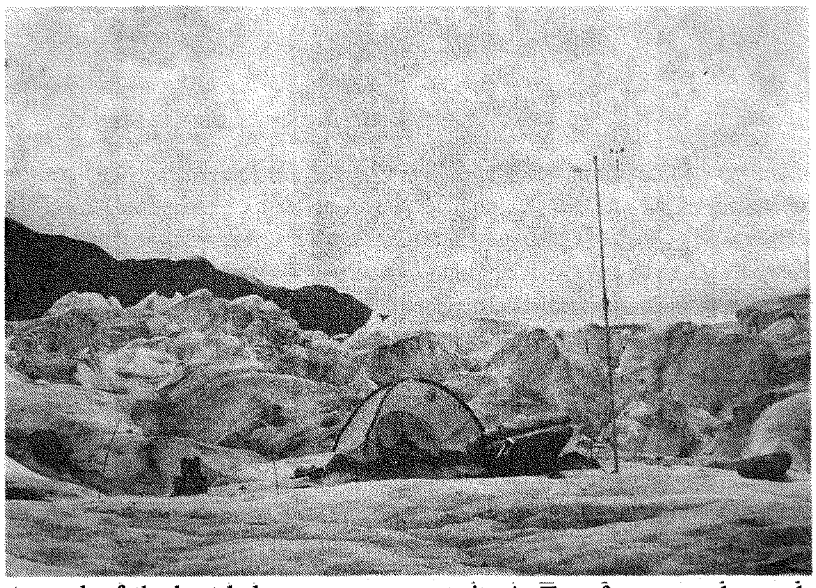

Fig. 3. Photograph of the heat balance measurement site A. Transformers and recorders were set inside the tent.

Q_M: Heat used for melting of ice
a: Albedo

Direct measurements were made of Q_{NR}, Q_{SW} and a. From these values, $Q_{SW}(1-a)$ and Q_{LW} were obtained. Q_C was assumed to be zero because the ice temperature near the surface was 0°C. Q_M was calculated from measurements of the surface lowering using stakes, assuming the ice density to be 0.85 g/cm³. Q_S and Q_L were calculated by postulating logarithmic profiles of air temperature, wind speed vapor pressure. The equations used for the calculation were the following:

$$Q_S = \rho C_p k^2 \frac{TU}{[\ln(z/z_0)]^2}$$

$$Q_L = \rho L k^2 \frac{(e-e_0)\,U}{[\ln(z/z_0)]^2} \cdot \frac{0.622}{P}$$

where

ρ: Density of air
C_p: Specific heat of air
k: Karman constant
L: Heat of sublimation
$e-e_0$: Vapor pressure at z and z_0
U, T: Wind speed and air temperature at z
z_0: Roughness length
P: Atmospheric pressure

In the calculation $z = 1.5$ m and $z_0 = 0.002$ m derived from the measurement of the vertical profile for wind speed were used. e_0 was assumed to be 6.1 mb. The results are shown in Figures 4 and 5. Figure 4 shows the melting of ice, that is, the lowering of the ice surface. This was measured three times a day. Daytime ablation was larger than nighttime ablation and varied from 1.6 to 6.0 mm/h. A low value is seen on the 29th which was a day with overcast and rain, and as a result the global radiation was low. The nighttime ablation amount varied from 1.4 to 2.2 mm/hr, relatively constant throughout the period. Figure 5 shows the heat balance components shown separately for heat sources and heat sinks. The four at the left are for the daytime value from the 29th to 1st. Q_M, $Q_{SW}(1-a)$ and Q_{LW} varied much among these days, but the turbulent term Q_S+Q_L was about constant. This seems to be due to the existence of a glacier wind here, which was nearly constant on this glacier (Report 4). On the right the total amount of daytime balance and the balance extrapolated to the whole 4 days are shown as a percentage of the total heat source (100%). The latter was calculated by assuming that there are equivalent supplies of Q_S, Q_L and Q_{LW}, and no Q_{SW} in the nighttime. The whole day values shows that what kind of heat was used for melting the glacier as Q_M

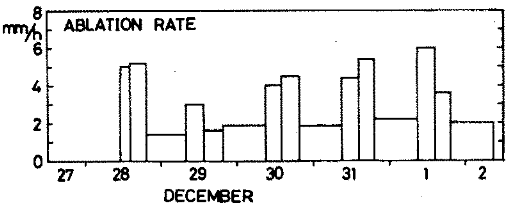

Fig. 4. Ablation rates in mm/h at site A during the observation period.

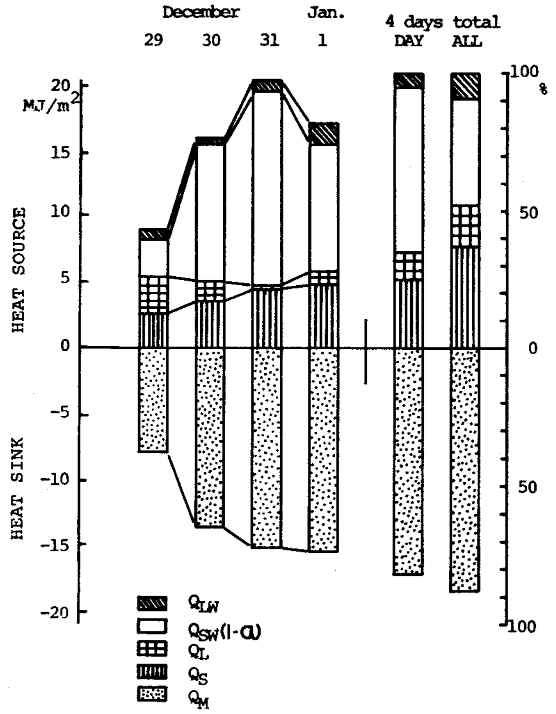

Fig. 5. Result of the heat balance measurement from December 28 to January 1. At the right side, the total value for the daytime on each day is shown. At the left, the mean value of daytime and whole day for four days are shown in percentage.

is the only term in the sink. Q_{LW} was 9%, Q_L was 15%. $Q_{SW}(1-a)$ was 39% and Q_S was 37%. The percentage of the turbulent term Q_L+Q_S was more than 50%. As this period had a little larger Q_{SW} than the average, this percentage of Q_L+Q_S may be a little higher for the whole observation period. Q_{LW} was in the heat source part, probably due to the strong temperature inversion.

5. Glacier flow at the terminus

Calving occurred almost continuously at the terminus. It can be assumed that the ice at the terminus is grounded at the bottom, from lagoon depth data. In order to see the movement

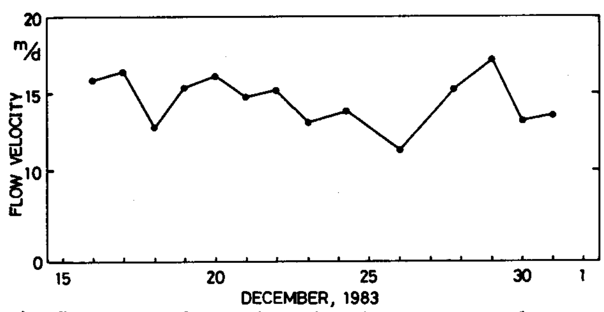

Fig. 6. Velocity of glacier flow at terminus. The value shown are two-day running mean values.

of ice at the terminus, the positions of the top of the seracs near the terminus were measured almost every day from December 15 to January 1. The results are shown in Figure 6. The theodolite used here was not good enough for detailed discussion, so, two-day average values of the daily flow value of ice are shown. The average value of flow was 14 m/d. The variation shown in the figure can not be determined to be significant, at the present. The seracs which were used for measurements were approximately 800 m from the side of the glacier which is 1/4 of the glacier width at the terminus.

6. Formation of supra-glacial pond and extraordinary outflow at the terminus

There was one occasion during the observation period, when there was an extraordinary outflow at the terminus. There were no detailed measurements of the outflows, but as it seems

Table 3. Progress of the extraordinary outflow at the terminus and the formation of the supra-glacial pond at site A.

Date	Hour	Terminus	Site A
Dec. 13	10:45		Small pond was forming
Dec. 14	10:30		Enlarging
Dec. 15	08:00		Enlarging
	16:40		Enlarging
	21:00	No upwelling	
Dec. 16	07:00	Extraordinary upwelling occurring	
	21:00	Continuing	
Dec. 17	09:00	Continuing	
	14:00	Upwelling terminated	
Dec. 18	10:20		Pond disappeared

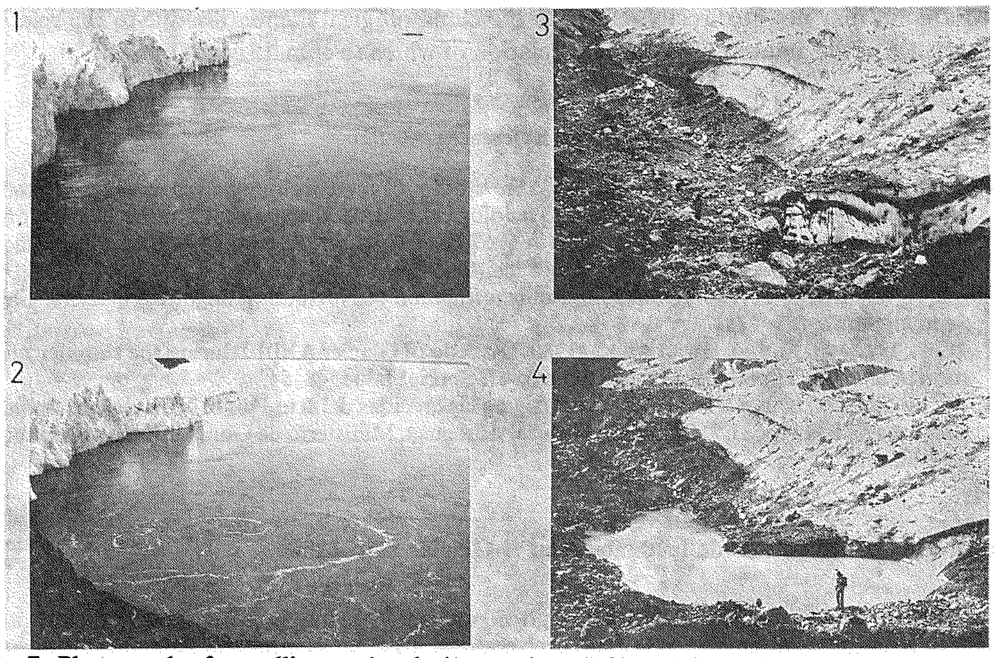

Fig. 7. Photograph of upwelling at the glacier terminus (left) and formation of the supra-glacial pond (right). The photos are at 1: December 18, 17:00, usual situation; 2: December 16, 09:00; 3: December 18, 12:00, usual situation; 4: December 15, 11:00.

to be an important glacio-hydrological phenomenon, it will be mentioned here.

Similar phenomena occurring in the Patagonia Icefield area has been cited in ENOMOTO and ABE (1983) and PEÑA and ESCOBAR (1983). The extraordinary outflow occurred at the terminus near observation site MS from December 16 to 17, and preceeding to that there was a formation of a supraglacial pond at site A. The progress of these phenomena and photographs of the site are shown in Table 3 and Figure 7. From this progress it can be said that strong discharge of outflow which was observed as upwelling of water on the lagoon surface at a position of 200 m from the terminus lasted for at least one and a half days. A supraglacial pond had formed before this and disappeared after this. From this situation, it seems that after the pond had formed to a moderate size, it started to discharge. The pond at site A was about 20×40 m and 4 m in depth at its maximum. This pond alone cannot explain the abnormal amount of water that was discharged. As can be seen from ablation of the glacier surface, December 13–15 showed an abnormal high value, due to the high value of global radiation. From these facts the following explanation can be proposed at the present. High ablation due to high insolation produced much melted water which could not be drained through the usual channels established in the glacier. As a result, many ponds formed on the glacier and in the early morning of December 16, a channel in the ice had broke or some catastrophic event like Jökullalp occurred. It stopped when all of the accumulated water flowed out. At the moment this phenomenon cannot be discussed further due to lack of data.

7. Concluding remarks

The ablation process on San Rafael Glacier takes two forms, melting at the surface and calving at the terminus. The amount lost by both processes seems to be of the same order from simple calculation. This means that fluctuation in the mass balance and also the position of the terminus may not be directly related to the climatological fluctuation due to the relative importance of the amount of calving the relation of which to climate is not known.

References

ENOMOTO, H. and ABE, Y. (1983): Reconnaisance studies of meteorology and glaciology in Steffen and Jorge Montt Glaciers, Patagonia. Glaciological and Meteorological Studies in Patagonia, Chile, by Japanese Research Expeditions in 1967–1982 (NARUSE R. ed.), Data Center for Glacier Researches, Japanese Society of Snow and Ice, 11–14.

NARUSE, R. and ENDO, T. (1967): Glaciological investigation of Northern Patagonian glaciers, Chile. Seppyo, **29**(6), 167–176.

OHATA, T., IKEGAMI, K. and HIGUCHI, K. (1980): Albedo of Glacier AX010 during the summer monsoon in Shorong Himal, East Nepal. Seppyo **41**, Special Issue, 48–54.

PEÑA T. H. and ESCOBAR, C. F. (1983): Análysis de las crecidas del Río Paine, XII Región. Publicatión Interna EH No. 83/7. Dirección General de Aguas. Ministerio de Obras Públicas, República de Chile, 78 p.

Resumen. Características de la ablación en el Glaciar San Rafael

El Glaciar San Rafael es un glaciar largo de casi 40 km, que se caracteriza por una alta precipitación sólida anual en el área de acumulación. El área de ablación en su parte inferior se desarrolla en una zona templada-húmeda. La línea de nieves en el período de observación

se ubicó aproximadamente a 1.000 m. Se midió las tasas de ablación, balance energético y movimiento del glaciar.

La Fig. 3 muestra la tasa de ablación (fusión superficial) en los puntos A a J indicados en la Fig. 1 y en el mapa del apéndice. En la zona inferior, la ablación en equivalente de agua fue de 7,0 cm/d, y decreció con la altura. La ablación en la neviza fue de 1 a 2 cm/d. A partir de esta figura, se considera que se estaba produciendo ablación en cierto grado sobre la extensa área de acumulación sobre los 1.200 m. Hay una marcada tasa de ablación en los puntos C y G. Esto no se debe a la diferencia de albedo que se mustra a la derecha, sino que probablemente se debe al fuerte viento glacial que se produce en el lugar como producto de la topografía del glaciar. En las Fig. 4 y 5 se muestra el resultado del estudio del balance energético en el punto A durante 5 días a fines de Diciembre. La ablación durante el día varió bastante, desde 1,6 a 6,0 mm/h, pero en las noches era casi constante, de 1,4 a 2,2 mm/h. Los términos del balance energético para el día y la noche en un período de 4 días muestran que el aporte de calor de la radiación de onda corta y onda larga fue del 48 %, calor latente 15 % y calor sensible 37 %. Los intercambios turbulentos contribuyen más de la mitad de la energía empleada en fusión de hielo, que es el único término de pérdida de energía.

Desprendimientos en el frente del glaciar eran muy frecuentes. La velocidad del flujo del glaciar en el frente fue de 14 m/d como promedio. A partir de un cálculo simple de pérdida de masa por ablación de nieve y hielo en superficie, y pérdida de masa por desprendimiento en el frente, se estimó que estos dos valores eran aproximadamente del mismo orden. Esto significa que aquí la relación entre la fluctuación climática y la fluctuación del glaciar sería muy complicada.

Se observó en un período una descarga extraordinaria de agua en el frente del glaciar que duró un día y medio. Precediendo este fenómeno, se formó un lago sobreglacial que luego desapareció. A partir de datos meteorológicos y de ablación este fenómeno puede ser explicado a una alta radiación global desde el 13 al 15 de Diciembre, la tasa de ablación estaba sobre lo como sigul. Debido normal en ese período. El exceso de agua de fusión que no podía desaguar a travé de los canales en el glaciar empezó a formar un lago sobreglacial. En la mañana del 13 de Diciembre ocurrieron procesos drásticos en el glaciar, resultando en una descarga extraordinaria en el frente. No se conocen aun con precisión los mecanismos.