Report 4

Meteorological observations at San Rafael Glacier

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Abstract. As part of the meteorological environmental study of the Patagonia Northern Icefield, many observations were made near the ablation area of San Rafael Glacier from November 30, 1983 to January 4, 1984. Four stations were established between altitudes of 30 and 1160 m a.s.l.

The outstanding meteorological feature here was the high cloud amount of 9/10 on the average, except for a few days in the middle of December. Related to this, global radiation was low at a mean value of 12.8 MJ/m^2d (305 ly/d). This is only 30% of the incident flux at the top of the atmosphere. Rainfall showed a cyclic change determined by the passing of the trough centered at higher latitudes. Wind speed showed a fairly constant value of 2–5 m/s for the whole period due to the existence of a glacier wind, that is, a downslope gravity wind. The thickness of the wind was more than 100 m when it was strongest. This wind occurred almost constantly, over most of this glacier.

The upper station was maintained for about 20 days. Air temperature, wind speed and precipitation were compared with those at other sites. The total amount of precipitation here was 20% more than that at the terminus, and frequency of rainfall also 20% more. The difference in this total amount is due to the higher rate of precipitation, not to the frequency of rainfall. Additionally, snow crystal observations were made to obtain informations on the height and thickness of cloud in this area.

1. Introduction

As part of a meteorological study in the Patagonia Northern Icefield, continuous observations were made in the terminus area of San Rafael Glacier. There have been no systematic meteorological observations related specifically to the glaciers in this area in the past. San Rafael Glacier is approximately 40 km long and more than 10 km wide in the accumulation area, and about 3 km wide near the terminus. The precise size of the glacier has not been determined yet due to lack of detailed measurements of the surface morphology of the icefield. The terminus runs into sea named Lagoon San Rafael.

The aim of the meteorological observations was to determine the meteorological environment of the glaciers in this region in the ablation season of the glacier.

2. Observation sites and measured meteorological elements

Four main meteorological observation sites were established along the glacier. These sites are shown in Figure 1 and also in Map 2 (see front page). MS (104 m a.s.l.) was the main observation site and continuous observations were made from November 30, 1983 to January

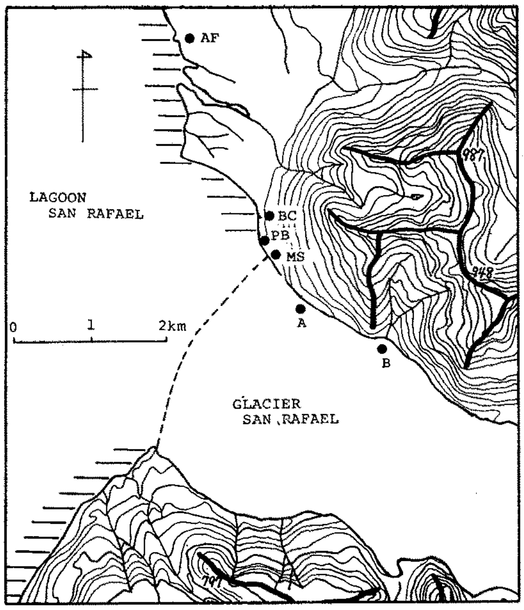

Fig. 1. Map showing the position of the meteorological observation sites near the glacier terminus.

4, 1984. Some hydrometeorological observations were made at BC (70 m a.s.l.) which was the camp site. High altitude observations were made at UC1–3 (731–1160 m a.s.l.). Pilot balloon observations were made at PB (30 m a.s.l.) near MS. In the analysis the meteorological data taken at the San Rafael Meteorological Station (6 m a.s.l.) of the Chilean Air Force are used. This station is shown as AF in Figure 1. The meteorological elements observed at MS and upper camps are shown in Table 1. Among these observations made in the terminus area, air pressure and cloud amount and type, cloud photographs, raindrop size distribution and precipitation samples were observed and measured at BC, slightly away from the glacier.

Other observations made for short periods in this area are listed in Table 2.

3. Variation of meteorological elements during the observation period

In Figure 2, every meteorological element observed at site MS is shown. Three-hourly values are shown for air temperature, relative humidity, wind speed and cloud amount. The precipitation amount is the three hour total value. The global radiation at the bottom of the figure is the daily total value.

The cloud amount is nearly 10 for most of the period. A few days such as December 13–15, and 20th have low values. The average cloud amount was approximately 9.0 for all of December. Precipitation amount shows a cyclic change, strong rainfall occurred in the latter half of the month. The number of days without rainfall was 10 days in December. Comparison with the large-scale pressure field is shown in Report 3. The time of precipitation coincides with the passing of a deep trough which is centered around 60 to 70°S latitude. The trough in the latter half of December penetrated deeply into lower latitudes, resulting in strong rainfall at MS, where the ones in the former half had only little influence in this region.

Air temperature and humidity do not show any relation to the other meteorological ele-

Table 1. List of meteorological elements observed at MS and upper sites.

a) Site MS (BC): Observation period. November 30, 1983–January 4, 1984

Items		Frequency		
		Continuous	Every 3 hours	At random
Air temperature	dry	O	O	
	wet		O	
Relative humidity		O		
Air pressure		O		
Wind speed		O		
Wind direction			O	
Global radiation		O		
Precipitation amount		O	O	
Cloud amount and type			O	
Cloud photo			O	
Rain droplet size distribution			O	O
Precipitation samples			O	

b) Sites UC1–3: Observation periods are shown in the table

Items		UC1		UC2		UC3	
		C	E	C	E	C	E
Air temperature	dry	Dec. 9–16	Dec. 9–11, 16		Dec. 11–14	Dec. 17–Jan. 1	Dec. 17–24
	wet	Dec. 9–16	Dec. 9–11, 16		Dec. 11–14	Dec. 17–Jan. 1	Dec. 17–24
Relative humidity		Dec. 9–16			Dec. 11–14	Dec. 17–Jan. 1	Dec. 17–24
Precipitation amount		Dec. 9–16	Dec. 9–11, 16		Dec. 11–14	Dec. 17–Jan. 1	Dec. 17–24
Wind speed			Dec. 9–11, 16		Dec. 11–14		Dec. 17–24
Wind direction*							
Global radiation							Dec. 17–24
Cloud amount and type*			Dec. 9–11, 16		Dec. 11–14		Dec. 17–24
Cloud photo			Dec. 9–11, 16		Dec. 11–14		Dec. 17–24
Rain droplet size distribution			Dec. 9–11, 16		Dec. 11–14		Dec. 17–24
Precipitation samples			Dec. 9–11, 16		Dec. 11–14		Dec. 17–24

C: Continuous observation
E: Every 3 hours
*For these elements, sometimes they were observed every 1 hour.

Table 2. Minor observations made at various sites.

Minor obsesvations

Item	Period	Times	Site	Remarks
a) Traverse observation of meteorological elements (Wind speed, wind direction, air temperature, cloud amount and type)	Dec. 2–Jan. 2		10 sites	
b) Long term precipitation observation along the glacier	Dec. 2–Jan. 2		10 sites	
c) Pilot ballon obs. of wind	Dec. 1–Jan. 2	33	site PB	
d) Vertical profile of wind and air temperature up to 100 m	Dec. 14–Jan. 1	20	site MS	
e) Continuous cloud obs.	Dec. 12–Jan. 6		site BC	Photographs
f) Snow crystal observation	Dec. 22, 30		site UC	Replica Method
g) Cloud deformation observation	Dec. 20			

ments. These elements show relatively good diurnal change from December 10 to 18 when global radiation was large. The daily range of air temperature was approximately 7°C in fair weather.

Wind speed showed a fairly constant value of 2 to 5 m/s during this period despite the

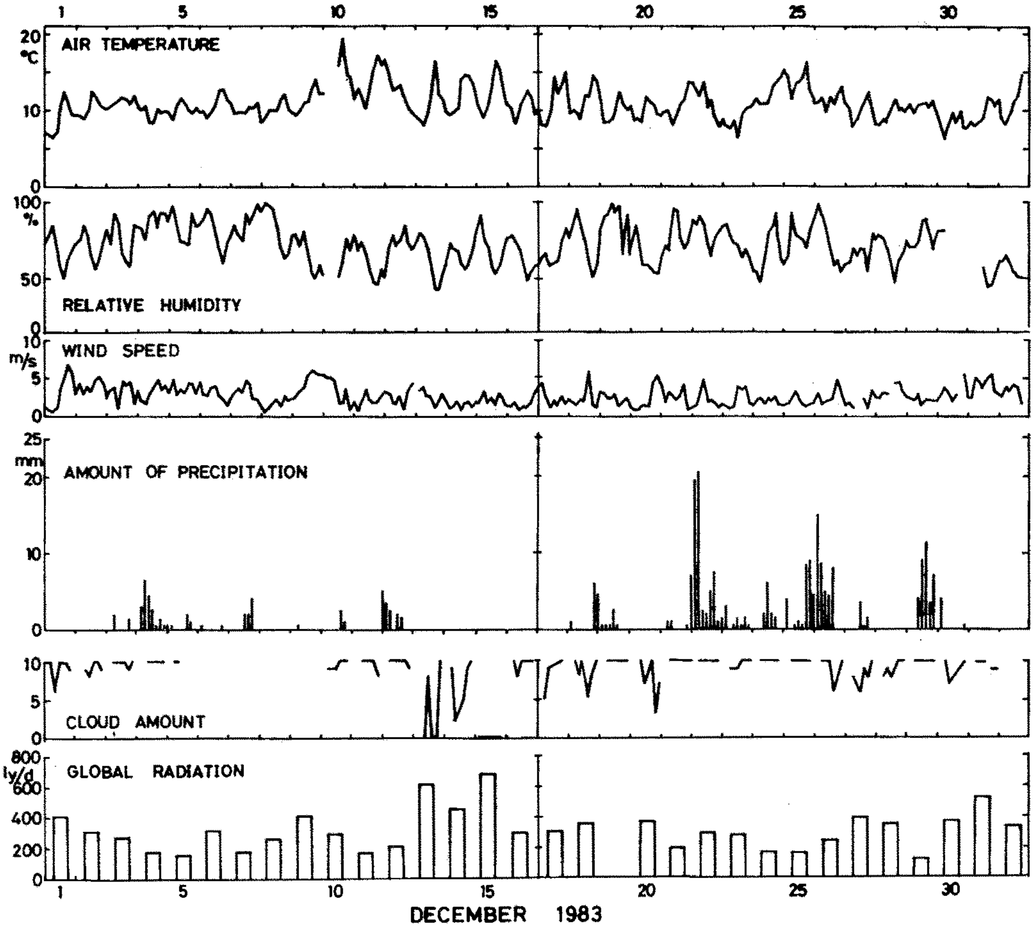

Fig. 2. Six meteorological elements at MS for the whole observation period. Air temperature, relative humidity, wind speed and cloud amount are shown for every three hours, precipitation for three-hour total value and daily total value for global radiation.

variations in the upper wind field. This characteristic will be discussed further in the latter section.

Global radiation ranged from 4.5 to 28.7 MJ/m²d (108 to 685 ly/d), 12.8 MJ/m²d (305 ly/d) on the average. This is about 30% of the incident solar radiation at the top of the atmosphere. This low value is due to the high cloud amount here.

4. Local circulation near the terminus

There was a frequent occurrence of local glacier wind near the terminus area, and it also was observed at higher ablation area during the traverses of this glacier. The strength of this wind varied from place to place. The direction of this glacier wind was easterly which is the direction of the slope along the glacier. This is opposite to the predominant direction of the upper wind which is west.

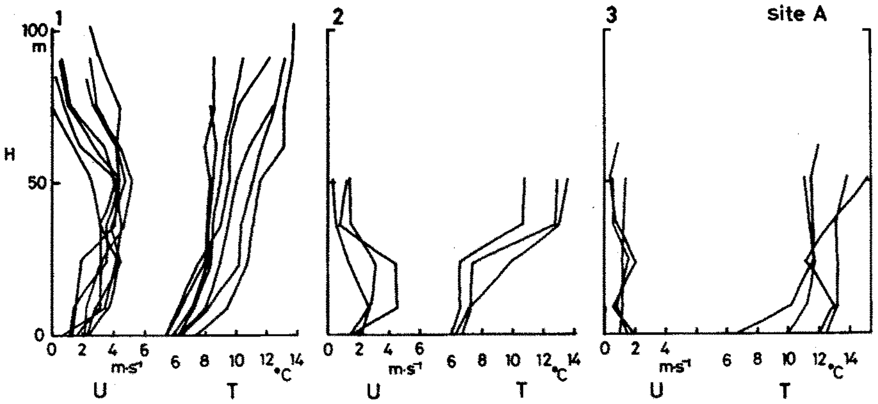

Fig. 3. Wind and air temperature profiles for glacier winds observed near the slope at MS. 1: glacier wind deeper than 50 m; 2: glacier wind shallower than 50 m; 3: not glacier wind.

Observations of this wind were made in the daytime on a slope where meteorological station MS was established. The slope was approximately 35 degrees and vertical distribution of wind speed, wind direction and air temperature up to the height of 100 m above the glacier surface were measured within 20 minutes. We assumed that the wind was constant during this period, and the distribution along the slope is the same as the profiles above the glacier. The results are shown in Figure 3. Vertical profiles are shown up to 100 m above the glacier surface. Case 1 is for high glacier winds with depth higher than 50 m, and case 2 for depth lower than 50 m. The profiles for case 3 are when glacier wind was not blowing. This can be considered as wind not of glacier origin. In case 1 the height of maximum wind speed (Z_m) was around 50 m and its strength (U_m) was 4–5 m/s. In case 2, z_m and U_m are smaller. The

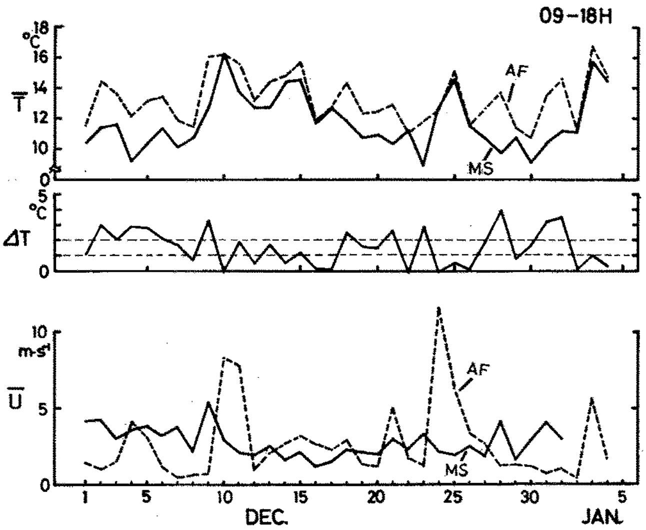

Fig. 4. Comparison of daytime air temperature ($\overline{T}$) and its difference (ΔT) and wind speed ($\overline{U}$) at MS and AF.

difference in these cases is probably due to the difference in the area of occurrence of this gravity wind. In case 1, this wind is blowing on the whole glacier, but in case 2, it is probably confined to the lower ablation area.

In order to see the daily change of this wind system, meteorological elements at AF (outside the influence of the glacier) and MS (inside) are compared for daytime hours (09:00–18:00) and are shown in Figure 4. Mean daytime air temperature ($\overline{T}$), its difference (ΔT) and mean daytime wind speed ($\overline{U}$) are shown. Air temperature at MS is usually lower than at AF, and ΔT shows the difference between −0.1 and 4.0°C. When the glacier wind is developed, site MS will be inside the cold air layer of the glacier wind, so ΔT can be considered a measure of the stability of the glacier wind at MS. ΔT more than 2.0°C occurred on 10 days, 1.0–1.9°C on 11 days and below 1.0°C on 10 days. It can be seen from the figure that on high ΔT days the wind speed is high. This is a plausible result. The wind speed is compared for two sites. At site C, wind speed is usually low but becomes strong on days when a trough comes to this area. In comparison, at site MS, wind speed is fairly constant between 2 and 5 m/s during this observation period, in spite of large variation at site AF. These difference arose due to the screening effect of the ridges along the side of the glacier to the upper wind, and also the strong occurrence of the glacier wind on this glacier. The glacier wind blew more than 90% of the whole period.

5. Pilot balloon observation at the terminus

From December 12 to January 1, pilot balloon observations were made once or twice a day near the terminus to determine the local air circulation here. Due to the presence of clouds, observations could not be made to high altitudes. The results are shown in Figure 5.

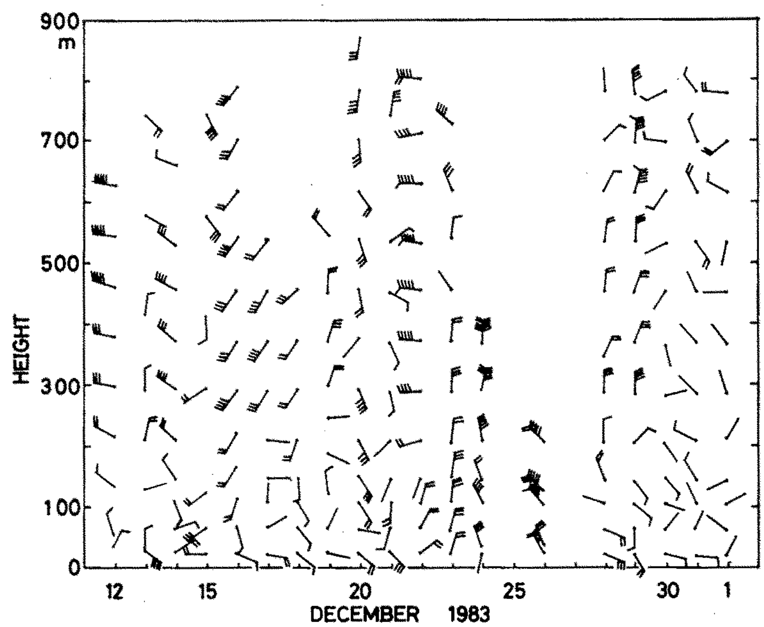

Fig. 5. Result of observation of the vertical wind profile near the terminus measured at PB. The direction of the feather shows the wind direction and one barb corresponds to 1 m/s.

Observations made in the morning are shown. When the upper level wind (700–800 m a.s.l.) was strong, the wind was in the same direction down to 150 m, weak in the lower layers. Under strong NW to N upper winds, such as from December 23 to 26, the wind was in the same direction down to 30 m. In case of weak upper winds, the wind direction of the lowest few hundred meters was arbitrary with an ESE glacier wind at the lowest levels.

The vertical wind profile near the terminus showed various profiles depending on the direction and strength of the upper wind as noted above. The profiles are probably determined by the interaction between the general wind pattern, topography of the area and the existence of a local wind field such as the glacier wind.

There were three days when observations were made twice a day, once in the morning and once in the late afternoon. No trace of land-sea breeze air circulation was found from these observations.

6. Meteorological observations at upper sites

Meteorological observations were made at the upper camps during the reconaissance of the accumulation area. The position of observation sites changed during the observation period due to the operation. Comparison with the lower site MS will be made on air temperature, precipitation and wind speed. In Figure 6, daily mean air temperature for upper stations and site MS are shown. Observation periods were December 10 to 16 for UC1 and December 18 to 31 for UC3. The average lapse rates between these two sites were 6.2°C/1 km and 3.8°C/1 km. The former observation site was near the side of the glacier, meaning that both UC1 and MS are in the same glacier wind system. On the other hand, UC3 was located on a nunatak, above the top of the glacier wind. So, in the latter case the lapse rate became small, due to the relatively low air temperature at MS.

Three-hourly precipitation amounts for MS and UC3 are shown in Figure 7. The total

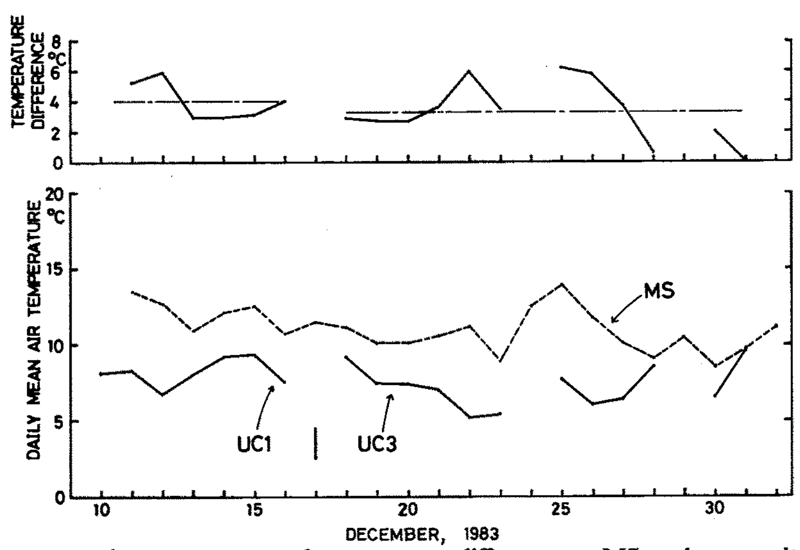

Fig. 6. Daily mean air temperature and temperature difference at MS and upper sites (UC1–3). Average temperature difference between MS and UC1, and MS and UC3 are shown by dashed line in the figure.

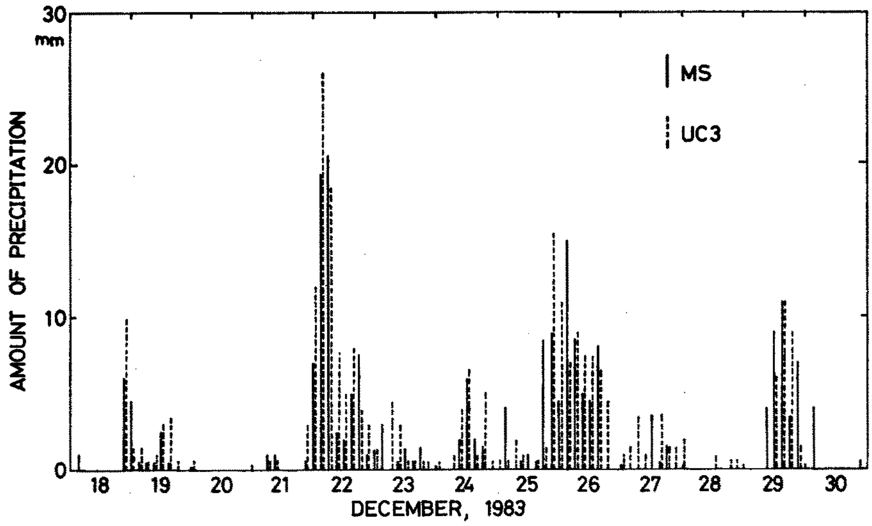

Fig. 7. Three-hourly precipitation amounts for MS and upper sites (UC1–3).

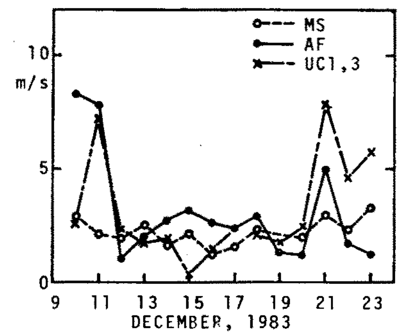

Fig. 8. Daily mean wind speed for MS, AF and upper sites (UC1–3).

amounts of precipitation for the period December 18 to 31 was 218 and 257 mm, respectively. UC3 had rain approximately 1.2 times more than MS. The number of cases when there was more than 0.5 mm of rainfall in three hours was 51 for MS and 62 for UC3. A difference in the frequency of rainfall exists. Although there is such difference, the discrepancy in the total amount is not due to this difference but to the difference in the amount during each rainfall period. In Figure 8, the daytime wind speeds for UC1–3, MS and AF are shown. The UC1–3 shows better correlation with AF than with MS. The reason seems to be that UC1–3 and AF reflect the daily variation in the strength of the upper wind, but MS is almost always under the effect of the glacier wind.

7. Snow crystal observation

Estimation of cloud condition by analyzing snow crystals observed on the ground is useful in studying the mechanism of accumulation of glaciers (Higuchi, 1976). Therefore, observation of snow crystals were carried out near UC3 by the formvar solution method. The ob-

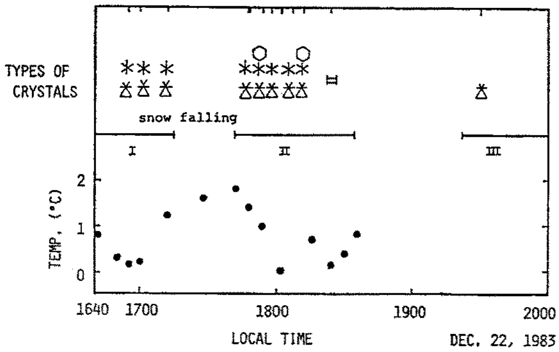

Fig. 9. Time variation of types of snow crystals, air temperature and duration of snowfall at the observation site.

servation site was at an altitude of 1460 m a.s.l. The mean daily minimum temperature was 4.3°C. at UC3 in the period December 18 to 31, but snowfall occurred on the 22nd and 30th. The result on the 22nd will be described.

Due to the passage of a cold front in the morning of 22nd in ths area, air temperature had begun to fall as seen in Figure 2. At the observation site heavy rainfall and strong wind occurred in the morning, and from 11:00 to 12:00 there was a hailstorm. The wind weakened in the afternoon but the rainfall continued. Snowfall began from about 16:00 and continued during the night, and observations were made from 16:40 to 19:30. Figure 9 shows the duration of snowfall, types of snow and air temperature at the site. The period of snowfall is divided into three stages. The total precipitation amount was 3.5 mm from 16:00 to 19:00 at UC3. During the observation period snowfall occurred three times intermittently, and the replicas were made 12 times.

The shapes of snow crystals were hexagonal plates, plate with simple extension, crystals with broad branches, stellar crystals, ordinary dendritic crystals, fernlike crystals, columns with plates and graupels. The relative frequency of graupels was about 60%. This is more than the percentage observed at Nepal Himalayas (Higuchi, 1976). In stage 1 only dendritic crystals and graupels were observed and graupels were mainly of hexagonal type. In stage 2, plate crystals and columns with plates were additionally obtained. All plates were small (0.3–0.5 mm) and nonrimed. These crystals seemed to have grown in the lower part of the cloud. On the other hand the size of dendritic type were 0.4 to 3.2 mm. As the columns with plates were observed at the end of this stage, the cloud condition changed. All of the crystals obtained in stage 3 were graupels. These crystals are usually formed under convective conditions.

It is difficult to estimate the thickness of the cloud layer from the size of snow crystals as the cloud seemed to have been convective in each stage. From the results in stage 1 and 2, the upper parts of the clouds were considered to be suitable for the growth of dendritic type. According to the temperature condition for the growth of natural snow crystals (Magono and Lee, 1966), the temperature of the cloud can be considered to have been lower than −12°C. Therefore the altitude of the cloud tops was about 3500 m a.s.l. at the minimum, assuming the wet adiabatic lapse rate of 0.66°C/100 m at 10°C and 700 mb. This height is higher than that of the mountain range at the east side of the icefield, which is about 2000–3000 m a.s.l. This is only one case but these studies of cloud height are important as cloud top over the icefield is considered to be the major factor causing the various patterns of cloud distribution and related meteorological phenomena in this area.

References

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Resumen. Observaciones meteorológicas en el Glaciar San Rafael

Como parte del estudio meteorológico del medio ambiente del Hielo Patagónico Norte, se hizo numerosas observaciones cerca del área de ablación del Glaciar San Rafael durante el período desde Noviembre 30, 1983 a Enero 4, 1984. Las observaciones principales fueron observaciones contínuas cerca del frente del glaciar (punto MS: 104 m s.n.m.) y cerca de la línea de nieve (punto UC1 a UC3: 731 a 1160 m s.n.m.) que se muestra en el mapa del apéndice. Las observaciones incluían temperatura del aire, humedad, velocidad del viento, nubosidad, precipitación, radiación global, fotografías de nubes, distribución del tamaño de gotas de lluvia y muestreo de precipitación. Además se observó la precipitación en un intervalo extenso a lo largo del glaciar, la estructura superior del viento y la temperatura del aire hasta los 100 m usando globos pilotos, y los cristales de nieve en cotas elevadas.

La figura 2 muestra la variación de los elementos observados en MS para el período completo. Aquí la característica más importante fue la gran nubosidad de 9/10 en promedio, excepto durante pocos días a mediados de Diciembre. En relación a esta gran nubosidad, la radiación global fue baja, con un promedio de 300 ly/d. Esto es sólo un 30% del flujo incidente en la capa superior de la atmósfera. La precipitación en forma de lluvia mostró cambios determinados por el paso de frentes centrados más altas. La variación de la temperatura del aire y la humedad no muestra ninguna relación con otros elementos meteorológicos. La amplitud diaria de la temperatura del aire fue aproximadamente de 7°C en condiciones de buen tiempo. La velocidad del viento mostró un valor bas tante constante de 2–5 m/s para todo el período. Esto es producto del viento glacial, esto es, viento que sopla hacia abajo por gravedad. El perfil de este viento se muestra en la Fig. 3. El espesor del viento era superior a 100 m cuando éste era más fuerte. Este viento era casi constante. A partir de travesías de reconocimiento, se encontró que este viento ocurría en todo el área de ablación hasta la línea de nieves.

La estructura vertical del viento cerca del frente del glaciar (Fig. 5) muestra que cuando el viento superior (700–800 m) es fuerte (mayor que 5 m/s) el viento inferior es también fuerte en la misma dirección. Pero bajo vientos superiores débiles, los primeros cientos de metros inferiores mostraron diferentes direcciones de viento con viento glacial abajo.

La estación superior fue operada durante 20 días aproximadamente. La geradiente de temperatura promedio entre este punto y MS fue de 0,64°C/100 m para UC1 y 0,36°C/100 m para UC3. Esta diferencia parece deberse al hecho que UC1 y MS están en el mismo sistema local de viento glacial mientras que UC3 no lo está. En UC1–3, la cantidad total de precipitación fue un 20% más que en MS, y la frecuencia de precipitación también un 20% mayor. La diferencia en la cantidad total se debe a la diferencia en el monto de cada precipitación y no a la frecuencia.