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Characteristics of precipitation and vertical structure of air temperature in the northern Patagonia

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Abstract

Meteorological observations were carried out from October 1985 to February 1986 along San Rafael Glacier, located at 46°37′S and 73°53′W. Major findings are as follows :

1) From the data collected at the meteorological stations located on the west side of Chile from 43°12′S to 53°10′S, it was found that it rains more heavily in winter than in summer in latitudes lower than 46°S. In contrast, it rains more heavily in summer than in winter at the terminus of San Rafael Glacier and in latitudes higher than 46°S, although the seasonal variation is rather obscure. Monthly mean amount of precipitation at higher latitudes is larger than that in lower latitudes throughout the year.

2) From the data collected by the Meteorological Office at Lagoon San Rafael from June 1981 to December 1985, it was found that both twelve-hourly amount of precipitation (P(12 hr)) and chance of having precipitation decrease with increasing surface air pressure (Pr). Precipitation rarely occurs when Pr is larger than 1020 mb. The mean annual amount of precipitation at the terminus of San Rafael Glacier in recent four years is 3.7×10^3 mm. The maximum annual, monthly and daily amounts of precipitation are 4.1×10^3, 5.6×10^2 and 1.27×10^2 mm, respectively.

3) From our radiosonde observation, it was noted that strong temperature inversion and a considerably stable layer below the level of 3 km appeared at the terminus of San Rafael Glacier during the period when an anticyclone centered in the Pacific Ocean off the coast of Peru spread over the northern Patagonia. Under this condition, air temperature below the level of 3 km was higher than 0°C.

4) The amount of precipitation increased with increasing altitude below the level of 639 m. The amount of precipitation on the icefield was estimated to be about three times larger than that at the terminus of San Rafael Glacier.

1. Introduction

Meteorological observations were carried out from October 1985 to February 1986 near the terminus of San Rafael Glacier (46°37′S, 73°53′W, 6.1 m a. s. l.), which will be referred to as BH hereafter. Major scientific objectives were focused on clarifying the characteristics of precipitation and the vertical structure of air temperature in the region. These are significant factors to consider in any discussion of the growth and shrinkage of the glacier.

Three automatically recorded rain-gauges were set at points of BH, C1(422 m) and C2(1040 m), and four totalizer rain-gauges were set at points G1(89 m), G2(209 m), C1 and G4(639 m) (see Map 2, folded in). Point G2 is located between points G1 and C1. Upper air soundings were carried out by radiosonde at BH in the daytime. Meteorological observations along San Rafael Glacier and at Soler Glacier were summarized by Inoue *et al.* (1987) and Fukami *et al.* (1987), respectively. Pictures of clouds over BH were taken by an 8 mm-film camera every 10 seconds at BH and by a 35 mm-film camera twice a day from an airplane of LADECO (Linea Aerea Del Cobre).

2. Seasonal variation of precipitation

Figures 1a and 1b show the monthly mean amount of precipitation (P(M)) at points 1 to 6 and 1′ to 6′.

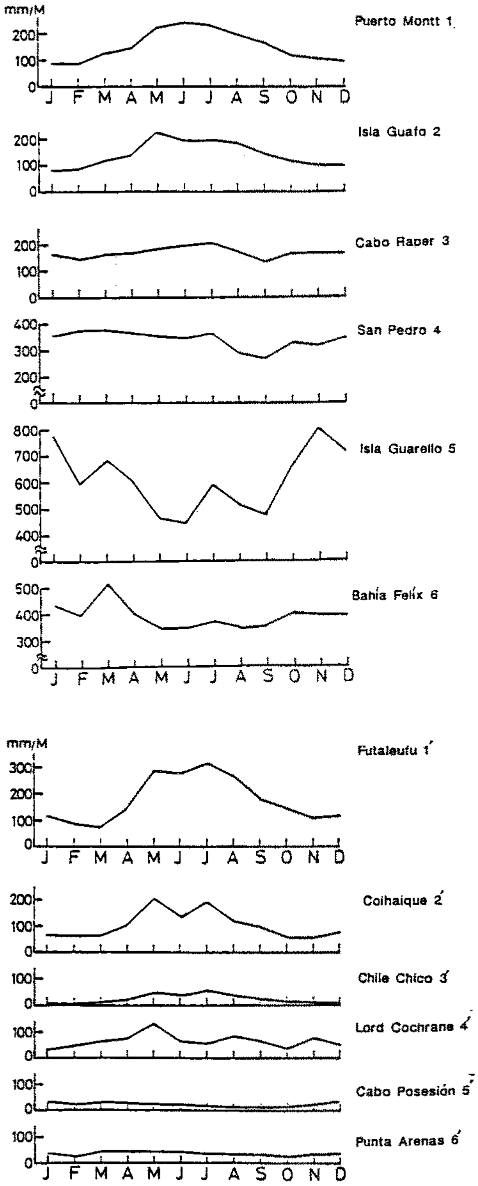

Fig. 1. Seasonal variations of the monthly amount of precipitation at the meteorological station from 1 to 6 (a) and from 1' to 6' (b). These values are averaged
from 1931 to 1960 in Puerto Montt (1), Isla Guafo (2) and Cabo Raper (3),
from 1933 to 1960 in San Pedro (4),
from 1949 to 1962 in Isla Guarello (5),
from 1921 to 1960 in Bahía Felíx (6),
from 1960 to 1984 in Futaleufu (1'),
from 1961 to 1985 in Coihaique (2') and Chile Chico (3'),
from 1980 to 1984 in Lord Cochrane (4'),
from 1915 to 1950 in Cabo Posesión (5') and
from 1988 to 1960 in Punta Arenas (6').

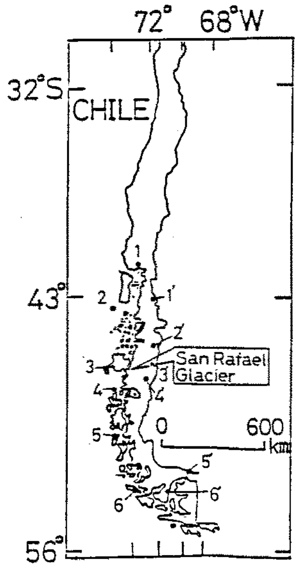

Fig. 2. Locations of each station at which statistics of precipitation were performed.

The locations of each point are shown in Fig. 2. There is a mountain chain between lines 1-6 and 1'-6'. As shown in Fig. 1a, it rains more heavily in winter than in southern summer at northern points from 1 to 3. In contrast, it rains more heavily in summer than in winter at southern points from 4 to 6, although the seasonal variation of P(M) is rather obscure than that at northern points. P(M) at southern points is larger than that at northern points. As shown in Fig. 1b, the amount of precipitation at points 1' to 6' is much smaller than that at points 1 to 6. This means that precipitation is concentrated in coastal regions and in the west side of the mountain slope, which will be discussed later.

Enomoto and Nakajima (1985) stated that precipitation does not show regular seasonal variation at BH, based on the scant data obtained by the Meteorological Office at Lagoon San Rafael for one year (1983). More detailed and prolonged work should be done to elucidate the seasonal variation of precipitation at BH. The Chilean Air Force has been making meteorological observations at BH since June 1981. The maximum annual, monthly and daily amounts of precipitation are 4.1×10^3 mm (1983), 5.6×10^2 mm (January 1982) and 1.27×10^2 mm (5 April 1983), respectively. Mean amount of precipitation in recent four years is 3.7×10^2 mm. Figures 3a and 3b show a hythergraph at BH and the relation between T_{sfc} and the frequency of precipitation, respectively. We de-

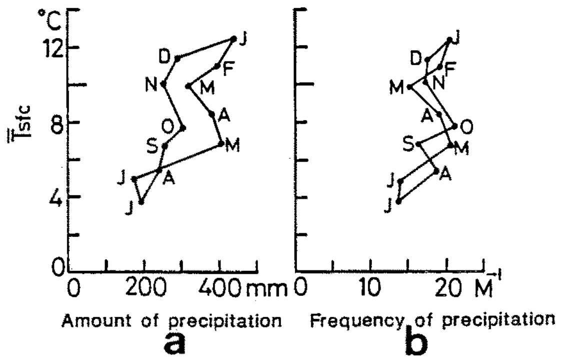

Fig. 3. Hythergraph (a) and the mean number of rainy days per one month (b) at BH.

fine the frequency of precipitation as the mean number of rainy days per one month when the daily amount of precipitation (P(D)) is larger than 0.1 mm. It rains more heavily from December to May (we will call this period as Period 1, hereafter) than from June to November (Period 2) at BH, but the frequency of precipitation is nearly the same throughout the year.

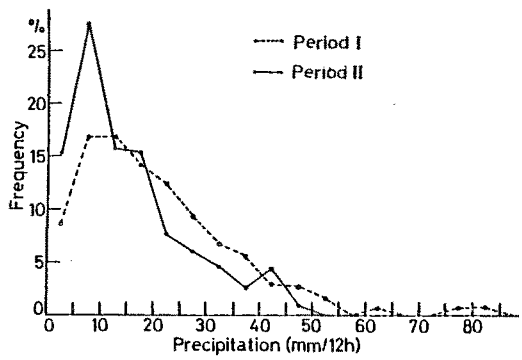

Fig. 4. Frequency distribution of the twelve-hourly amount of precipitation (P(12hr)) in Periods I and II averaged for recent four years.

Figure 4 shows the mean frequency distributions of the twelve-hourly amount of precipitation (P(12 hr)) measured at 9:00 or 21:00 LST in Periods 1 and 2. It is seen that the frequency of P(12 hr) larger than 20 mm is higher in Period 1 than that in Period 2. That is, heavy precipitation occurs more frequently in Period 1 than in Period 2.

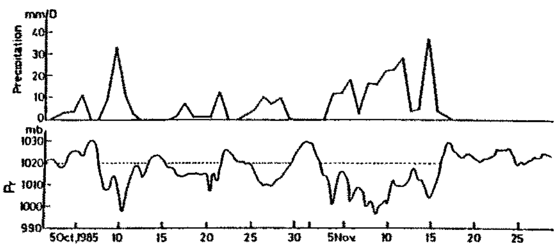

Fig. 5. Variation of surface air pressure (Pr) and the daily amount of precipitation (P(D)) with time observed from 1 Oct. to 29 Nov. 1985 at BH.

3. Surface air pressure and the amount of precipitation

Figure 5 shows an example of the variation of surface air pressure (Pr) and the daily amount of precipitation (P(D)) with time at BH. It is seen that precipitation occurred when the surface air pressure was below about 1020 mb. As we will show in section 5, the value of 1020 mb is a typical one defining anticyclones overlying the Pacific Ocean. This means that precipitation rarely occurs when anticyclones are present over the northern Patagonia. The figure also suggested the existence of a quantitative relation between the intensity of cyclone and the amount of precipitation. Naturally, the amount of precipitation is not determined only by the surface air pressure. However, the relation between the amount of precipitation and the surface air pressure is possibly one of indexes characterizing the climate of the place.

Table 1 shows the mean twelve-hourly (from 9:00 to 21:00 LST) amount of precipitation and chance of having precipitation (Cp) for each range of surface air

Table 1. Mean twelve-hourly (from 9 to 21 LST) amount of precipitation ($\bar{P}$(12 hr); mm) and chance of having precipitation (Cp; %) for each range of surface air pressure (Pr; mb) at 15 LST. N: Total number of days. σ: Standard deviation.

	Pr (m b)	975≦	980≦	985≦	990≦	995≦	1000≦	1005≦	1010≦	1015≦	1020≦	1025≦	1030≦	1035≦
Period I	$\bar{P}$(12 hr)	11.8mm	19	13.7	19.4	14.5	14.8	9.3	6.3	2.9	1.0	1.0	0	0
	σ	0	0	11.1	10.7	12.9	12.2	8.7	8.9	5.7	2.9	2.3	0	0
	Cp	100 %	100	100	100	97	94	83	74	46	25	23	0	0
	N	1	1	5	13	30	78	134	176	190	130	22	3	1
Period II	$\bar{P}$(12 hr)		12.5mm	11.5	9	9.6	7.4	6.8	5.4	3.2	1.1	0.3	0	
	σ		0	8.0	6.0	9.3	7.5	8.2	6.9	6.1	3.1	1.0	0.1	
	Cp		100 %	100	91	93	83	77	72	54	24	14	4	
	N	0	1	6	22	41	76	108	129	184	155	73	24	0

pressure (Pr) at 15:00 LST. These data were obtained by the Meteorological Office at Lagoon San Rafael from 1981 to 1985. Both $\bar{P}$(12 hr) and Cp decrease with increasing Pr in the statistically significant range (1000 mb $\leqq Pr <$ 1025 mb). $\bar{P}$(12 hr) is larger in Period 1 than in Period 2, and the gradient is larger in Period 1 (−0.67 mm/mb) than in Period 2 (−0.35 mm/mb) in the range. Cp is larger than about 50 % and smaller than 25 % when Pr is smaller than 1015 mb and larger than 1020 mb, respectively. This means that precipitation rarely occurs when Pr is larger than 1020 mb.

4. Cloud, precipitation and the vertical structure of air temperature at the terminus of San Rafael Glacier during the observational period

From our data on rainfall, the maximum hourly and three-hourly amounts of precipitation during the observational period were 11.5 and 28 mm, respectively. Figure 6 shows the percentage of each hourly amount of precipitation (P(1 hr)) to the corresponding amount of precipitation per half a day (P(12 hr)). The values of P(1 hr : Max), which shows the largest percentage in each range of P(12 hr), are 0.5, 1.5 and 3.5 mm, respectively. If P(12 hr) is divided by P(1 hr : Max), the value is nearly the same (~10) for the three ranges of P(12 hr). This fact suggests that the difference in the amount of P(12 hr) was not caused by the duration time of precipitation but by the amount of P(1 hr), that is, larger P(12 hr) was composed of larger P(1 hr).

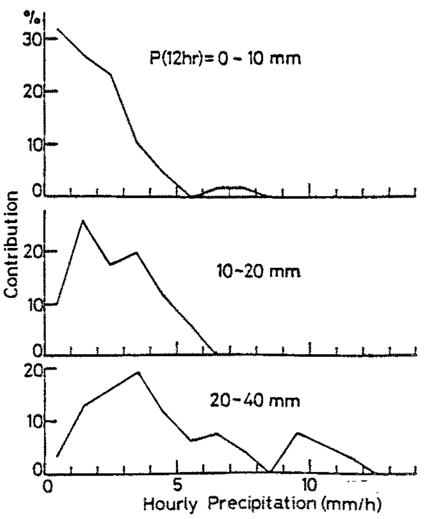

Fig. 6. Percentage in which each hourly amount of precipitation contributes to each range of twelve-hourly amounts of precipitation.

Two peaks appear clearly in the distribution of P(12 hr)=20~40 mm. This means that there were possibly two kinds of cloud systems when P(12 hr) was larger than 20 mm : one was composed of rain clouds which brought rather weak and long lasting precipitation, and the other was made up of rain clouds which brought rather strong and short lasting precipitation.

Figure 7 shows the time-height cross section of air temperature observed at BH. The height of freezing level (0°C level) was below 2 km from the ground surface before 16 November and above the level of 3 km after 18 November. When the height of freezing level was above 3 km, melting of surface ice or snow occurred in the whole area of the Northern Patagonia Icefield. There was no rain from 17 November to 1 December 1985 not only at BH but also in the whole of the northern Patagonia (Fukami *et al*., 1987). The absence of rain for such a long period of time at BH was an exceptionally unusual event. The features of vertical profile of air temperature after 17 November were the existence of temperature inversion and a very stable layer below the level 3 km.

As cold fronts associated with cyclones moved from the west (sea side) and/or the north to the east (mountain side) and/or the south, most of the rain clouds moved eastward and/or southward. Their types were N_s and C_b at BH, judging from photographs. Low level clouds were formed by forced lifting by mountains whenever the rain clouds moved eastward or southward. There was no rain when southerly and easterly winds blew. C_u type of clouds usually appeared, and both S_c and S_t types of clouds sometimes appeared only over the mountain side. When these clouds went down the slope of the mountain, they disappeared above Lagoon San Rafael because of the downward motion of air.

5. Atmospheric condition in synoptic scale during the observational period

Two main high pressure areas (H1 and H2) exist in the Pacific Ocean. H1 and H2 are called as subtropical high and subpolar high, respectively. Typical

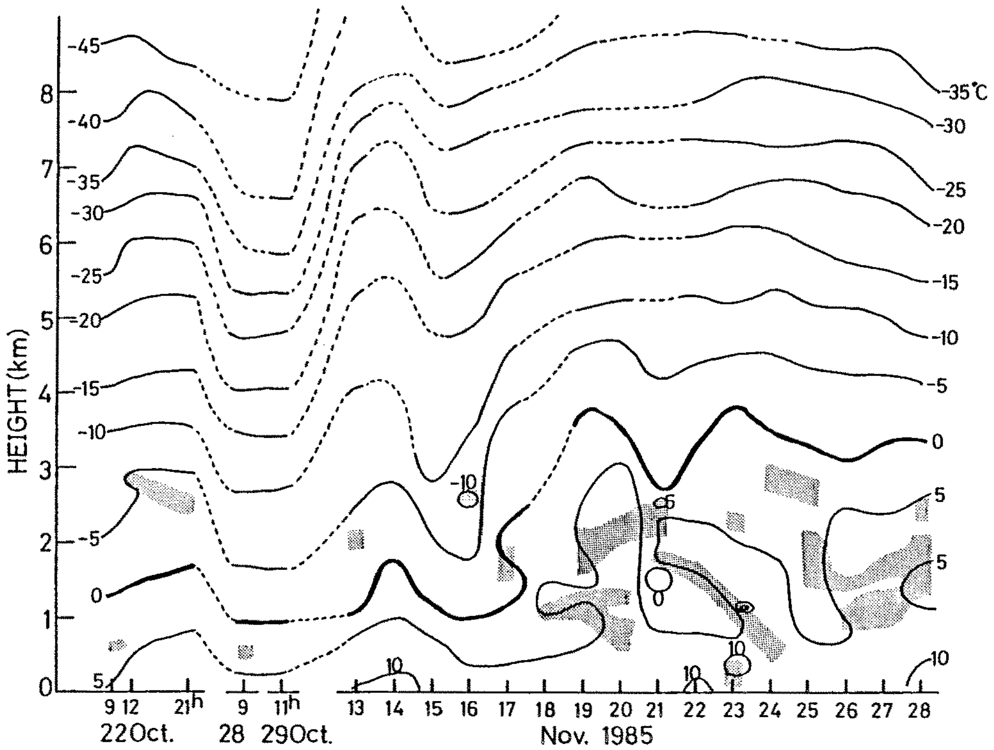

Fig. 7. Time-height cross section of air temperature above B.H. observed on 22, 28 and 29 Oct. and from 13 to 28 Nov.. Inversion layers are shaded.

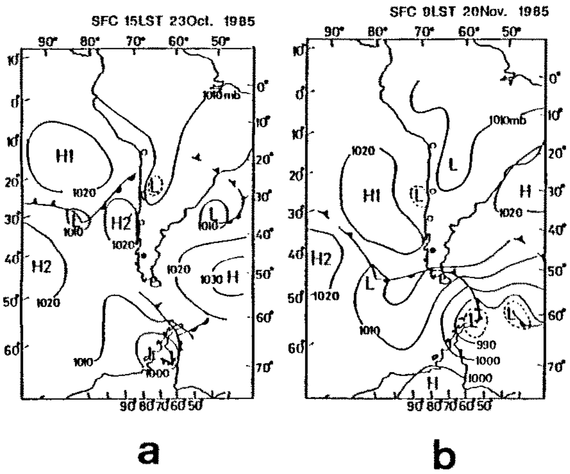

Fig. 8. Surface weather maps at 15 LST on 23 Oct. 1985 (a) and at 9 LST on 20 Nov. 1985 (b).

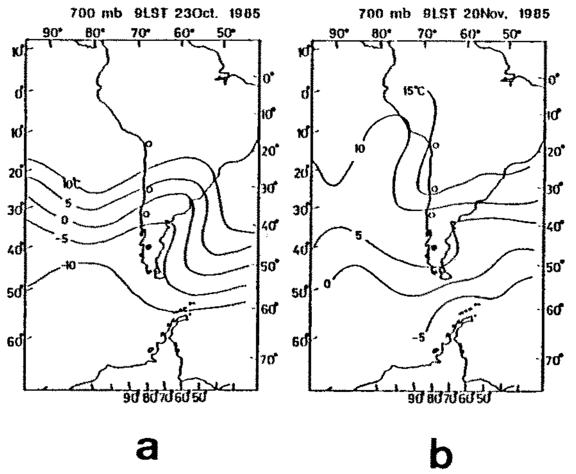

Fig. 9. Maps of air temperature at the level of 700 mb at 9 LST on 23 Oct. 1985 (a) and at 9 LST on 20 Nov. 1985 (b).

examples are shown in Figs. 8a and 8b. In Fig. 8a, anticyclone H2′ was separated from H2. There was no rain at BH when H1 or H2 spread over the northern Patagonia. Southern and eastern winds blew at BH when H1 and H2 spread over the northern Patagonia, respectively. On fine days before and after 1 November, H2 and H1 spread over the northern Patagonia, respectively. As shown in the maps of air temperature at 700 mb (Figs. 9a and 9b), warmer air invaded from the north only when H1 spread over the

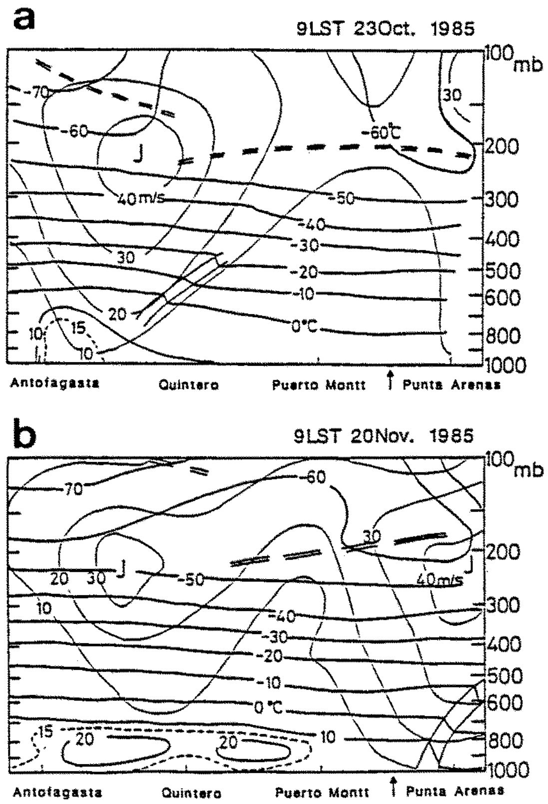

Fig. 10. Cross sections of wind and air temperature along the line from Antofagasta to Punta Arenas at 9 LST on 23 Oct. 1985 (a) and at 9 LST on 20 Nov. 1985 (b). Locations of the meteorological stations and San Rafael Glacier are shown by open and full circles, respectively.

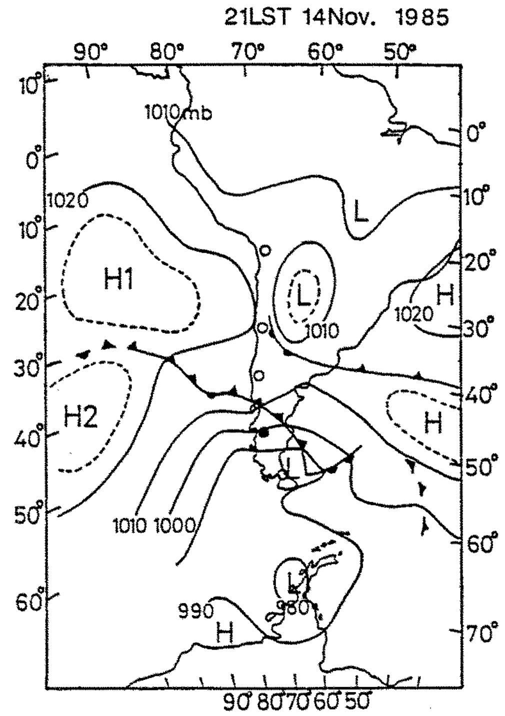

Fig. 11. Same in Fig. 8, except for 21 LST on 14 Nov. 1985.

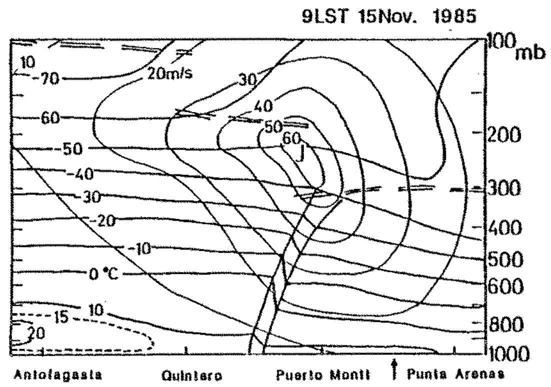

Fig. 12. Same in Fig. 10, except for 9 LST on 15 Nov. 1985.

northern Patagonia and cyclones moved southward.

Figures 10a and 10b show the typical range-height cross sections of wind and air temperature on fine days at BH. Data were obtained from the upper air soundings made at Antofagasta, Quintero, Puerto Montt and Punta Arenas. A surface cold front existed between Antofagasta and Quintero when H2 spread over the Patagonia region (Fig. 8a). In contrast, a surface cold front existed near Punta Arenas when H1 spread over the Patagonia region (Fig. 8b). As shown in Fig. 10b, there was a temperature inversion below 850 mb and a freezing level that existed above 700 mb in the air mass lying in a lower latitude than the front. The results are consistent with ours obtained by upper air soundings made at BH (see Fig. 7).

Precipitation occurred at BH when the cold front passed through the Patagonia. A typical example of a surface weather map was shown in Fig. 11. The cyclone moved from the west to the east and generally in succession. Figure 12 shows the cross section of wind and air temperature. The cold front exists between Quintero and Puerto Montt.

6. Increment of the amount of precipitation with altitude

Annual amount of precipitation around the accumulation area of San Rafael Glacier has not been elucidated so far. As stated in section 2, the amount of precipitation on the lee side of the mountains is quite small compared with that on the windward side of the mountains. This fact suggests that almost all water vapor is consumed on the windward side of the mountains.

Total amount of precipitation during the observational period was measured along San Rafael Glacier. Total amount of precipitation at each point during our observational period was divided by that at BH in order to elucidate the change in the amount of precipitation with altitude. In Fig. 13, the ratio of the total amount of precipitation is compared with the gradient of slope. In spite of the small difference in altitude between points BH and G1, a high value of the ratio (1.7) was obtained. The ratio increased with increasing altitude below the level of G4. However, it did not increase between the levels G4 and C2. The ratio of 0.5 was obtained when the total amount of precipitation at BH is compared with that at Base Camp on Soler Glacier, which is located on the east side of the Northern Patagonia Icefield. From these facts, we can safely expect that the annual amount of precipitation around the heart of the icefield is nearly three times larger than that at BH, i. e., 10,000 mm.

Figure 14 shows the distribution of contribution ratio of P(1 hr) to the total amount of precipitation at different altitudes (BH, C1 and C2). It is seen that the contribution ratio of large P(1 hr) increased with increasing altitude. Figure 15 indicates the frequency distribution of the duration time (hour) of precipitation with P(1 hr) $\geqq$ 0.5 mm. It was also found that the duration of precipitation increased with increasing altitude.

7. Summary and discussion

It rained more heavily in winter than in summer at the stations located in latitudes lower than 46°S. In contrast, it rained more heavily in summer than in winter at higher latitudes, although the seasonal variation is rather obscure. The monthly mean amount of precipitation at the former stations was larger than that at the latter stations throughout the year. It rained more heavily in Period 1 (from December to May) than in Period 2 (from June to November) at the terminus of San Rafael Glacier, but the number of rainy days did not show seasonal variation. Taljaard (1967) made a distribution map of cyclone centers in

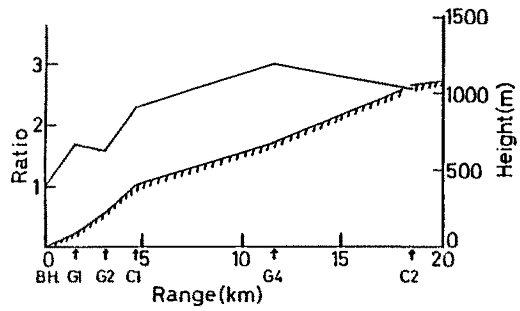

Fig. 13. Change of total amount of precipitation with altitude and the range-height cross section of glacier surface along the line from BH to C2.

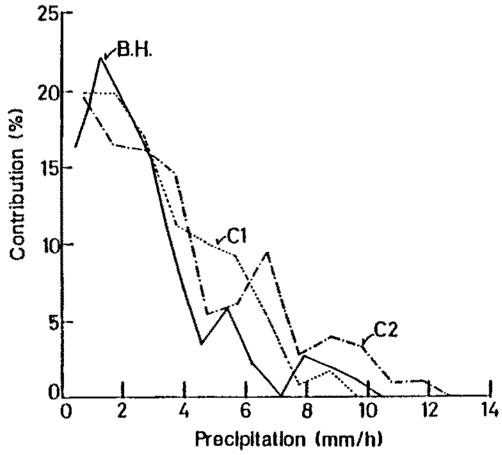

Fig. 14. Distribution of contribution ratio of P(1hr) to the total amount of precipitation at three different altitudes (BH, C1 and C2).

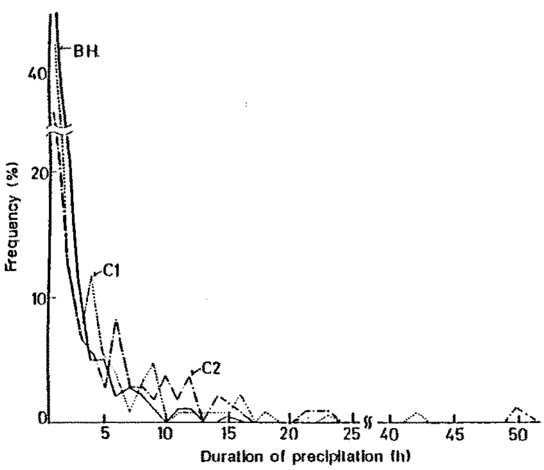

Fig. 15. Frequency distribution of the duration time (hour) of precipitation at BH, C1 and C2.

the Southern Hemisphere. He showed that areas with high concentrations of cyclone centers exist at a higher latitude in summer than that in winter. Our results presented above suggest that San Rafael Glacier is situated in the northern limit of heavy precipitation caused by cyclones in southern summer.

Both twelve-hourly amount of precipitation (P(12 hr)) and chance of having precipitation decreased with increasing surface air pressure (Pr) at BH. Precipitation rarely occurred when Pr was larger than 1020 mb. P(12 hr) is larger in Period 1 than in Period 2. The rate of decrease in P(12 hr) with Pr was statistically evaluated ; it was -0.67 mm/mb in Period 1 and -0.35 mm/mb in Period 2. These values can possibly be used as one of the indexes which characterize the climatic condition of a place.

The remarkable features of the vertical structure of air temperature above BH are the existence of both strong temperature inversion and a rather stable layer below the level of 3 km. Such a structure appeared only when an anticyclone centered in the Pacific Ocean off the coast of Peru spread over the northern Patagonia. In this case, the weather was fine at BH and the air temperature below the level of 3 km was higher than 0°C. When such a condition was satisfied, melting of ice would proceed rapidly, even on the icefield of the glacier. Therefore, attention should be paid to the anticyclone to estimate the mass balance of the glacier.

It was found that both intensity and duration of precipitation increased with increasing altitude. There are four general mechanisms that explain this result :

a) Upslope lifting with rapid hydrometeor formation and fall-out ;

b) seeder-feeder cloud mechanism ;

c) deep or shallow convection produced by convergence in the thermally created mountain-valley circulation ; and

d) deep or shallow convection produced by orographic lifting. Judging from the photographs taken from a LADECO airplane, there seemed to be no difference in the level of cloud top above the mountainous region and that above Lagoon San Rafael. Therefore, deep convection would not be produced on the mountain. More than one of these four mechanisms may be at work at any given time.

The ratio of total amount of precipitation between points BH and C2 was 2.6. As the mean annual amount of precipitation is 3.7×10^3 mm at BH, the annual amount of precipitation at the center of the icefield is estimated to be about 10,000 mm. The ratio had a tendency not to increase with increasing altitude above G4 (639 m). And the ratio between BH and Base Camp on Soler Glacier was 0.5. Therefore, it is suggested that the mean annual amount of precipitation on the icefield above C2 (1040 m) would not exceed 10,000 mm.

Acknowledgments

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Resumen

Características de la precipitación y estructura vertical de la temperatura del aire en el norte de Patagonia

Se realizó observaciones meteorológicas desde Octubre de 1985 a Febrero de 1986 cerca del frente del Glaciar San Rafael (46°37′ S, 73°53′ W). Los objetivos principales son clarificar las características

de la precipitatión y la estructura vertical de la temperatura del aire en la región.

Por medio de tres pluviómetros automáticos y cuatro pluviómetros totalizadores se midió la cantidad de precipitación a lo largo del Glaciar San Rafael. Durante el día en el frente del glaciar se realizó sondeos de la alta atmósfera con radiosondas. Los hallazgos más importantes son los siguientes :

1) A partir de la información recolectada en estaciones meteorológicas ubicadas en la costa occidental de Chile entre los 43°12′ S y los 53°10′ S, se encontró que a latitudes menores de 46° S la precipitación es mayor en invierno que en verano. Sin embargo, en el frente del Glaciar San Rafael y a latitudes mayores que 46° S, sucede lo contrario, a pesar que la variación estacional es poco clara. En latitudes altas la precipitación media mensual a través del año es mayor que en latitudes bajas (Fig. 1).

2) A partir de la información recolectada por la Dirección Meteorológica de Chile en Laguna San Rafael desde Junio 1981 a Diciembre 1985, se encuentra que tanto la precipitación en 12 horas (P(12 hr)) como la probabilidad de ocurrencia de precipitación decrecen al aumentar la presión atmosférica en superficie (Pr) (Tabla 1). Hay escasa precipitación a presiones mayores de 1020 mb. La precipitación media mensual en el frente del Glaciar San Rafael en los últimos cuatro años es de $3,7 \cdot 10^3$ mm. La precipitacion máxima anual, mensual y diaria es de $4,1 \cdot 10^3$, $5,6 \cdot 10^2$ y $1,27 \cdot 10^2$ mm, respectivamente.

3) A partir de nuestras observaciones de radiosonda, se encontró que cuando el anticiclón del Océano Pacífico se centraba frente a las costas de Perú, extendiéndose sobre el norte de Patagonia, en el frente del Glaciar San Rafael bajo el nivel de 3 km se presentaba una capa bastante estable con una fuerte inversión térmica. Bajo tales condiciones, la temperatura del aire bajo el nivel de 3 km era superior a 0°C.

4) Tanto la intensidad como la cantidad de precipitación aumentaban con la altura. Se estima que en el centro del campo de hielo la precipitación es unas tres veces mayor que aquella observada en el frente del Glaciar San Rafael, es decir del orden de 10.000 mm (Figs. 13, 14 y 15).