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Summer climate of the Northern Patagonia Icefield

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Abstract

The summer climate of the Northern Patagonia Icefield is outlined on the basis of observational data at seven stations from the west coast to the east slope including the icefield in 1985. The temperate and humid climate up to the altitude of the icefield on the western slope suggests that intense ablation of the glacier takes place in summer. The change in air mass stability causes an altitudinal increase of the temperature difference between warm/sunny and cold/rainy periods. The mid-summer, December and January, can be distinguished from the transitional months of October and November by the amplitude and periodicity of the daily mean temperature trend. Strong northerly wind followed by rain prevails both on the coast and icefield, while calm occurrs on the icefield during weak southerly wind followed by sunny weather prevails on the coast. Down-glacier wind prevails along the valley of San Rafael and Soler Glacier. These two winds show the respective natures of maritime and continental origins. A cold environment is produced on the glacier surface. The cold air increases in depth near the snout of San Rafael Glacier, and extends towards the upper part of glacier in mid-summer.

1. Introduction

Patagonia is known as the land confronting the "roaring forties". The heavy rainfall of 4000 mm per annum on the west coast and intense east-west climatic contrast are produced when continuous passage of cyclones along the polar front encounters the Andean Range throughout the year. However, sparse meteorological data in the ice-covered mountain areas make it difficult to analyze the physical mechanism of these striking climatic features.

The first preliminary work to study this mechanism on the Northern Patagonia Icefield (NPI) was done by the Glaciological Research Project in Patagonia (GRPP) in 1983-84. Nearly one month's meteorological observations were made on San Rafael and Soler Glaciers mainly in December of 1983 (Nakajima, 1985). Weather information on the icefield was collected by short-term observations. The remarkable increase of precipitation with altitude and the intense east-west climatic contrast represented by the frequent occurrence of föhn in the Soler area were demostrated by their report (Ohata *et al.*, 1985a, b ; Kobayashi and Saito, 1985).

Longer-term observation were made through a widely distributed meteorological network from October 1985 to January 1986 by the second GRPP. The observation covered almost the whole glacier ablation season. Nearly three months' meteorological data at three stations (100, 400, 1000 m a. s. l.) in the San Rafael area and two months' data at two stations (300, 400 m) in the Soler area were collected. The precise altitudinal distribution of precipitation, temperature and humidity were obtained from the western coast to the eastern flank. In this paper current meteorological observations on the San Rafael Glacier are outlined. Subsequently, mean condition and time-series change of the meteorological elements at each station including the Soler area are presented. The analyses of the precipitation and cloud, and the de-

Table 1. Stations and elements of the meteorological observation in the San Rafael area and the average climatic summary (*AT*: temperature, *RH*: relative humidity, *VP*: vapor pressure, *R*: temperature lapse rate between BH and each station, *AP*: atmospheric pressure, *q*: specific humidity, *Qr*: global radiation). (R : automatic recording, M : meter reading or visual observation).
* year-round observatory maintained by Meteorological Office of Chile.
** No record during the DS observation.

Station Alt. (m)	BH * (6)	G1 (89)	C1 (422)	C2 (1040)	DS (1296)
Duration		Oct. 24- Feb. 6	Oct. 20- Feb. 5	Oct. 26- Feb. 1	Nov. 16- Dec. 2
Nr. days		106	109	99	17
A. Pres.	R	–	–	R**	R
A. Temp.	R	R	R	R	R
R. Humid.	R	R	R	R**	R
Wind	M	R	M	M	M
Precip	M	M	R	R	M
Weather	M	M	M	M	M
AT (°C)	10.4	8.5	7.8	4.9	
RH (%)	83	79	85	84	
VP (mb)	10.49	8.69	8.86	7.06	
R (°C/100m)	–	2.3	0.63	0.53	
AP (mb)	1015.2	–	–	895.1	
q (g/kg)	6.4	5.3	5.7	4.9	
Qr (MJ/m^2)	14.8	15.1	15.4	–	

tailed observations on the Soler Glacier are given in the individual papers (Fujiyoshi *et al*., 1987 ; Fukami *et al*., 1987).

2. Meteorological observations and mean climatic condition of San Rafael area

An outline of the meteorological observation in the San Rafael area is shown in Table 1. The stations were chosen along the San Rafael Glacier (see Map 2, folded in). Three stations (G1, C1, C2) were established on rock terraces elevated around ten to several tens of meters above the glacier surface. Short term observations were made at DS, situated in the heart of the icefield. An observation denoted by "M" is a temporal visual observation limited to the daytime. BH is a year-round observatory maintained by the Meteorological Office, Chilean Air Force.

The climatic summary of four stations averaged in the whole obsevation period are shown in the lowest columns of the table. Apart from this summary, the most striking fact obtained by our observation is that the maximum precipitation occurs at an altitude of around 700 m (Fujiyoshi *et al*., 1987). Fuenzalida also states that the peak precipitation appears to occur well below the ridge line in the area just north of NPI (Miller, 1976). The altitudinal change of the global radiation is not evident below C1. The high values of the relative humidity of nearly 80% show that the humid condition is kept up to the height of the icefield. The mean temperature is above freezing point and the water vapor pressure is supersaturated over the ice surface up to the height of the icefield. This means that both sensible and latent heat are transported to the glacier surface in the mean ; consequently, a large amount of ice melting occurs throughout the glaciers of NPI in this season.

The temperature lapse rate between BH and each station height is estimated using the surface temperature. A detailed discussion of the surface temperature lapse rate will be given in section 5. The mean atmospheric condition of the San Rafael area during the whole period represented by the lapse rate of 0.53° C/100 m between BH and C2 is close to the wet adiabatic lapse rate.

The climatic data at G1 is anomalous compared with the values at BH, which is 2 km in distance and 80 m in elevation from G1. The extremely large lapse rate of 2.3°C/100 m and small specific humidity compared with the neighboring two stations imply a local cold climate around G1. This is revealed by the frequency distribution of wind direction at four stations including the Soler area shown in Table 2. Wind directions were measured clockwise from due north with 60° intervals due to the accuracy limitation

Table 2. Percentage frequency of the wind direction (in degree from due north) at four stations. Observation intervals; BH (09, 15, 21 h), G1 (hourly), C2-DS and BC (every 3hrs from 09 to 21 h).

	San Rafael Glacier		Soler Glacier	
	BH	G1	C2-DS	BC
calm	10	0	29	11
30	6	6	44	1
90	2	69	9	0
150	46	8	1	4
210	4	0	2	1
270	4	8	1	78
330	29	8	15	5

of the wind vane employed at G1. Northerly wind followed by rainy and southerly wind followed by sunny weather prevail on the west coast. On the icefield, the wind is mainly from the north, and calm condition increases when weak southerly wind blows at the coast. The wind direction at the valley station is definitely concentrated at 90° at G1 and 270° at BC. They are down-valley winds. The local climate may be caused by this wind.

3. Time-series of temperature

The daily mean and 5-day moving average (*Tav*) of air temperature at four stations of the San Rafael area and the daily precipitations in the San Rafael and Soler areas are shown in Fig. 1. The precipitation in the Soler area is decreased but synchronized with that of the San Rafael area. The increases of temperature coincide well with no-rain periods. The 15-day continuous no rain period from the middle of November is most pronounced. The mid-summer, December and January, can be distinguished from the transitional months of October and November with large amplitude and periodicity of *Tav*. The trend of *Tav* at BH differs from the other three stations in December. *Tav* of BH increases from the middle of the month, though it decreases at the other three stations. The decrease of *Tav* at C2 is delayed to G1 and C1.

The temperature lapse rate (R) between BH and the other stations is estimated using the surface data to find the atmospheric stability in the lowest 1000 m, shown in Fig. 1c. The trend of R(BH-C2) has roughly a negative correlation with *Tav* at C2 throughout the period. This means that warm and cold air masses are followed by stable and unstable atmo-

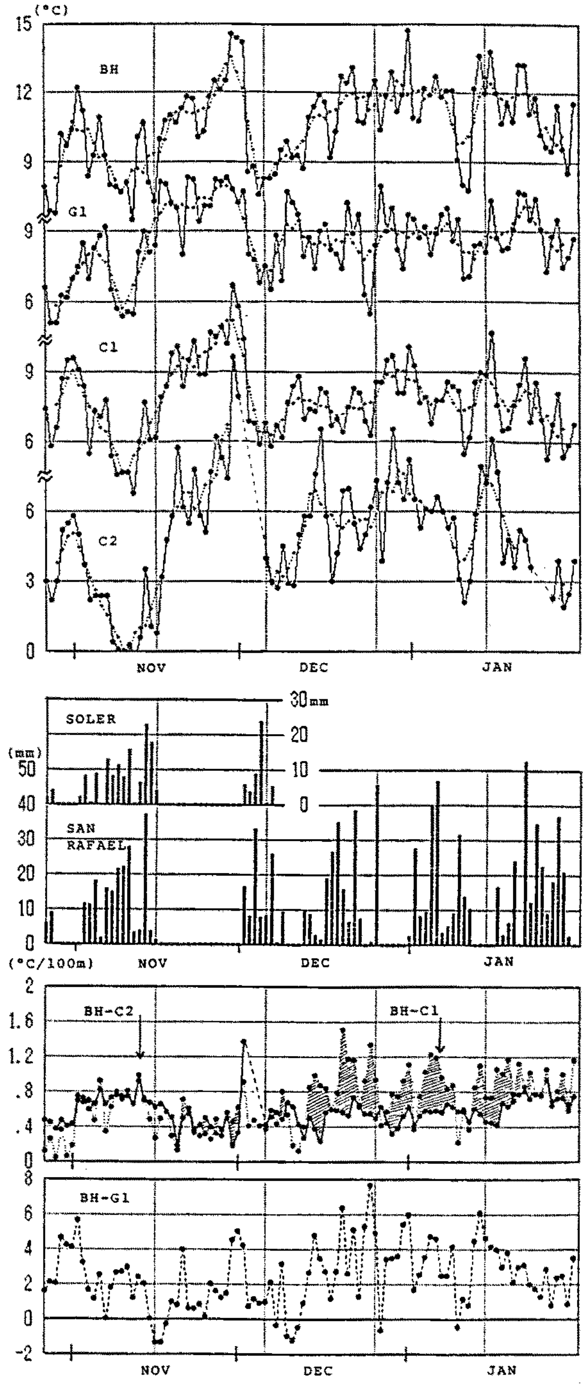

Fig. 1. (from top) a) Mean daily (solid line) and 5-days moving average (dotted line) of the air temperature at four stations of San Rafael area. b) Daily precipitation at Soler and San Rafael area. c) Temperature lapse rate between BH and C2 (solid line) and between BH and C1 (dotted line). d) Temperature lapse rate between BH and G1.

sphere, respectively. R(BH-C1) shows a drastic change in mid-summer. It is smaller than R(BH-C2) in November, while it becomes larger in December and January with a marked several-day periodicity.

R(BH-G1) is much larger than other R values. This is obviously ohe effect of the prevailing cold glacier wind at G1. R(BH-C1) becomes closely corelated with R(BH-G1) in December and January. Since R(BH-G1) is regarded as the index of the development of the glacier wind at G1 (Ohata *et al.*, 1985a), the increase of R(BH-C1) in mid-summer is can be explained by horizontal extension of the glacier wind up to C1 in this season.

4. Local climate and east-west climatic contrast

Some stations are under the influence of the local glacier climate and may not represent the large scale atmosphere as mentioned in the foregoing section. Each station temperature is compared with that of the free atmosphere obtained from radio sondes launched at BH (Fujiyoshi *et al*, 1987). From the results shown in Fig. 2, the temperature of the station and the free atmosphere are almost same at C1 and C2, though the station temperatures are cooler at G1 and DS regardless of rainy/sunny weather condition. Both C2 and DS are located on the vast snowfield, and the local wind is not evident there. The lowered station temperature at DS might be the normal condition of the icefield. Since the instruments are installed at the screen height above the snow at DS and the radio sondes were launched mainly around 09hLT, the surface air layer is stably stratified, and cooling must be effective. Unlike at DS, C2 is settled on the rock terrace of a nunatack and the instruments were elevated several tens of meters from the snow surface. The effect of surface cooling may vanish within this altitude.

Climatic data at seven stations of NPI are compared. Among the Soler stations, GL is located on the glacier and BC is on the ground 1 km down from the snout of Soler Glacier. Concurrent observations at San Rafael, Soler area and on the icefield including radio soundings were made in November. To distinguish synoptic, local and microclimatological effects, data are summarized for rainy (Nov. 3-16) and sunny (Nov. 17-Dec. 1) periods and shown in Table 3.

The temperature differences between rainy and sunny periods at C2 and BC are as large as 6°C ; the differences increase with altitude along the San Rafael glacier. Surface temperature lapse rates ($R1$) between C2 and each station are estimated. Since the temperatures at C2 are regarded as almost same as those of the free atmosphere, $R1$ is considered to show the temperature anomaly from the synoptic condition at each station. The lapse rates ($R2$) between the corresponding altitudes of the free atmosphere estimated from one-a-day radio sondes launched around 09 hLT are also shown for the San Rafael stations above the height of G1. $R2$ (BH-C2) is considered to be the same as $R2$(G1-C2) due to its small altitude difference. The deviation of $R1$ from $R2$ is small except at G1. The above temperature difference for rainy and sunny periods can be explained by the air mass change in the free atmosphere as shown by the

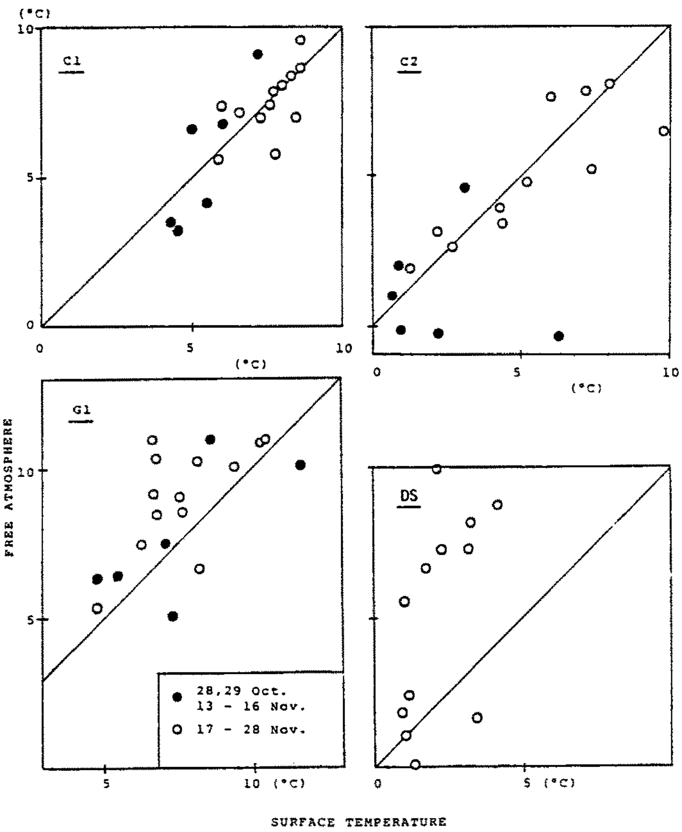

Fig. 2. Air temperature at each station and free atmosphere.

Table 3. Climatic summary at seven stations during rainy (R) and sunny (S) periods in November. *T*: temperature (°C). *R*: lapse rate of surface temperature (°C/100 m), *R1*; between C2 and each station, *R2*; same layer of free atmosphere with *R1* is estimated. *RH*: relative humidity (%). *VP*: vapor pressure (mb). *CA*: cloud amount (in tenths). *WD*: prevailing wind direction (degree). *V*: mean wind speed (m/s).

station (altitude)		San Rafael Glacier BH (6)	G1 (89)	C1 (422)	C2 (1040)	DS (1296)	GL (378)	Soler Glacier BC (277)
T	R	8.8	7.5	6.1	1.4		5.1	7.3
	S	11.7	10.5	9.9	7.3	3.0	8.7	13.5
R1	R	0.72	0.64	0.76			0.58	0.80
	S	0.43	0.34	0.42		1.68	0.22	0.84
R2	R		0.71	0.72				
	S		0.46	0.40				
RH	R	84	83	89	93		70	76
	S	72	72	75		68	59	59
VP	R	9.67	8.53	8.31	6.00		5.98	7.54
	S	9.70	8.79	8.85		4.98	6.40	8.33
CA	R	9				10		8
	S	5				3		1
WD		0/180	90			0	270	270
V	R	4.4	2.6				3.3	2,2
	S	3.3	2.9				3.1	2,3

remarkable difference of *R2* for rainy and sunny periods.

The average synoptic situation of NPI can be shown by *R1*(BH–C2) and *R1*(BC–C2). On the western slope it is conditionally unstable in the rainy period and absolutely stable in the sunny period. However, on the eastern slope the lapse rate is nearly dry adiabatic both in sunny/rainy periods. This large lapse rate is not produced by the differece in the surface condition between BC and C2, because there is no marked difference of *R1* in sunny/rainy periods. Considering the prevailing down-valley wind of the Soler area, the temperature of BC might be governed by adiabatic descent of the air flow from the icefield represented by the temperature at C2. This assumption also explains the large temperature difference between sunny and rainy periods at C2 and BC. However, the small temparature difference between sunny/rainy periods at GL and extremely low temperature at DS are inconsistent with this assumption.

The mean diurnal courses of the temperature at C2, DS, GL and BC are shown in Fig. 3. Those at C2 and BC have similar patterns both in rainy and sunny periods. The daytime increase of temperature is small at GL and DS compared with the other two stations. This is marked in sunny periods. A peculiarity of the location common to DS and GL is that the stations are in contact with snow or ice surface. Not only is the surface absorption of solar radiation small but the absorbed energy is used not for air temperature rise but ice/snow melting.

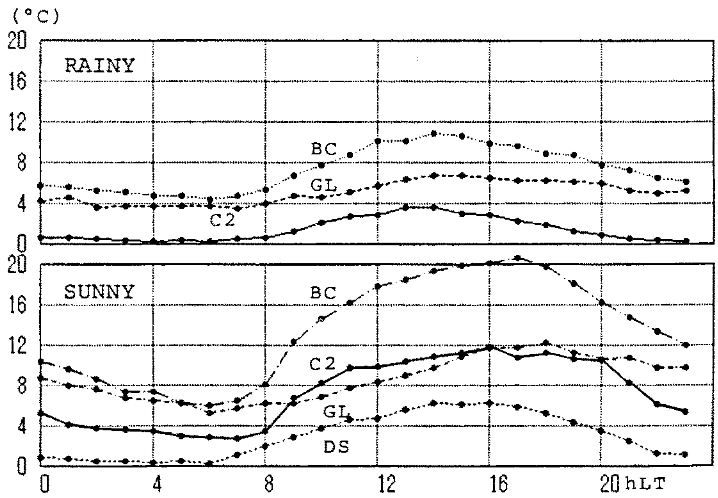

Fig. 3. Mean diurnal course of the air temperature at C2, DS, GL and BC in rainy and sunny periods in November. LT is GMT minus 3 hours.

5. Local down glacier wind

The down glacier wind in the valley and its effect on the local climate was frequently referred to in the preceding sections. The difference in the nature of the wind of San Rafael and Soler Glaciers is discussed in this section. Distinction of the two wind is difficult from the directional constancy (Table 2) and mean wind speed (Table 3). The wind speed at BC is considered to be decreased by the windward moraine hills (Fukami *et al.*, 1987) and it cannot be said that the wind force is decreased leaving the glacier. This is substantially different with the wind of San Rafael Glacier. The latter vanishes within 1 km from the glacier snout. The mean diurnal course of the wind, temperature and humidity at G1 and GL in sunny/rainy periods are shown in Fig. 4. The daytime increase of wind force is common for each case and it is most noticeable at GL in sunny period. The dependence of the wind speed on the temperature is not obvious at G1, because the marked difference between sunny and rainy periods in the temperature change is not found for the wind speed. The temperatures at the two stations are considered to be influenced by the wind of glacier origin and cannot be regarded as an index of the driving force of the wind.

The vapor pressure seems to be more correlated with wind force. The vapor pressure increase is associated with the wind speed at G1. However, a negative correlation is found at GL ; this is marked in the sunny period. Namely, the air becomes humid at G1 and dry at GL with increasing wind force. The wind at GL can be regarded as having the nature of a föhn. The vapor at San Rafael is super-saturated over ice and cannot be regarded as evaporated from the glacier surface. The principal reason for the opposite nature of humidity at GL and G1 is the difference in the nature of the air mass entrained during travel over the glacier. The wet maritime air over the San Rafael area and dry continental air over the Soler area might be substantial. Further discussions of the nature of the wind are given in separate papers (Inoue, 1987 ; Fukami *et al.*, 1987).

6. Concluding remarks

The climatic summary obtained by our observations at each station of NPI is a mixture of synoptic, local and microclimatic scale products. The effect of the glacier surface is dominant for the latter two. The following findings can be noted from the separation of the individual effects.

The negative deviation of the temperature from the free atmosphere is shown at stations in close

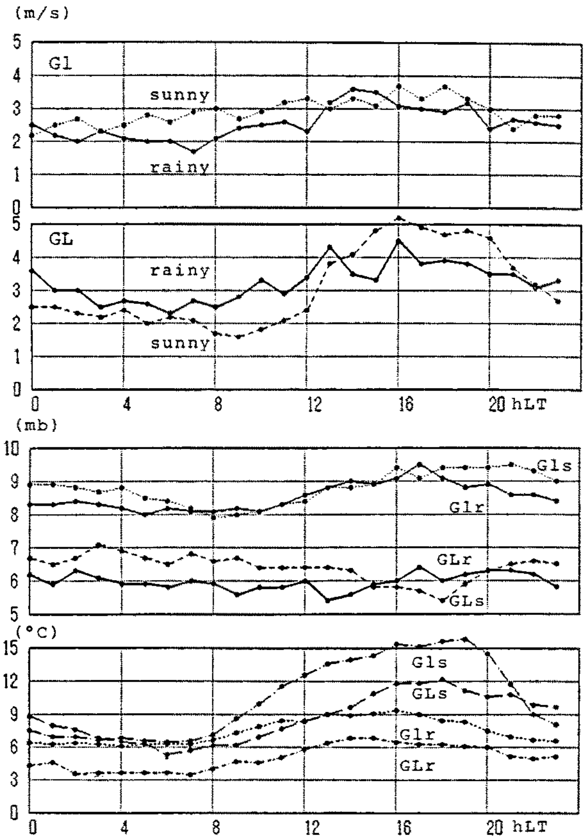

Fig. 4. Mean diurnal course of the meteorological elements in rainy and sunny periods (from top) wind speed a) at G1 ; b) at GL ; c) vapor pressure at G1 and GL ; d) temperature at G1 and GL.

contact with the glacier surface ; cold environments are produced.

The increased temperature difference between rainy/sunny periods with altitude is mainly caused by synoptic conditions. Stable and unstable conditions of the atmosphere below the level of NPI are produced by the passage of warm (sunny) and cold (rainy) air masses. This is most pronounced by the lower warm and upper cold air mass in the middle of December.

The dominant wind is northerly followed by rain over the area from the west coast up to the icefield. The southerly breeze on the coast and calm on the icefield take place in sunny periods. The predominant down-glacier wind prevails in the valleys of San Rafael and Soler Glacier.

Föhn is observed frequently in the Soler area (Kobayashi and Saito, 1985) ; several cases of föhn were found during the current observations (Fukami *et al.*, 1987). However, they are not produced by the typical process of rain on the western slope and dry adiabatic compression on the eastern slope. This is clear because the föhn in the Soler area is most pronounced during sunny periods. The dry air flow on Soler and the moist one on San Rafael Glacier may be produced by the nature of the air masses on the west and east slopes.

The mid-summer, December and January, can be distinguished from the preceding transition months by the trend of mean daily temperature at each station. The increase of the temperature lapse rate between BH and C1 may be produced in accordance with the change of the season to mid-summer. One possible explanation for this increase is the horizontal extension of the San Rafael glacier wind. Through the current observations made mainly in October and November, various climatic remarks are appended to the results of the first GRPP observations in December. Year-round observations are needed for complete understanding of the NPI climate.

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Resumen

Clima de verano en el Hielo Patagónico Norte (HPN)

Durante el verano austral de 1985-86 se realizó observaciones meteorológicas en siete estaciones en la zona de los Glaciares San Rafael y Soler, incluyendo el campo de hielo. En este trabajo se resume las observaciones y resultados de la zona del Glaciar San Rafael.

Tal como se aprecia en la Tabla 1, el clima húmedo y temperado que existe hasta la cota del campo de hielo sugiere que durante el verano ocurre una intensa ablación glaciar. Los meses de pleno verano, Diciembre y Enero, pueden ser distinguidos de los meses de transición de Octubre y Diciembre por la amplitud y periodicidad en la temperatura media diaria del aire (ver Fig. 1). Tanto en la costa como en el campo de hielo prevalece un fuerte viento norte seguido de precipitación, mientras que cuando prevalece en la costa débil viento sur seguido de buen tiempo, en el campo de hielo ocurren períodos de calma. La variación en la estabilidad de la masa de aire provoca un aumento altitudinal en la diferencia de temperatura entre períodos cálidos con sol y períodos fríos lluviosos.

El contraste climático este-oeste y el clima local del glaciar fue analizado usando información climática de la zona del Glaciar Soler (Tabla 3). La Fig. 2 muestra que sobre la superficie del glaciar se desarrolla un medio ambiente frío. El aumento diario de temperatura en la superficie del glaciar es pequeño ; en especial esto se aprecia durante períodos de sol en la Fig. 3. Una similar zona fría es producida cerca del frente del Glaciar San Rafael, tal como se muestra en la Fig. 2. La superficie de esta zona aumenta en la mitad del verano en la parte inferior del glaciar (Fig. 1). A lo largo de los valles San Rafael y Soler prevalecen vientos en dirección aguas abajo del glaciar (Tabla 2). A pesar que en estos dos valles la velocidad del viento aumenta en general durante el día, solamente se observa una relación directa entre dicha velocidad y la tempe-

ratura para el Glaciar Soler (ver Fig. 4). La correlación entre la velocidad del viento y la presión de vapor es positiva en el Glaciar San Rafael y negativa en el Glaciar Soler. Estos dos vientos muestran una respectiva naturaleza de origen marítimo y continental.