Bulletin of Glacier Research 4 (1987) *25−30*

Wind regime of San Rafael Glacier, Patagonia

Jiro Inoue
Disaster Prevention Research Institute, Kyoto University, Uji 611 Japan

(Received December 17, 1986 ; Revised manuscript received January 19, 1987)

Abstract

The wind on the glacier near the snout of San Rafael Glacier was analyzed from a continuous record from October to November, 1985. A predominant glacier wind was found 70 % of the time, while mountain and valley winds share the remaining time with external general wind. Although the glacier wind shows a diurnal change, there is no difference in the frequencies for day and night. The non-stationary nature of the glacier wind is suggested by the following features. The depth and period of the glacier wind increase and the temperature decreases with increasing velocity. The wind velocity observed 4 km upstream from the glacier snout is small and stationary, and rarely exceeds that near the snout. The frequency of the glacier wind decreases when the external wind is strong northerly. This wind may disturb the production of the glacier wind over a large horizontal area.

1. Introduction

A persistent glacier wind on the ablation area of San Rafael Glacier was found by Ohata *et al.* (1985). According to their observations near the snout in December, 1983, the glacier wind has an average speed of 4-5 m/s and frequency of 90 % in the daytime.

The glacier wind is driven by the potential temperature difference between the glacier surface and the free atomosphere (Defant, 1957). The glacier surface can be regarded as kept at the freezing point, and the atmosphere below the icefield height has positive temperature throughout the observation period (Inoue *et al.*, 1987). Below this height a gravity wind may occur wherever the glacier surface slopes. San Rafael Glacier has marked sloping from the ice plateau at an altitude of 700 m, and the average inclination is 75 m/1 km. The driving force of the gravity wind deduced from the above inclination and the summer mean temperature of 8° C (from October to January) at Cl (422 m, the middle of the ablation area) are fairly large. However, the surface wind on the glacier is frequently replaced by an external general wind ; glacier wind more than 10 m/s was not found in pilot-balloon observations (Ohata *et al.*, 1985). Ohata *et al.* suggested that the glacier wind is limited in the vertical and horizontal scale.

The present author discusses the nature of the wind based on the continuous record on San Rafael Glacier made from October 17 to November 27, 1985.

2. Statistical summary of the wind

Station Gl (89 m) was established on the right bank of San Rafael Glacier 200 m upstream from the snout (see Map 2 folded in). The anemograph was set up on the rock terrace of Gl elevated 15 m above the glacier surface. Every 10 minutes, values of wind speed and direction were recorded from October 17 to December 8. The detailed scheme of meteorological observations including the station network are described by Inoue *et al.* (1987). Employed for this analysis are the data from October 7 through November 27 without discontinuance. The accuracy of the direction is ±30°, limited by the vane that was used.

The frequency distributions of the wind direction at Gl for day and night are summarized in Table 1. The data at BH (Meteorological Office of Chile, 2 km NW from G1) are also tabulated. The wind at G1 with directions concentrated around 90° is the glacier wind. There is no difference in the frequency of the glacier wind between day and night. The prevailing northerly (330°) and southerly (150°) winds with total

Table 1. Frequency distribution of the wind direction at G1 and BH.

	G1(864)			BH(127)			
(deg)	(%)	08-19 h	20-07 h	(%)	09 h	15 h	21 h
cal m	0.3	1	2	10	9	0	4
30	5.9	9	42	6	2	1	4
90	68.8	294	300	2	1	0	1
150	8.3	36	36	46	11	24	23
210	0.3	1	2	4	2	2	1
270	8.1	44	26	4	1	1	3
330	8.2	36	35	29	16	15	6

frequency of 75 % at BH decrease to 17 % at G1. These winds can be regarded as external general winds at G1 in respect to the absence of diurnal change for these directions. The frequencies in the directions of 30° and 270° at G1 show the marked diurnal change. The nocturnal ratios are larger in the directions of 30° ; the reverse is the case in that of 270°. These two winds are possibly mountain wind which occurrs on the slope of the right bank and valley wind along San Rafael Glacier, respectively. The latter can be regarded also as the compensation flow of the glacier wind. The dominant five wind directions at G1 are classified into four groups by their nature, *i. e.*, glacier wind, general wind, mountain wind, valley wind.

The average diurnal course of the hourly wind speed, temperature and water vapor pressure at G1 and C1 are shown in Fig. 1. The averaging period for the latter two elements is from November 3 to December 1, during which sunny and rainy days occurred almost equally. The average wind speed change was roughly same as that of the glacier wind due to its predominace. The wind speed was constant at night and increased with temperature rise showing a maximum around 14 hLT (GMT-3 hrs). The diurnal change of the wind speed was correlated more closely with the temperature change at C1 than with that at G1. The temperature at G1 continued to increase after the occurrence of the maximum wind speed. This pattern of temperature change is different than those at the other two stations. The extremely small temperature difference between G1 (89 m) and C1 (422 m) compared with that at C1 and C2 (1040 m) is due to the cooling effect of the glacier wind. This may explain the temperature rise with decreased wind force at G1. Since the temperature at C1 represents the status of the free atmosphere during this period (Inoue *et al.*, 1987) and the glacier surface is maintained at the freezing point, it can be regarded as an external parameter for the driving force of the glacier wind. The maximum temperature at C1 is twice that of the minimum, while the maximum wind speed is 1.6 times as large as the minimum value. The wind force is not proportional to the temperature deficit of the glacier surface.

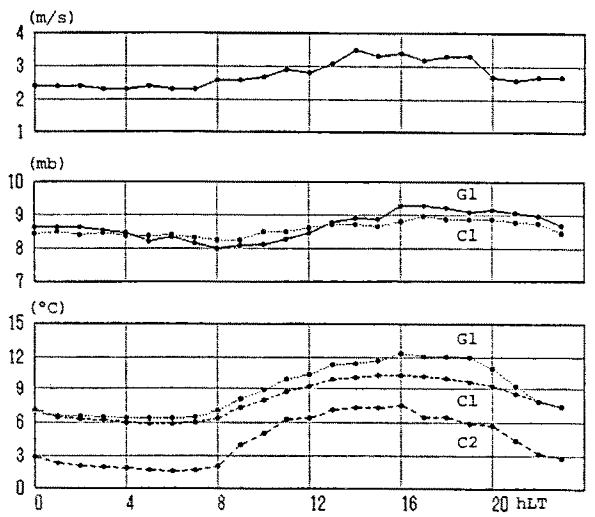

Fig. 1. (from top) a) Mean diurnal change of wind speed at G1, b) vapor pressure at G1 and C1 and c) air temperature at G1, C1, C2.

The water vapor pressures at G1 and C1 increase closely correlated with the air temperatures. Since the values of vapor pressure are super-saturated for ice, evaporation from the glacier surface does not occurr. The water vapor may originate from the ambient moist maritime atmosphere and become entrained in the air current over the glacier.

3. Vertical and horizontal extents of the glacier wind

The time series change of hourly values of the wind speed at G1, temperature and wind direction at G1 and C1 from October 28 to November 1 are shown in Fig. 2. The wind direction data at C1 are limited

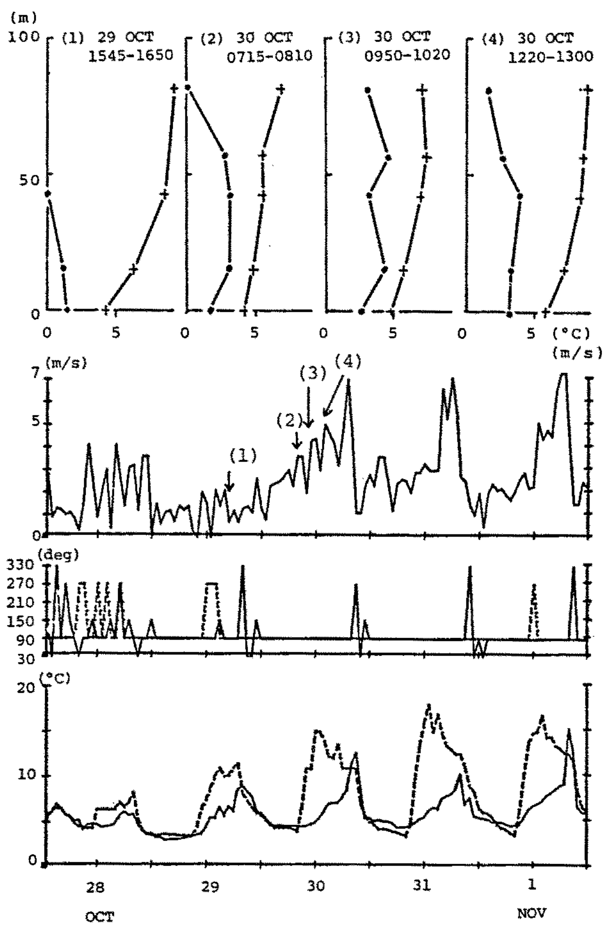

Fig. 2. (from top) a) Vertical profiles of wind and temperature over the glacier at G1. Hourly changes of b) wind speed, c) prevailing wind direction and d) air temperature at G1 and C1 (dotted line) from October 28 to November 1.

to the daytime (06-20 hLT) and shown as either 90° (down glacier) or 270° (up-glacier). The weather was rainy on the 28th and 29th and sunny after the 30th of October. The glacier wind developed from the 30th with a periodic diurnal change. The development of the glacier wind was followed by a pronounced temperature difference between G1 and C1. The sudden increase of wind speed is associated with rapid decrease of temperature at C1. The temperature at G1 shows a marked increase when the wind decreases. The temperature decrease and wind speed increase are correlated both at G1 and C1.

The vertical structures of the wind and temperature were observed at G1 from October 29th to 30th. Four rock terraces forming the right bank of the glacier are used for the wind and temperature profile measurements. G1 is located on the second terrace from below. Three minutes averaged values of the wind measured at each terrace were converted through the ratio to the wind record at G1. The average time necessary to obtain one profile was around 40 minutes. The glacier wind gradually increased in speed during the period of profile observations. The depth of the glacier wind is below 40 m for profile (1) and below 80 m for (2) ; however, it may be above 100 m for (3) and (4). Similar profiles were found by Ohata *et al.* (1985). The vertical increase in depth with the development of the glacier wind is obvious from profiles (1)-(3).

The wind speed and direction every 10 minutes during the period when the vertical profile observations were made are shown in Fig. 3. The periodicity (T) of around 30 minutes is found in the time series change of wind speed (V) from 15 hLT of the 29th through early morning of the 30th. A non-glacier wind blew when the glacier wind decreased. The values of T are obviously larger than the buoyancy oscillation with the normal period less than ten minutes. T becomes larger with the development of the glacier wind. If the longitudinal scale (L) of the glacier wind is assumed to be $L = V \times T$, the increase in velocity and depth of the glacier wind is associated with the development in horizontal extent, too. The longitudinal extent of the glacier wind is estimated as 2.7 km for $V = 1.5$ m/s with $T = 30$ min. and 11 km for $V = 3$ m/s with $T = 60$ min. The distance between G1 and C1 is 4 km and that from the 700 m-high plateau to G1 is 10 km. The well developed glacier wind has the extent to cover the whole ablation area.

4. Relation to the general wind

Wind other than of glacier origin blew frequently when the glacier wind was weak as shown in the previous section. The hourly time series changes of wind and temperature from November 3 to 8, during which the glacier wind did not develop, are shown in Fig. 4. Diurnal change is not found either in the wind speed nor the temperatures of G1 and C1. This is marked compared with Fig. 2. A temperature inversion between G1 and C1 does not occur when the glacier wind is not prevalent. The isolated peak values of wind speed are not necessarily of glacier origin but more likely are northerly wind.

The daily averaged wind speed (WS) at G1 from

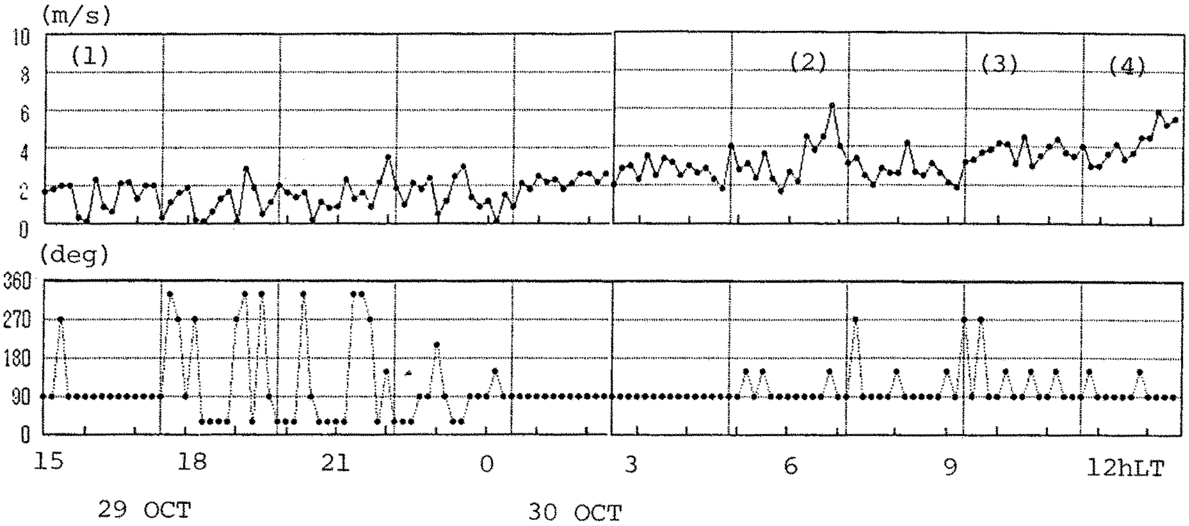

Fig. 3. Wind speed (above) and wind direction (below) every 10 minutes from 15h October 29 to 14h October 30. Inserted numbers show the vertical profile measurements.

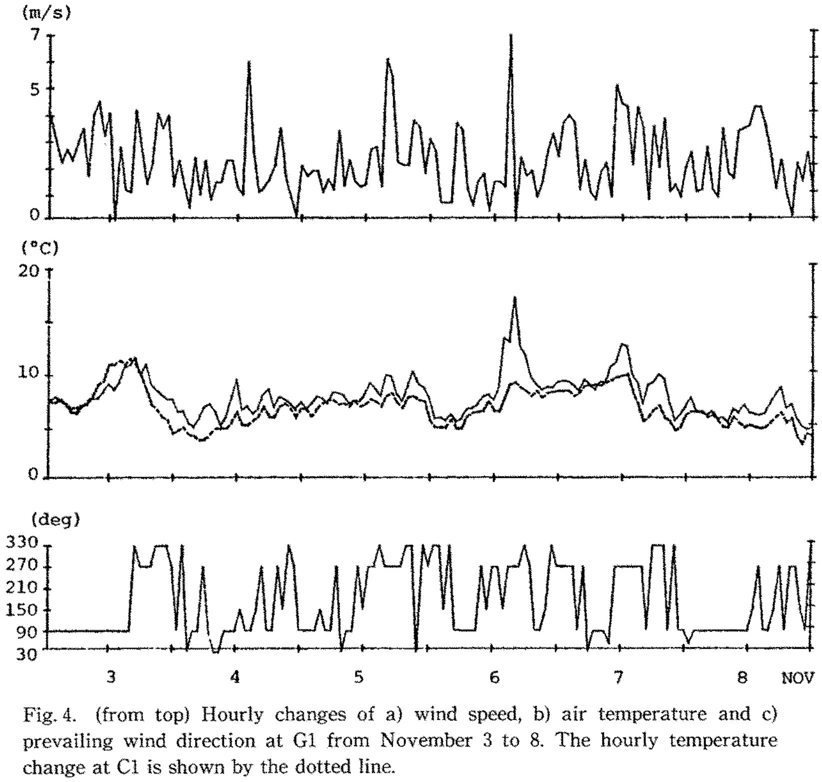

Fig. 4. (from top) Hourly changes of a) wind speed, b) air temperature and c) prevailing wind direction at G1 from November 3 to 8. The hourly temperature change at C1 is shown by the dotted line.

October 17 to November 27 is shown in Fig. 5 a) b) with the percentage frequency of the occurrence of the glacier wind. The average wind speed does not differ much regardless of the prevalence of the glacier wind. The daily temperature lapse rates (R) between BH and G1 and U, V components of the wind at BH are shown in Fig. 5 c) d). The positive correlation of WS with R (Ohata *et al.*, 1985) is not obvious except at the end of October when the glacier wind developed. Since the present observations were concentrated in

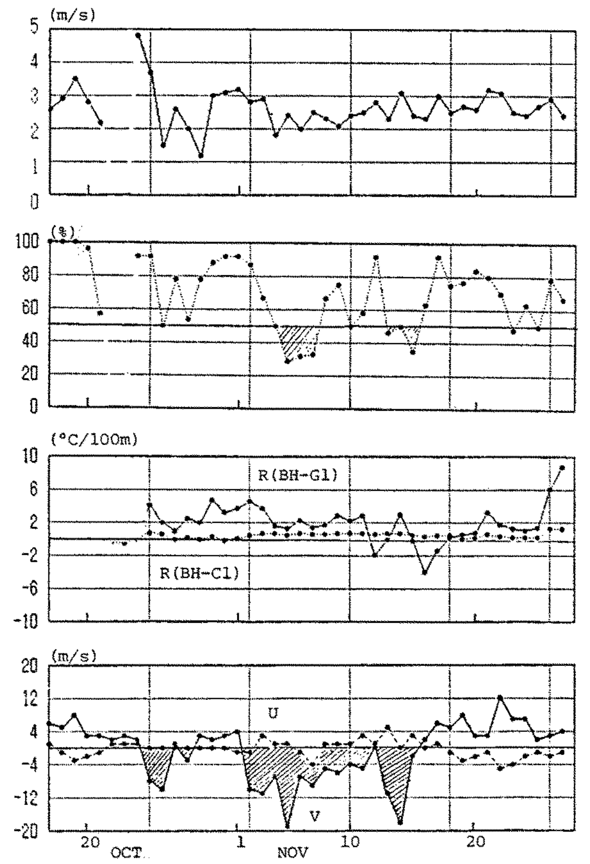

Fig. 5. (from top) Daily variations of a) wind speed, b) percentage frequency of the glacier wind at G1, c) temperature lapse rates of BH-C1 and BH-G1 and d) U and V components of the wind at BH. The areas of northerly wind are shaded.

the transient season to midsummer, the glacier wind was not fully developed and a marked relationship between WS and R might not have been established.

The wind at BH is governed mainly by a large V-component. Northerly wind occurred even at the height of the icefield and it became calm when weak southerly wind blew at BH (Inoue *et al.*, 1987). The frequency of the glacier wind decreased when strong northerly wind occurred.

5. Discussion

The glacier wind observed near the snout of San Rafael Glacier can hardly be regarded as stationary through the timeseries change of the wind having rapid increase and decrease as shown in Fig. 2. The temperature decrease followed by wind velocity increase and *vice versa* show evidence that the air is cooled by the glacier surface during the down-glacier movement. The accelaration of the wind velocity from C1 to G1 was measured during the daytime from November 16th. The hourly wind speed at G1 varied with values between 2 and 6 m/s, while at C1 it was fairly constant at around 1.5 m/s and rarely exceeded the wind speed at G1.

A semi-persistent cold environment is produced at G1 in summer, and extends to C1 in mid-summer (Inoue *et al.*, 1987). A strong glacier wind may have enough depth of more than 100 m and enough longitudinal extent to cover the whole ablation area. An explanation of the extension of the cold region might be given by the longitudinal extension of the glacier wind.

The existence of the northerly external wind may disturb the establishment of the glacier wind. Two effects of the disturbance of the glacier wind can be considered. One is the direct action on the established glacier wind near the glacier snout (remember the isolated peak values of northerly in Fig. 4). The other is indirect but possibly fundamental for the development of the glacier wind. A strong wind other than in the down-glacier direction may disturb the development of the glacier wind at the upper part of the glacier where the topographical barrier does not exist ; henceforth, the horizontal extent of the glacier wind is decreased.

The frequency of the glacier wind is not different for day and night in spite of the marked diurnal change of the wind speed. This may be associated with the fact that the frequencies of external wind at G1 has the same ratio for day and night. The average northerly wind speeds at BH is 5, 7 and 4 m/s for 08, 14 and 21 hLT during the observation period. Namely, the external wind which disturb the development of the glacier wind is strong in daytime and weak at night, while the ambient temperature is lower at night than in daytime. These two opposite effects may cancel so that similar frequencies of the glacier wind occurred for day and night.

The present conclusion is not always applicable to the result obtained in 1983 (Ohata ; personal communication). The inconsistencies might result not only from the difference in the observed months but in the selection of the observation location.

References

Defant, F. (1951) : Local wind. in Compendium of Meteorology, American Metorol. Soc., 655-672.

Inoue, J., Kondo, H., Fujiyoshi, Y., Yamada, T., Fukami, H. and Nakajima, C. (1987) : Summer climate of the Northern Patagonia Icefield. Bulletin of Glacier Research, **4**, 7-14.

Ohata, T., Kondo, H. and Enomoto, H. (1985) : Meteorological observations at San Rafael Glacier. Glaciological studies in Patagonia Northern Icefield, 1983-1984. Data Center for Glacier Research, Japanese Society of Snow and Ice, 22-31.

Resumen

Régimen de viento en el Glaciar San Rafael, Patagonia

Se analizó el viento cerca del frente del Glaciar San Rafael a partir de un registro contínuo desde Octubre a Noviembre de 1985. El fuerte viento norte de superficie viene acompanãdo de precipitación, mientras que el débil viento sur está asociado a buen tiempo. En el frente del glaciar se encontró que el viento glaciar (90°) era predominante, ocurriendo un 70 % en total, mientras que el viento de montaña y valle (30°, 270°) comparten el resto del tiempo junto al viento externo general (150°, 330°), tal como se muestra en la Tabla 1. En el frente del glaciar se produce un clima local frío debido al viento glaciar. A pesar que este viento muestra una variación diurna (ver Fig. 1), no hay diferencia en las frecuencias entre el día y la noche.

Debido a las siguientes características se sugiere una naturaleza no estacionaria del viento glaciar : el espesor del viento glaciar aumenta y la temperatura disminuye con un aumento de velocidad, tal como se muestra en la variación temporal del viento y estructura vertical en la Fig. 2 ; el período del viento glaciar también aumenta con su desarrollo como se muestra en la Fig. 3 ; la escala longitudinal del viento se estima que varía entre 3 a 10 km ; la velocidad del viento observada 4 km aguas arriba del frente del glaciar es pequeña y estacionaria, y raramente excede aquella medida en el frente ; la variación temporal de la velocidad del viento y la temperatura sin condición de viento glaciar (Fig. 4) son totalmente distintas a aquellas en que sí ocurre tal condición (Fig. 2) ; la frecuencia del viento glaciar decrece cuando ocurre un fuerte viento externo general de dirección norte (Fig. 5).

Dado que también prevalece viento norte de baja altura al nivel del campo de hielo, este viento puede provocar disturbios de gran magnitud horizontal en el desarrollo del viento glaciar. La frecuencia similar durante el día y la noche del viento glaciar puede deberse al débil viento norte nocturno.