Katabatic Wind on Melting Snow and Ice Surfaces (I)

Stationary Glacier Wind on a Large Maritime Glacier

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Abstract

Observations of the strong and persistent glacier wind were made on the 40 km-long San Rafael Glacier ($46^{\circ}41'S$, $73^{\circ}51'W$) in the Patagonia Northern Icefield, Southern Chile, South America. From observations near the glacier terminus, glacier wind characteristics in the warm summer season were revealed to be as follows. The wind blows at a frequency of 80 to 90 % during the summer season. In the strongest and also most frequent case, the thickness is more than 100 m and maximum wind speed is 5 m/s. The strong and persistent glacier wind is due to the large scale of this glacier. The main regulating factor for the day to day variation in the occurrence of the glacier wind is the upper air wind speed. When the upper wind is strong, the glacier wind is suppressed and the depth of the glacier wind is shallow. The factor determining the diurnal variation of this wind is the temperature of the ambient air outside the influence of the glacier. There exists a periodicity of 1 to 3 hours in the wind speed of the glacier wind on developed days. The continuance of this wind system after it leaves the glacier is limited to a short distance. Analyzing wind data on glaciers in various regions of the earth, glacier size seems to affect the surface wind speed, probably due to the existence of these glacier winds.

1. Introduction

Wind¹ systems observed on snow and ice masses (hereafter denoted as SIM) in the summer season can usually be classified into three types according to scale. They are the (1) general wind usually having a scale of more than 100 km, (2) local scale wind, which develops in a valley or the mountain range where SIM exist, and (3) the SIM scale wind which occurs within the SIM. This third wind system is an interesting phenomenon as its occurrence is due to the existence of the SIM itself. One of the type (3) winds is the down-slope katabatic wind which occurs when the ambient air temperature over the SIM is higher than $0^{\circ}C$, the air above the surface cools due to the sensible heat transported to the surface for melting of snow and ice. This wind is usually called a "glacier wind", "snow patch wind" or simply "katabatic wind", and is one characteristic air circulation seen on a melting SIM. This wind was recognized quite early on glaciers in the European Alps (Tollner, 1931; Ekhardt, 1934), and has been studied by Hoinkes (1954a, 1954b), Streten and Wendler (1967), Martin (1975) and others. A similar katabatic wind occurring on snow patches has been stud-

ied by Ohata and Higuchi (1979). The main purpose of these studies has been only the wind structure, that is, the vertical distribution of wind speed and air temperature. As analysis of the frequency of occurrence or the meteorological conditions determining development has not been done sufficiently until now, these problems will be investigated in detail along with general characteristics of the glacier wind in the present work. As this wind system is a self-generating wind and heat transported to the snow and ice surface by turbulence is used for melting snow and ice, it is an important phase in the SIM-climate relation.

A strong stationary-glacier wind was observed on a large maritime glacier (San Rafael Glacier) in Patagonia Northern Icefield during a glaciological and hydrological study in the austral summer of 1983-1984. This observation was part of the scientific research work in the Expedition to the Northern Patagonia Icefield (Nakajima, 1985). Preliminary observational results have been written in Ohata *et al.* (1985b), and results of later work in 1985-86 in Inoue (1987). In the present paper, characteristics of the glacier wind at San Rafael Glacier will be discussed in detail and its influence on the local climate on the SIM will be discussed. A theoretical

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Fig. 1. Map of Patagonia Northern Icefield (Nakajima, 1985). The observation area is hatched. Spanish notations in the map are as follows. pto: port, lago: lake, monte: mount, laguna: lagoon, Gl.: Glacier.

treatment of this wind system will be given in part II (Ohata, 1989a), and the effect of this wind system on ablation of the SIM will be discussed in Ohata (1989b).

2. Observation site

A map of the Patagonia Northern Icefield is shown in Fig. 1. This is one of two large Icefields situated in the southernmost part of South America. Mean annual precipitation amount in this region is estimated to be more than 3500 mm at the foot of the Icefield and probably more than 5000 mm at the main accumulation area of this Icefield; this is the main reason for the existence of a large icefield here. This high precipitation is due to the strong westerly wind of which the center axis is located to the south of the Northern Icefield throughout the year.

The main observations were made on San Rafael Glacier ($46^{\circ}41'S$, $73^{\circ}51'W$) on the western side and Soler Glacier ($46^{\circ}54'S$, $73^{\circ}10'W$) on the eastern side of the Icefield. The results which will be shown here were obtained near the terminus of San Rafael

Glacier. San Rafael Glacier runs down from a wide accumulation basin in which the surface and bottom topography is still unknown. The total length from the ridge to the glacier terminus is approximately 40 km, but the outlet part where the width narrows and inclination becomes steeper (approx. 3°) is about 25 km. The observations were made near the terminus. A map of this part of the glacier is shown in Fig. 2. Continuous meteorological observations were made by the Chilean Air Force at site AF (6 m a.s.l.) 3 km away from the terminus. Temporary observation sites were sites MS (103 m a.s.l.), A (100 m a.s.l.) PB (40 m a.s.l.) and BC (50 m a.s.l.) shown in the Figure. Site MS was 52 m above the glacier surface and general meteorological observations were made for the whole period. Site A was located a little upvalley from MS on the glacier, and short term meteorological observations and a heat balance study was made there. The 1.5 m level air temperature and wind along the slope intersecting site MS to 150 m a.s.l. were measured. The transverse cross section of the slope at site MS

Fig. 2. Map of the terminus area of San Rafael Glacier. The observation sites on the ground are AF, BC, PB and MS. Sites A and B are on the glacier.

Fig. 3. Transverse cross section of glacier and side slope at sites MS and A. S1 to S9 are the points where wind speed and air temperature measurements were made.

Fig. 4. The vertical profile of wind speed and air temperature of wind based on observation at the slope near MS. Types 1 and 2 are the case of glacier wind, and type 3 of non-glacier wind.

is shown in Fig. 3. S1 to S9 is the observation position, and S5 is site MS. In the figure the cross section at site A is also shown. Measurements were made at random in the daytime, and it is considered that these values represented the vertical profile of these two elements above the glacier as the slope was very steep and adjacent to the large scale glacier as seen in Fig. 3. Furthermore, pilot balloon observations of lower level (up to 2000 m a.s.l.) wind were made daily at site PB in the latter half of the observation period. The observation period was from December 1, 1983 to January 4, 1984 and time used in the paper is the Local Standard Time.

3. Observational results

3.1 Vertical structure of glacier wind

Profile measurements were made 19 times during the daytime from 08:00 to 17:00. The glacier wind was identified from the vertical profile of wind speed and wind direction. The height (h) of the glacier

wind was determined by taking the top as the height where the wind direction differed from E-SE or the wind speed became lower than 1 m/s. The observed profiles were classified into three cases as follows,

- Type 1: Deep glacier wind (total 12 cases),
- Type 2: Shallow glacier wind (total 5 cases),
- Type 3: Non-glacier wind (total 2 cases).

Type 1 and 2 were determined from the height h . Type 1 is a glacier wind deeper than 50 m, and type 2 is one shallower than 50 m. Type 3 was the case which wind direction was different from E to SE. Type 1 was most frequent. The height (h) of the glacier wind varied from 30 to 120 m. The maximum wind speed (U_m) and its height (h_m) ranged from 3.0 to 5.5 m/s, and from 10 to 60 m respectively.

In order to see the typical profile of types 1 and 2, mean profiles of wind speed and air temperature for cases when h was 90-120 m for type 1 (7 cases) and h was 40 to 50 m (3 cases) were taken, and they are shown in Fig. 4. These cases were selected

because h in these cases was distributed in a small range. In type 1, the height (h) is more than 100 m, maximum wind speed (U_m) is 4.5 m/s and the height of $U_m(h_m)$ is 50 m. In type 2, it is $h = 45$ m, $U_m = 3.5$ m/s and $h_m = 10 - 15$ m. The strength of the temperature inversion (temperature difference between the air not affected by the glacier wind and the screen level above the glacier) seems to be approximately the same in types 1 and 2. A similar profile for type 3 (non-glacier wind) was also taken. In this type, no maximum is seen in the wind speed profile and the temperature profile shows only a weak inversion. The high type 1 can be considered as the profile of the representative glacier wind which occurs here, from its high frequency. This type occurs when the general wind field is weak as will be discussed in sec. 3.3. Defant (1951) noted that there are glacier winds of height more than 100 m, but did not show observational data. The present observation of glacier wind occurring on San Rafael Glacier shows that such a thick glacier wind actually exists.

Another characteristic which can be seen is the height of h_m . When we take the ratio h_m/h as the parameter of the position of h_m within the glacier wind, it is approximately 0.5 in the present case. This value is quite large, for example, compared with other observations of katabatic winds (Ohata and Higuchi, 1979; Martin, 1975) or the theoretical equation of Prandtl (1952) in which it is 0.25. This is probably due to the roughness of the glacier surface. Deep crevasses and seracs more than 10 m high were common on this glacier; and these conditions are different from the surfaces on which previous observations were made. On a surface of large roughness, the drag force at the surface will be large and this will tend to increase h_m .

The frequency of occurrence of glacier winds can be deduced from the frequency of glacier wind profiles although the sample number is small. The above data show that glacier winds blow 89 % (17/19) of the selected times.

3.2 Time variation of glacier wind

3.2.1. Day to day variation

In Fig. 5, meteorological elements related to the development of glacier winds are shown for the period from December 1 to January 4. The elements shown are $\bar{T}_{AF}$ and $\bar{T}_{MS}$, $\Delta T = \bar{T}_{AF} - \bar{T}_{MS}$, $\bar{U}_{AF}$ and $\bar{U}_{MS}$, where $\bar{T}_{AF}$ and $\bar{T}_{MS}$ are the screen height air temperature at sites AF and MS, and $\bar{U}_{AF}$ and $\bar{U}_{MS}$ are the wind speed at 10 m level at AF and 2 m level at MS. The data are mean values in daytime (09:00-18:00). $\bar{T}_{AF}$, the ambient air temperature, is considered to be not influenced by the glacier. There was a 100 m altitude difference between AF and MS, but the value $\bar{T}_{AF}$ itself is assumed to be the air temperature outside the effect of

the glacier at the altitude of MS. So, this temperature difference ΔT can be considered as the strength of the temperature inversion. ΔT ranged from -0.1 to 3.9°C . All days will be classified into three grades according to the value of ΔT , that is,

A: strong inversion ($2^\circ\text{C} < \Delta T$)

B: moderate inversion ($1 < \Delta T < 2^\circ\text{C}$)

C: weak inversion ($\Delta T < 1^\circ\text{C}$).

The numbers of days which fell into the three grades are 12, 10 and 13 days respectively. Wind speed $\bar{U}_{MS}$ showed a smaller day to day variation than $\bar{U}_{AF}$. In Fig. 6, the relation between ΔT and $\bar{U}_{MS}$ is shown. ΔT and $\bar{U}_{MS}$ has a positive correlation, which is expected to occur when the predominant wind is thermally driven. If it is not a thermally driven wind system it should show the opposite tendency, that is negative correlation, as when wind speed increases, diffusion will be higher and vertical air temperature gradient smaller. In this figure, a positive correlation can be clearly seen on all 35 days. It can be said that the predominant wind system on this glacier in this season is a glacier wind judging from the positive relation between ΔT and $\bar{U}_{MS}$.

3.2.2. Diurnal variation

Micrometeorological observations on the glacier were made from December 28 to January 2 at site A. The diurnal variation of the glacier wind can be discussed using these data and data at sites MS and AF. In Fig. 7, the detailed diurnal variation of air temperature and wind speed at three sites (AF, MS and A) and wind direction at site A are shown for a grade A day (December 31) and grade C day (December 29). Although sites MS and A are not in the exact same area, the data at sites A and MS be considered as the data 2 and 50 m above the glacier surface. The data at AF are considered to represent conditions outside the influence of the glacier.

On a grade A day (December 31), the wind direction at site A was constant from upglacier, which means that a glacier wind was blowing continuously. This corresponds to the large air temperature difference between AF and MS, and MS and A. Although there are no wind direction data in the nighttime, it can be considered that the daytime glacier wind continued into nighttime. This is due to the fact that in spite of the small air temperature difference between AF and MS at the beginning of the night (21:00), a large air temperature difference between MS and A was maintained throughout the nighttime. This implies the existence of a shallow glacier wind. This wind in the nighttime was not of the nocturnal katabatic wind type due to radiational cooling, as the net radiation balance at the glacier surface was downward even at night during this period due to high cloud amount and existence of an inversion on the glacier (Ohata *et al.*, 1985c; Ohata *et al.*, 1986). The

Fig. 5. Day-to-day variation of meteorological elements related to the development of glacier wind from December 1, 1983 to January 4, 1984. $\bar{T}_{AF}$, $\bar{T}_{MS}$; Air temperature at AF and MS; $\bar{U}_{AF}$, $\bar{U}_{MS}$; Wind speed at AF and MS; $\Delta T = \bar{T}_{AF} - \bar{T}_{MS}$.

Fig. 6. The relationship between ΔT and $\bar{U}_{MS}$ in Fig. 5.

Fig. 7. Diurnal variation of meteorological elements related to the development of the glacier wind at sites AF, MS, and A for grade A day (Dec. 31) and grade C day (Dec. 29). *T* and *U* are air temperature and wind speed. The wind directions shown were obtained at site A.

wind at AF (U_{AF}) was weak at 0.5 to 2.0 m/s. In contradiction to this, U_{MS} and U_A , which can be considered to be within the glacier wind layer, increased gradually in the forenoon from the nighttime mean value of 2.5 m/s, and showed a maximum wind speed of nearly $U_{MS} = 5$ m/s and $U_A = 3.5$ m/s around 18:00. This variation in wind speed correlated well with the variation in $\Delta T = T_{AF} - T_A$ which was 4 to 5°C in the morning and 7 to 8°C in the afternoon. This is physically understandable as stronger temperature contrast between A and AF and decreased atmospheric stability of ambient atmosphere due to increase in T_{AF} will increase the glacier wind. This was a day of continuous high glacier wind of type 1 shown in sec. 3.1.

On a grade C day (December 29), the wind direction at site A was mostly down-glacier, but this was interrupted for a few hours in the afternoon by wind from an other direction. On these occasion T_A increased. Throughout the day, there was only a small temperature difference between AF and MS, but there was still a large difference between MS and A of 4 to 5°C. This means that a glacier wind shallower than 50 m blew most of the day. Wind speed was very similar at the three sites, and did not show a diurnal variation as on December 31.

The present result supports the estimate of the frequency of glacier wind in sec. 3.1 which was based on only 19 independent observations. It was shown that even on days of weak temperature inversion (grade C) which occupied 37 % (13/35) of the whole period, low glacier wind predominated in the daytime. Considering these facts, the frequency of glacier wind in the whole period can be said to be 80 to 90 %.

Another interesting result for grade A day (December 31) is the periodicity of the fluctuation in the wind speed. In the nighttime, the cycle is 2 to 3 hours and in the afternoon 1 to 2 hours. Velocity fluctuations of mountain winds or drainage wind (sometime referred to as surges) which have been reported in some papers (Tyson, 1968a; Tyson, 1968b) show periodicity of 0.5 to 2.5 hours. This periodicity is similar to the present observation. The wavelength of such surges can be taken as

$$l = c \times u$$

where c is the period of wind variation and u the mean wind speed. In both day and night l falls in the range between 20 and 25 km. This scale roughly corresponds to the length of the outlet part of the glacier from the upper icefield where inclination increases. There may be some clues in this for explaining the mechanism of glacier wind.

3.3 Determining factor of occurrence and thickness

It was found in the previous section that glacier wind changes in its strength and thickness, and

sometimes it is interrupted. Taking into account the physical basis of development of glacier wind in a warm temperature environment of glacier wind will be investigated. The diurnal term was discussed in the previous subsection. The effect of external parameters on a day-to-day basis will now be examined.

The air temperature of the ambient atmosphere is roughly proportional to the inversion strength, as the snow and ice surface is maintained at 0°C. However, there was no relation between T_{AF} and U_{MS} on a day-to-day basis in the observational data, probably because the range of T_{AF} was small, from 11 to 16°C. The vertical stability of the ambient atmosphere is another factor, but no data are available at the present. Other factors are geostrophic force and diffusion of the cold air layer due to strong upper winds. Geostrophic force does affect katabatic winds in Antarctica (Ohata *et al.*, 1985a). However, it will not have any effect here because the katabatic force ($g\theta' \sin \alpha / \theta_a$) is of the order of 10^{-2} m/s² and the geostrophic force (fv) is only 10^{-3} to 10^{-4} m/s².

Next, in order to see the effect of the upper wind, the relation between U_{MS} and mean upper air wind speed (250–400 m a.s.l.) U_u was taken and is shown in Fig. 8. These observations were made between 08:00–10:00 in the forenoon. U_{MS} is the wind speed at site MS at the time of upper air observations. The points are classified into 3 grades according to the temperature difference $\Delta T = T_{AF} - T_{MS}$ at the observation time. This is the same as ΔT taken in sec. 3.2.1, but in the present case it is based on hourly air temperature data at the time of upper air observation, not the daytime mean value. The upper air wind was mainly in the NW to SW direction. In the figure, the approximate relation between U_{MS} and U_u is shown by a broken line. The expected relation between U_u and U_{MS} , which was calculated by assuming a logarithmic profile up to 300 m with z_0 of 1 to 10 cm is shown by the shaded area. Under a strong upper wind, the relation between U_{MS} and U_u settles around the range of the calculated value and ΔT is small. In contrast to this, under a weak upper wind, wind speed U_{MS} is stronger than the estimated value and ΔT is of grade B or A, which means ΔT is large. U_{MS} becomes a minimum around $U_u = 3.0$ m/s.

In Fig. 9, the relation between glacier wind thickness h and U_u is shown. h is based on the profile measured at the slope of site MS in the daytime on days when pilot balloon observations were made. Only cases when a glacier wind was blowing are included. The data are scattered, but there is an inverse relation between h and U_u . It can be said from this that strong upper wind decreases the glacier wind thickness. As U_m of the glacier wind has a positive correlation with h (sec. 3.1), glacier wind thickness and strength are shallower and weaker under a

Fig. 8. Relationship between the upper air wind speed (U_u) and wind speed at site MS (U_{MS}). Cross; $\Delta T < 1^\circ\text{C}$: Black circle; $1 < \Delta T < 2^\circ\text{C}$: Open circle; $2^\circ\text{C} < \Delta T$. The expected relationship between U_u and U_{MS} assuming a logarithmic profile is shown by the hatched area. See text for calculation method.

Fig. 9. Relationship between upper air wind speed (U_u) and glacier wind thickness (h).

stronger upper wind. It must be noted that the wind direction in this series of observations was limited to NW–W–SW, which was the predominant wind direction during the observation period. The scattering of data in the figure may be due to the scatter

in the wind direction.

Two processes can be conceived for the decrease in thickness. One is a local effect, and the other is an areal effect. The former process is diffusion of cold air in the upper layer of the glacier wind

Fig. 10. Frequency of wind direction at sites MS and BC in the daytime shown by a wind rose. Calm cases are shown by numbers at the center by percentage.

when the upper wind is strong. This process is discussed in Toritani (1985) for nighttime nocturnal drainage wind. The latter process can be explained as follows. A strong upper wind in the terminus area usually means a much stronger wind speed on the upper part of the glacier and the Icefield. In these cases, it will be difficult for the glacier wind to be formed in the upper areas of the glacier, so the glacier wind will be limited to the lower part of the glacier. This results in shallow and weak glacier wind near the terminus region. These two processes are conceivable. It cannot be determined at present which process dominates in the present case.

According to the preceding discussions, in the warm summer season, the main factor regulating day-to-day variation in the glacier wind is the upper air wind speed. When the upper wind is very strong, no glacier wind can exist. Under a moderate wind speed the glacier wind exists but is shallow. On days with a weak upper wind, the glacier wind predominates and the factor determining the diurnal variation in the strength of the glacier wind is the ambient air temperature. As the ambient air temperature is high in the afternoon, and low at nighttime, the glacier wind is strong in the afternoon, and weak at nighttime.

In the present observations, no clear relation between strength of the glacier wind and the air temperature of the ambient atmosphere on a day-to-day basis was found, probably due to the narrow range of values of mean daily air temperature. However, this should be the most important relation deter-

mining the seasonal trend of wind on glaciers. If the present observations were continued much longer and included days in seasons of lower air temperature, the occurrence of glacier wind and its strength and thickness might prove to have a stronger relation with the ambient air temperature.

3.4 Effect of glacier wind system to the surrounding environment

The continuance of a glacier wind system after it leaves the glacier will now be examined. There were a few occasions when the author approached the terminus of the glacier by boat on developed glacier wind days. There was an abrupt change in air temperature 1.5 to 2.0 km from the terminus. Although data are scarce, this length seems to be the limit of the effect of the glacier wind below the terminus.

There were measurements of wind direction at site BC (base camp) shown in Fig. 2. This was 400 m from the terminus. The frequencies of wind direction at MS and BC are compared using wind roses in Fig. 10. The number of data were more than 100 in the daytime for both sites. At MS, 73 % of the winds was from the E, which is the direction of the glacier wind, but at BC, the percentage of wind directions from the glacier, that is SE, was most frequent but was only 25 %. The continuance of the glacier wind in this direction seems to be limited.

Tollner (1931) showed that a glacier wind flows further down the slope from the glacier terminus, but, considering the present observations, this ef-

Fig. 11. The relationship between the distance of the observation site from the upper end of the SIM (L) and the mean wind speed (U) for various SIM cited in Table 1.

fect seems to be limited. This is probably because Lagoon San Rafael is flat.

4. Discussion

4.1 Comparison with glacier wind on a smaller scale SIM

Previous studies of glacier wind were on smaller scale SIM. These studies are Ohata and Higuchi (1979) on a 0.3–1 km snow patch, and Hoinkes (1954a) and Martin (1975) on glaciers a few km in length. The ambient air temperatures in these 3 cases were similar, 10 to 15°C at the observation site in the ablation area.

First, the wind speed and thickness of the glacier wind on the large scale San Rafael Glacier were stronger and deeper than on a small scale SIM. For example, h_m in the above three previous studies was $h_m = 0.7 - 7$ m, and in the present case approximately $h_m = 15 - 60$ m.

Second, the frequencies of these glacier winds were different. The frequency of glacier wind at Tsurugisawa snow patch (< 1 km) is estimated to be about 20 % (Ohata and Higuchi, 1979), and at San Rafael 80 to 90 %. Although the general climate is different at the two sites, there is one clear cause of this difference. The Tsurugisawa snow patch is located in only one portion of the valley, as a small scale SIM usually is. So the predominant local wind system on days with calm upper wind was a mountain and valley wind system. The development of a glacier wind was disturbed by this larger scale wind system. On the other hand, San Rafael Glacier covered the whole mountain slope and no predom-

inant mountain valley wind system occurred. Furthermore, land-sea breeze is also conceivable as it is located near to the ocean, but was not observed. The glacier wind was the only local wind system occurring in the region of the glacier. This shows that the scale of the SIM, which is related to the ratio of ground surface and snow/ice surface in one valley or slope, has a strong influence in determining the frequency of glacier wind. These can be considered to be the two extreme cases of a large scale and small scale SIM. So, on a moderate size glacier, it will probably show an intermediate character.

It can be said from the above discussion that the size of a SIM has a strong influence on the development of a glacier wind and the frequency of its occurrence.

4.2 Mean wind speed on various SIM in the ablation season

Due to the existence of the characteristic wind system discussed here, there should be some relation of mean wind speed to the length of the SIM. If other factors such as general climate were the main regulating factor there would be no relation to the length. There are many reports of wind measurement on glaciers and some reports on other SIM in the summer season related to ablation studies. They are listed in Table 1. Only measurements made for periods longer than seven days were selected. The relation between mean wind speed (U), usually observed at screen height for the whole observation period, and distance from the upper end of the SIM (L) is shown in Fig. 11. The observation period

Table 1. List of SIM for which the data are used in Fig. 11.

Name of glacier	Location	Distance L (km)	Period	Wind Speed U (m/s)	Reference
1. Gergeti Gl.	Caucasus, USSR	7.5		5.2	Voloshina (1986)
2. Biafo Gl.	Karakorum, Pakistan	25.0	July 29 – Aug. 4	6.0	Nishimura et al. (1983)
3. San Rafael Gl.	Patagonia, Chile	25.0	Dec.1 – Jan.4	3.8	Ohata et al. (1985b)
4. Ampere Gl.	Kerguelen Is.	15.0	Jan.8 – Mar.3	5.0	Poggi (1977)
5. McCall Gl.	Brooks Range, Alaska	6.0	July 1 – 11	3.1	Wendler and Ishikawa (1973)
		1.0	July 1 – 11	1.8	
		6.0	July	2.4	Wendler and Weller (1974)
			June	2.3	
6. Lemon Creek Gl.	Juneau, Alaska	1.0	Aug.5 – 20	1.5	Wendler and Streten (1969)
7. Worthington Gl.	South Central Alaska	4.5	July 16-Aug.1	2.1	Streten and Wendler (1968)
8. AX010 Gl.	Shorong Himal, Nepal	1.0	June 11 – 29	1.5	Ohata and Higuchi (1980)
9. No.1 Gl.	Tian Shan, China	1.0	July 5 – 25	3.0	Ohata et al. (1989)
10. Castner Gl.	South Central Alaska	11.0	June 24 – July 12 (6 days)	2.4	Streten and Wendler (1967)
11. Mapyx Gl.	Caucasus, USSR	0.8	June 10 – 30, Aug.1 – 25	2.2	Davidovich (1975)
12. Mittlere Lóven Gl.	Spitzbergen	3.8	July 16 – Sept.3	1.9	DES (1969)
13. Kesselwandferner	Oetztal Alps	1.0	Aug.11 – 19, Aug.28 – Sept.8	3.0	Ambach and Hoinkes (1963)

varies but it can be considered representative of the summer season. There is a positive correlation between wind speed and length. Furthermore, there is a minimum value in the relation between the two shown by the broken line. The existence of this line can be regarded as due to the size effect of glaciers on wind speed, probably due to the occurrence of glacier wind. The points are distributed above the broken line and it fluctuates much to higher U . This is probably due to the effect of the upper wind which is different at each SIM. The existence of a minimum line in the relation between U and L can be explained solely by glacier wind but in general, nocturnal drainage wind exists in the nighttime and will also have an effect.

5. Concluding remarks

A strong and persistent glacier wind was observed on a large maritime glacier in Patagonia, although it is situated in a relatively strong westerly wind region. This is the one of the largest-scale glacier winds observed. The obtained results and comparison with previous works can be summarized as follows.

(1) Glacier wind blows at a frequency of 80 to 90 % during the summer season although the strength and scale of the wind varies. The strongest and most frequent glacier wind is more than 100 m thick with a maximum wind speed of 5 m/s.

(2) Compared with other observational results on SIM in warm environments, this stationary glacier wind seems to occur due to the large scale of this glacier.

(3) Mean daytime wind speed has a positive correlation with the air temperature difference between sites on the glacier and the nearby ground surface.

(4) During the warm summer season, the main external factor regulating the occurrence of the glacier wind day to day is the wind speed above the glacier wind. The glacier wind is strongest and thickest on days when the upper wind is weak. The external factor which has the strongest effect on diurnal variation of this wind is the diurnal temperature cycle of the ambient air, which determines the temperature contrast between the ambient air and glacier surface and atmospheric stability of the ambient air.

(5) The effect of this wind system on the surrounding environment is limited, 1.5 to 2.0 km in the direction of the glacier and less than 400 m from the glacier terminus in a direction 30 degrees from the direction of the glacier.

(6) Considering summertime surface-wind speed data on various glaciers, a scale effect of glaciers on the wind speed was found. This seems to be partly due to the existence of the daytime glacier wind.

For further research, measurements of the areal distribution of wind speed along the glacier are needed. As this wind system is primarily a self-

generating wind, it will be interesting to investigate the thermal effect on the glacier itself.

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融解している雪氷面上での斜面下降風 (I)

—大規模海洋性氷河の定常的な氷河風—

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南米チリの北パタゴニア氷床のサン・ラファエル氷河 ($46^{\circ}41' \text{S}$, $73^{\circ}51' \text{W}$) で氷河風の観測を行った。氷河末端付近の観測から、この氷河風について次のことが明らかとなった。厚さが 100 m を越え、最大風速が 5 m/s を越える氷河風が観測された。また、氷河外の日中平均気温が 10°C より高い夏期期間中、この風は 80～90% の頻度で発生していた。強くまた安定性のあるこの氷河風は、この氷河が大規模 (長さ $\approx 40 \text{ km}$) であることによる。この氷河風の発生、強さの日々変化に影響を与えているのは、雪氷面付近の冷却気層を拡散させる一般風の強さである。一般風が強いと、氷河風の厚さは減少する。氷河風の日変化と強い相関をもつのは、氷河の影響を受けない一般場の気温である。また、氷河風が発達している日には、風速に 1～3 時間の周期性がみられる。この風は氷河から離れると、比較的短い距離で弱まる。文献をもとに地球上の雪氷塊上での融雪 (氷) 期における地上風速をまとめると、規模の大きい雪氷塊ほど風速が強いという関係がみられた。これにも、氷河風の影響が強く現れていると考えられる。