—研究論文—
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Measurements of Drifting Snow at Mizuho Camp, East Antarctica, 1974–1975

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南極みずほ観測拠点における地吹雪量の測定

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要旨：第15次南極地域観測隊に参加して，みずほ観測拠点において地吹雪量測定を行った．引出し箱型地吹雪計を改良した結果，サイクロン型地吹雪計とほぼ同じ捕捉率（≒0.55）をもつことがわかったので，引出し箱型地吹雪計を用いて雪面上1mまでの高さの各層における地吹雪量を風速分布とともに詳細に解析した．得られた地吹雪密度分布から，地吹雪は雪面上約25cmの高さまではサルティションの卓越している層であり，それより上部では地吹雪粒子が渦拡散により浮遊している層であると考えた．地吹雪輸送量は雪面上10mの高さでの風速値と良い相関があった．この関係を用いると，みずほ観測拠点での全地吹雪輸送量は，約 0.64×10^6 ton・km^{-1}・year^{-1} と見積もることができた．

Abstract: Measurements were carried out simultaneously of drifting snow and wind speed over the surface from 1974 to 1975 at Mizuho Camp using an improved drawer-type drift collector which had a collection efficiency of about 0.55. From the obtained profile of spatial distribution of drift mass flux, it is considered that a layer from the surface to a height of about 25 cm is the one in which the saltation of snow particles prevails and a layer on top of it is the one in which snow particles are suspended by turbulent diffusion. A significant correlation was found between the total drift transport and the wind speed at the height of 10 m above the surface. The total drift transport at Mizuho Camp evaluated from this correlation was about 0.64×10^6 ton・km^{-1}・year^{-1}.

1. Introduction

It has been considered that drifting snow must play an important role in the mass budget of the ice sheets in Antarctica and Greenland (*cf.* PEARY, 1898; LOEWE, 1933). For the estimation of the total snow drift transport, the

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drift transport formula was obtained from the Byrd snow drift project (BUDD *et al.*, 1966). LOEWE (1970) used the formula to evaluate the mass of drifting snow transported by the wind on ice sheets. From the obtained results, he discussed the contribution of drifting snow to the mass budget, considering that it is not so important on extensive ice sheets, but constitutes a substantial item for small ice caps.

The glaciological project supervised by T. ISHIDA has been performed for the purpose of investigating the mass budget in Mizuho Plateau of East Enderby Land from 1969 to 1976. It is important to evaluate the mass of drifting snow which comes into and goes out of Mizuho Plateau.

Models of drifting snow have been derived from a considerable number of studies carried out on drifting snow accompanied by the wind. Among them two models are strongly supported. One of the most representative models of drifting snow is based on an application of the work of BAGNOLD (1941) conducted for sand, in which the snow transport in low levels should consist mainly of the same mechanism as the sand transport which is so called "saltation" (MELLOR and RADOK, 1960; OURA and KOBAYASHI, 1968). The other model in which drifting particles are suspended in and transported by the turbulent air is based on an application of the turbulent transfer theory for drifting snow initiated by SHIOTANI and ARAI (1953) and confirmed by multilevel drift measurements (DINGLE and RADOK, 1961). The two models were examined by the results of detailed measurements of drifting snow from the surface to the height of 1 m and by the extrapolated values therefrom to the height of 20 m above the snow surface.

2. Instruments

The horizontal mass flux for a finite time interval was measured at various heights across a unit length, perpendicular to the wind direction, by using a

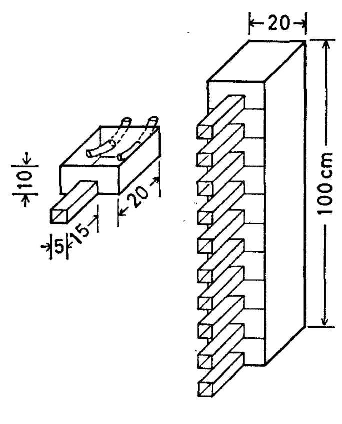

Fig. 1. A drawer-type drift collector and its unit designed to measure the horizontal mass flux of drifting snow; collection efficiency: 0.55.

drawer-type drift collector which was designed by KOBAYASHI (1975) and has undergone several improvements by INOUE, one of the authors; namely, the inlet window was extended 10 cm longer than that of KOBAYASHI's and two pipes were provided at the outlet in order that the air could be ventilated easily out of the drawer without removing captured drifting snow particles. Schematics of the improved collector are shown in Fig. 1. It was found from the results of observations at the outlets of the drawers that the amount of snow particles that escaped therefrom was small. Therefore, the collection efficiency of the collector is assumed to be the same as an aerodynamic efficiency which shows the efficiency of air flowing into the inlets of the collector. The aerodynamic efficiency of the collector was determined to be 0.55 in the range of wind speeds from 10 to 20 $m \cdot s^{-1}$ by the wind-tunnel calibrations (KOBAYASHI, 1975).

3. Measurements and Results

3. 1. Drift mass flux

Fig. 2 shows a typical profile of drift mass flux on the logarithmic scale at heights from the snow surface to 1 m; open circles and open triangles represent values of mass flux measured by an improved drawer-type collector for wind speeds

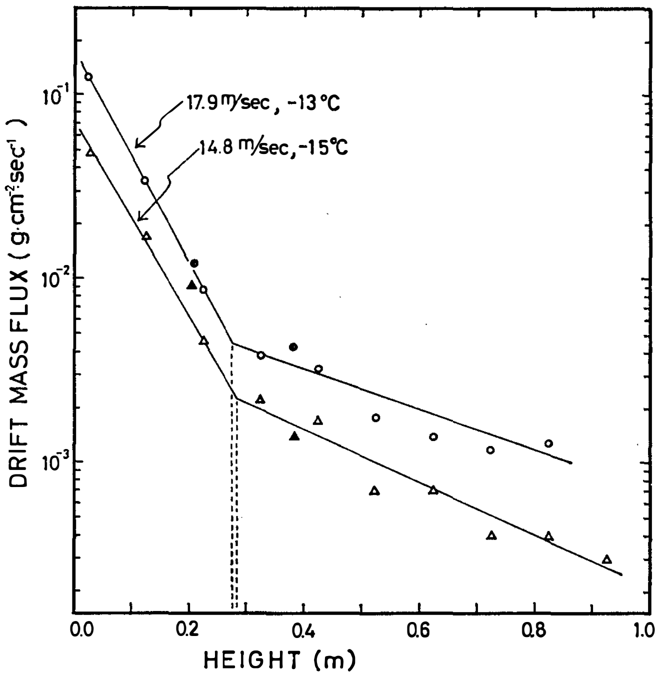

Fig. 2. Log drift mass flux vs. height above the surface, where open circles and solid circles represent mass fluxes measured by a drawer-type collector and cyclone-type collectors, respectively. A bending point is positioned at about 27 cm in each run of measurement.

(at the height of 10 m) of 17.9 and 14.8 $m \cdot s^{-1}$ and air temperatures (at the height of 2.5 m) of −13 and −15°C, respectively. Two solid circles and two solid triangles represent values of mass flux measured by cyclone-type collectors (OURA *et al.*, 1967) concurrently with the measurements mentioned above. As it is clear from the figure, the results by the different methods almost agree with each other. Therefore, it may be confirmed that the efficiencies of the two types of collectors are almost equal. Moreover, it was determined by a wind-tunnel experiment that the cyclone-type collector had much the same aerodynamic efficiency as the drawer-type collector (KOBAYASHI, 1975); thus, the efficiencies of both collectors agree with each other in both the wind-tunnel and field. Measurements were carried out at Mizuho Camp from July 1974 to February 1975 and the data obtained are reported by INOUE (1977).

As is obvious from Fig. 2, there exists a clear discontinuity in the gradient of the line, and this discontinuity is observed in each run of the measurements. A bending point where two lines fall in is positioned at about 27 cm above the surface in each run. The heights corresponding to bending points obtained from each run of measurements are observed at around 25 cm for wind speeds ranging from 13.0 to 20.6 $m \cdot s^{-1}$. These bending points have been reported for drifting snow in Japan (TAKEUCHI *et al.*, 1975) and also for sand storms (ISHIHARA and IWAGAKI, 1952). It is suggested from these facts that the existance of a bending point in a mass flux profile might have its origin in the change of the mechanism of drifting snow at a specific height.

3. 2. Wind speed

Wind speeds were measured simultaneously at 20 different times at one site of Mizuho Camp where five-minute mean wind speeds were measured at the height of 3.5 m automatically by using a windmill-type anemometer (KAWAGUCHI, 1975). Meanwhile, at 11 times out of them ten-minute mean wind speeds were measured at the heights of 3.7, 1.7, 0.9 and 0.4 m above the surface by using Robinson-type anemometers. As for the wind speeds at the 11 times, they were extrapolated to the wind speeds at the height of 10 m, using the logarithmic law for wind speed by which the mean wind speed at the height z can be derived from the following eq. (1):

$$V_z = \frac{V_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \qquad (1)$$

where V_* is a friction velocity, z_0 is a surface roughness length and $\kappa(=0.4)$ is von Karman's constant. As for the wind speed at the rest of times, namely, nine times, they were also extrapolated to the wind speeds at the height of 10 m by the following procedure. First, a relationship was obtained between

Table 1. Temperatures, wind speeds at the height of 10 m, roughness lengths, friction velocities, fall velocities and total drift transports. Wind speeds at the height of 10 m in brackets are values obtained by means of least squares from wind speeds at the 3.5 m height on the basis of their relationship with the extrapolated wind speeds at the 10 m height.

Temperature (°C)	Wind speed V_{10}(m/s)	Roughness length $z_0 \times 10^{-5}$(m)	Friction velocity V_*(m/s)	Fall velocity w(m/s)	Drift transport Q_0^{20}(g/m·s)
−48	(12.7)	(4.7)	(0.39)	(0.19)	25
−36	(14.8)	(14)	(0.54)	(0.26)	92
−35	(14.8)	(14)	(0.54)	(0.26)	61
−32	(16.9)	(43)	(0.69)	(0.34)	223
−32	15.8	25	0.60	0.30	127
−30	16.8	80	0.71	0.34	169
−35	13.3	9.0	0.46	0.23	43
−48	18.2	120	0.81	0.37	254
−38	16.6	32	0.64	0.33	147
−42	20.6	250	0.99	0.48	689
−32	(21.0)	(375)	(0.99)	(0.48)	490
−50	14.2	9.0	0.49	0.28	87
−35	13.1	7.5	0.44	0.18	51
−42	13.0	5.0	0.43	0.22	29
−38	17.8	80	0.76	0.40	139
−39	15.5	7.0	0.52	0.24	82
−9	(15.8)	(24)	(0.61)	(0.30)	81
−13	(17.9)	(73)	(0.77)	(0.37)	140
−15	(14.8)	(14)	(0.54)	(0.26)	60
−17	(16.9)	(43)	(0.69)	(0.34)	124

wind speeds at 3.5 m by the windmill-type anemometer and wind speeds extrapolated to the height of 10 m from measurements at the 11 times; then this relationship was applied to the wind speeds at the nine times by means of least squares. Wind speeds given in Table 1 represent values obtained by extrapolation and values in brackets obtained by the foregoing procedures.

3. 3. Drift density

According to SHIOTANI and ARAI (1953), snow particles which are carried along by turbulent diffusion are counterbalanced by falling snow particles in a steady state. On the assumption that the mass transfer coefficient can be replaced by eddy viscosity, that the vertical particle velocity is constant at all heights and equal to the terminal fall velocity, and that the horizontal particle velocity is equal to the wind velocity, SHIOTANI (1953) derived the snow drift density from the following eq. (2):

$$\frac{n_z}{n_1}=\left(\frac{z}{z_1}\right)^{-\frac{w}{\kappa V_*}}, \qquad (2)$$

where n_z is a snow drift density at the height z, the subscript "1" represents a reference level, and w is a terminal fall velocity.

As snow drift density and wind speed at each height can be determined from the results of these measurements, the terminal fall velocity, w, can be calculated by use of eq. (2). The obtained values of fall velocity are also shown in Table 1. The fall velocity is linearly proportional to V_{10}, the wind speed at the height of 10 m above the surface, having the relation with the regression coefficient of 0.96:

$$w=-0.255+0.035\cdot V_{10}. \qquad (3)$$

Drift densities obtained at various heights, together with wind speeds extrapolated to the height of 10 m, are shown in Fig. 3. From eq. (2) it is considered that the drift densities represent a linear relation to the heights on the double logarithmic scale. The state shown by this linear relation is called "suspension". As is clear from the obtained results, the densities are aligned fairly well on the regression lines.

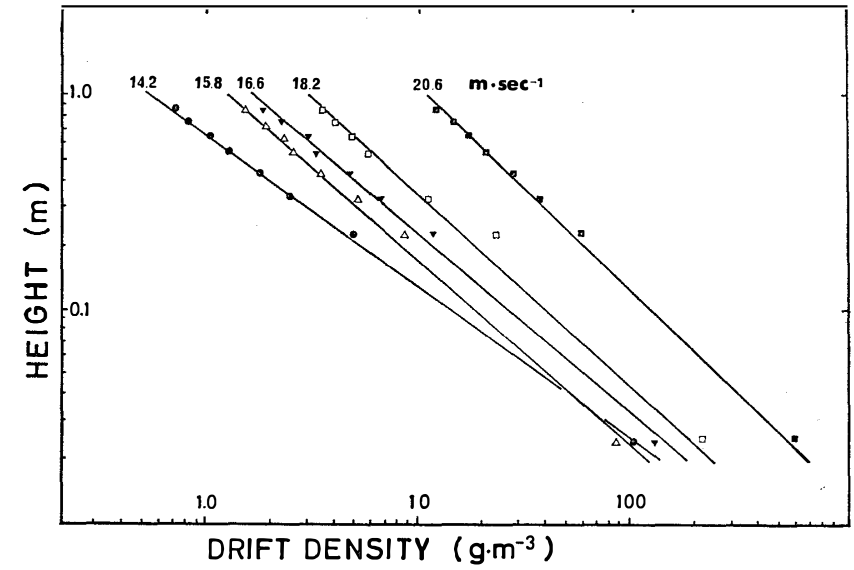

Fig. 3. Log height vs. log drift density together with wind speed at the height of 10m. In the case of a linear relation between drift density and height on a double-log scale, the state represented by this relation is called "suspension".

As shown in Fig. 4, the drift density (n_{z_0}) at the height z_0 and the height (B) where the drift density reaches 0.1 g·m^{-3} are obtained by extrapolation of the regression lines given in Fig. 3. Assuming the minimum capacity of the

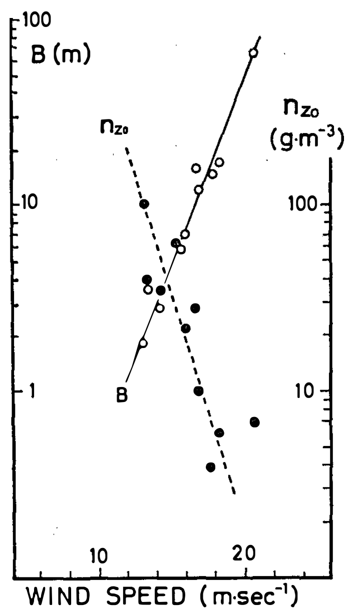

Fig. 4. A solid circle represents the drift density $n_{z0}(g \cdot m^{-3})$ at the height $z_0(m)$ and open circle represents the height $B(m)$ where the drift density reaches $0.1\,g \cdot m^{-3}$ which is expected to be the lowest density.

collector to be about $0.1\ \mathrm{g \cdot m^{-3}}$ in density, it is adequate that the height of 20 m is adopted as the upper limit of drift height. BUDD *et al.* (1966) adopted the upper limit of drift height to be 300 m since the logarithmic law for the wind profile can be held up to this height concerning the measurements at Byrd Station, but this value is considered an overestimate for Mizuho Camp which is different topographically and climatically from Byrd Station.

3. 4. Drift transport at Mizuho Camp

Mizuho Camp is situated on a slope, where the katabatic wind prevails; this prevailing wind has an almost constant direction of ESE throughout the year (SASAKI, 1974). Therefore, the two-dimensional model was introduced under the conditions that the katabatic wind flowed without changing its direction and the phenomenon of drifting snow occurred within a finite depth. Using this model, the rate of drift transport Q_{z1}^{z2} per unit width of flow between two given heights z_1 and z_2 is given by :

$$Q_{z1}^{z2}=\int_{z_1}^{z_2} q_z\, dZ, \qquad (4)$$

where q_z is a drift mass flux at the height z. As mentioned in the previous section, the height of 20 m is adopted as the upper limit value of z_2 in eq. (4). The regression lines of a drift transport from the surface to the height of 1 m are extraporated from 1 m to 20 m in height. Drift transports versus wind speeds at the height of 10 m are shown in Fig. 5. The equation fitting to all the obtained values is :

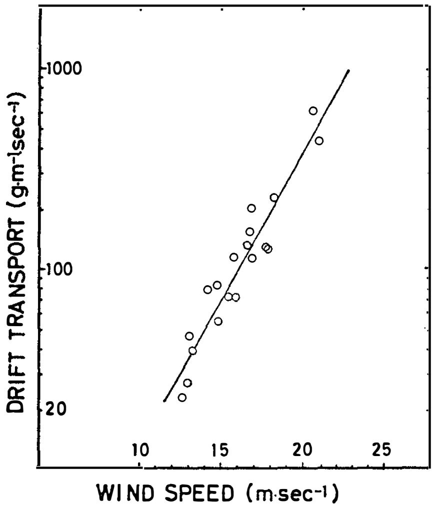

Fig. 5. Log drift transport from the surface to 20 m height vs. wind speed at 10 m height. The regression line gives eq. (5).

$$\log Q_0^{20}(\mathrm{g\cdot m^{-1}\cdot s^{-1}}) = -0.365 + 0.150 \cdot V_{10}(\mathrm{m\cdot s^{-1}}), \qquad (5)$$

where the logarithmic drift transport has the standard deviation of ± 0.11.

For the estimation of the change of drift transport with wind speed, the potential amount of snow which blows past Mizuho Camp has been calculated from the distribution of wind speed at Mizuho Camp using the average values for a period from 1971 to 1974 (INOUE, in preparation). Daily mean wind speeds, frequencies of wind speed and annual transports are shown in Table 2.

Table 2. Daily mean wind speeds, frequencies of wind speed and annual transports obtained from eq. (5).

Daily mean wind speed (m/s)	Frequency (d/yr)	Annual transport (t/km·yr) × 10³
1	0	0
3	3	0.3
5	41	8.6
7	67	28.0
9	98	81.7
11	80	133.1
13	52	172.7
15	18	119.3
17	5	66.1
19	1	26.4
Total	365	636.2

Using eq. (5), the total transport of Mizuho Camp can be estimated to be about 0.64×10^6 ton·km^{-1}·year^{-1}. However, for the same data the Byrd formula derived by BUDD *et al.* (1966) gives the estimate of the total transport to be about 3.0×10^6ton·km^{-1}·year^{-1}. Hence, the value given by the Byrd formula is several times larger than the value given by eq. (5).

4. Discussion

From the mass flux profile, a space in which drifting snow takes place may be divided into three layers according to heights: the first (I) is from the surface to 25 cm; the second (II) is from 25 cm to 1 m; the third (III) may be obtained from 1 m to 20 m by extrapolation using the profile in the second layer. A drift transport in each layer versus friction velocity is shown in Fig. 6 and their regression lines are given by the following equations:

$$\begin{aligned} &(\mathrm{I}) \quad Q_{0.0}^{0.25} \propto V_*^{2.9} \\ &(\mathrm{II}) \quad Q_{0.25}^{1.0} \propto V_*^{3.5} \\ &(\mathrm{III}) \quad Q_{1.0}^{20.0} \propto V_*^{5.0}. \end{aligned} \qquad (6)$$

It is considered as the most probable model for the first layer that drift

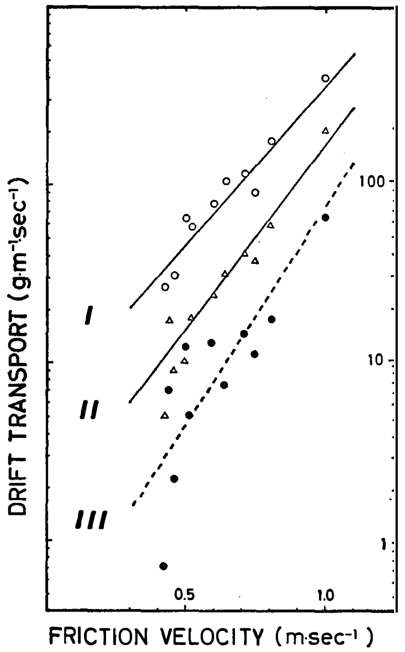

Fig. 6. Log drift transport in each layer vs. friction velocity. Drift space is divided into three layers: the first layer (I) from the surface to 0.25 m; the second layer (II) 0.25 to 1.0 m; the third layer (III) from 1.0 m to 20.0 m.

transport is provided by the mechanism of saltation, where the total transport derived is proportional to the friction velocity to the third power (BAGNOLD, 1941). Assuming that Bagnold's saltation theory can be applicable to drifting snow, the first layer in this case is defined to be the saltation layer from the fact that eq. (6) agrees well with the power law of saltation. Moreover, KAWAMURA (1948) pointed out that the logarithmic drift mass flux derived by saltation is proportional to height and this can be clearly observed in Fig. 2. Both the second and the third layer can be considered to have a fairly different mechanism from that of the first layer. These layers are defined to be suspension layers as clearly observed in Fig. 3. As for the surface drifting snow, therefore, it is satisfactory to consider that there exists a suspension layer superimposed on a saltation layer. Using this model, the existence of the bending point in the mass flux profile is clearly understood. In the case of weak snow drift in Hokkaido, TAKEUCHI *et al.* (1975) presented the same model as the foregoing. They found the bending point was positioned at about 8 cm above the surface.

The relationship given by BUDD *et al.* (1966) for drift transports versus wind speeds at Byrd Station in the layer between the levels of 1 mm and 300 m above the surface has been commonly used; the relationship concluded that the intermediate layer from 12.5 cm to 2 m did not contribute significantly to the total transport, whereas the higher layer from 2 m to 300 m played an important role. But it is difficult to consider that drifting snow reaches the height of 300 m above the snow surface at Mizuho Camp. To elucidate the difference of drifting snow at the two regions, it was tried to calculate a transport for each layer at Mizuho Camp to compare with the results of Byrd Station. The values when the wind speed at 10 m above the snow surface is 20 m·s^{-1} are

Table 3. A comparison of snow drift transport at Mizuho Camp in this paper with that of Byrd snow drift project data quoted from BUDD *et al. (1966).* Q_a^b *means a snow drift transport* ($g\cdot m^{-1}\cdot s^{-1}$) *for a layer from a(m) to b(m) in height when wind speed at the 10 m height is 20 m·s^{-1}.*

Q_a^b \ Station	Mizuho Camp	Byrd snow drift project data
$Q_{10^{-3}}^{0.125}$	100	300
$Q_{0.125}^{2}$	175	170
Q_{2}^{300}	16	500

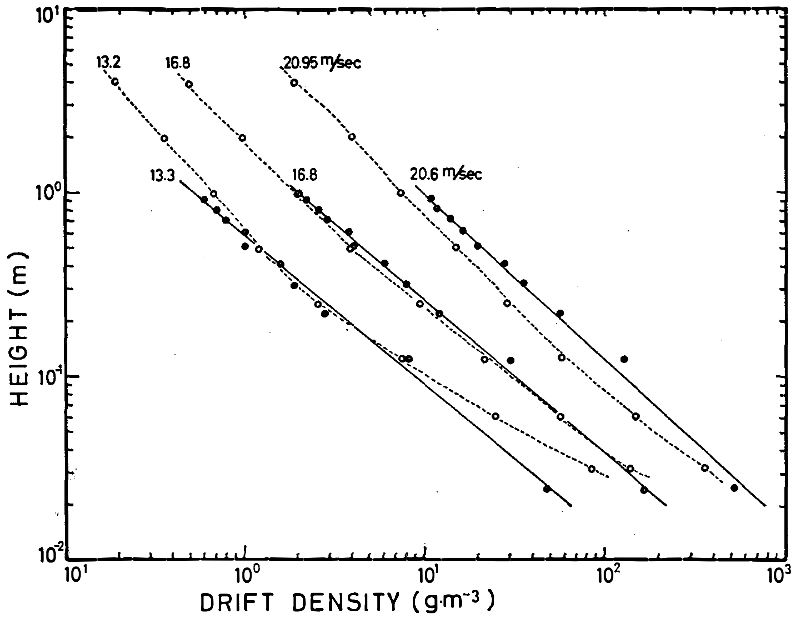

Fig. 7. A comparison between the log drift densities vs. log heights at Mizuho Camp (solid circles) and Byrd Station (open circles) with wind speeds at the height of 10 m.

shown in Table 3. What is evident on comparison is that the height of drifting snow at Mizuho Camp is much lower than that at Byrd Station, while the drift transport between 0.125 and 2.0 m coincides well with each other. Fig. 7 indicates the results of drift density profiles with different wind speeds at 10 m, where solid circles and open circles show the ones at Mizuho Camp and Byrd Station, respectively. The values at Byrd Station are due to BUDD *et al.* (1966). It is obvious from Fig. 7 that the results of measurements in this paper have the similar values to the ones at Byrd Station between the surface and 2 m in height. At height over 2 m, however, there seems to be a large discrepancy between the two cases. It is, therefore, necessary to measure directly the drift densities whithin the upper drifting layer in the near future.

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