NUMERICAL SIMULATION OF STRONG KATABATIC WINDS AT SYOWA AND MIZUHO STATIONS, ANTARCTICA

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***Abstract*:** The vertical profiles of the wind speed and air temperature and the wind spiral are studied in the case of the typical strong katabatic wind observed by radiosondes at Syowa and Mizuho Stations, Antarctica. The vertical profiles of the two horizontal wind components, eddy diffusivity, shear stress and local value of Monin-Obukhov length are calculated with the numerical model of the katabatic winds developed by ADACHI (Nankyoku Shiryô, **67**, 64, 1979). The numerical solutions of the katabatic wind profiles agree well with the observed ones at Syowa Station.

1. Introduction

It is well known that the katabatic winds in Antarctica blow down along the ice slope on the Antarctic coast. However the vertical structure of the katabatic winds are not yet clear sufficiently.

In the case of Syowa Station (69°00′S, 39°35′E, on East Ongul Island), MORITA (1968) reported some characteristics of the observed surface wind referring to BALL's theory (1956, 1960). ADACHI (1973, 1974) and MAKI (1974) observed the profiles of the wind speed, air temperature and atmospheric turbulence in the surface boundary layer, and ADACHI (1980) reported on the observation of the hydraulic jumps of the katabatic winds.

The above-mentioned studies were restricted to the atmospheric surface layer. ADACHI (1979) researched on the atmospheric boundary layer (ABL) at Syowa Station and developed a numerical model of the katabatic wind.

In the case of Mizuho Station (70°41′53″S, 44°19′54″E, an inland 270 km away from Syowa Station), SASAKI (1974, 1979) reported some characteristics of the atmospheric surface layer, and KOBAYASHI and YOKOYAMA (1976) and KOBAYASHI (1978) reported on the observations of the radiosondes. No researches on the numerical simulation of the katabatic wind at Mizuho Station have been made so far.

It is the purpose of this study to simulate the vertical profiles of the strong katabatic winds and to present the veritcal profiles of the eddy diffusivities, shear stress and local value of Monin-Obukhov length, which were not observed directly in ABL at the two points, Syowa and Mizuho Stations in Antarctica.

2. Observed Data

2.1. Data observed at Syowa Station

The aerological data of rawinsonde in 1969–1971 at Syowa Station (see JAPAN METEOROLOGICAL AGENCY, 1971a, b, 1973) are used in this study to analyze the typical strong katabatic winds. The selection conditions of the data are as follows;

(a) 03 local time data.

(b) Clear sky condition; total cloud amount is equal to or less than 1.

(c) Strong wind condition; surface wind speed is equal to or larger than 8 m/s.

(d) Height of the maximum wind speed is less than 500 m from the ground surface.

The 14 data are selected out from the data of the above-mentioned three years under the four conditions described above.

The selected wind and air temperature data are analyzed by the following procedure. First, the observed wind direction and speed are converted into northerly and easterly wind components. Next, the vertical profiles of the two wind components are averaged by the eye on the selected data. Then, the averaged values are again converted into the wind direction and speed.

Air temperatures subtracted from the surface values are averaged by the eye on the selected data.

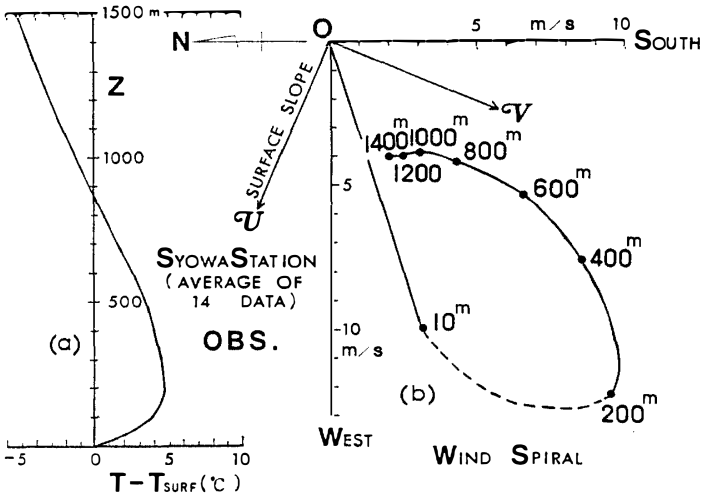

Fig. 1. Observed vertical profile of air temperature (a) and observed wind spiral (b) at Syowa Station. $T - T_{SURF}$: Air temperature subtracted from the surface value. z: Height from the snow surface. u: Wind component of maximum surface slope coordinate. v: Wind component of the coordinate intersected at right angles to u.

Figure 1 shows the vertical profile of the mean air temperature and the mean wind spiral of the typical katabatic wind observed at Syowa Station. The broken line indicates the insufficiency of the number of the data between 10 and 200 m heights from the ground surface.

Characteristics of the wind spiral are that the height of maximum wind speed is equal to or less than about 200 m heights and the wind spiral is counterclockwise which is caused by Coriolis force in the Southern Hemisphere. The angle between the line of the maximum surface slope in the coastal region of Antarctica near the Ongul Strait

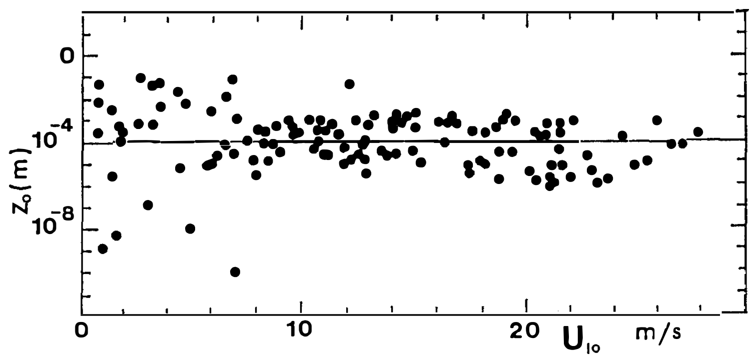

Fig. 2. Roughness length vs. wind speed observed at Syowa Station (after ADACHI, 1973).

and the flow line of the surface wind is 40 degrees.

Figure 2 shows the roughness length observed at Syowa Station by ADACHI (1973). As in this figure, the roughness length is around 0.01 cm at Syowa Station when the surface wind speeds are larger than about 8 m/s. The roughness length is used as a boundary condition of the numerical simulations of the katabatic winds. The details of the boundary conditions will be described later.

2.2. *Data observed at Mizuho Station*

Observational results of the radiosondes, which were called RABAL, at Mizuho Station in 1973 were reported by KOBAYASHI and YOKOYAMA (1976) and KOBAYASHI (1978).

As the number of the observations is only seven, we do not average them, but pick up only one data observed at 1420 LT April 23 in 1973, which is an example of the typical katabatic winds at Mizuho Station. Figure 3 shows the vertical profiles of the wind speed (a), air temperature (b) and wind spiral (c).

Characteristics of the observed data are that the height of maximum wind speed

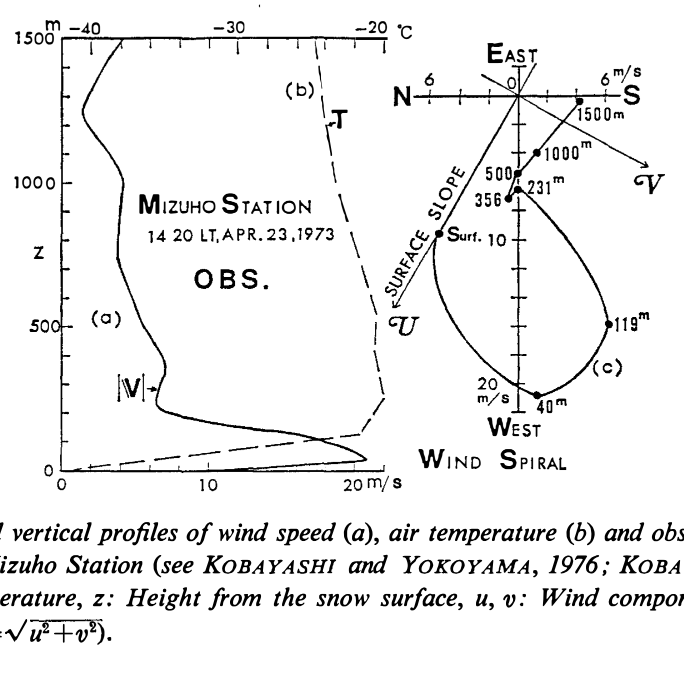

Fig. 3. Observed vertical profiles of wind speed (a), air temperature (b) and observed wind spiral (c) at Mizuho Station (see KOBAYASHI and YOKOYAMA, 1976; KOBAYASHI, 1978). T: Air temperature, z: Height from the snow surface, u, v: Wind components, $|V|$: Wind speed ($=\sqrt{u^2+v^2}$).

is about 40 m where the wind speed has a sharp peak, and the vertical gradient of the air temperature is larger than that at Syowa Station and then the wind spiral is counterclockwise similar to the case of Syowa Station.

3. Model of the Numerical Simulation of Katabatic Wind

3.1. Governing equations

The simulation model is the same as the one developed by ADACHI (1979). Characteristics of this model are that the effects of the stabilities, the baroclinisities and the slope are taken into consideration and not only wind components but also eddy diffusivity are treated as being unknown values in the non-linear differential equations.

The present assumptions are as follows;

(a) The stationary condition.

(b) The z component of wind vector is zero on the sloped terrain.

(c) The wind vector is independent on x and y coordinates, and dependent only on z coordinate.

(d) Monin-Obukhov's similarity theory holds in each height of ABL.

(e) Local value of Monin-Obukhov length is defined by the heat and momentum flux of each height layer.

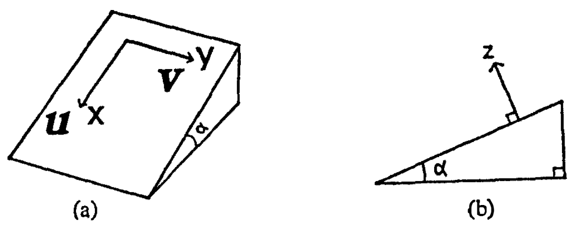

Fig. 4. Coordinate system for governing equations.

The coordinates system used in this model is illustrated in Fig. 4. The z coordinate is approximately vertical as the slope of the surface is very small. However, the x component of the gravity cannot be neglected as the sloping surface is very long and wide.

The present governing equations are the following;

$$0=\frac{\mathrm{d}}{\mathrm{d}z}\left(K\frac{\mathrm{d}u}{\mathrm{d}z}\right)+f(v-v_g)+g\cdot\sin\alpha\cdot(\Theta-\theta)/\bar{\Theta}\,, \tag{1}$$

$$0=\frac{\mathrm{d}}{\mathrm{d}z}\left(K\frac{\mathrm{d}v}{\mathrm{d}z}\right)-f(u-u_g)\,, \tag{2}$$

$$K=kz|\tau/\rho|^{1/2}/\phi\,, \tag{3}$$

$$\phi=(1+12\,z/L)^{1/2}\,, \tag{4}$$

$$\tau/\rho=K\frac{\mathrm{d}V}{\mathrm{d}z}\,, \tag{5}$$

$$q/C_p\rho=-K\frac{\mathrm{d}\theta}{\mathrm{d}z}\,, \tag{6}$$

$$z/L = -k(g/\theta)(q/C_p\rho)z/|\boldsymbol{\tau}/\rho|^{3/2}, \tag{7}$$

$$\boldsymbol{V} = u + iv, \tag{8}$$

$$\boldsymbol{V}_g = u_g + iv_g, \tag{9}$$

$$\boldsymbol{\tau} = \tau_x + i\tau_y, \tag{10}$$

$$u_{gk} = u_g, \tag{11}$$

$$v_{gk} = v_g + v_k, \tag{12}$$

$$v_k = -(g/f)\cdot\sin\alpha\cdot(\Theta-\theta)/\bar{\Theta}, \tag{13}$$

$$\boldsymbol{V}_{gk} = u_{gk} + iv_{gk}, \tag{14}$$

$$|\boldsymbol{V}| = \sqrt{u^2+v^2}, \tag{15}$$

$$|\boldsymbol{V}_{gk}| = \sqrt{u_{gk}^2 + v_{gk}^2}, \tag{16}$$

$$|\boldsymbol{\tau}| = \sqrt{\tau_x^2 + \tau_y^2}, \tag{17}$$

$$i = \sqrt{-1}. \tag{18}$$

List of symbols

x: Along slope coordinate (see Fig. 4a),
y: Rectangular to x (see Fig. 4a),
z: Normal coordinate to x-y plane (see Fig. 4b),
u: Wind component (x-axis),
v: Wind component (y-axis),
K: Eddy diffusivity,
f: Coriolis parameter ($f<0$),
g: Gravity acceleration,
Θ: Potential temperature at the top of the inversion layer of air temperature,
θ: Potential temperature,
$\bar{\Theta}$: Mean potential temperature,
α: Slope of flow line,
u_g: Geostrophic wind component (x-axis),
v_g: Geostrophic wind component (y-axis),
k: Von Karman constant ($k=0.41$),
ϕ: Non-dimensional wind shear function,
L: Local value of Monin-Obukhov length,
$\boldsymbol{\tau}$: Shear stress vector,
ρ: Air density,
q: Heat flux,
C_p: Specific heat,
z_0: Roughness length,
$\boldsymbol{V}$: Wind vector,
$\boldsymbol{V}_g$: Geostrophic wind vector,
v_k: Effect of cold sloping surface,

V_{gk}: Resultant vector of geostrophic wind vector and effect of cold sloping surface.

Equations (1) and (2) are the equations of the air motions. The third term of eq. (1) represents the effects of the ice slope. Equations (3) and (5) are the relation of eddy diffusivity and shear stress at each level. Equation (4) is a non-dimensional wind shear function, which was developed and tested for the baloclinic and neutral or stable ABL by ADACHI (1979, 1982).

3.2. *Boundary conditions and input data*

Boundary conditions of this simulation model are as follows;

$$V=0\,,\quad \text{at}\quad z=z_0$$

$$V=V_g\quad \text{and}\quad \tau/\rho=0\,,\quad \text{at}\quad z\rightarrow\infty\,.$$

Input data of this simulation model are as follows;

(a) Potential temperature profile $\theta(z)$

Observed potential temperature profile is used in this model.

(b) Geostrophic wind profile $V_g(z)$

As the vertical profiles of the geostrophic wind components were not observed in this study, the geostrophic winds are approximated by the methods of fitting to the observed wind components in the upper layer and extrapolating linearly from the upper layer to the surface.

In the case of Syowa Station the range of the height of this upper layer is taken to be from 1000 to 1500 m above the ground surface. In the case of Mizuho Station the one of this upper layer is taken to be from 500 to 1500 m above the ice surface as the inversion layer is thinner than that at Syowa Station.

(c) The slope of the flow line (α)

According to SHIMIZU *et al.* (1978), the Antarctic coastal slope near Syowa Station is 41×10^{-3}, and the surface slope is around 3×10^{-3} at Mizuho Station.

The slope of the flow line in the upper layer is horizontal and the one in the surface layer is equal to the slope of the terrain as in Fig. 5. It seems that the slope of the flow line is a function of the height from the surface.

However, as the z component of wind vector is neglected in the present model,

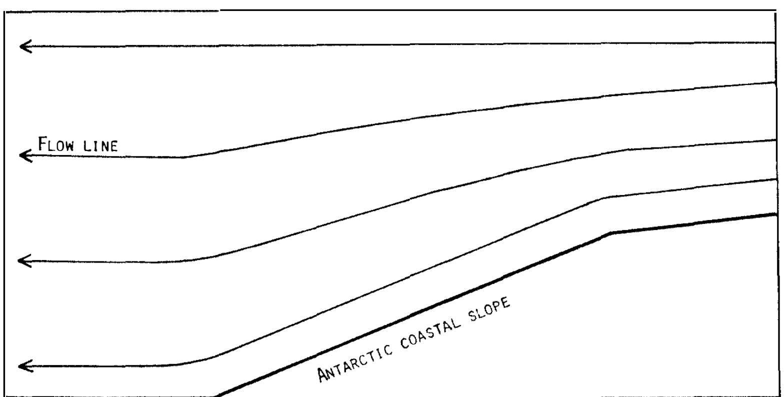

Fig. 5. Schematic flow lines of katabatic wind over Antarctic coastal slope.

we should consider an approximate function which expresses the effect of the cold sloping surface.

(d) Effect of the cold sloping surface $v_k(z)$

Equation (13) should be used for estimating this effect. However, we cannot estimate the effective value of the slope in the case of Syowa Station because Syowa Station is about 6 km far away from the Antarctic coast in the up-wind direction. Therefore, the resultant vectors of geostrophic wind and the effects of the cold sloping surface are estimated by the method of fitting to the y component of the observed wind from 400 to 1000 m heights and extrapolating linearly from this upper layer to the surface.

In the case of Mizuho Station v_k is assumed by the following equations;

$$v_k = v_k(0)\cdot(h-z)/h \,, \tag{19}$$

$$v_k(0) = -(g/f)\cdot\sin\alpha\cdot\Delta\theta/\overline{\Theta} \,, \tag{20}$$

$$g = 9.8 \,, \tag{21}$$

$$f = -1.4\times10^{-4} \,, \tag{22}$$

$$\alpha = 3\times10^{-3} \,, \tag{23}$$

$$\Delta\theta/\overline{\Theta} = 0.0823 \,, \tag{24}$$

$$h = 260 \,. \tag{25}$$

$v_k(0)$: v_k at $z=z_0$,

h: Depth of the inversion layer of the air temperature.

It is assumed simply that eq. (19) is a linear function of z in this study.

3.3. *Procedure of calculation*

The non-linear differential equations are solved by the combination of the approximation method and the relaxation method. This combination method was employed by ADACHI (1970, 1979, 1982).

4. Results and Discussion

4.1. *Case of Syowa Station*

Figure 6 shows the calculated vertical profiles of the two horizontal wind components (u, v) under the two different conditions of the roughness length and the observed ones. The solid lines indicate the calculation in the case of $z_0=1$ cm. The broken lines indicate the calculation in the case of $z_0=0.1$ mm. The black circles indicate the observation. The dot-and-dash lines indicate the components of the assumed geostrophic wind (u_g, v_g) and the resultant vector of the geostrophic wind vector and the assumed effect of the cold sloping surface (V_{gk}).

The two calculated wind components agree well with the observed wind components as in Fig. 6.

Figure 7 shows the calculated vertical profiles of the eddy diffusivities (K), the non-dimensional wind shear functions (ϕ), the atmospheric stabilities (z/L) and the friction velocities (u_*). We cannot compare these values with the observational ones because of the lack of the observation of the turbulence in ABL. However,

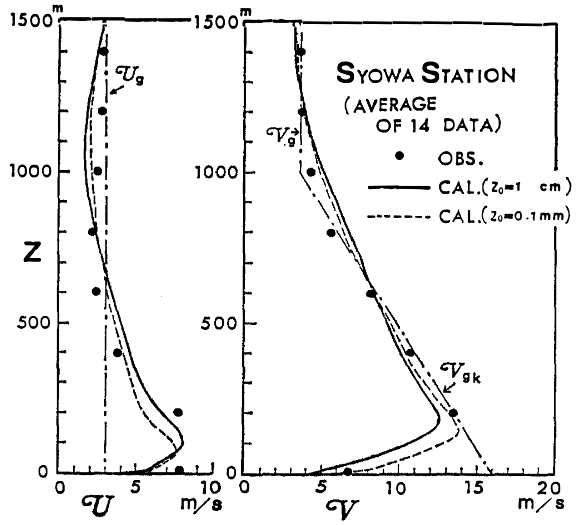

Fig. 6. Comparison of the observed wind components with calculated ones under the two conditions of z_0 at Syowa Station. u: Wind component of x-axis, v: Wind component of y-axis.

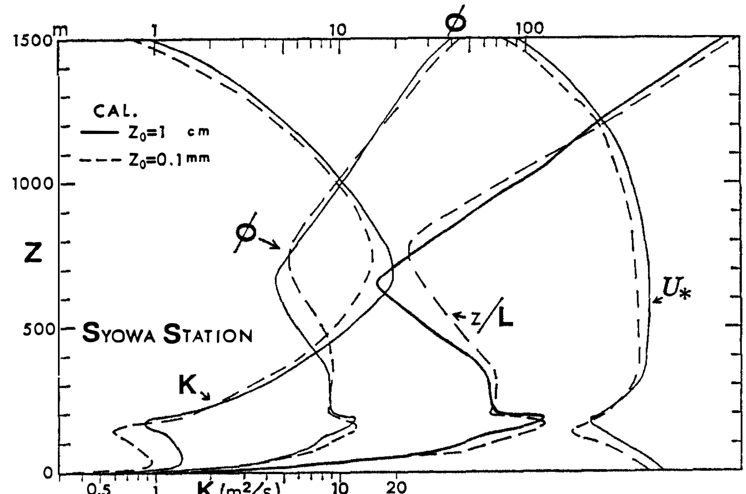

Fig. 7. Calculated vertical profiles of K, ϕ, z/L and u_* under the two conditions of z_0 at Syowa Station. K: Eddy diffusivity, ϕ: Non-dimensional wind shear function $=(1+12\,z/L)^{1/2}$, z: Height from the snow surface, L: Local value of Monin-Obukhov length, u_*: Friction velocity, z_0: Roughness length (=1 or 0.01 cm).

these calculated values at the height between 200 and 700 m depend upon the vertical gradient of V_{gk} as in Fig. 7. Because from eqs. (3) and (5), the eddy diffusivity is rewriten as follows,

$$K=k^2z^2\left|\frac{\mathrm{d}V}{\mathrm{d}z}\right|\Big/\phi^2\,. \tag{26}$$

Then, from the boundary condition in the upper layer,

$$K \to k^2 z^2 \left| \frac{\mathrm{d}V_{gk}}{\mathrm{d}z} \right| \Big/ \phi^2 , \text{ as } z \to \infty . \tag{27}$$

4.2. Case of Mizuho Station

Figure 8 shows the calculated vertical profiles of the two horizontal wind components (u, v) under the two different conditions of the roughness length and the observed ones. The symbols are the same as Fig. 6. The calculated maximum wind speeds are underestimated as in Fig. 8. However, the heights of the calculated maximum wind components agree almost with observation. The estimation of the effect of the cold sloping surface (v_k) is the subject for a future study.

Figure 9 shows the calculated vertical profiles of the eddy diffusivities (K) and the friction velocities (u_*) under the two different conditions of the roughness length.

Figure 10 shows the calculated vertical profiles of the non-dimensional wind shear functions (ϕ) and the atmospheric stabilities (z/L).

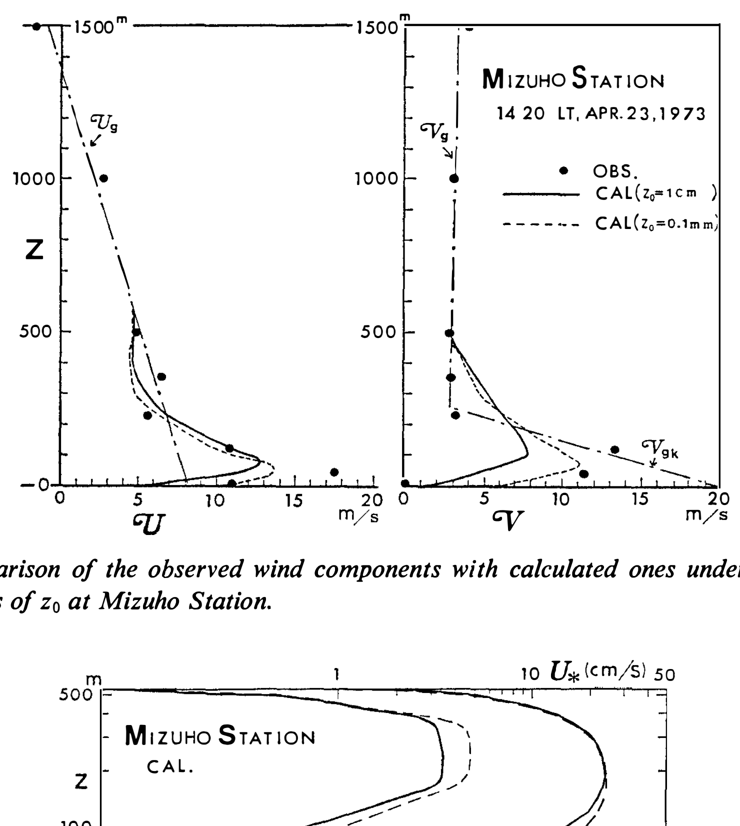

Fig. 8. Comparison of the observed wind components with calculated ones under the two conditions of z_0 at Mizuho Station.

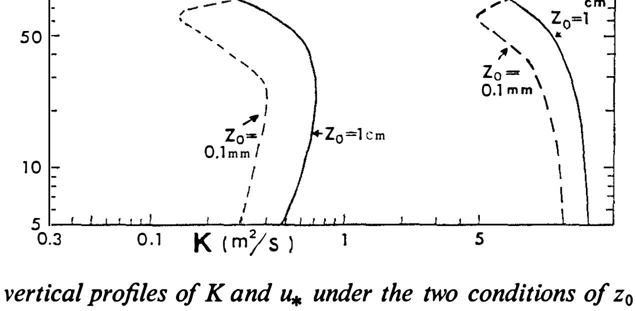

Fig. 9. Calculated vertical profiles of K and u_* under the two conditions of z_0 at Mizuho Station. K: Eddy diffusivity, u_*: Friction velocity, z_0: Roughness length (=1 or 0.01 cm).

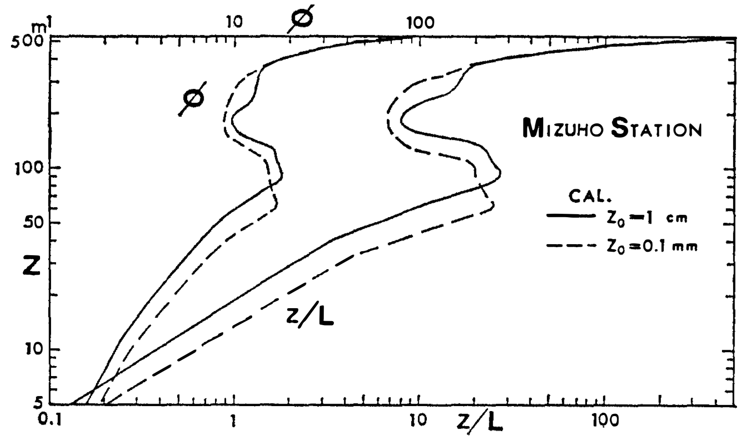

Fig. 10. Calculated vertical profiles of ϕ and z/L under the two conditions of z_0 at Mizuho Station. ϕ: Non-dimensional wind shear function $= (1+12\, z/L)^{1/2}$, z: Height from the snow surface, L: Local value of Monin-Obukhov length, z_0: Roughness length ($=1$ or 0.01 cm).

5. Concluding Remarks

In the case of Syowa Station the present numerical solutions of the katabatic wind profile agree well with the observed ones. The calculated results of the eddy diffusivity, shear stress and local value of Monin-Obukhov length are qualitatively reasonable.

In the case of Mizuho Station the present numerical model successfully simulated the pattern of the strong katabatic wind profile. However, the calculated maximum wind speeds are underestimated.

It is the subject for a future study to find the real effect of the cold sloping surface to the structure of ABL at Syowa and Mizuho Stations.

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