Coefficients of Resistance to Cold-Air-Drainage Winds of a Grass-Covered Slope

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INTRODUCTION

Cold-air-drainage (CAD) winds occur during calm and clear nights on slopes and this phenomenon is closely related to the thermal environment of people, animals, and plants. The driving force of CAD winds is the surplus of density, or the deficit of potential temperature produced by radiative cooling in the surface air layer on a slope, and is resisted by the ground surface and the surrounding atmosphere. The coefficients of resistance of the ground surface and the surrounding atmosphere change with the CAD wind speed. The observations made on a grass-covered slope of Mt. Kuju showed that the resistance exerted by the surrounding atmosphere was much larger than that by the ground surface, and the sum of two coefficients of resistance decreased by one order of magnitude when the CAD wind speed exceeded some critical value.

JOKE WORDS: Cold-air-drainage wind, CADL, Coefficient of resistance, Potential temperature deficit

OBSERVATIONS

The cold-air-drainage (CAD) wind is one of the most familiar local winds in Japan. It is driven by the surplus of density, or the deficit of potential temperature produced by radiative cooling in the surface air layer, therefore the CAD wind speed is affected by the vertical profile of potential temperature. On the other hand, there are two kinds of resistance forces that are exerted on the cold-air drainage layer (CADL); one is the force exerted by the ground surface and the other is that by the surrounding atmosphere. They were assumed to be proportional to the drainage speed squared, the coefficient of proportionality being the coefficient of resistance. These coefficients of resistance of the ground surface and the surrounding atmosphere are not constant but change with CAD wind speed.

This paper describes the results of analyzing the observations taken on a grass-covered slope of Mt. Kuju and estimating the coefficient.
Where follows: assume that potential temperature increases with upward and origin at an arbitrary position on the slope, the left that of potential temperature. Let us put the right figure shows the profile of the CAD wind speed and properties at heights of CAD wind on a slope with the slope angle of $\theta$. The solution to Eq. (6) is written as

$$
\hat{u} = \frac{\hat{u}_0}{h_{CD}} \int_0^\infty \frac{h}{\sin\theta} \left[ (C_a + k) \frac{\partial \hat{u}}{\partial z} \right] dz \tag{7}
$$

where $u$: $x$-component of the CAD wind speed at height $z$, $\hat{u}$: potential temperature difference between two heights $z$ and $h$ or the potential temperature deficit ($= \overline{\partial\phi} (h_0) - \overline{\partial\phi} (z)$), $\hat{u}_0$: characteristic potential temperature in CADL and $g$: acceleration due to gravity. $C_a$ and $k$ are the coefficients of resistance of the ground surface and the surrounding atmosphere to CAD winds, respectively. If the second term on the right of Eq. (2) can be neglected, or $\partial (\bar{\partial} \hat{u})/\partial x \approx 0$, Eq. (2) is simplified as

$$
h \frac{\partial}{\partial z} \left[ \hat{u} + h g \frac{\partial \hat{u}}{\partial z} \sin\theta - (C_a + k) \hat{u} \right] \frac{\partial \hat{u}}{\partial z} \tag{6}
$$

The solution to Eq. (6) is written as

$$
\hat{u} = \int_0^\infty \left[ \hat{u}_0 \exp(-z/L) \right] + \frac{\hat{u}_0}{h_{CD}} \int_0^\infty \frac{h}{\sin\theta} \left[ (C_a + k) \frac{\partial \hat{u}}{\partial z} \right] dz \tag{7}
$$

where

$$
\hat{u}_0 = \frac{1}{L} \left[ \int_0^\infty \frac{h}{\sin\theta} \left[ (C_a + k) \frac{\partial \hat{u}}{\partial z} \right] dz \right] \tag{8}
$$

MODEL

Figure 2 shows the two dimensional model of the CAD wind on a slope with the slope angle of $\theta$. The right figure shows the profile of the CAD wind speed and the left that of potential temperature. Let us put the origin at a arbitrary position on the slope, $x$ axis positive down the slope, $z$ axis normal to the slope positive upward and $\hat{u}$ axis positive vertically upward. Here we assume that potential temperature increases with $\hat{u}$ linearly in the CADL, the gradient $\overline{\partial\phi}$ being expressed as follows:

$$
\overline{\partial\phi} = \hat{u} \sin\theta + \frac{\partial \hat{u}}{\partial z} \tan\theta
\tag{1}
$$

Table 1. Observation stations and instruments

<table>
<thead>
<tr>
<th>Station</th>
<th>Altitude (m ASL)</th>
<th>Variables</th>
<th>Instruments</th>
<th>Heights (m AGL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>930</td>
<td>Wind speed &amp; direction</td>
<td>Propeller–type anemometer</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature &amp; humidity</td>
<td>Aspirated HUMICAP sensor</td>
<td>0.85, 2.4, 4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Net radiation</td>
<td>Net radiometer (CAMPBELL, Q-7.1)</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar radiation</td>
<td>Pyranometer (CAMPBELL, LE200X)</td>
<td>2.1</td>
</tr>
<tr>
<td>W_s</td>
<td>903</td>
<td>Wind speed &amp; direction</td>
<td>Propeller–type anemometer</td>
<td>2.5</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Firstly, nights when CAD winds blew were identified based on the wind direction and net radiation (Komoda et al., 2006). As a result, six nights (Sep. 25–26; 27–28; Oct. 3–4; 4–5; 5–6; 15–16, 2000) were selected for this analysis. Figure 3 shows the time changes in wind speed and direction observed during the night Oct. 3–4, 2000. Before the integrations can be performed in Eqs. (3)–
(5), the vertical profile of wind in CADL should be
determined. Since we do not have precise data on the
profile, we assume the polynomial expression proposed
by Mori et al. (1999). If the thickness of CADL is 20 m
(Mori et al., 1999), $\hat{u}$ is nearly equal to $u$ at a height of
2.5 m.

We calculated the gradient of the potential tempera-
ture $\hat{\theta}$ from Eq. (1), using the potential tempera-
tures at heights of 4.5 m and 0.85 m. Because $\hat{\theta}$ is equal to
the potential temperature deficit at the height of $\hat{\theta} = h/2\cos$ $\frac{\theta}{2}$, $\hat{\theta} = \hat{\theta} = \hat{h}/2\cos \theta$. Other variables were specified as $g =
9.8 \, \text{ms}^{-2}$; $B = 285 \, \text{K}$ (average for the six nights) and $\theta =
7^\circ$.

Substituting the measurements of wind speed at
2.5 m height at Station M ($x = 0$) and Station $W_1$ ($x =
220 \text{m}$) into Eq. (7) we can get the sum of two coeffi-
cients of resistance, $C_p + k$. However $\hat{u}$, also include
$C_p + k$ (Eq. (8)), so we cannot perform the calculation
explicitly. Thus, we compared the wind speed observed
at Station $W_1$ with that calculated from Eq. (7) using the
wind speed at Station M and tentative values of $C_p + k$;
that is 0.02 and 0.002. Figure 4 shows the relationship
of the wind speed at Station $W_1$ between the observed
($u_{\text{obs}}$) and the calculated ($u_{\text{cal}}$) from Eq. (7). When wind
speed was relatively low ($u_{\text{obs}} < 3 \, \text{ms}^{-1}$), the calculated values obtained using $C_p + k = 0.02$ gave good estimates,
though they showed some scatter. However, when wind
speed was high ($u_{\text{obs}} > 3 \, \text{ms}^{-1}$), the calculated was much
smaller than the observed. In the case of strong wind
($u_{\text{obs}} > 3 \, \text{ms}^{-1}$), the calculated values obtained using $C_p +
k = 0.002$ gave good estimates. This means that the
higher the wind speed is, the smaller is the coefficient of
resistance.

Nappo and Rao (1987) showed that the entrainment
factor $E$, which is equivalent to the coefficient of resis-
tance $k$, could be written as

$$E = 0.10(\sin \theta)^{2/3}$$

(10)

where $\theta$ is the slope angle. Substituting 7 degrees into
$\theta$ gives $E \approx 0.02$. If the value of $C_p$ is one order of mag-
itude smaller than that of $k$, this relation gives good
estimates of $k$ for the case of $u_{\text{obs}} < 3 \, \text{ms}^{-1}$. However, it
seems that Eq. (10) overestimates the coefficient of
resistance exerted by the surrounding atmosphere as
the wind speed becomes higher.

The coefficient of resistance exerted by the ground
surface is known to decrease with wind speed and to
approach a constant called the bulk coefficient, which
seems to be much smaller than 0.002 in this case.
Therefore, it was revealed by this analysis that the coeffi-
cient of resistance exerted by the surrounding atmos-
phere to CAD winds also decreased with the CAD wind
speed.

**CONCLUDING REMARKS**

The CAD wind is driven by the surplus of density or
the deficit of potential temperature produced by radia-
tive cooling in the surface air layer on a slope, and is
resisted by the ground surface and the surrounding
atmosphere. The observations made at a grass-covered
slope of Mt. Kuju revealed that the sum of the coeffi-
cients of resistance exerted by them decreased with
increasing the CAD wind speed. When wind speed was
relatively low ($u_{\text{obs}} < 3 \, \text{ms}^{-1}$), the calculated values obtained
using $C_p + k = 0.02$ gave good estimates, though they
showed some scatter. However, in the case of strong
wind ($u_{\text{obs}} > 3 \, \text{ms}^{-1}$), the calculated values obtained using $C_p +
k = 0.002$ gave good estimates. This means that the
higher the wind speed is, the smaller is the coefficient of
resistance. The coefficient of resistance exerted by the
ground surface is known to decrease with wind speed
and to approach a constant, which was estimated to be
much smaller than 0.002 in this case. Therefore, it is
concluded that the coefficient of resistance exerted by
the surrounding atmosphere to CAD winds also
decreased with increasing the CAD wind speed.
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REFERENCES


