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

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http://hdl.handle.net/2324/9263
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.

OBSERVATIONS

The observations were made at Kuju Agricultural Research Center (KARC) of Kyushu University located on the slope facing south–southeast of Mt. Kuju (Oita, 1787 m ASL), the average slope angle being about 7 degrees (Fig. 1). The experimental slope was covered with grass, the height being less than several tens of centimeters, and it was dotted with trees and buildings such as quarters and stockyards. There were no obstacles, however, on the slope between Station M and Station W (Fig. 1).

The observations were taken from July through November in 2000. The horizontal distance between the two stations M and W was 220 m. The information on the instrumentation at each station is shown in Table 1. All observations were 10–min averages and taken at intervals of 10 min.
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 $\Theta$ axis positive vertically upward. Here we assume that potential temperature increases with distance from the origin to a first approximation.

Then one dimensional momentum equation in $x$-direction of cold air in CADL is expressed as follows (Mahrt, 1982):

$$\frac{\partial}{\partial x} (h \hat{u} \hat{v}) = h g \sin \Theta - \cos \Theta \left( \frac{\partial \hat{u}}{\partial z} \right) - (C_n + k) \hat{u}^2$$  \hspace{1cm} (2)

where $h$: thickness of the CADL, ($\Theta$) as being invariable with distance from the origin to a first approximation. $\hat{u}$: $x$-component of the CAD wind speed at height $z$, $\hat{v}$: potential temperature difference between two heights $z$ and $h$ or the potential temperature deficit ($= \hat{\theta} (h) - \hat{\theta} (z)$). $C_n$ and $k$ are the coefficients of resistance of the ground surface and the surrounding atmosphere to CAD winds, respectively.

When $\hat{u}$ changes with fetch in the downslope direction, the thickness of CADL and the profile of wind speed in CADL inevitably changes. However, since the length of fetch is 220 m at this observation site, we assume that the effects of these changes are negligible. If $\hat{u}$ are evaluated at two points on the slope, we can calculate the coefficients of the sum of two coefficients of resistance, $C_n + k$.

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)–

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 (KONA, KDCS–4)</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature &amp; humidity</td>
<td>Aspirated HUMICAP sensor (VAISALA, HMP350)</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, LI200X)</td>
<td>2.1</td>
</tr>
<tr>
<td>W_2;</td>
<td>903</td>
<td>Wind speed &amp; direction</td>
<td>Propeller–type anemometer (KONA, KDCS–4)</td>
<td>2.5</td>
</tr>
</tbody>
</table>
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 temperature $\theta$ from Eq. (1), using the potential temperatures at heights of 4.5 m and 0.85 m. Because $\hat{\theta}$ is equal to the potential temperature deficit at the height of $\hat{\theta} = h/2 \cos \theta$, $\hat{\theta} = \hat{\theta} = h/2 \cos \theta$. Other variables were specified as $g = 9.8 \text{ms}^{-2}$, $T_s = 285 \text{K}$ (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 W4 ($x = 220$) into Eq. (7), we can get the sum of two coefficients of resistance, $C_D + k$. However $\hat{u}$ also include $C_D + k$ (Eq. (8)), so we cannot perform the calculation explicitly. Thus, we compared the wind speed observed at Station W4 with that calculated from Eq. (7) using the wind speed at Station M and tentative values of $C_D + k$; that is 0.02 and 0.002. Figure 4 shows the relationship of the wind speed at Station W4 between the observed ($u_{o4}$) and the calculated ($u_{c4}$) from Eq. (7). When wind speed was relatively low ($u_{o4} < 3 \text{ms}^{-1}$), the calculated values obtained using $C_D + k = 0.02$ gave good estimates, though they showed some scatter. However, when wind speed was high ($u_{o4} > 3 \text{ms}^{-1}$), the calculated was much smaller than the observed. In the case of strong wind ($u_{o4} > 3 \text{ms}^{-1}$), the calculated values obtained using $C_D + k = 0.002$ 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 resistance $k$, could be written as

$$E = 0.10 \sin(\hat{\theta})^{0.5}$$

(10)

where $\hat{\theta}$ is the slope angle. Substituting 7 degrees into $\hat{\theta}$ gives $E \hat{\theta} 0.02$. If the value of $C_p$ is one order of magnitude smaller than that of $k$, this relation gives good estimates of $k$ for the case of $u_{o4} < 3 \text{ms}^{-1}$. 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 coefficient of resistance exerted by the surrounding atmosphere 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 radiative 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 coefficients of resistance exerted by them decreased with increasing the CAD wind speed. When wind speed was relatively low ($u_{o4} < 3 \text{ms}^{-1}$), the calculated values obtained using $C_D + k = 0.02$ gave good estimates, though they showed some scatter. However, in the case of strong wind ($u_{o4} > 3 \text{ms}^{-1}$), the calculated values obtained using $C_D + k = 0.002$ 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.
ACKNOWLEDGEMENTS

The authors wish to thank Drs. T. Nishimura, Y. Ono, A. Goto and Mr. K. Ichinose for their assistance in setting up and maintaining the field equipment. They also wish to thank Prof. T. Maki of Kyushu University for his encouragement.

REFERENCES


