# ROUGHNESS EFFECT ON VAPOR TRANSFER FOR SURFACE HOAR GROWTH

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ABSTRACT: In order to examine the roughness effect of surface hoar crystals on their growth and obtain a relation between surface roughness and the amount of sublimation, field observations of surface hoar formation were carried out in the three seasons of 1993 to 1996 in Hokkaido, northern Japan. The sublimation rate increased linearly with the product of the vapor pressure gradient and the wind speed. This relation made it possible to estimate the sublimation rate of surface hoar by a bulk method from the meteorological data. The bulk transfer coefficient of water vapor was roughly constant ($2.4\times10^{-3}$, dimensionless) when the surface hoar crystals were small, whereas it showed some increase as the hoar crystals grew to several millimeters in height. The coefficient was expressed as $(2.0+9S)\times10^{-3}$, where S (kg m$^{-2}$) is the total amount of sublimation, or $(2.0+0.4d)\times10^{-3}$, where d (mm) is the major axis of surface hoar crystal. These relation indicate that a positive feedback system exists on the mechanism of surface hoar formation.

KEYWORDS: surface hoar, bulk transfer coefficient, surface roughness

## 1. INTRODUCTION

Surface hoar is one of the most frequently occurring types of weak layer and has long been of interest to avalanche researchers (*e.g.* Perla and Martinelli, 1976). Surface hoar crystals are caused by sublimation (solid condensation) of water vapor in the atmosphere onto a snow surface, and often form under nocturnal, clear and humid conditions with perceptible wind. These meteorological conditions suitable for surface hoar growth have been discussed by Lang *et al.* (1985), Breyfogle (1987), Colbeck (1988) and Höller (1998). Recently, a transfer coefficient of water vapor was obtained from field observations (Hachikubo *et al.*, 1994; Hachikubo and Akitaya, 1997) and the sublimation rate of surface hoar can be estimated from meteorological conditions.

Assessing the formation of the surface hoar layers remains an additional challenge for operational avalanche forecasting. A numerical model, named *Crocus*, has been developed to simulate the energy and mass balance at the snow surface and the evolution of snow-cover stratigraphy as a function of meteorological conditions (Brun and others, 1989, 1992). Mingo (1995) and Mingo and McClung (1998) applied *Crocus* and compared potential surface hoar periods from a calculation of latent heat exchanges with the observed surface hoar periods. Hachikubo (2001) simulated the time evolution of the heat balance when surface hoar formed and the validity of the turbulent transfer coefficient in *Crocus* was discussed. These numerical simulation showed promising results and further detailed examination has been expected by researchers.

This paper is intended as an investigation of the bulk transfer coefficient of water vapor $C_e$. In a practical snow model, $C_e$ is needed for calculating a latent heat flux which is one of the heat balance components at the snow surface. When the surface hoar crystals grow up to several millimeters in height, it seems reasonable to suppose that they disturb the air flow more or less and increase the turbulence. This effect may contribute to the increase in the transfer coefficient of water vapor. Hachikubo and Akitaya (1997) reported that $C_e$ increased as the surface hoar grew to several millimeters in height. In this study, field observations of surface hoar growth were carried out to clarify the roughness effect on $C_e$ quantitatively.

## 2. OBSERVATION SITE AND METHODS

Observations were carried out on selected clear and humid nights in the three seasons of January to March 1994, December 1994 to March 1995 and December 1995 to March 1996. The site is located on a mountain ridge near the avalanche-research station (240m above sea level, 45°N, 142°E) of the Institute of

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Detailed information on the observational methods and instrumentation used has been given by Hachikubo and Akitaya (1997). Air temperature, relative humidity, wind speed and net radiation were measured at 1m height and averaged for 30 minutes. Snow surface temperature was also measured with six copper-constantan thermocouples (accuracy: ±0.1°C) and the mean value of these readings was adopted. A drop of water was frozen onto the tips of the thermocouples, and they were then set on the snow surface so that the sensor was like a small ice-particle on snow and the snow surface temperature would be correctly measured.

The vapor sublimation rate was obtained directly by the weight change of a sublimation gauge; 20-mm thick snow block on an aluminum plate of 0.5 × 0.6m². The sublimation gauge was set on a shallow pit which was adjusted to the depth of the plate beforehand. The measurements were carried out every 30 minutes with an electric balance during nighttime and the hoarfrost under the plate was scraped carefully by a plastic card. The difference between the snow surface temperature on the device and that of natural snow was negligibly small.

To obtain a relation between crystal size of surface hoar and total amount of sublimation, microscopic photographs were taken on 27 to 28 December 1994 and the major axis of the crystal was measured on a microscopic photograph at each stage.

## 3. RESULTS AND DISCUSSION

### 3.1 Bulk transfer coefficient of water vapor

Figure 1 shows the sublimation rate plotted against the product of wind speed at 1m height and vapor pressure difference between 1m height and the snow surface $\Delta P$. A good linear relationship (R=0.90) exists in the positive range of sublimation, although the number of data in the negative part of the sublimation rate was small since the measurements focused on the surface hoar formation. This graph indicates that the sublimation rate of surface hoar can be estimated by the bulk method (*e.g.* Stull, 1988),

$$E = C_e \rho u_z (q_z - q_s) , \qquad (1)$$

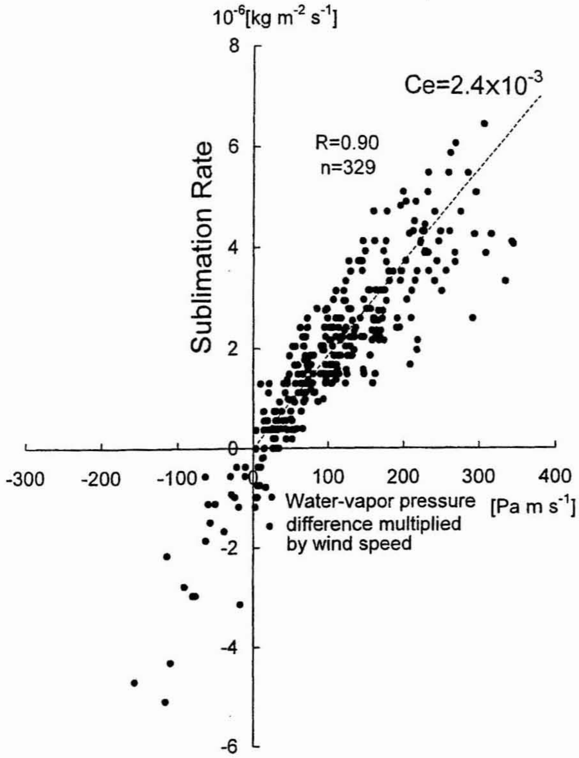


Figure 1: Vapor sublimation rate plotted against the product of $\Delta P$ and wind speed (1m height).

where $E$ is the water vapor flux (kg m$^{-2}$ s$^{-1}$) and taken positive downward, $C_e$ the bulk transfer coefficient of water vapor, $\rho$ the density of air (kg m$^{-3}$), $u$ the wind speed (m s$^{-1}$) and $q$ the specific humidity. The subscripts $z$ and $s$ mean heights of $z$ and the snow surface. Since $q \cong 0.622 p_w / p_{air}$ (Sutton, 1953), where $p_w$ is water vapor pressure and $p_{air}$ is atmospheric pressure (Pa), Equation (1) becomes

$$E = \frac{0.622}{p_{air}} C_e \rho u_z \Delta P . \qquad (2)$$

Substituting the data of Figure 1 in Equation (2), we obtained the mean value of $C_e$ as $2.4\times10^{-3}$ at 1m height. It agrees approximately with the semiempirical value of $2.1\times10^{-3}$ at 1m height obtained by Kondo and Yamazawa (1986). Accordingly, it must be noted that the sublimation rate of surface hoar can be roughly estimated from meteorological elements, which are air temperature, surface temperature, relative humidity and wind speed.

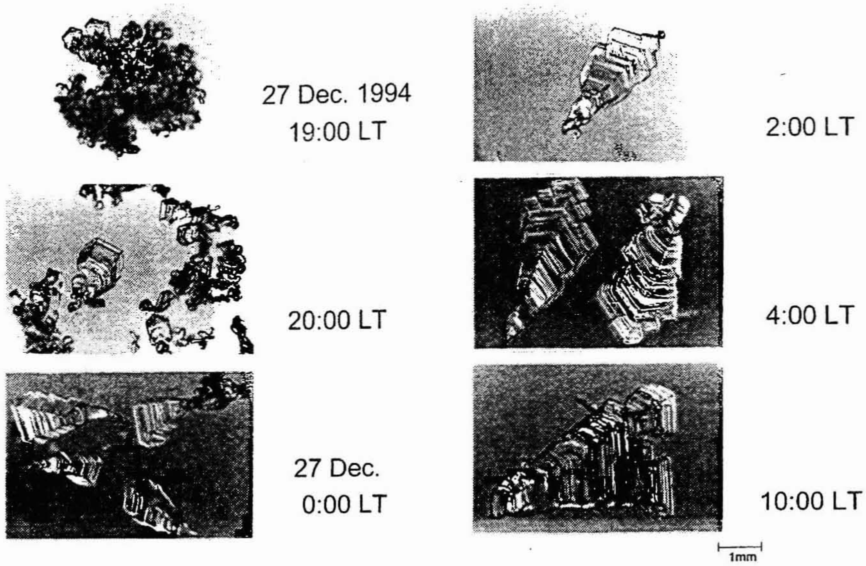


Figure 2: Photographs of surface hoar crystals developed on 27 to 28 December 1994.

### 3.2 <u>Relation between roughness and the amount of sublimation</u>

In the field observation, surface hoar crystals seemed to be flattish and rather thick ice plates. Figure 2 shows the development of surface hoar on 27 to 28 December 1994. We can clearly see that they almost kept the shape of long triangle or rhombus during the growing processes. Hence, we assume that a major axis of surface hoar crystal represents the height of the individual roughness elements on the snow surface.

Figure 3 shows the relation between the amount of sublimation $S$ (kg m$^{-2}$) and the crystal size, *i.e.* major axis of surface hoar crystals. $S$ is obtained by the time variation of $E$,

$$S = \int_0^t E dt . \qquad (3)$$

Surface hoar developed up to 3mm on 27 to 28 December 1994, and the photographs of surface hoar crystals were taken every an hour from 18:00 to 6:00. Although the number of the data is small and the standard deviations at each stage are large, we can see that the major axis increased almost linearly with the amount of sublimation. From this graph we obtained a regression equation as,

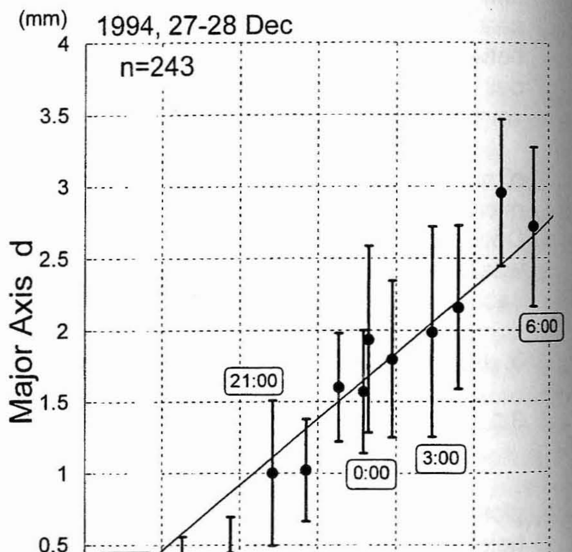


Figure 3: Major axis of surface hoar crystals plotted against the amount of sublimation, observed on 27 to 28 December 1994. Black circles and bars show the mean value and the standard deviation at the time, respectively.

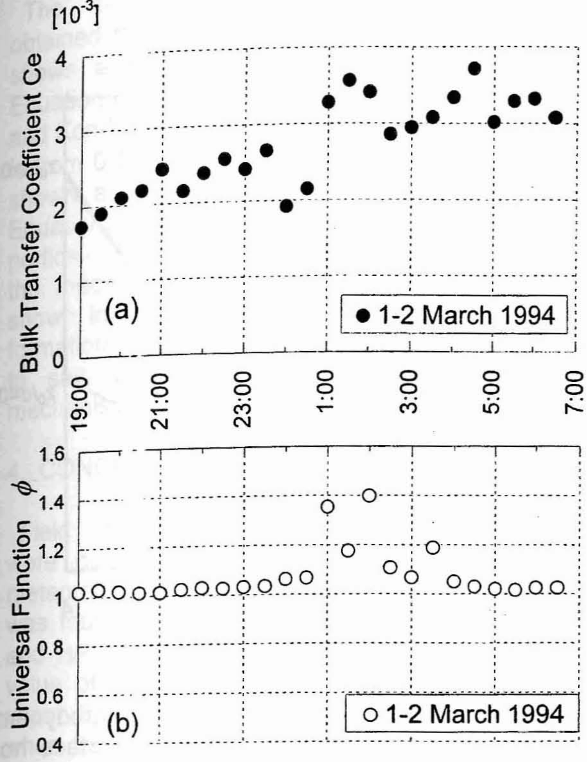


Figure 4: Time variations of the bulk transfer coefficient $C_e$ and the universal function $\phi$ on 1 to 2 March 1994. (a) $C_e$. (b) $\phi$.

$$d = 23S\,, \qquad (4)$$

where $d$ is the major axis of surface hoar crystal (mm).

5.2 <u>Increase in bulk transfer coefficient</u>

In the progress of large surface hoar formation (up to 5mm in grain size) on 1 to 2 March 1994, $C_e$ calculated from Equation (2) increased generally with time as shown in Figure 4a. This tendency seemed to be shown when the surface hoar was well-developed.

According to Stull (1988), $C_e$ is expressed theoretically as follows,

$$C_e = \frac{\kappa^2}{\phi_m \phi_e \ln\frac{z}{z_0} \ln\frac{z}{z_e}}\,, \qquad (5)$$

where $\kappa$ is Kármán's constant, $\phi_m$ and $\phi_e$ dimensionless stability functions of momentum and vapor transfer, respectively, $z$ a reference height and $z_0$ and $z_e$ aerodynamic roughnesses of momentum and vapor transfer, respectively.

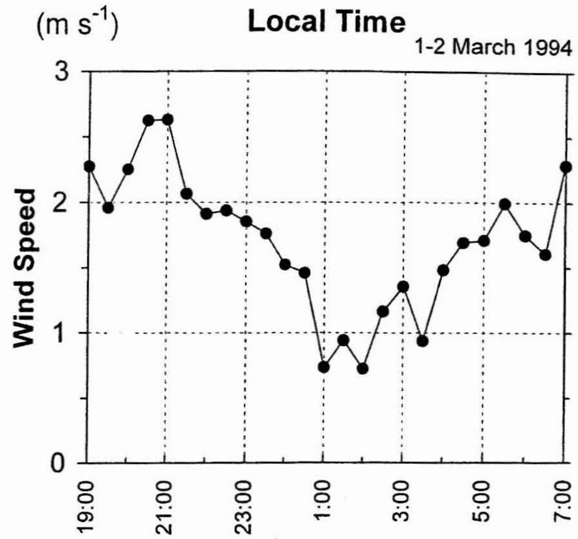


Figure 5: Time variations of wind speed at 1m above the snow surface on 1 to 2 March 1994.

The stability functions $\phi_m$ and $\phi_e$ are expressed with an index of air stability (Thom, 1975) as given by

$$\begin{cases} \phi_m = \phi_e = (1 - 5R_B)^{-1} \\ \qquad \text{when } 0 \le R_B \le 0.2\,, \\ \phi_m{}^2 = \phi_e = (1 - 16R_B)^{-0.5} \\ \qquad \text{when } R_B \le 0\,, \end{cases} \qquad (6)$$

$$R_B = \frac{g(T_z - T_s)z}{T_m u_z{}^2}\,, \qquad (7)$$

where $R_B$ is the bulk Richardson number (*e.g.* Oke, 1987), $g$ the gravitational acceleration (m s$^{-2}$) and $T$ the temperature (K). $T_m$ is the mean air temperature that is supposed to be $T_z$. If we assume that $z_e$ equals to $z_0$, we can simply express $C_e$,

$$C_e = \frac{\kappa^2}{\phi^2 (\ln\frac{z}{z_0})^2}\,. \qquad (8)$$

$\phi$ is the function of air stability as shown in Equation (6). Since $C_e$ is a function of reference height $z$, air stability expressed as $\phi$, and aerodynamic roughness $z_0$, we first discuss the effect of the air stability.

Figure 4b shows the time variation of $\phi$ obtained from Equations (6) and (7). $\phi$ theoretically exceeds 1 when the air is unstable condition ($R_B < 0$), but the air is stable during

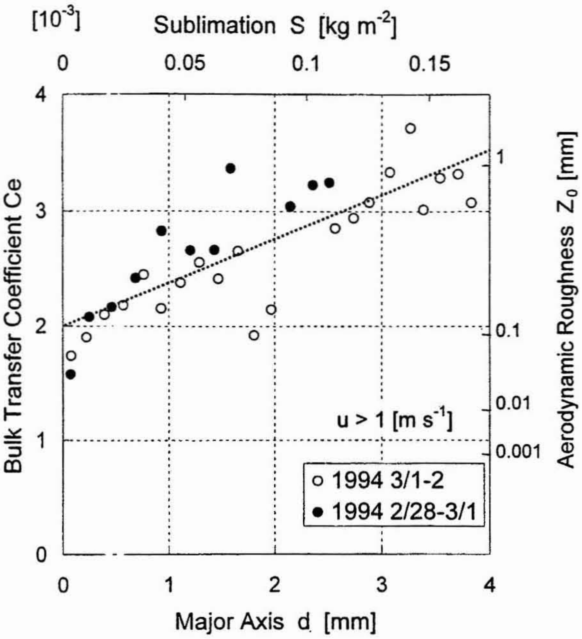


Figure 6: Relation between the bulk transfer coefficient and the major axis of surface hoar crystals. The upper and the right axis show the amount of sublimation and the aerodynamic roughness, respectively.

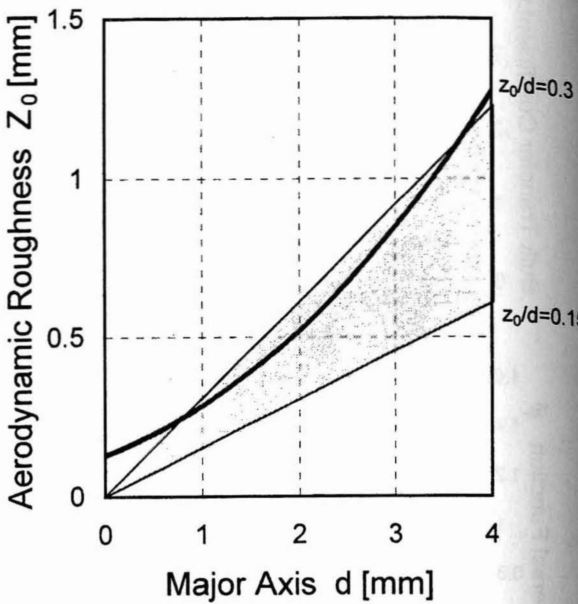


Figure 7: Relation between the aerodynamic roughness and the major axis of surface hoar crystals. The equation (9) is shown as the thick line, and the shaded portion means the relation reported by Takeuchi and Kondo (1981).

surface hoar period. Ishikawa and Kodama (1994) observed in snowmelt seasons that the bulk transfer coefficient of heat $C_h$ was scattered widely and difficult to specify at wind speed of less than 1.5 m s$^{-1}$ at 1m height. Thus we can see that the large fluctuation of $\phi$ that appeared at midnight in Figure 4a was mainly due to low wind speed as seen in Figure 5 and less turbulence. We should notice that except for midnight from 0100 to 0330 LT, $\phi$ was kept constant around 1, which means it was near neutral condition. Therefore, we can say that the change in $\phi$ is not the cause of the increase in $C_e$.

Second, the change of aerodynamic roughness $z_0$ might cause the increase in $C_e$. $z_0$ is defined as the height where the wind speed becomes zero assuming a logarithmic wind profile, and there is a one-to-one correspondence between $z_0$ and roughness elements though it is not equal to the height of roughness elements (Stull, 1988).

Figure 6 shows the relation between $C_e$ and the major axis of surface hoar crystals $d$ obtained from the amount of sublimation with Equation (3) and (4). The data on 28 February to 1 March and 1-2 March 1994 were plotted in this graph, but the data in which the wind speed was lower than 1 m s$^{-1}$ were removed. We see the increase in $C_e$ is due to the increase in $d$; when surface hoar crystals grow up largely, we should consider the dependency on the roughness. A regression equation is,

$$C_e = (2.0 + 0.4d) \times 10^{-3}. \qquad (9)$$

From Equation (4), Equation (9) is also expressed as,

$$C_e = (2.0 + 9S) \times 10^{-3}. \qquad (10)$$

For practical use, the sublimation rate will be estimated from meteorological data using Equation (3) and (10) step by step.

On the other hand, Kondo and Yamazawa (1986) noted that the value of $C_e = 2.1\times10^{-3}$ on a flat snow surface was obtained semiempirically and should be sufficiently accurate for practical purposes, but they did not consider an increase of the surface roughness such as surface hoar growth. $C_e$ agrees fairly well with the value of $2.0\times10^{-3}$ from Equation (9) or (10) when surface hoar crystals are not formed.

The aerodynamic roughness $z_0$ can be obtained from $C_e$ using Equation (8). Figure 7 shows a relation between $z_0$ and $d$, where Equation (9) is plotted as a thick line. Takeuchi and Kondo (1981) reported that a ratio of $z_0$ to $d$ is from 0.15 to 0.3 on a snow surface, which is shown as the shaded portion. In Figure 7, Equation (9) is almost included in the shaded portion. Accordingly, Equation (9) agrees with the theory of the bulk transfer coefficient as shown in Equation (8). So the surface hoar formation itself leads to the increase in $C_e$, that is to say, a feedback system exists on the mechanism of surface hoar sublimation.

## 4. CONCLUDING REMARKS

Field observations of surface hoar formation were carried out with the measurements of meteorological elements. A linear relationship was found between the vapor sublimation rate and $\Delta P$ multiplied by wind speed. The mean value of the bulk transfer coefficient of water vapor $C_e$ was $2.4\times10^{-3}$ at 1m height. However, when surface hoar crystals grew to several millimeters in size, $C_e$ increased with time. $C_e$ was expressed as $(2.0+9S)\times10^{-3}$, where S (kg $m^{-2}$) is the total amount of sublimation, or $(2.0+0.4d)\times10^{-3}$, where d (mm) is the major axis of surface hoar crystal. The cause of the increase of $C_e$ was considered to be the increase of surface hoar height, which may induce an increase of aerodynamic roughness. Hence, it seems reasonable to conclude that the surface hoar formation itself leads to the increase in the transfer coefficient, that is to say, a positive feedback system exists on the mechanism of surface hoar formation.

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