Estimation of Blowing Snow and Related Visibility Distributions above Snow Covers with Different Hardness

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ABSTRACT

The mass flux and the related visibility distributions associated with blowing snow above the snow covers with different hardness are estimated based on the experimental and observational results on the blowing snow structure. The difference in the distributions between the loose and semihard snow covers is large under weak to moderate wind conditions and it becomes small as the wind speed increases. The visibility at z=2.4m is about a few times larger than that at z=1.2m regardless of snow hardness. In the case of semihard snow cover, the following results are obtained: When the wind speed is 12-14m/s, the visibility at z=1.2m is below 300m and that at z=2.4m is above 300m, which means that only the drivers of small automobiles have a risk of suffering poor visibility. If the wind speed exceeds 14m/s, the visibility at z=2.4m as well as that at z=1.2m are below 300m, which leads to the poor visibility for both small and big automobiles.

INTRODUCTION

Traffic accidents and traffic jams are sometimes caused by snowdrift and poor visibility in snowy regions as a result of blowing snow. In order to overcome these snow disasters, not only snow fences and snow break forests are placed along roads but also the information system based on meteorological observations and visibility monitoring is getting popular. Furthermore, blowing snow forecast is going to be undertaken for controlling the traffic. For example, the National Research Institute for Earth Science and Disaster Prevention has started a project to predict snow disasters in a test area, such as snow avalanche, blowing snow, snow accretion and snow conditions on roads. Weather forecast, including snowfall, and snow metamorphism forecast will be incorporated into the disaster prediction scheme. The present study is a part of this project.

According to Bagnold (1941), the motion of snow particles in the atmosphere is classified into three, that is, creep, saltation and suspension. Creep is a rolling motion of large particles on the snow surface. Saltation is a bounding motion of particles that is confined in a thin layer over the snow surface. Some additional snow particles, which are separated from the snow texture due to the collision of particles on the snow surface, are ejected into the atmosphere. Most of the transported snow during the blowing snow event is due to creep and saltation. The suspension above the saltation layer is maintained by turbulent diffusion and the snow particles in this layer reduce visibility.

The structure of blowing snow has been studied observationally and experimentally. In the field, the distribution of snow particles has been measured with various types of snow gauges. Budd *et al.* (1966) and Schmidt (1982) revealed the suspension layer structure. Takeuchi *et al.* (1975) observed the blowing snow near the snow surface and clarified the saltation layer structure. In the laboratory, mainly with a cold wind tunnel, the research on the blowing snow has been focused on the saltation layer due to the limit of the wind tunnel size. Sugiura *et al.* (1998) carried out experiments to investigate the saltation layer structure paying attention to the particle size dependency. Sato *et al.* (2001a) obtained the relationship between the saltation layer structure and some conditions such as wind speed, snow temperature and the hardness of snow. The numerical models of blowing snow have been developed based on observational and experimental results (e.g. Uematsu *et al.*, 1991; Liston and Sturm, 1998)

Actually, it is difficult to recognize the boundary between the saltation and suspension layers, which may depend on the size of snow particles moving in the atmosphere. Although the snow particles in the suspension layer are originally ejected from the snow surface and caught by the turbulence, the transition from saltation to suspension has not been fully understood yet.

In this study, we will propose a practical method to estimate the blowing snow and the related visibility reduction by taking the meteorological and snow conditions into account. The vertical distributions of mass flux and visibility associated with blowing snow above the snow covers with different hardness will be shown. The method is based on the previous observational results as well as the experimental results on the saltation layer structure by Sato *et al.* (2001) and Sato and Kosugi (2001).

METHOD

We will apply the theoretical expression for the mass flux profile of drifting sand to the blowing snow. The expression was derived by Kawamura (1948) as follows, by assuming that sand particles with a single size are ejected vertically from the surface and their ejection speed is given by the Maxwell distribution:

$$q(z) = q_0 \exp(-z/(\pi h_0)), \qquad (1)$$

where h_0 is the average of the attainable height of ejected particles (hereafter, saltation height), and $q(z)$ and q_0 are the mass fluxes at the height of z and at the surface, respectively. By fitting Eq.(1) to the mass flux profile of blowing snow measured in the wind tunnel and the two parameters, h_0 and q_0, were determined. Since the diameter of snow particles ranges from several tens to several hundred micrometers, the values of h_0 and q_0 obtained should characterize the mean state of blowing snow. Although h_0 and q_0 are independent variables in the derivation of Eq.(1), both will actually depend on the conditions of meteorology and the snow surface that can be changed in the course of metamorphism.

Saltation height, h_0(cm), is found to be given by

$$h_0=0.057U_{10}-0.1 \qquad \text{for loose snow cover,} \qquad (2a)$$

h_0=0.175U_{10} -0.3 for semihard snow cover, (2b)

where U_{10}(m/s) is the wind speed at z=10m, which was converted from the wind speed in the wind tunnel using its relation to the friction velocity, u_*, and assuming the logarithmic wind profile (Eq.(9)). To perform the blowing snow experiments, we disintegrated the compacted snow and sieved it on the floor of the wind tunnel. The loose snow means that the bonding of the accumulated snow particles was very weak (hardness was about 23kPa), and the semihard snow corresponds to the snow whose bonding was formed again by sintering (hardness was about 47kPa). Previous researchers have shown that the saltation height is proportional to u_*^2. However, our experiments revealed that h_0 is a linear function of wind speed as shown in Fig.1. This is probably due to the fact that the size of the ejected snow particles increases as the wind speed increases.

The snowdrift transport rate Q was obtained by integrating the measured mass flux profile from the surface to the height of 30cm. Figure 2 shows the relationship between Q and U_{10} for the loose snow cover, where U_{10} is also converted from the wind speed in the wind tunnel. The relationship can be expressed as:

Q=0.00025$U_{10}^{3.1}$, (3)

where the unit of Q is g/cm/s. Eq.(3) is within a range of the previous observational results. The blowing snow in the wind tunnel was considered to be saturated in the case of loose snow (Sato *et al*., 2001). But in the case of semihard snow, it was not saturated and was in the state of development even at the leeward end of the test section. We will consider the saturated blowing snow in this study also for the semihard snow, which requires longer fetch distance than the length of wind tunnel. Therefore, the snowdrift transport rate is also given by Eq.(3) for the semihard snow cover.

The snowdrift transport rate due to saltation, Q_{sal}, can be given by integrating Eq.(1) from

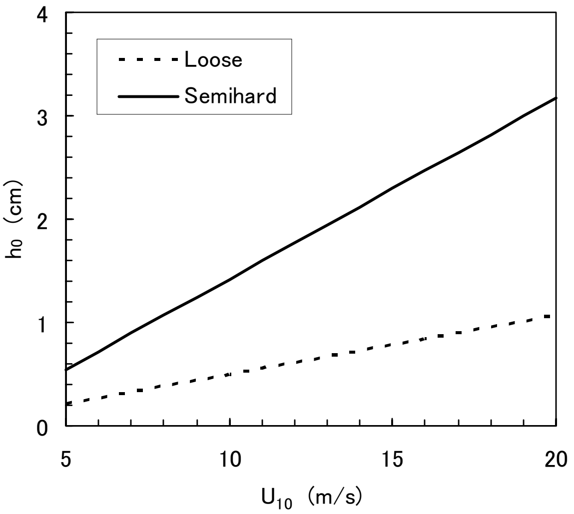


Fig.1 Relationship between the saltation height and the wind speed at z=10m for loose and semihard snow covers.

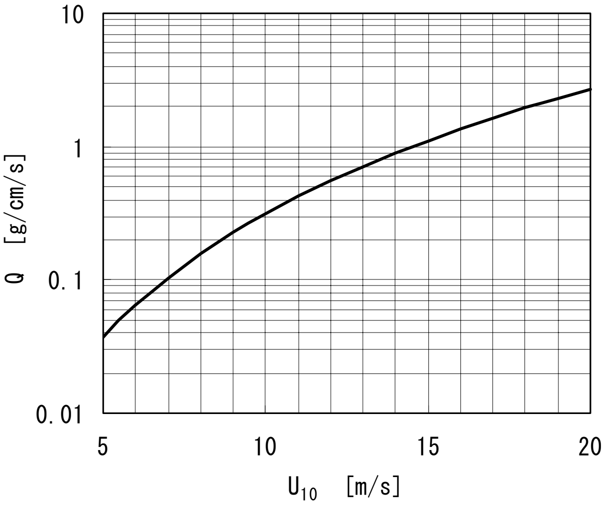


Fig.2 Relationship between the snowdrift transport rate and the wind speed at z=10m for loose snow cover.

the surface to the infinity as:

$$Q_{\mathrm{sal}} = \pi h_0\, q_0. \tag{4}$$

Assuming that Q is equal to Q_{sal}, the parameter q_0 is obtained as

$$q_0 = Q_{\mathrm{sal}} /(\pi h_0). \tag{5}$$

The upper limit of the applicability of Eq.(1) is not specified in its theoretical derivation. In this study, however, the height where the measured mass flux profile begins to deviate from Eq.(1) is specified to be the top of the saltation layer and it is designated as h_{sal}. Field observations showed that the ratio, h_{sal} / h_0, changes from 5 to 9 as the air temperature rises (Sato and Hiagshiura, 1990). We adopt

$$h_{\mathrm{sal}} / h_0 = 5, \tag{6}$$

which corresponds to the air temperature of -5 to -7C.

Turbulent diffusion theory can be applied in the suspension layer (Shiotani, 1953), and the snow concentration, n, is given by

$$n(z) = n_{\mathrm{sal}} \left(\frac{z}{h_{\mathrm{sal}}}\right)^{-\frac{w}{ku_*}}, \tag{7}$$

where n_{sal} is the snow concentration at the lower boundary of the suspension layer, which is assumed to be identical to the top of the saltation layer, and w is the settlement speed of snow particles. Actually the settlement speed depends on the particle size. However, a constant value of 0.3m/s is substituted for w in this study, which does not differ much from the observational results by Budd *et al.* (1966).

The value of n_{sal} can be calculated from Eqs.(1)-(6) together with the definition of mass flux,

$$q(z)=n(z)u(z), \tag{8}$$

and the logarithmic wind profile,

$$u(z) = \frac{u_*}{k} ln\left(\frac{z}{z_0}\right), \tag{9}$$

where u is the wind speed and z_0 is the roughness length, which is assumed to be 0.1mm in this

Table 1 Summary of the variables of the saltation layer above loose and semihard snow covers.

						at $z=h_{\mathrm{sal}}$		
Snow Type	U_{10} (m/s)	h_0 (cm)	h_{sal} (cm)	Q (g/cm/s)	q_0 (g/cm^2/s)	q (g/cm^2/s)	n (g/cm^3)	U (m/s)
Loose	5	0.22	1.1	3.66E-02	5.39E-02	1.10E-02	5.39E-05	2.0
	10	0.50	2.5	3.16E-01	2.01E-01	4.10E-02	8.54E-05	4.8
	15	0.78	3.9	1.11E+00	4.53E-01	9.22E-02	1.19E-04	7.8
	20	1.07	5.3	2.72E+00	8.13E-01	1.66E-01	1.52E-04	10.9
Semihard	5	0.54	2.7	3.66E-02	2.14E-02	4.35E-03	1.79E-05	2.4
	10	1.42	7.1	3.16E-01	7.07E-02	1.44E-02	2.53E-05	5.7
	15	2.29	11.5	1.11E+00	1.54E-01	3.14E-02	3.42E-05	9.2
	20	3.17	15.9	2.72E+00	2.73E-01	5.56E-02	4.35E-05	12.8

study.

Eqs.(7)-(9) yield the mass flux distribution in the suspension layer as a function of wind speed at z=10m. The visibility, V (m), during the blowing snow event can be estimated from the mass flux of blowing snow, q (g/cm^2/s), by using the following equation:

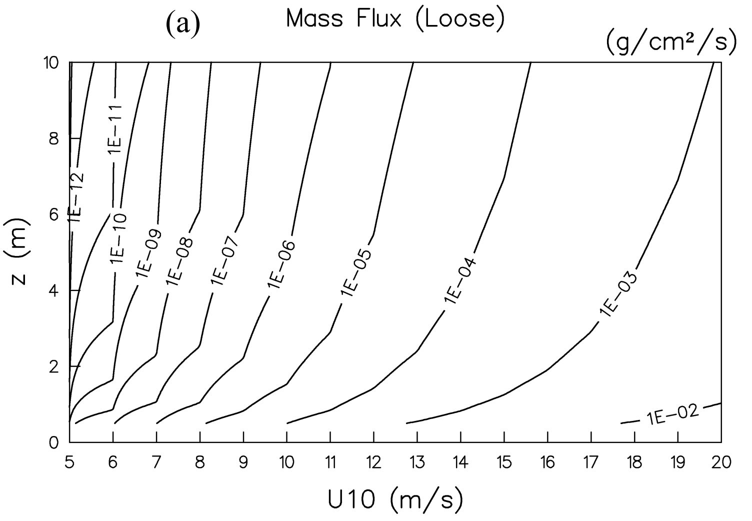
$$V = 0.354q^{-0.82}, \qquad (10)$$

which was formulated by Takeuchi and Fukuzawa (1976).

RESULTS

The variables of the saltation layer above the snow covers with different hardness are summarized in Table 1. As compared with the semihard snow cover, the saltation height, h_0, and the top of the saltation layer, h_{sal}, are smaller in the case of loose snow cover. Since the snowdrift transport rate, Q, is the same between the two kinds of snow cover, the mass flux at the surface, q_0, is greater for the loose snow cover. The values of the mass flux, q, and the snow concentration, n, at the top of the saltation layer (bottom of the suspension layer) are greater above the loose snow cover than above the semihard snow cover.

Figure 3 shows the mass flux distribution between z=0.5m and 10m as a function of the wind speed at z=10m. The mass flux is smaller above the loose



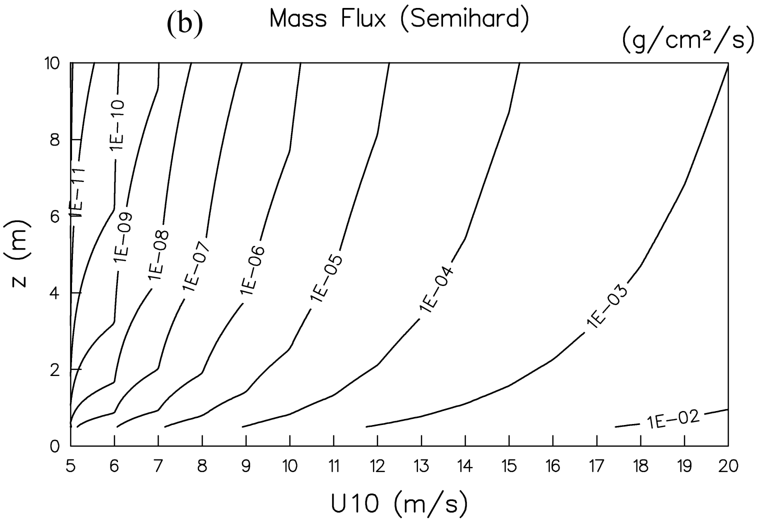
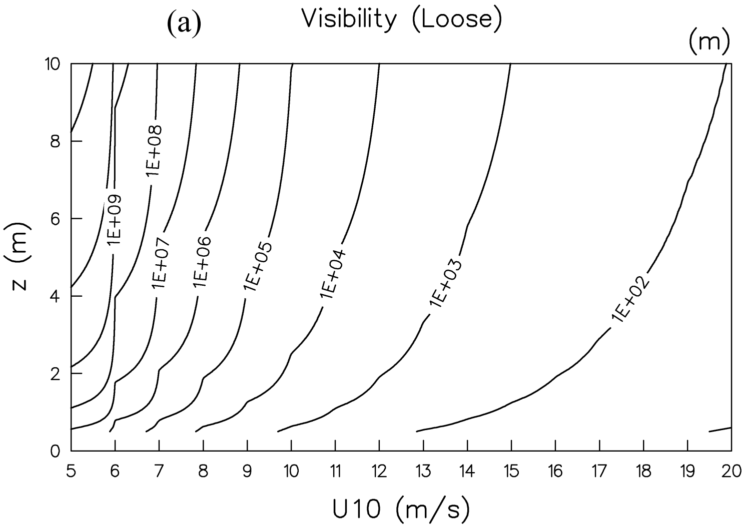


Fig.3 Vertical distribution of mass flux as a function of the wind speed at z=10m for loose snow cover (a) and for semihard snow cover (b).

snow cover as compared with the semihard snow cover, which results from the fact that the top of the saltation layer is lower though the snow concentration at that height is greater (see Table 1). The turbulent diffusivity for the snow particles is assumed to be given by ku_*z in the derivation of Eq.(7), which causes weaker diffusion at lower height of the atmosphere. Since the suspension layer above the loose snow cover exists from lower height, the weaker diffusion leads to the smaller snow concentration and mass flux within the suspension layer. The difference in the mass flux between the two kinds of snow cover tends to become small with the wind speed, which is due to the fact that the snow concentration at the top of the saltation layer increases with the wind speed above the loose snow cover more than above the semihard snow cover. The mass flux decreases rapidly with height under weak wind condition, and the vertical gradient of the mass flux becomes small as the wind speed increases because of the enhanced turbulent diffusion.

The distribution of the visibility calculated from the mass flux is shown in Fig.4 as a function of the wind speed at z=10m. As the visibility is roughly proportional to the reciprocal of the mass flux, it decreases with the wind speed and poorer visibility is found near the snow surface. The difference in the visibility between the two kinds of snow cover is large when the wind speed is weak and vice versa, and



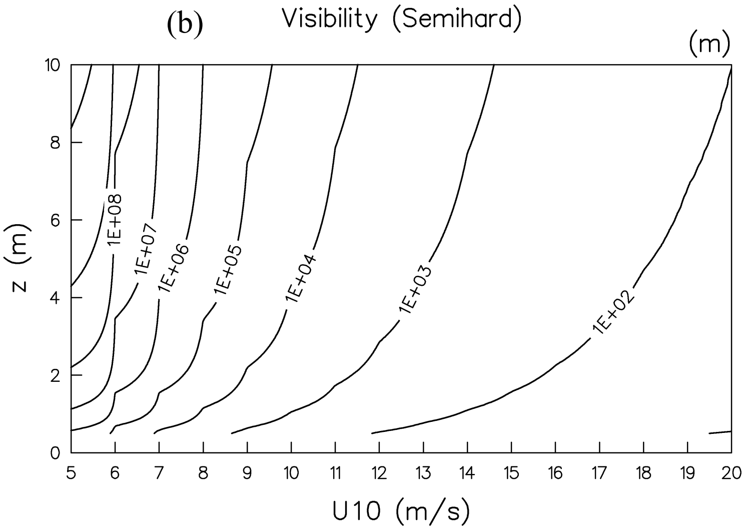


Fig.4

Vertical distribution of visibility as a function of the wind speed at z=10m for loose snow cover (a) and for semihard snow cover (b).

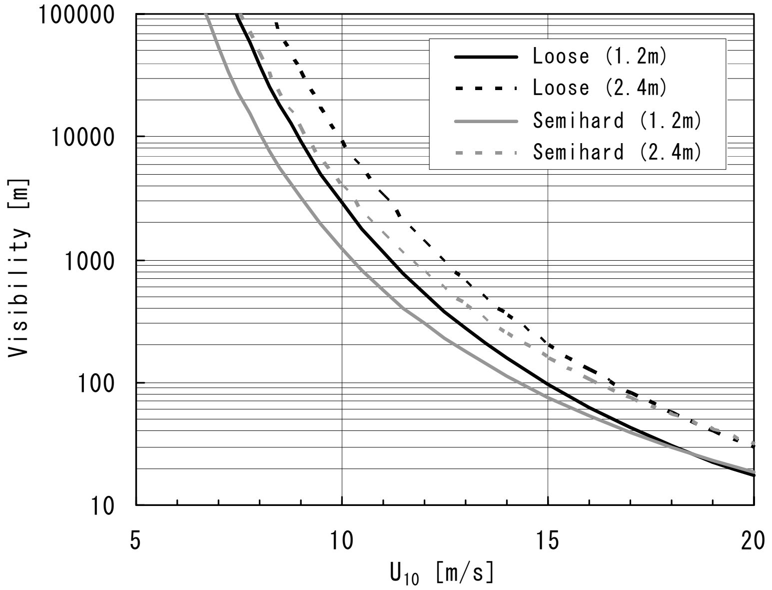


Fig.5
Relationship between the visibilities at z=1.2m and at z=2.4m and the wind speed at z=10m for loose and semihard snow covers.

the difference is small under the condition of the visibility less than 300m, where traffic troubles occur.

For convenience of application, the visibilities at z=1.2m and z=2.4m, which correspond to the heights of driver's eyes for small and big automobiles respectively, are plotted in Fig.5 as functions of the wind speed at z=10m. Generally the visibility above the loose snow cover is better than that above the semihard snow cover; the former is about twice larger than the latter when the wind speed is 11m/s and the difference tends to become small as the wind speed increases. The visibility at z=2.4m is about a few times larger than that at z=1.2m regardless of snow hardness. Within the wind speed range from 12 to 14m/s, the visibility at z=1.2m is blow 300m and that at z=2.4m is above 300m in the case of semihard snow cover, and only the drivers of small automobiles have a risk of suffering poor visibility. If the wind speed exceeds 14m/s, the visibility at z=2.4m as well as that at z=1.2m are below 300m in the case of semihard snow cover, which leads to the poor visibility for both small and big automobiles.

CONCLUDING REMARKS

The present study showed the mass flux and the related visibility distributions associated with blowing snow above the compacted snow with different hardness. These distributions depend on the hardness of snow mainly under weak to moderate wind conditions. The case of new snow and the case accompanied by snow fall are beyond the scope of this study, which should be the remaining subjects together with taking account of the horizontal development of blowing snow with fetch distance.

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