SURFACE HOAR GROWTH FROM VALLEY CLOUDS

Sam Colbeck[1*] and Bruce Jamieson[2]
[1]Lyme, New Hampshire, USA
[2]Dept. of Civil Engineering, Dept. of Geology and Geophysics, University of Calgary, Calgary, Canada

ABSTRACT: Avalanches release from buried surface hoar layers which form when stratus clouds extend across valleys on consecutive nights. Water vapor diffusion over distances of more than a meter is much too weak to account for the growth so non-diffusive movement in some form is necessary. The most likely mechanism for the formation of surface hoar is rapid deposition of vapor as the cloud thickens and moves up the snow slope. Since the time over which deposition could take place on any given night is short, successive nights are needed to produce a substantial deposit of hoar.

KEYWORDS: surface hoar, stratus cloud, snowpack stratigraphy, snow slab avalanches

1. INTRODUCTION

It is well established that slab avalanches can release on buried layers of surface hoar but the growth of surface hoar itself is not well understood. Lang et al. (1984) made field observations while Colbeck (1988) described the micrometeorological environment. More recently, Föhn (2001) simulated the formation and ablation processes of surface hoar. The basic problem with the growth of surface hoar is that it seems to form when the snow surface is cooled substantially by outgoing, long-wave radiation, but this is usually associated with a dry, clear sky. The challenge is: where does the moisture come from?

Based on observations in a maritime climate, Breyfogle (1987) reported two meteorological scenarios for surface hoar growth:

1. Radiation to a clear sky following frontal passage or diurnal surface warming with little wind.
2. Vapour transport at the periphery of a supercooled stratus cloud.

As an example of Brefogle's (1987) second scenario, Figure 1 shows a band of surface hoar deposited on trees in the Columbia Mountains near Revelstoke, British Columbia in November 1997. In an unrelated weather pattern in December a few years later, Figure 2 shows a valley cloud forming in the evening at the same elevation that surface hoar was deposited in previous nights.

* Corresponding author: scolbeck@tpk.net, 311 Goose Pond Road, Lyme, New Hampshire, 03768, 603-795-2653

Figure 1. Photo of a horizontal band of hoar frost that formed on trees in the Columbia Mountains near Revelstoke, British Columbia in late November 1997.

Figure 2. Valley cloud starting to form at the right side of the photo at the same elevation as a band of hoar frost formed on trees in previous nights.

Here we look at a specific setting similar to Brefogle's second scenario; surface hoar grew at a fixed elevation on both sides of a valley in the Cariboo Mountains of Canada in mid March 2002 and avalanches released from those bands of buried surface hoar in mid April 2002 (Figures 3 and 4). We observed this phenomenon on both sides of the valley for a kilometer along the valley.

Figure 3. One of many wet slab avalanche that released on buried surface hoar in mid April 2002 at the same elevation in the Thunder River valley of the Columbia Mountains. The surface hoar formed at this elevation in mid March 2002.

Figure 4. Field worker points at wet slab of one of the Thunder River avalanches that released on the buried surface hoar in mid April 2002. The arrow points at the buried surface hoar layer.

The hoar growth was apparently controlled by layers of stratus clouds which formed in the valley on successive nights; in this area these clouds can be present for five to ten consecutive nights. We describe the mechanism of growth where the inclined snow surface can radiate to space and cool while the moisture source, the cloud, is close enough to supply large quantities of moisture to facilitate rapid crystal growth on the snow surface. The growth of hoar-type crystals requires abundant moisture to facilitate rapid growth and their large size and sharp edges, compared to other types of snow crystals, clearly indicate that ample moisture is available during growth. The details of their shape, especially the sharp edges on the crystal tops, show that the moisture is coming from above and not from the snow itself.

We seek a process that will grow surface hoar crystals to a length of 2 cm over 10 consecutive nights. Assuming 10 hours of growth per night, this requires that the growth rate exceed 0.02 cm/h, or at least 2 mm per night. Volumetrically, we assume one crystal per cm^2, a crystal width of 0.5 cm and thickness of 0.05 cm. The mass deposition rate of the surface hoar is therefore required to be at least 4.59E-4 g/cm^2-h, which we call a^*.

2. GROWTH UPSLOPE FROM A FIXED CLOUD

If the entire thickness of the cloud extends all the way to the sides of the valley so that the cloud is in contact with the valley sides, the snow surface upslope from the cloud could radiate to space and cool. At the same time, the close proximity of the cloud to the snow suggests that moisture could be transferred to the snow above the cloud by diffusion through the air. We look at this as a problem in vapor diffusion in several ways:

2.1 <u>Isothermal conditions with unlimited water vapor</u>

Using an emissivity of 1.0 for water substance and a perfectly dry atmosphere, the flux density (F_R) of the radiative loss is given by

$$F_R = \sigma T^4 \qquad (1)$$

where σ is the Stefan-Boltzmann constant and T is the surface temperature. If T is 263° K, the radiative loss is 0.0273 J/cm^2-s. Since the latent heat of sublimation of water substance is 2834 J/g, the growth rate of surface hoar at a sustained temperature of cloud and snow surface of 263° K would be about 0.0347 g/cm^2-h. This would produce very large surface hoar each hour, which does not generally happen because the growth rate is limited by the need for water vapor diffusion to the snow surface. Diffusive processes in general are very slow over distances such as a meter and so the growth rate is limited by how much water vapor can be delivered to the surface.

2.2. <u>Water-to-ice diffusion</u>

Stratus clouds consist of liquid water droplets which, at subfreezing temperature, have a higher equilibrium vapor pressure over them than ice does. Thus water vapor would diffuse to the snow surface from the cloud simply because they consist of difference phases of water substance. The difference in vapor pressure between liquid water and ice reaches a maximum at about 263°K. The flux of water vapor in air (F_v) is given by

$$F_v = -D_v \frac{d\rho_v}{dx} \qquad (2)$$

where D_v is the diffusion coefficient for water vapor in air, ρ_v is the vapor density and x is distance. At the maximum value of the difference in vapor pressure between water and ice, this mechanism would only produce about 5.38E-7 g/cm^2-h at a distance of only 100 cm from the edge of the cloud. This is a negligible amount of deposition on the snow surface and suggests that very little hoar could form by this mechanism. Taking into consideration that the vapor pressure is higher over the small water droplets because of their high curvature does not change this conclusion.

2.3 Temperature effects

It is likely that the cloud top and the snow surface would be at different temperatures even though both are radiating to space. When a valley cloud forms adjacent to snow slopes, the temperature difference between them can reach 5^{0}K (pers. comm., George Koenig). Temperature differences are a much more powerful mechanism for moving water vapor because the vapor density over water substance is more strongly dependent on temperature than on curvature or phase differences. Temperature gradients drive the most rapid metamorphism in the snow cover although in that case the grain-to-grain distances over which the vapor must diffuse are about 1 mm. In this case we are concerned with diffusing water vapor from relatively warm water droplets in the cloud to a cooler ice surface. Using Equation (2), the flux could be as much as 2.32E-5 g/cm^2-h at a distance of 100 cm from the edge of the cloud. While this is two orders of magnitude stronger than the previous mechanism, it is still too weak to account for much growth. This mechanism might be important if the cloud progressively moved up along the snow surface during the night and we will look at that process later.

3. GROWTH WITH HORIZONTAL CLOUD FLOW

When a cloud forms in the valley it brings moisture directly to a section of snow. The liquid water content of a stratus cloud is about 0.3 g/m^3 (Fletcher, 1962) and the water vapor content at saturation at 263^0 K is 2.45 g/m^3. Thus a 100 m thick cloud with no internal motion covering a flat surface could bring about 0.0275 g of ice per cm^2 of snow surface, which is certainly enough moisture to grow surface hoar during one night. However, 100 m of cloud covering the snow surface would shut off the radiative cooling so hoar would not grow at all.

We now look at surface hoar growth on a snow slope with a cloud, which is in close proximity to the surface, but is thin at the valley sides. Dan Berry, helicopter pilot for Vancouver Island Helicopters operating in the Columbia Mountains of western Canada, observed the edges of stratus clouds in these valleys and stated that these clouds can be thin near the edges. While we believe this is only true during the morning hours and not at night when the hoar is growing, we look at the possibility that the cloud forms and then diffuses or is drained horizontally to the snow surface thus supplying the moisture needed for hoar growth. In this scenario moisture near the edge of the cloud would deposit on the snow surface and moisture within the cloud would move toward the valley sides. The moisture migration would not be fast enough to maintain a high cloud density along the edges and thus helicopters would be able to fly through these clouds at their edges. However, there is enough moisture in the cloud to build surface hoar in one night. If a typical cloud adjacent to a 30^0 snow slope is 1000 m wide, 100 m thick and 2.75 g/m^3 dense, it contains enough moisture to feed snow slopes on both sides of the valley with 0.069 g of ice per cm^2 of surface. If only a fraction of this moisture is able to migrate to the snow surface on one night it would be sufficient to grow a substantial amount of surface hoar.

3.1. *Movement by diffusion in the cloud*

First we look at moisture flow by diffusion from the middle of the cloud toward the snow surface. While diffusive processes are slow the cloud contains liquid droplets which might enhance the vapor diffusion by acting as vapor sources. The cloud is in contact with the snow surface over a horizontal distance L_D and there is a flux of water vapor F_D into the contact area from the valley cloud. The surface slope is θ, the cloud thickness at distance L_D and the rest of the cloud has a constant thickness of H as shown in Figure 5.

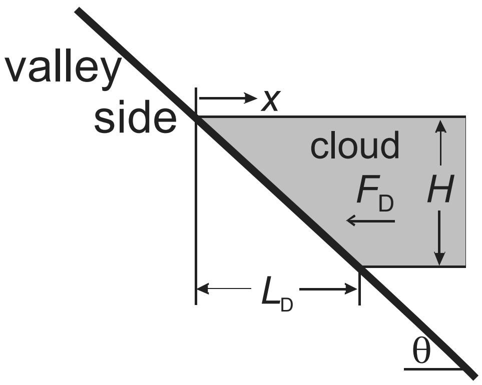

Figure 5. Diagram of cloud supplying water vapour to the snow surface at the side of the valley.

In the cloud over the snow surface, $0 \le x \le L_D$, the flux of water vapor is taken as negative. Continuity over this region requires that

$$-F_D H = a L_D \tag{3}$$

where a is the accumulation rate perpendicular to the snow surface, which is taken as constant. Assuming the cloud over the snow is thin enough to allow unrestricted radiative loss from the snow surface, the deposition rate is given by Equation (1) divided by the latent heat of sublimation, L_s, or

$$a = \frac{F_R}{L_s} \tag{4}$$

Taking a as a^*, tan θ as H/L_D and using Equation (2), the vapor-density gradient at L_D is given by

$$\left.\frac{\partial \rho_v}{\partial x}\right|_{L_D} = \frac{a^* L_D}{H D_v} \tag{5}$$

Therefore the change in density across the deposition zone would have to be about $a^*(L_D)^2/HD_v$. If the thickness of the cloud is 100 m, the surface slope is 30^o, the vapor diffusion rate is 0.22 cm^2/s, and the density of the cloud at origin is zero, then the density of the cloud at L_D would have to be 6000 more than that of cloud! The calculated value of the cloud density would be less if we assumed that the outgoing radiation is reduced by the presence of the overlying cloud and/or if we increased the coefficient of diffusion of water vapor in the cloud to account for both the effect of the water droplets as a source of moisture as the cloud density decreases toward the snow slope and the possible movement of the water droplets under the influence of gravity. However, it is best to treat the non-diffusive processes separately. Clearly diffusion is too slow.

3.2. Movement by horizontal flow within the cloud

We assume the cloud forms and remains at a constant thickness H, the sinks are at the valley sides where water vapor is deposited to form surface hoar, and the source of that vapor is the cloud. There would be sources and sinks feeding and ablating the cloud if there were vertical air movement in the valley but the cloud forms during a temperature inversion and we assume the air column in the valley is stable. The cloud forms from condensation as the temperature decreases below the dew point and no vertical flow occurs, i.e. stratus clouds are not convective. We also assume that the processes are symmetric about the center of the valley ($W/2$) so that the horizontal flux within the cloud is zero at the center and cloud density ($\rho_{c,max}$), which includes both liquid water and water vapor, is a maximum there. Accordingly, the flux is toward the sloping snow surfaces and the cloud density is a minimum there, as the visual evidence shows.

The flux of mass in a gas is given by Equation (2) if the flow is purely diffusive but we take the flow of the cloud (F_c) as being proportional to the pressure gradient which, for a constant temperature in an ideal gas, is proportional to the density gradient, or

$$F_c = -C\frac{\partial \rho_c}{\partial x} \tag{6}$$

where the constant C depends on the viscous properties of the cloud and the density of the cloud (ρ_c) varies with space and time. As the mass in the cloud moves toward the snow surface the cloud density will necessarily decrease over time. Continuity requires that

$$\frac{\partial F_c}{\partial x} + \frac{\partial \rho_c}{\partial t} = 0 \tag{7}$$

where t is time. Combining these two equation gives

$$C\frac{\partial^2 \rho_c}{\partial x^2} - \frac{\partial \rho_c}{\partial t} = 0 \tag{8}$$

The real part of the solution to this equation is

$$\rho_c = \rho_{c,\max} \cos\left(\frac{\pi}{2}\left(1-\frac{2x}{W}\right)\right)\exp\left(\frac{-C\pi^2 t}{W^2}\right) \quad (9)$$

The cloud density reaches a maximum at *x* equal to *W*/2, the middle of the valley, and time equal to zero. The cosine profile would be established as the cloud forms and then water mass would drain toward the snow surface as time evolves. Using continuity, the unknown constant C has to be about five orders of magnitude greater than the diffusion coefficient to meet the minimum deposition rate, *a**. If the cloud can flow this fast by horizontal flow due to the horizontal density gradient, it would deposit about 32% of it mass each night to feed hoar growth.

This is an attractive explanation for supplying moisture to grow hoar and, if gravity drainage in a cloud occurs this fast, the actually speed of flow would only be about 12 m/h towards the snow surface. However, it seems unlikely that visibility is reduced sufficiently at the cloud-snow contact over the entire night to prove that there is a large horizontal gradient in the density. This cosine profile requires that, at x equals 50 m, the cloud density would be reduced to 31% of its maximum density. The visual range (m) in fog is about 5*R*/LWC where *R* (µm) is the droplet size and LWC (g/m^3) is the liquid water content (Jiusto, 1981). Accordingly, in this scenario the visual range would increase rapidly toward the edge of the cloud where there is rapid drainage toward the snow surface due to the cloud's horizontal density gradient.

Near the top of the cloud, the snow surface has a wider sky view favorable to greater radiative cooling and surface hoar growth, as shown in Figure 6. We are unsure of the width of the zone of thin cloud in relation to the cloud thickness; consequently we do not know the magnitude of this sky view effect.

However, we doubt there are nightly gaps at the edge during hoar growth, so we seek another explanation for the observed surface hoar.

4. GROWTH WITH VERTICAL MOVEMENT OF CLOUD TOP

As the valley cools following the departure of the sun, the temperature profile inverts to such a degree that the dew point temperature exceeds the actual temperature at some level. There a cloud begins to form and immediately interferes with the loss of radiant energy from the valley floor.

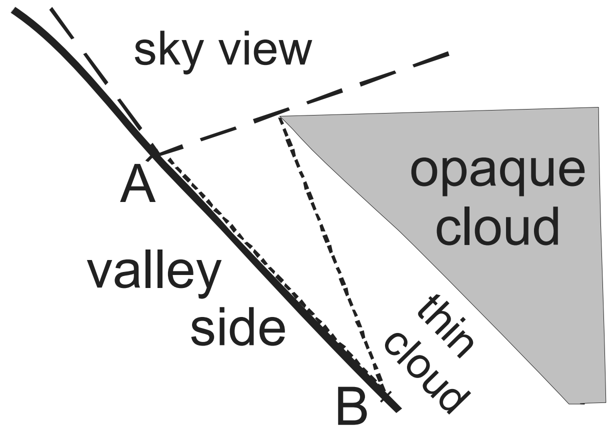

Figure 6. Vertical section showing zone of thin cloud near the snow surface. If thin cloud exists during periods of surface hoar growth, the snow surface close to the cloud top, near Point A, would have a wider sky view (dashed line) and thus greater radiative cooling. At Point B lower on the slope, the snow surface would have a narrower sky view (dotted line) and less radiative cooling.

While we assume that the base of a stratus cloud in one of these valleys is stationary overnight, the top moves upward as the cloud thickens overnight. This happens because the top of the cloud radiates to space, cools to the dew point and grows upward. Fiegel'son (1966, p. 217) reported maximum cooling in a layer approximately 2-4 m thick at the cloud top if the liquid water content is comparable to the rest of the cloud. Assuming the cloud is in contact with the snow surface, deposition would occur on the snow surface by the cloud because the surface is also cooling by radiative loss (Figure 7). After a short period of deposition the thickening cloud would shut off the radiative loss and stop the growth.

If the cloud reaches a total thickness of 100 m over 10 h, its vertical rate of ascent is 10 m/h. We hypothesize there is a gap in the cloud which due to the rapid condensation on the snow surface (Figure 7); this is a small-scale version of the gap described in article 3.0 above. If this gap is 2 m vertically, any point on the surface would be in close proximity to the cloud but be exposed for 720 s as the cloud passes over it. Assuming the humidity is low enough to accommodate the escaping radiation but high enough to cause rapid crystal growth over ten consecutive nights, Equation (4) shows that we could expect a hoar deposit of 0.069 g/cm^2.

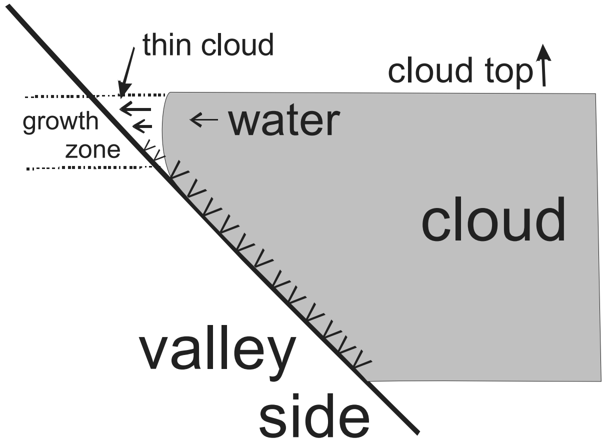

Figure 7. Diagram of cloud contacting the side of the valley and growth zone for surface hoar adjacent to the top of the cloud which is ascending as the air cools to the dew point.

This would give us a hoar crystal every cm^2 of size 3 cm by 0.5 cm by 0.05 cm. From the discussion in 3.2 above this growth rate could be supplemented by horizontal flow of the cloud towards the gap which would help sustain the humidity there. Clearly this mechanism is powerful enough to explain the growth of surface hoar during multiple nights of cloud formation.

5. CONCLUSIONS

Avalanches released from buried layers of surface hoar that formed when stratus clouds extended across valleys on consecutive nights. Water vapor diffusion over distances of more than a meter is much too slow to account for the growth so non-diffusive movement in some form is necessary. It seems that a stationary cloud could flow horizontally to the surface and that a gap could form at the snow-cloud contact over the entire thickness of the cloud. This suggests that the cloud supplies the surface with moisture while the surface is cooled by radiating to space through the thin edge of the cloud. However, these gaps are not reported during the night when hoar grows.

Thus the most likely mechanism for the formation of surface hoar is the rapid deposition of hoar as the cloud thickens and moves up the snow slope. Since the time over which deposition could take place on any given night is short, successive nights are needed to produce a substantial deposit of hoar. There do appear to be small gaps on the upper edges of thickening clouds suggesting that the cloud is being depleted by deposition to the surface and that the cloud is thin enough in the gap to accommodate radiative cooling of the snow surface.

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