The Role of Moisture in Surface Hoar Growth

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In January 2007, surface hoar formed in the Columbia Mountains between Revelstoke and Rogers Pass—but only between about 1700 and 1300 metres in elevation. The layer plagued travel decisions through the season, and later resulted in an accident at Hall Mountain in March of 2007. With that layer, perhaps one of the questions that went through your mind was: "Why only those elevations?"

Great question. Most of you are probably shouting “cloud!” as an answer, but what proves easy in intuition does not prove so easy in physics. Let us dig further. Whenever you hear *surface hoar*, you may be thinking: Cold. Clear. Night. Or you may be even thinking: Calm or slight air currents. Protected. Open to the sky.

Figure 1: Debris from an avalanche which ran on the January 2007 surface hoar layer. (Photo: ASARC)

When surface hoar gets discussed in conjunction with specific elevations, more words come up: Cloud. Inversion. Humidity. Now we are getting down to the issue of moisture. But how many of us have those words on the tip of our tongue every time we think of surface hoar? The link between elevation and surface hoar—drawing our attention to clouds as a moisture source—can help our understanding of surface hoar formation in general.

In this article, we will show that surface hoar needs a lot of moisture to grow. We will talk about how things like temperature, diffusion, and other forces all simply assist in moisture transport, and that without lots of water we truly have no surface hoar. We will start here with how crystals themselves form, then move on to how moisture plays a part in that process, then do some calculations on how much water we actually need, and finally we will bring clouds back into the picture.

A Short Course in Equation-less Snow Physics

Let us start at the beginning. First of all, molecules wiggle. More heat means more wiggling and jostling between molecules, and it also means that molecules inhabit more space. From this, it would seem that water vapour in the air just wiggles around, touches the snow, freezes on the snow, and forms surface hoar. Easy, right?

In physics, it is not quite that simple. At the most basic level, we actually don't know how surface hoar forms. In fact, we don't really even know how snowflakes in the air form, because it all happens at the chaotic molecular level. For example, we know that crystal formation changes from making plates to making needles at -5° C, then back again to plates and dendrites at around -10° C, and then back *again* to needles at -20° C. But why? No one really knows yet.

Despite the mystery, we do know a lot. Looking at the small picture, water molecules in the air form vapour, which then nucleate around tiny non-water particles to form ice. Then, more water vapour reaches and contacts that ice and forms crystals. Looking at an even smaller picture, you could do years of math concerning curvature, crystal structure, and so on (Libbrecht, 2005). There is lots to know, and lots to learn. But for our purposes, we will simplify and say that the main process that governs water molecules becoming crystals is diffusion.

A Short Course in Equation-less Thermodynamics

Which brings us to this question: What, exactly, is diffusion? Well, diffusion is sort of like a molecule party in a room. All the molecules dance around, taking up space more or less equally in the room (no one likes to be crowded). When molecules at the edges of the room leave, the party doesn't just stay crowded in the center; the remaining molecules move outward to take up the space. That way, no one stays too crowded. This tendency is known as the ideal gas law, and relates the space and the number of molecules to the temperature in the room.

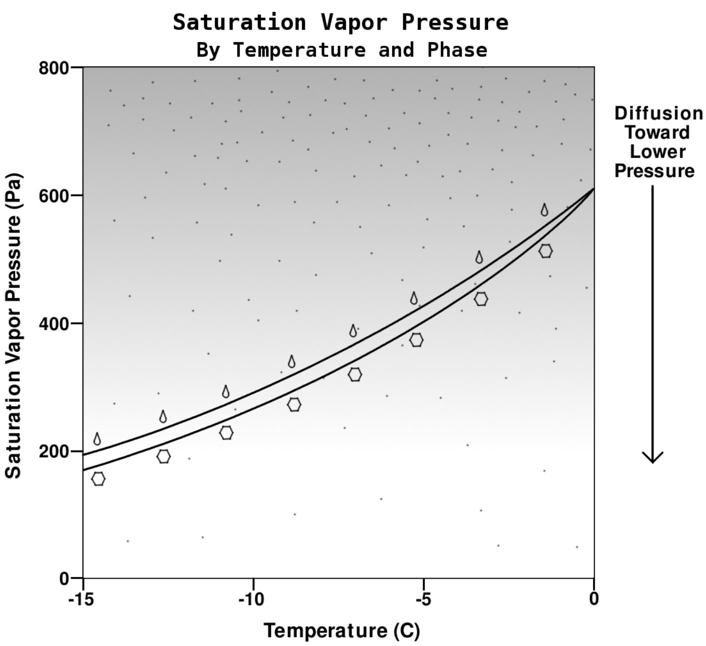

Figure 2: The vapor pressure of water (upper curve with droplet symbols) versus ice (lower curve with ice symbols) at different temperatures, after The Avalanche Handbook [2]. Having higher vapor pressure next to lower vapor pressure is like having a stretched slingshot: the bigger the difference, the bigger the 'stretch', and the more the crowded water molecules (top) want to launch toward the lower pressure (bottom).

But molecules, being the strange and wonderful things that they are, can also bond with the walls of the room, especially if those walls are made of other water molecules in the form of ice. In fact, the vapour pressure over ice is lower than it is over water, as shown in Figure 2. Higher "vapour pressure over water" simply means that if a water molecule dancing in the air comes close to ice, then it *wants* to become part of the ice. It feels less crowded on the ice. This tendency increases as the ice gets colder and the water gets warmer, as one can see by following the lines in the graph.

Beyond the growth from the microscopic pressure difference over ice versus water (known as phase-driven diffusion), we also have a more macro form of vapour pressure that can drive ice—and thus surface hoar—growth rates. Sam Colbeck and colleagues call it *lateral diffusion*, and this second type of vapour pressure comes from water molecules in a humid air mass (or cloud) wanting to move out toward the ground or sky. This type of vapour pressure comes from how crowded the water molecules feel in the humid air, and thus it directly drives the speed at which they move outwards and deposit on the ground.

Thus, the difference in vapour pressure governs the speed of diffusion, which in turn governs the speed of deposition of water vapour on ice, including ice in the form of surface hoar. This process of deposition-via-diffusion depends on three things: (1) The number of water molecules already present, (2) The vapour pressure felt by (and created by) those molecules to want to push themselves out of the air and toward the ice, and (3) The temperature, which drives the rate at which things occur. Remember, more heat means more wiggling and jostling, which means water vapour makes contact with ice more often.

Water, Water Everywhere...

For water vapour to deposit on the surface in the form of surface hoar, we need a lot of water vapour. We need so much water vapour, in fact, that the water vapour molecules need to feel crowded enough that they just want to sprint toward the ground surface. By one estimate (Colbeck, 2008), 20 mm surface hoar formation can be achieved by depositing 0.000459 g/cm^2 of ice in a ten-hour night.

That might not sound like much, but sitting here typing this in a room with 75 percent relative humidity at 15° C, I have about 0.0000096 grams of water per cubic centimetre in the air around me (that is about 0.0000005 moles or 320 quadrillion water molecules). That might seem like a lot, but the surface hoar mass estimate above requires a nightly deposit of 0.000026 moles of water, or about 15 quintillion molecules per square centimetre. Now that's a lot!

Following this hypothetical situation, that means for every square centimetre of nightly surface hoar, we need absolutely every single last molecule of water out of 47 cubic centimetres of the sort of air I am breathing now. And to do that we would need an enormous vapour pressure gradient to make all of those molecules want to leave their air and become ice. Not to mention that colder air holds less water; 0° C air can hold about a third of the water vapour that my 15° C air can hold.

Figure 3: Cloud beginning to form in the afternoon in the Columbia mountains. Its corresponding frost band footprint from the previous night appears along defined elevation bands. (Photo: Bruce Jamieson)

Next, remember that those calculations are per square centimetre. Imagine a column of cubic centimetres of air reaching out from the snow, all donating their water molecules to the ground. In that model, and re-doing the calculation with 0° C air, the above numbers would mean that every single last molecule out of the air nearly a metre and a half above the snow would have to come close enough to the ice to deposit on the surface in order to form that surface hoar layer. In reality, all the molecules cannot simply evacuate their air; the molecules from above must come down to balance the new absence, and those above them, and so on, which affects the air many times that in height.

Not to mention all the time and force needed for the quintillions of water molecules to wiggle down through all that space! Even with the role of wind included—which proves to be a complicated issue itself through the studies cited in references 3 (Feick, 2007) and 4 (Hachikubo, 1997)—we still need all of those molecules in all of that air to somehow get close enough to the snow to jostle onto it and deposit as surface hoar.

The Role of Clouds

Let us return to the original question: Where does that water vapour come from? The easy answer at first seems to be clouds since they have lots and lots of water, right? Again, not so simple.

Clouds affect temperature—both on the surface and in the air—because they affect radiation. Snow needs longwave radiation to have an escape route to the sky; it vents its daytime heat and gets cold again mostly by emitting longwave. Remember, the snow being colder helps phase-driven diffusion onto surface hoar. It also makes the vapour pressure gradient toward the snow stronger since colder areas hold less water and all the water in the warm areas want to go to the uncrowded cold areas which have lower vapour pressure.

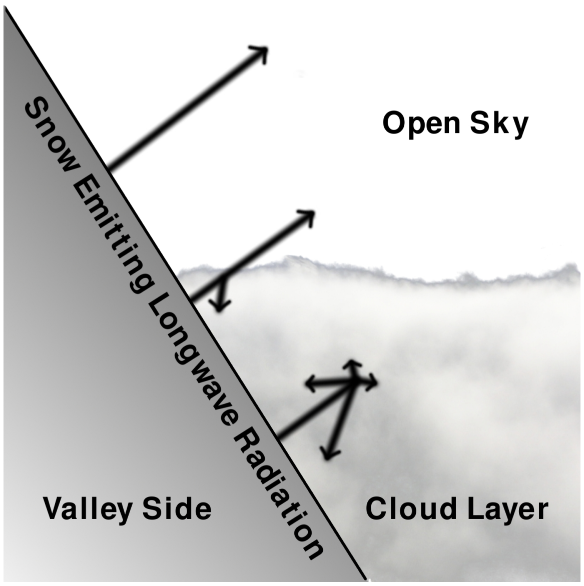

Figure 4: The effect of clouds on longwave radiation escape. Within the cloud layer, the escaping radiation gets reflected and diffused back to the snow. Even with a relatively stationary cloud, however, there may be a portion of the valley side which receives moisture from the cloud but manages to emit some longwave through thin, non-continuous cloud sections (middle arrow from snow surface).

But longwave radiation in particular is easily diffused and re-radiated by clouds. Think of how your shadow has fuzzy edges on the ground because the visible shortwave radiation at the edges gets diffused by the air. The same thing would appear with longwave radiation but to a much, much fuzzier degree if you could see the "shadows" from blocked longwave. Clouds do an especially great job of taking longwave radiation in and then just spitting it back out—re-diffused in all directions.

So snow can't get cold enough below a cloud because the longwave radiation that snow emits into a cloud just comes right back. Thus, even though the cloud is a great source of moisture, the vapour pressure gradients within the cloud would have to be enormous to drive diffusion. When ground and cloud are at the same temperature, Colbeck and colleagues estimate the cloud would need to be 8200 times as dense as a normal cloud to make the molecules feel crowded enough to want to deposit on the ground in the amounts we need!

Two things may be at work here. First, clouds don't stay still. They move up and down in elevation, and they move back and forth parallel to the ground. They can also shrink and grow. In Figure 3 one can see a tiny whiff of cloud growing, but the deposition on the trees is from cloud and humidity in the previous night. This fluctuation can give the snow a chance to cool off when the cloud leaves, and refresh moisture when the cloud returns.

Second, even when clouds do stay still, they have thicker parts and thinner parts. In Figure 4 one can imagine that snow at the top of a cloud may have just the right mix of being able to vent its longwave radiation and yet use the moisture from the cloud.

The Future

What this all means boils down to the following: Surface hoar needs lots of water vapour to grow. A huge amount of focus has been given to surface hoar formation occurring on cold, clear nights. As you now know from this article, those cold temperatures help drive the microscopic vapour pressures of water over ice, and they also help drive the "lateral diffusion" vapour pressures. But cold, clear nights don't just create water out of nowhere. And since surface hoar also forms on trees, we cannot always point to the daytime melting of the snow as a source of its own water. Humidity, cloud moisture, and other water sources may play an equally large role in surface hoar formation as the typical "cold and clear" setup.

As always, the more we know, the more we realize what we do not know. For example, even if we have water, it can sometimes be deposited as surface hoar, and sometimes as rime. The two pictures in Figure 5 show that other things may also be at work here, namely vapour or droplet size.

Figure 5: Different deposition methods of water: surface hoar plates on pine needle tips (left), and rime feathers in and around a pine needle bunch (right). Both formed in the same surface hoar formation cycle, January 2009. (Photos: Cora Shea)

Regardless, from this thought experiment, we can help improve our future directions. When nights are truly cold and clear, think of where humidity might be: in visible, condensed cloud form or otherwise. When clouds exist, try to think like the snow and find where it may be venting enough longwave radiation to cool. Will locations of clouds or non-visible “cloud formations” of humidity eventually help us to map surface hoar? Probably, but today no one can say exactly how. But the next time you see surface hoar, take a look around and ask yourself: where *did* all that water come from?

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