A MECHANISM FOR COOLING-RELATED SLAB AVALANCHE RELEASE

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ABSTRACT: Strong anecdotal evidence exists suggesting cooling is an important factor for slab avalanche release. Despite this, a viable mechanism for it has not yet been formally proposed. This paper describes a mechanism combining enhanced cohesion of the upper slab (caused by a cooling-driven reduction in viscosity) with lateral variations in the weak layer depth. A critical component of the model is that sufficient creep is retained in the mid portion of the slab. This enables higher strain rates to be transmitted to a part of the slope where the weak layer is buried at a shallower depth. As a result of the model constraints, it is likely the physical state of the snowpack corresponding to that described in the model occurs under very specific conditions. This is consistent with observations of the phenomenon, which indicate cooling-driven slab avalanches are relatively uncommon, but when they do occur, often happen within a specific window a short time after the onset of cooling. Other potential mechanisms are also examined. These are: thermal expansion or contraction of the slab; increased brittleness of the slab; and changes to weak layer properties.

1. INTRODUCTION

Atwater (1954) recognised rapid temperature change as one of his ten factors important for snow avalanches. He stated, “A sudden drop [in temperature] increases the tension, particularly in the slab”. Jamieson et al. (2001) noted experienced professionals consider periods of rapid cooling to be sometimes associated with avalanche release. Perla (1970) produced a graph of hazard probability versus temperature change for two levels of summed avalanche magnitude. For the lower summed avalanche magnitude level (which may relate to occasional or surprise avalanches) an increase in hazard probability was observed when the temperature dropped by 10 degrees or more. For the higher summed avalanche magnitude level (likely related to storm cycles), this relationship was not seen.

Goddard (2012) produced a database of avalanche activity considered by professionals to have resulted from rapid air temperature cooling, which she defined as cooling from 0°C to a temperature below 0°C (cool down avalanches). 63 % of the 40 respondents in her survey had experienced a cool down avalanche, with 21 % reporting a cool down avalanche led to an incident or close call. Despite this, many forecasters commented that they still regarded periods of cooling as generally more stable compared with periods of warming; cool down avalanches were frequently surprise events The vast majority (98 % of 360 events) of cool down avalanches were slab avalanches and 61 % of were described as glide releases. At least 27 cool down avalanches occurred during the first hour of the sun leaving the slope in question.

In the most widely accepted model of slab avalanche release (McClung, 1979; McClung, 1981), shear fracture in the weak layer is precipitated by strain softening. This mechanism allows time-delayed avalanches to occur with no external forcing (except for gravity) on the slope in question. The possibility remains, therefore, for avalanche observations to be made during periods of air temperature cooling, but for which the cooling factor is inconsequential to the avalanche release.

2. PROPOSED MECHANISM FOR COOLING RELATED AVALANCHES

The release mechanism proposed here relies on the observed increase in the stiffness of snow as it cools (McClung and Schweizer, 1996; Schweizer,

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1998) as well as spatial variability in the start zone. The slope in question must have a weak layer buried at a relatively shallow depth in one region and a relatively deep depth in others. Figure 1 shows a suitable slope configuration.

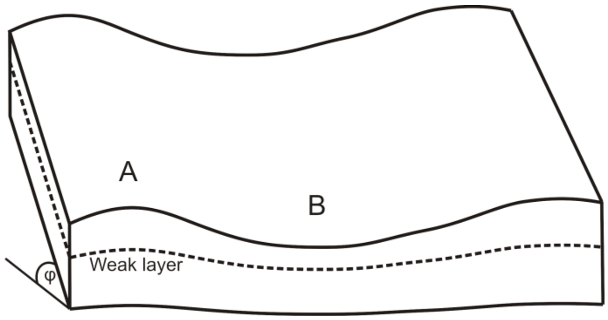

Figure 1. Possible slope configuration for cooling related avalanche.

At a point on the slope where the weak layer is deeply buried (Point A, Figure 1), a profile of the total deformation within the snowpack due to creep and glide may resemble that in Figure 2A. At this point, critical strain rate gradient is not reached at the weak layer; deformation may be accommodated by the viscous properties of the snowpack. At a shallow point (Point B, Figure 1), the total deformation profile is different, with less total deformation but a similar strain rate gradient (Figure 2B). The profile in Figure 2B is valid for situations when the upper snowpack at Point B is uncoupled or viscously coupled to the slab at Point A. This situation is permissible if the upper snowpack is relatively warm and can accommodate strain in the transitional areas by viscous deformation.

If the upper slab cools, the stiffness of the upper slab will increase. In this case, Point B will become more directly coupled to Point A (Figure 3). This will perturb the deformation profile, increasing both the strain rate and strain rate gradient, particularly within the upper snowpack. Given the right weak layer properties (poorly bonded, and shallow at the point of initiation), it is possible this additional strain may no longer be accommodated by viscous deformation. In this case, the weak layer will fracture and an avalanche will release.

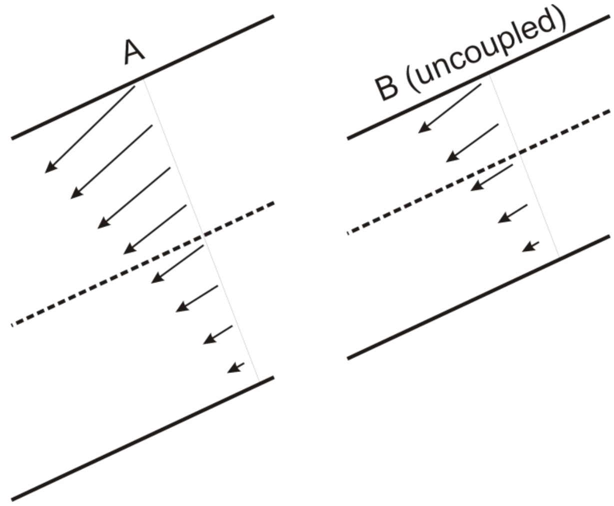

Figure 2. Deformation profiles for thick snowpack region (A) and thin snowpack region (B).

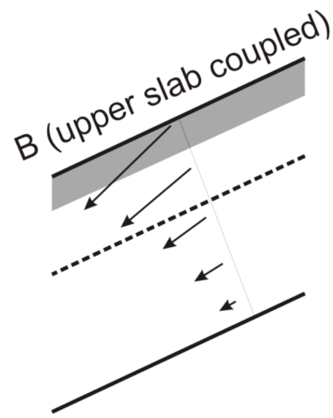

Figure 3. Deformation profile for a thin snowpack region coupled to a thick snowpack region by a cohesive upper slab.

3. TIME DEPENDENCE

There is a trade-off between the coupling effect of the upper slab, which may locally increase the strain rate gradient provided the underlying strain rates remain relatively high, and the overall reduction in strain rates caused by more sustained cooling of the slab. Rapid cooling is required that cools the upper slab to provide coupling but retains some relatively warm snow just below to provide enhanced strain rates. Eventually, after a longer period of cooling, strain rates in a good portion of the upper slab (30 to 40 cm) will diminish and, as a result, the likelihood of exceeding the critical strain rate gradient within the snowpack is reduced.

4. TEMPERATURE PENETRATION INTO THE SLAB

Bakermans (2006) measured temperature drops at a depth of 10 cm below the snow surface in the order of 5°C over a period of 1 to 3 hours. This study, however, was not focussed on finding the maximum rate of cooling. The same study measured a 0.3°C reduction in temperature at 10 cm below the surface over a period of only 10 seconds by shading the snow surface from direct incoming radiation. It seems plausible to expect temperature reductions in the order of 10°C per hour in the top 10 cm of the snowpack during conditions favouring rapid cooling (warm, sunny/hazy late-day conditions transitioning to clear early evening conditions, combined with the passage of a cold front). Bakermans (2006) measured temperature drops at 15 cm below the surface in the order of half of those measured at 10 cm; at 20 cm below the surface, drops were in the order of a quarter of those at 10 cm.

5. OTHER MECHANISMS

5.1 Density changes

Ice contracts slightly as it cools. However, the effect of cooling on snow density is not well studied. Due to the high porosity of snow and its highly ductile nature, it is most likely that small changes in the size of individual grains would be accommodated by grain rearrangement within the snow matrix, resulting in little or no change to the bulk density of the snow.

5.2 Weak layer changes

For weak layers greater than 40 cm deep, it is unlikely critical changes to weak layer properties are responsible for cooling related avalanches, since the insulating properties of the snow prevent changes occurring within the critical time frame. For very shallow weak layers, it is most likely the cooling would increase fracture toughness of the weak layer (McClung and Schaerer, 1996), decreasing the likelihood of avalanching.

5.3 Brittleness changes

In addition to becoming stiffer, snow also becomes more brittle as it gets colder. However, the critical location where an increase in brittleness would have an effect on snowpack stability is at the weak layer. As discussed above, in most situations, the weak layer will be below the depth of influence of cooling. For shallow weak layers, the decrease in strain rates combined with an increase in the fracture toughness likely counter any increase in brittleness over the critical time period.

6. SUMMARY

A plausible mechanism for cooling-related avalanches is proposed, which relies on the coupling of the upper slab between relatively deep snowpack areas and relatively shallow snowpack areas. This upper slab coupling concentrates strain rate gradients at the weak layer in shallow snowpack regions for a relatively short time period following the onset of cooling.

The model allows for increased strain rate gradients to be generated at the weak layer with no changes to weak layer properties. This is required, as it is unlikely the weak layer is directly affected by temperature changes.

Empirical observations indicate cooling-related avalanches are relatively infrequent. When they do occur, they can be large and destructive, are usually surprising, and frequently occur within one hour of the sun leaving the slope. The proposed model supports these observations.

Some cooling-related avalanches may be incorrectly labeled as such, and could instead result simply from time-delayed strain softening at the weak layer.

Further development of a numerical model would help validate this mechanism. It would also help identify more specific meteorological and snowpack conditions favouring cooling-related avalanches.

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