ON SURFACE WARMING AND SNOW INSTABILITY

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ABSTRACT: Warming is believed to be one of the most prominent causes of snow instability – although experimental evidence is rare. We know that – due to the low thermal conductivity of snow – warming at the snow surface rarely affects the weak layer temperature. In the case of dry-snow slab avalanches, instability is not due to weakening of the weak layer, but is believed to be due to increased deformation within the near-surface layers of the slab. Solar radiation can penetrate the surface and effectively reduce the stiffness of the upper layers. Changing slab properties directly affect snow instability in many ways. Whereas measurements have shown that the surface layers in fact creep more rapidly due to warming, field evidence is mostly lacking on how these changes affect snow instability. This might be because the effects of surface warming are subtle and/or only observable under certain slab/weak layer conditions.

1. INTRODUCTION

Apart from precipitation and loading by wind, a rapid increase in air temperature and/or in solar radiation is commonly considered as the main meteorological factor contributing to snow instability under dry-snow conditions. Despite the fact that the rule of thumb "A rapid significant increase in air temperature leads to instability" is widely stated in avalanche education (e.g. Munter, 2003), data to support this rule are rather sparse.

After an avalanche release often no other obvious external factor can be found. Harvey and Signorell (2002) reported that in 20% of the recreational accidents in the Swiss Alps an increase in air temperature (from the day before the accident) was the only indicator of instability. On the other hand, in many of the statistical avalanche forecasting models, temperature – but also the temperature difference – ranks consistently low among the meteorological forecasting parameters (e.g. Davis et al., 1999; Schirmer et al., 2009; Schweizer and Föhn, 1996). In fact, in some of the leading textbooks (McClung and Schaerer, 2006; Tremper, 2008) the effect of warming on snow stability is not denied, but one can read between the lines that the effect is probably relatively small or only prominent under very special circumstances. Still, temperature (and radiation) is listed as one of the five main contributing factors (terrain, precipitation, wind, temperature/radiation and snow stratigraphy) in Schweizer et al. (2003). They suggested that instability would be due to changing slab rather than weak layer properties, and that radiation would be more efficient than rapid warming in causing instability. It seems clear that the temperature effect on snow slab failure is not due to decreasing strength of the weak layer with increasing temperature (McClung, 1996). Harvey and Heierli (2009) suggested surface warming to be more relevant for skier triggering than for natural release.

In the following we will shortly review some key elements on surface warming and its effects on snow instability – this is not a comprehensive review of the temperature effect.

2. DEFINITIONS, PROPERTIES AND PROCESSES

To set the stage we first define the relevant terms and conditions. First of all, we focus on dry-snow conditions and dry-snow slab avalanches. With surface warming we mean that in the surface layers of the snowpack, i.e. in the upper layers of the slab, snow temperature increases. The temperature increase is due to a net energy flux directed into the snowpack which indicates an energy gain (King et al., 2008). The net surface flux is the sum of surface fluxes (shortwave radiation, longwave radiation, and turbulent fluxes of sensible and latent heat) neglecting advective (e.g. latent or sensible heat added by precipitation or blowing snow) and ground heat fluxes. Describing conditions for a negative net surface flux (snowpack gains energy) is complex, but occur mostly when either the net solar radiation flux, or the sensible heat flux, or both are rather large and di-

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rected towards the snow surface – and cannot be compensated by loss due to the net longwave radiation flux. In other words, surface warming predominantly occurs with intense solar radiation and/or an air temperature significantly warmer than the snow surface temperature accompanied by wind (wind is a necessary condition).

Since the thermal conductivity of snow is low, the energy added to the snowpack by sensible heat travels slowly from the snow surface to the layer beneath (e.g. Fierz et al., 2008). In contrast, the energy input by shortwave solar radiation more efficiently warms the surface layers as the radiation penetrates into the near-surface layers (so that the energy is released within the snowpack). However, shortwave radiation penetration strongly decreases with increasing distance from the snow surface. Compared to solar radiation, an increase in air temperature by 10°C from one day to the next will affect the snowpack to a depth of, say, 20 cm much later and in attenuated form. Diurnal changes in air temperature over snow covered surfaces are mostly not significant for surface warming, but diurnal changes in snow temperature in near-surface layers are predominantly due to absorbed solar radiation. These changes can be measured as deep down as 40-50 cm, but the magnitude at this depth is insignificant. Typically significant surface warming takes place in the uppermost 20-30 cm (Fierz, 2010). A temperature increase of 10°C in a depth 10 cm below the snow surface is commonly observed on sunny days (Bakermans and Jamieson, 2008).

By the way, cooling – the opposite effect – is mainly due to heat loss by outgoing longwave radiation. The low thermal conductivity will cause cooling to take more time than warming by penetrating shortwave radiation.

Having identified the sources, conditions and magnitude for surface warming we move on to the effect of changing snow temperatures on the mechanical properties of snow, and ultimately to stability. With snow being a high-temperature material – within a few degrees of its melting point – there is no doubt that changes in snow temperature strongly affect the mechanical properties, even more so as the melting point is approached. Based on strength measurements in the cold laboratory, McClung and Schweizer (1999) concluded that the stiffness (effective modulus) of snow would be the property most sensitive to temperature, and strength being much less influenced. With increasing temperature the stiffness decreases – in other words, deformation in the near-surface layers increases, both in slope parallel as well as vertical direction (settlement). In fact, the increased deformation has recently been observed (Exner and Jamieson, 2009). If the temperature change in the near-surface layers is due to the instantaneous release of energy from absorption of shortwave radiation, the change in mechanical properties is rapid as well. The change of mechanical properties, in terms of the modulus, has recently been measured with the snow micro-penetrometer (SMP) (Schneebeli and Johnson, 1998). A couple of hours of energy input by shortwave radiation caused the effective modulus of the surface layers to decrease by almost an order of magnitude (Reuter, personal communication).

3. POTENTIAL MECHANISMS FOR PROMOTING INSTABILITY

For a dry-snow slab avalanche to release, a weak layer below a cohesive slab is required. An initial failure in the weak layer has to be initiated, and needs to develop into a self-propagating fracture below the slab. Once the slab is detached and friction is overcome, the slab accelerates, moves downslope and breaks up. Surface warming is an external perturbation ("trigger") that acts over a much wider area than, say, a skier. However, for the perturbation to have an effect the existence of a critical slab-weak layer combination is probably essential.

Our present understanding of dry-snow slab avalanche release is largely based on (linear elastic) fracture mechanics. The elastic modulus of ice does not much depend on temperature (Mellor, 1975). However, the behavior of snow is not perfectly brittle – even not for snow slab failure, so that delayed elastic (or viscoelastic) effects come into play. Therefore we always refer to the effective modulus or stiffness (rather than to the truly elastic Young's modulus).

We now look at the two processes of failure initiation and fracture propagation. In the case of natural release, failure initiation from damage accumulation, i.e. sub-critical crack growth is due to the increased deformation in the topmost slab layers. This will increase the strain rate even down at the depth of the weak layer though warming has not reached the weak layer. This can be shown, for instance, by finite element (FE) modeling (Habermann et al., 2008). As snow strength is rate-sensitive it seems plausible that surface warming may under already critical conditions lead to an initial failure.

In the case of skier triggering, failure initiation is due to the localized load by the over-snow traveler. Measurements of the skier's impact indicate that the stress at the depth of the weak layer increases when the surface layers are relatively warm and cohesive (Camponovo and Schweizer, 1997; Exner and Jamieson, 2008; Schweizer et al., 1995) which is in agreement with FE modeling (Wilson et al., 1999). Again, failure initiation is thought to become more likely due to changes in slab properties.

For fracture propagation, the question is how surface warming affects the energy release rate. As with strength, the specific fracture energy of the weak layer will not change as warming will not have an effect at the depth of the weak layer. Measurements on the fracture toughness in tension with cantilever-beam experiments in the cold lab indicated that the fracture toughness decreases with increasing temperature up to about -8°C. Schweizer et al. (2004) found that at warmer temperatures, results became more scattered, suggesting an increase of toughness towards the melting point. They argued that the increase of toughness towards the melting point seemed plausible given the observation that artificial triggering by explosives becomes less efficient once water has reached the depth of the weak layer.

As the slab stiffness decreases, the energy release rate should increase so that shorter critical crack lengths result (assuming that the specific fracture energy of the weak layer remains unaffected) – equivalent to higher fracture propagation propensity. Whereas it has been possible to confirm the change of modulus in the slab due to surface warming with SMP measurements, measuring the corresponding change in critical crack length in propagation saw tests (Gauthier and Jamieson, 2006) was not conclusive – at least based on a preliminary analysis (Reuter, personal communication). We suppose that either the changes were too small and/or hidden in the scatter caused by spatially variable weak layer and slab properties.

Furthermore, FE modeling indicates that the effect of warming the upper slab layers on the energy release rate depends strongly on the properties of the lower slab layers – not affected by the warming. For example, if the weak layer is overlain by a crust the effect on the energy release rate is small when surface warming softens the upper layers. This finding suggests that surface warming is most efficient in the case of relatively thin new snow slabs (usually less than 50 cm, McClung and Schaerer, 2006, p. 97) – in agreement with observations by experienced practitioners.

While there are fascinating examples of deep slab natural avalanches during warming, a causal effect cannot be explained by current theory. Even in hindsight, not all avalanches have an identifiable “trigger”.

4. CONCLUSIONS

We have revisited the effect of surface warming on dry-snow slab release. Whereas the effect of warming to 0°C (surface becomes moist or wet) on loose snow avalanching is strong, the effects we discuss on dry-snow slab release seem subtle. Without certain preconditioning, e.g. stratigraphy of the snowpack, surface warming will probably not cause instability.

Instability always stems from changes in slab properties. Increased deformation due to reduced stiffness of the surface layers increases the strain rate in the weak layer, increases the energy release rate, or increases the skier stress at depth. All these effects are immediate and promote instability (whereas delayed effects tend to rather promote stability) (McClung and Schweizer, 1999). Surface warming is most efficient with warming by solar radiation as radiation penetrates the surface layers where the energy is released. Surface warming due to warm (relative to the snow surface) air temperatures is a secondary effect – except in the case when a moderate or strong wind blows.

When doing field tests such as the PST, shorter crack length should be observed with ongoing surface warming. So far, evidence is rare; in general, it seems difficult to collect field data that support our view on how surface warming affects snow instability.

ACKNOWLEDGEMENTS

We acknowledge the contributions by Thomas Exner and Benjamin Reuter on the topic of surface warming.

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