

## Thermal energy in snow avalanches

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**ABSTRACT:** Avalanches can exhibit many different flow regimes from powder clouds to slush flows. Flow regimes are largely controlled by the properties of the snow released and entrained along the path. Recent investigations showed the temperature of the moving snow to be one of the most important factors controlling the mobility of the flow. The temperature of an avalanche is determined by the temperature of the released and entrained snow but also increases by frictional and collisional processes with time. The aim of this study is to investigate the thermal balance of an avalanche. Infrared thermography technology was used to assess the surface temperature before, during and just after the avalanche with a high spatial resolution. Manually measured snow temperature profiles along the avalanche track and in the deposition area allowed quantifying the temperature of the eroded snow layers. This data set allows to calculate the thermal balance, from release to deposition, of an avalanche and to discuss the magnitudes of different sources of thermal energy in snow avalanches.

**KEYWORDS:** snow avalanche, thermal energy, snow entrainment, infrared radiation thermography

### 1 INTRODUCTION

It is well known that avalanches can exhibit many different flow regimes (Gauer et al., 2008) and mass entrainment is not the only controlling factor that determines the flow form of the avalanche (Bartelt et al., 2012). Data on front velocities, run out, flow regimes and powder clouds revealed that different avalanches can form for similar initial conditions and on the same avalanche path depending on the inherent snow cover properties. Recently, it has been shown that snow temperature inside the avalanche can significantly change its flow dynamics (Naaïm and Durand, 2012; Steinkogler et al., 2013). Potential sources of thermal energy are friction processes or entrainment of warmer snow (Vera et al., 2012). Measuring temperature inside a flowing avalanche or in its deposit has proven to be difficult due to technical constraints or because measurements can not be conducted due to safety reasons. In addition to manual snow profiles we therefore investigate the application potential of infrared radiation thermography (IRT) technologies in the field of avalanche dynamics. IRT has been applied to many cryospheric research problems, such as

measuring spatial snow surface temperature variations on snow pit walls (Shea and Jamieson, 2011). Many technical challenges and shortcomings of IRT for snow applications, e.g. photographic viewing angle (Dozier and Warren, 1982) are known but many possible applications in snow science are recently discussed (Schirmer and Jamieson, 2013).

### 2 METHODS & DATA

Multiple avalanches were artificially released in winter 2012/13 at the Flüelapass field site close to Davos (Switzerland). Here we will discuss a selected avalanche out of this data base.



Figure 1. Flüelapass field site close to Davos (Switzerland). Red line indicates the outline of the avalanche. Colored crosses indicate locations of manual snow profiles.

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The north-east facing slope covers 600 vertical meters and deposits of larger avalanches typically reach the lake located at 2374 m a.s.l. (Figure 1). Observations and remote measurements can safely be conducted from a near road. The slope angle ranges from 50° in the rock face in the upper part to 20° at the beginning of the run-out zone with an average of 30° of the open slope around 2600 m a.s.l..

In all experiments the cornices at the ridge at 2900 m a.s.l. were triggered with explosives. Mass contributions by the cornices are usually relatively small compared to entrained snow on the open slope below. Furthermore, entrainment of snow in the gullies of the rock face is not assumed to contribute a significant amount since regularly occurring (small) avalanches continuously erode the snow cover. This is especially true for the discussed avalanche (Figure 2) where a significant amount of snow was entrained below the rock face.

During the experiment, clear sky conditions, light to moderate winds, small relative humidity and cold air temperatures prevailed. Since the avalanche was triggered after a storm, most of the released snow was new snow. Yet, the presented avalanche entrained deeper layers due to the secondary release below the rock face (Figure 2).



Figure 2. Avalanche at the Flüelapass field site released by artificial triggering of the cornices on the ridge. Note the significant secondary release below the rock face.

Manual snow profiles (according to Fierz et al., 2009) were conducted in the release zone, i.e. just below the rock face, along the track in the undisturbed snow and in the deposition zone. In addition an IRT camera was used to record snow surface temperatures before, during and after the avalanche. We used an InfraTec VarioCAM hr 384 sl that operates in the long wave infrared spectral range (LWIR) ranging from 7.5 to 14  $\mu\text{m}$ .

The acquired snow surface temperatures by the IRT camera, further called Tss-IRT, were compared to manually performed snow surface temperature measurements at the avalanche deposits and the snow surface of the erosion layer was compared to the corresponding layers in the snow profile. Both measurements showed to be in good agreement in the range of.  $\pm 1^\circ\text{C}$ .

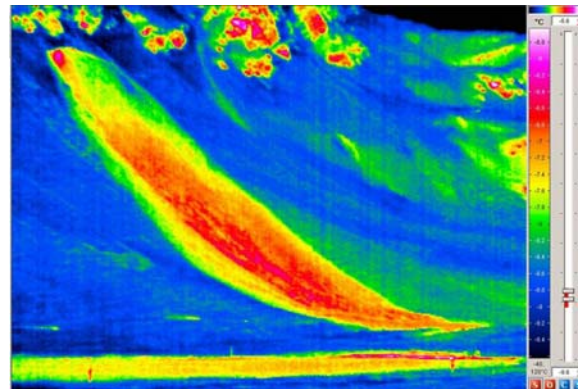


Figure 3. Snow surface temperature measurements acquired with IRT camera after the avalanche stopped and the powder cloud disappeared.

### 3 SOURCES OF THERMAL ENERGY

The total warming of the avalanche is apparent by comparing the snow temperature profile in the deposition zone (red curve in Figure 4) to a profile at the same elevation but outside the deposits (green curve in Figure 4). Calculating the average snow temperature over the entire deposition depth (red curve), i.e. 0.8 m, results in  $-6.4^\circ\text{C}$ . The average of the undisturbed snow (green curve) results in  $-8.8^\circ\text{C}$ .

To investigate the total warming of  $\sim 2.4^\circ\text{C}$  and give a rough estimate of the magnitude of the sources of thermal energy in the investigated avalanche, we partition the total warming into warming due to entrainment of snow and friction. Other potential sources of thermal energy, e.g. entrainment of air or adiabatic warming, were not considered in this calculation since they were graded as negligibly

small and in this paper we are aiming only to calculate an order of magnitude.

A rough interpolation of the snow temperature profiles (Figure 4) yields an increase of temperature due to entrainment of approximately  $0.7^{\circ}\text{C}$  and can therefore not be the exclusive source of thermal energy since it cannot explain the total temperature increase of  $2.4^{\circ}\text{C}$ .

The increase in temperature due to friction was calculated by assuming that all potential energy is transformed to heat. Calculating for an elevation drop of 300 m, corresponding to the slope below the rock face until the run-out zone, results in an increase in temperature due to friction of  $1.5^{\circ}\text{C}$ .

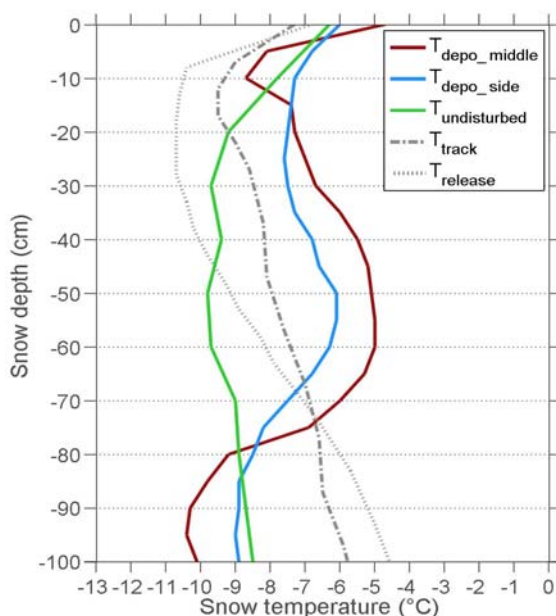


Figure 4. Snow temperature measurements conducted in the release zone ( $T_{\text{release}}$ ), along the path in the undisturbed snow ( $T_{\text{track}}$ ), in the deposition zone ( $T_{\text{depo\_middle}}$ ,  $T_{\text{depo\_side}}$ ) and the undisturbed snow cover in the run-out zone ( $T_{\text{undisturbed}}$ ). Colors are in accordance to profile locations in Figure 1.

### 3 CONCLUSIONS

We conducted real-scale avalanche experiments at the Flüelapass field site above Davos (Switzerland) to investigate the sources of thermal energy or temperature increase in the avalanche. A further goal was to test the usability of infrared radiation thermography (IRT) in this context. The measured local data allowed a rough partitioning of the total temperature increase ( $2.4^{\circ}\text{C}$ ) into sources of thermal energy due to friction ( $1.5^{\circ}\text{C}$ ) and entrainment of snow ( $0.7^{\circ}\text{C}$ ).

The IRT data allowed to observe the avalanche phenomenon ‘with different eyes’ and provides a lot of potential for more detailed research in the field of avalanche dynamics, both quantitative and qualitative but has not yet been used in the analysis presented here. It is still necessary to verify the measurements and define to which extent absolute snow surface temperatures can be measured. Then, the spatial distribution of surface temperatures can help in the interpolation of profile temperatures measured by hand.

Our results allow for a more comprehensive understanding of snow temperatures in avalanche flow and their consequences on flow regimes. This information can directly be used to verify and enhance the performance of avalanche dynamics models (Christen et al, 2010) and are thus of great interest for practitioners.

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