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The effect of surface warming on slab stiffness and the fracture behavior of snow

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Surface warming is among the most complex contributory factors that need to be considered when forecasting dry-snow slab avalanches. The aim of the present study is to quantify surface warming with respect to the contributing meteorological processes and to investigate in situ crack propagation propensity under conditions of surface warming. The energy fluxes at the snow surface, partly measured and partly modeled with the snow cover model SNOWPACK, were used to determine the energy input into the snow cover. Stiffness of the near-surface layers and its changes with daytime warming were derived from penetration resistance measurements with the snow micro-penetrometer (SMP) and related to the energy input. Changes in fracture behavior were assessed with the propagation saw test (PST). An average reduction in stiffness by a factor of about 2 was observed in near-surface snow layers when the cumulative energy input at the surface exceeded 300 kJ m^{-2}. At the depth of the weak layer (~40 cm) changes were rather small; in particular for the specific fracture energy no trend was detected with warming. Critical cut lengths tended to decrease with decreasing slab stiffness, suggesting that surface warming increases crack propagation propensity. However, the effect seems to be subtle. It is suggested that a pre-existing weakness and significant energy input are required for surface warming to promote instability.

1. Introduction

Temperature and radiation are often listed among the five essential contributory factors for avalanche formation (e.g. Schweizer et al., 2003). In statistical analyses, however, air temperature often does not show up as important factor (e.g. Perla, 1970; Schweizer and Föhn, 1996), possibly since it is only important in some instances. Schweizer and Föhn (1996) rated daytime warming as a minor contributor to instability compared to other parameters such as new snow depth. As the latter is a good indicator of avalanche danger it is often hard to determine the true driving force: critical amount of new snow or surface warming. Harvey et al. (2002) analyzed meteorological parameters on days with more than three accidents in the Swiss Alps between 1970 and 1999. On about 20% of these avalanche days they found no other indicator of instability than a rise in air temperature between the accident day and the day before. They noted that the "temperature rise" is one of the most difficult parameters for forecasters.

Obviously, snow properties are highly temperature dependent. Increasing snow temperatures are related to lower stiffness values (McClung and Schaerer, 2006; Schweizer, 1998). McClung and Schweizer (1999) summarized the temperature effect on snow-slab stability and suggested that with regard to skier triggering the decrease of slab hardness (stiffness) is the most important consequence of warming. Bakermans and Jamieson (2009) developed a model to calculate near-surface daytime warming. Intended to serve as a forecasting tool for warning services it provides quantitative estimates of the magnitude of daytime warming, which seems useful when evaluating snow instability. Avalanche forecasting services frequently predict a rise in avalanche danger in the course of the day due to daytime warming. We found the corresponding wording in about 20% of the Swiss bulletins issued in the months of November to March when typically dry-snow conditions prevail. High avalanche activity is occasionally reported on days just after a snowfall followed by an increase in air temperature.

The stress distribution in the snowpack caused by additional loading depends on snow layering (e.g. Schweizer, 1993). Even though the weak layer, which is involved in dry-snow slab avalanche release, is not affected, a change of the physical properties of the slab layers may affect stability. McClung (1996) proposed that changes of slab properties through warming may influence the fracture behavior. Heat conduction and the absorption of shortwave radiation in upper slab layers cause temperature changes within the slab (e.g. Fierz, 2011). Wilson et al. (1999) have used finite element (FE) modeling to investigate the effect of slab properties under warming on skier stability. The associated reduction in stiffness had an effect on the peak stress and the peak strain in the weak layer.

A change of slab stiffness influences the two main processes involved in slab avalanche release: fracture initiation (subcritical length) and crack propagation. Schweizer and Camponovo (2001) measured the skier's zone of influence and found a critical depth of influence of

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a few tens of centimeters. Lately, Exner and Jamieson (2008) performed pressure measurements in the snow cover to observe the stress bulb below a skier after warming. Softer slabs would seem to promote fracture initiation. Based on extended column test (ECT) results Simenhois and Birkeland (2008) suggested stability scores to decrease under surface warming. They observed cracks to propagate more frequently in the afternoon, when the snow surface had warmed, than in the morning. Since with the ECT the effects on crack initiation and propagation cannot be separated, it remains unclear what contributed to the observed change in test results.

Recently, Schweizer et al. (2011) have analyzed a dataset of propagation saw test results (Gauthier and Jamieson, 2008a). Whereas they focused on deriving fracture properties of weak layers, we use the dataset (slightly extended) to study how surface warming affects the processes of avalanche formation. First, we investigate the influence of warming on the stiffness of slab layers, and then focus on the effect these changes have on the fracture behavior of the slab-weak layer system. To quantify surface warming the energy input at the snow surface was calculated using the numerical snow cover model SNOWPACK. We determined the stiffness of the slab layers from the penetration force signal recorded with the snow micro-penetrometer (SMP). The results of the propagation saw test (PST) collected in the field were used to determine the specific fracture energy by FE modeling. The slab stiffness, the specific fracture energy of the weak layer and critical cut length were then compared to the energy input.

2. Data

2.1. Field measurements

During each of 9 days with prominent daytime warming, we performed a series of propagation saw tests in conjunction with snow micro-penetrometer measurements on sunny slopes in the surroundings of Davos, Eastern Swiss Alps (Fig. 1).

The propagation saw test (PST) was found to be a good indicator for crack propagation propensity (Gauthier and Jamieson, 2008b). The effect of surface warming on the fracture behavior was measured with overall 168 PSTs on 9 days (Table 1). The weak layer to be tested was identified with a compression test (CT) (Jamieson, 1999).

The SMP is a snow micro-penetrometer introduced by Schneebeli and Johnson (1998) to measure the penetration resistance with high spatial and temporal resolution. In total 366 penetration resistance measurements were performed with the SMP on the 10 field days described in Table 1. We always measured to a depth of 75 cm (slope normal) to include the slab, the weak layer and the upper basal layers.

The experimental setup (Fig. 2) was designed to enable several measurements during a day while keeping effects of spatial variability between subsequent measurements small, i.e. perform corresponding SMP and PST measurements close to each other. On a given slope on a specific day, we repeatedly performed at least three SMP and PST measurements (Fig. 2). In at least three adjacent pits, we measured penetration resistance along with crack propagation characteristics approximately every hour. The pits were arranged along a contour line of the slope. In each pit up to six penetration resistance measurements were recorded, every one corresponding to a PST, beginning with number 1. Furthermore, every SMP measurement can be assigned to a reference SMP measurement. Reference measurements were all taken in the morning at the very beginning of the test sequence and were recorded about 50 cm apart from each other. A snow temperature profile was recorded approximately every hour, just before the SMP and PST measurements. The snow surface was shaded to minimize the absorption of shortwave radiation by the thermometer. These data provided the maximum daytime warming at a depth of 10 cm and at the depth of the weak layer. In addition,

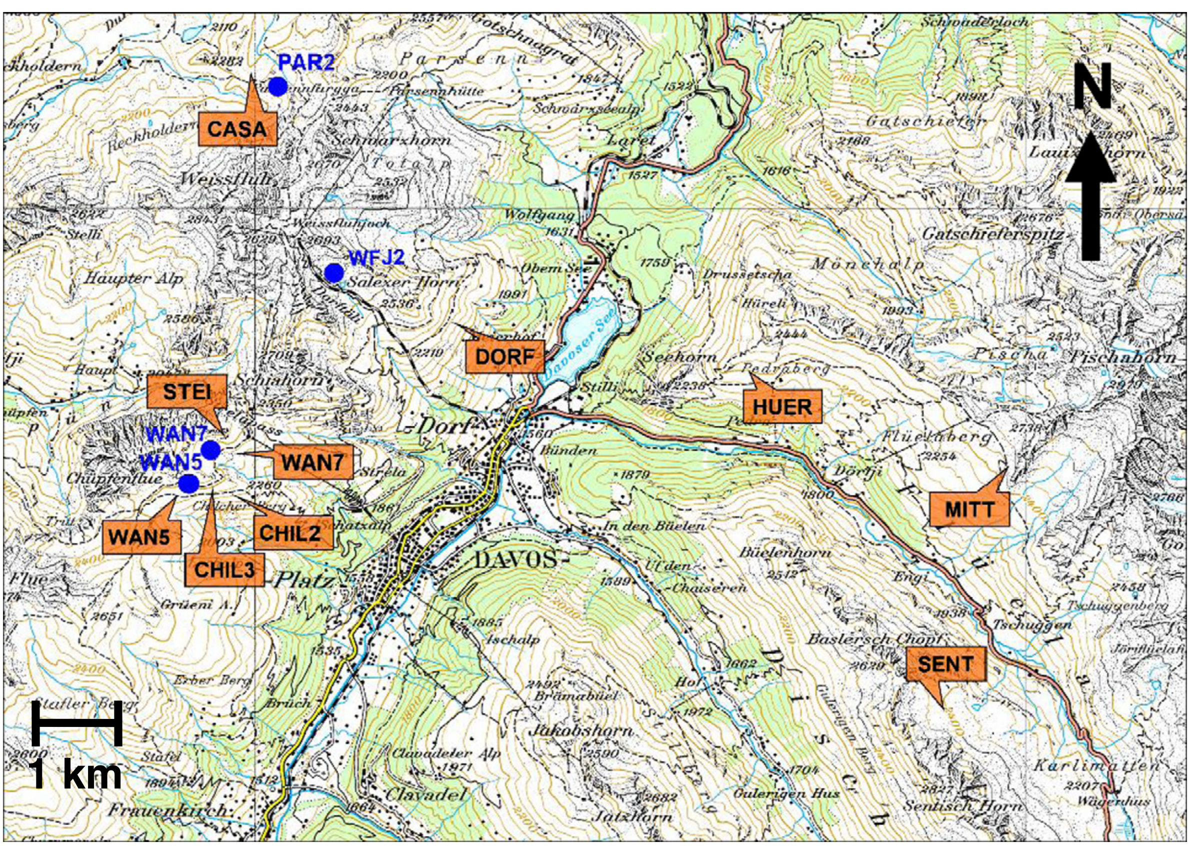

Fig. 1. Map of research area. Orange boxes with arrows point to field sites, symbols as explained in Table 1. Locations of weather stations are indicated by blue points: Abbreviations as in Table 1. Reproduced with permission of swisstopo (JA100118).

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Table 1
Characteristics of field days including date, site, elevation, slope angle, aspect and slab density as well as number of PST and SMP measurements (PST/SMP) and abbreviation of AWS used for simulations.

Symbol	Date	Site	Elevation (m a.s.l.)	Slope angle (°)	Aspect	Slab density (kg/m^3)	PST/SMP	AWS
CHIL2	8 Feb 2010	Chilcher Berg	2410	25	SE	172	18/34	WAN5
HUER	15 Feb 2010	Hüreli	2200	20	S	266	15/30	WFJ2
WAN7	16 Feb 2010	Steintälli	2430	30	E	179	18/36	WAN7
STEI	25 Feb 2010	Steintälli	2400	30	S	249	18/36	WAN7
DORF	3 Mar 2010	Dorfberg	2200	30	SE	279	14/28	WFJ2
WAN5	8 Mar 2010	Vord. Latschüel	2480	20	SW	264	18/36	WAN5
CHIL3	12 Mar 2010	Chilcher Berg	2460	30	S	258	23/46	WAN5
MITT	18 Mar 2010	Mittelgrat	2480	30	W	212	24/42	WFJ2
CASA	6 Apr 2010	Casannapass	2250	20	SW	120	-/36	PAR2
SENT	23 Mar 2011	Sentisch Horn	2410	15	NE	230	20/42	WFJ2

a manual snow profile including density measurements for all relevant layers and a Rutschblock test were conducted.

2.2. Meteorological data

To calculate the energy input into the snow cover with the snow cover model SNOWPACK the following meteorological quantities were required: incoming shortwave radiation (S_{IN}), reflected shortwave radiation (S_{OUT}), incoming longwave radiation (L_{IN}), snow surface temperature, air temperature, wind speed, wind direction, relative humidity, and snow depth. Data from the automatic weather station located closest to the field measurement site were preferred (Fig. 1). If there were data gaps, e.g. resulting from instrument failure, data from the Weissfluhjoch study plot above Davos were extrapolated. The uncertainty resulting from measurement errors will be discussed below.

3. Methods

In the following we describe how we obtained the energy input, the stiffness of the slab and the specific fracture energy of the weak layer. For statistical analyses, we choose a level of significance $p = 0.05$; i.e. for $p < 0.05$ trends were considered statistically significant.

3.1. Modeling the energy input

The numerical snow cover model SNOWPACK was used to perform slope simulations for field sites and dates listed in Table 1. Reflected longwave radiation (L_{OUT}) was calculated from modeled snow surface temperature. SNOWPACK was driven with Neumann boundary conditions assuming a neutrally stratified atmospheric boundary layer (Bartelt and Lehning, 2002). We decided to have SNOWPACK run with the assumption of a neutrally stratified boundary layer, as the model underestimates the turbulent transfer in slope simulations when stability corrections are applied (Landl, 2007; Stössel et al., 2010). To make sure that reasonable values of turbulent fluxes are obtained in our particular cases, we carried out a sensitivity study of snow surface temperatures for slope simulations. We only found small differences of snow surface temperature in model outputs with neutral stability assumptions and runs with applied stability corrections, i.e. in the range of 1 °C.

According to (King et al., 2008) the energy balance can be expressed as follows:

$$dH/dt = S_{IN} - S_{OUT} + L_{IN} - L_{OUT} + H_S + H_L$$

where H is the snowpack's internal energy per unit area, H_S is the flux of sensible heat and H_L is the flux of latent heat. Here, radiative fluxes into the atmosphere were chosen to have a negative sign; the ground heat flux and the energy added by precipitation were neglected. To know whether the snowpack gains (warming or melting) or looses energy (cooling or freezing) the change of internal energy must be considered. By time integrating the energy flux balance with a time step of 15 min the energy input (dH) for a certain time was calculated. The change in internal energy dH describes the energy which becomes available to the snowpack within a certain time. This approach does not enable us, however, to tell where the energy is deposited. For instance, shortwave radiation is partly reflected at the snow surface and partly attenuated by the ice matrix the further it penetrates. Hence, energy is set free instantaneously in layers below the snow surface. We consider the cumulative energy input at the snow surface as an integral measure of warming.

3.2. Deriving slab stiffness from SMP measurements

By comparison with the manual snow profile the corresponding snow layers in the SMP signal were identified (Kronholm et al.,

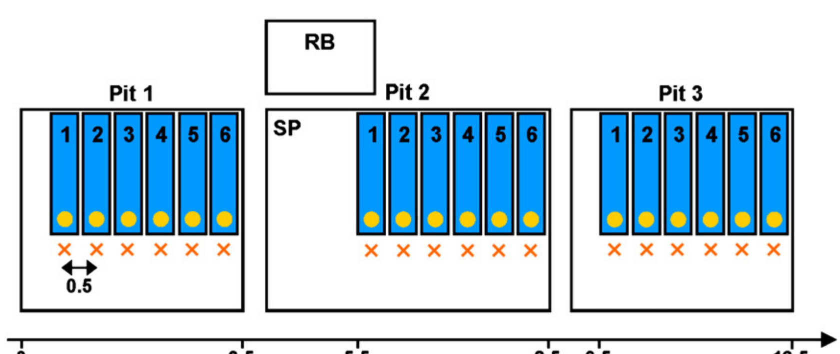

Fig. 2. Experimental setup: 3 pits with each 6 PST measurements (blue) and 12 SMP measurements: orange crosses denoting initial SMP reference measurements and yellow dots denoting SMP measurements at time of PST. Location of Rutschblock (RB) and snow profile (SP). Scale shows distances in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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2004). Interfaces of layers were picked manually in all SMP signals and saved as meta data. So, each section of the penetrometer signal (corresponding to one snow layer) was analyzed and snow properties were derived. The typical layer thickness ranged between 0.5 and 10 cm. The SMP signals were processed with a MATLAB routine based on the work by Marshall and Johnson (2009). The behavior of snow is not purely elastic, except for very short times or very small deformation; otherwise it includes delayed elastic and viscous components (Shapiro et al., 1997). With both measurements (SMP and PST) deformation is neither small nor fast enough to be purely elastic, but includes non-elastic components. We therefore refer to stiffness or use the term effective modulus to describe the observed mechanical behavior of snow. The values of stiffness derived from the SMP signal, i.e. the modulus as defined by Marshall and Johnson (2009), were accepted without any further fitting, because they were in the same range as reported by Camponovo and Schweizer (2001). Moreover, a comparison with high speed camera analysis of beam tests confirmed that the appropriate order of magnitude was obtained (van Herwijnen and Heierli, 2010).

3.3. Calculating fracture mechanical parameters from PST measurements

To perform a PST a column with a width of 30 cm cross-slope and a length of 120 cm upslope was isolated with a snow saw to a depth well below the weak layer. The ends of the column were cut slope perpendicular. The weak layer was saw cut in upslope direction. Slab height, slope angle, critical cut length and type of fracture arrest were recorded (Gauthier and Jamieson, 2008a).

The PST is the appropriate field test because the crack propagation propensity is measured. With the PST fractures are not only classed in propagating and non-propagating fractures, but the cut length which is a continuous quantity is recorded. Hence, the PST is most likely to respond to small changes in crack propagation propensity. The data obtained from PST measurements were used together with the stiffness obtained from the SMP measurement to model the specific fracture energy of the weak layer as described by Sigrist and Schweizer (2007).

4. Results

On all field days the CT revealed the existence of a fairly prominent weak layer in the snowpack (Table 4) and substantial daytime warming in the top 10 cm of the snowpack was observed (Table 2). The weak layers consisted all of persistant grain types: in seven cases facets and/or rounding faceted particles were observed, in the remaining two cases rounding facets and depth hoar crystals were observed. Slab layer thickness was 40 cm on average; average slab density was 223 kg m^{-3}. Most frequent grain types in the top 15 cm of the slab were rounded grains and decomposing and fragmented precipitation particles. The maximum snow temperature rise at 10 cm depth was 4.6 °C on average, whereas it was only 1.2 °C at the depth of the weak layer. Based on snow temperature measurements we assume that on 6 out of 10 days near-surface slab layers may have become moist; however, on all these days the snow surface was neither moist in the morning, nor did the slab become moist below a depth of 15 cm.

4.1. Stiffness of the slab

In order to observe changes in slab stiffness the values derived from SMP measurements performed during the day were related to the nearest reference measurement performed at the beginning of the day. Warming of the slab layers was quantified by the cumulative energy input derived from the surface energy flux balance. The ratio of stiffness of the measurement at a given time and the reference measurement is related to the calculated energy input in Fig. 3. Layers

Table 2
Snow temperatures: initial temperature at the beginning of a measurements series and maximum change per day for a depth of 10 cm below the snow surface (T_{-10cm}, ΔT_{-10cm}) and at the depth of the weak layer (T_{WL}, ΔT_{WL}).

Date	Site	T_{-10cm} (°C)	ΔT_{-10cm} (°C)	T_{WL} (°C)	ΔT_{WL} (°C)
8 Feb 2010	Chilcher Berg	−9.2	6.4	−3.5	1
15 Feb 2010	Hüreli	−8.5	5.4	−5.9	1.4
16 Feb 2010	Steintälli	−10.8	3.1	−7.6	0.9
25 Feb 2010	Steintälli	−3.7	3.7	−1.3	1.1
3 Mar 2010	Dorfberg	−5.4	4.9	−0.7	0.7
8 Mar 2010	Vord. Latschüel	−15.5	7.3	−7.5	2.3
12 Mar 2010	Chilcher Berg	−4.4	2.6	−3.8	1
18 Mar 2010	Mittelgrat	−7.2	4.8	−5.0	1.6
6 Apr 2010	Casannapass	−5.4	3.2	−1.7	0.8
23 Mar 2011	Sentisch Horn	−4.9	4.7	−2.1	0.8

located within the top 5 cm of the slab (typically one or two layers) were considered.

A semi-logarithmic plot was chosen to display the relative change of the effective modulus, which spanned over three orders of magnitude. Exponential fitting of the data confirmed a trend towards decreasing values of the effective modulus for increasing energy inputs. To reduce the effective modulus of the top most layer by about 50% an energy input of about 300 kJ m^{-2} was required. For a cumulative energy input larger than about 500 kJ m^{-2} stiffness decreased in all topmost layers (Fig. 3). Fig. 4 shows the lines of the exponential trends for the relative change of effective modulus observed in all slab layers. The observed reduction in stiffness decreased with layer depth and was not observed in layers located deeper than 20 cm below the surface. This observation agrees with measurements of the snow temperature with depth and confirms that warming of the snow mainly occurs in near-surface layers (e.g. Fierz, 2011). The stiffness in near-surface layers varied more than in deeper slab layers. This observation is reflected in higher root mean square errors (Table 3).

4.2. Specific fracture energy

The first PST measurement in pit number 1 (Fig. 2) was used as the reference for the measurements later conducted in this pit. The change of specific fracture energy with ongoing warming was related to this initial test. Fig. 5 contains the results of 168 PST experiments performed on the 9 field days in February/March 2010 and March 2011.

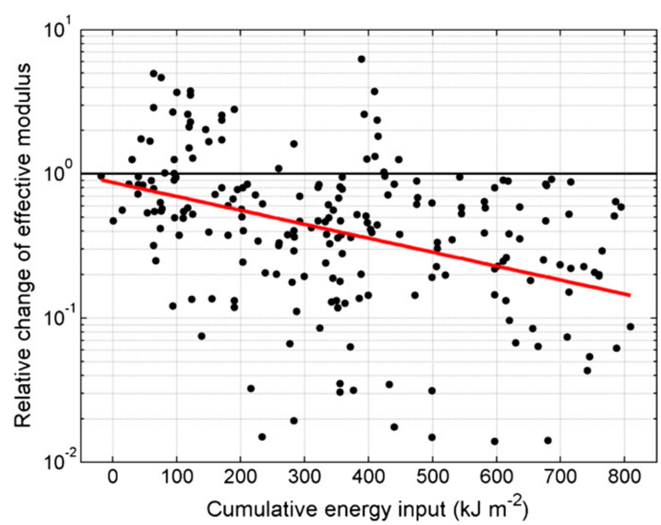

Fig. 3. Relative change of effective modulus (stiffness) vs. cumulative energy input for layers located within the top 5 cm of the slab with trend line ($N = 215$, $p \ll 10^{-4}$).

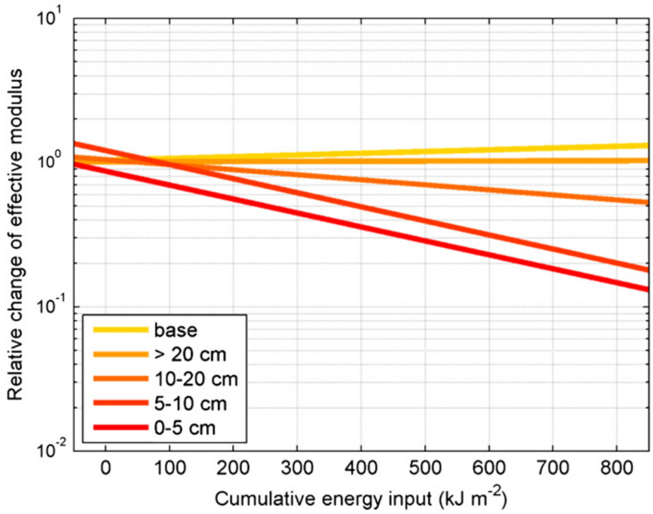

Fig. 4. Trend lines for the relative change of effective modulus in a given range of depth vs. cumulative energy input (see Table 3 for fit parameters).

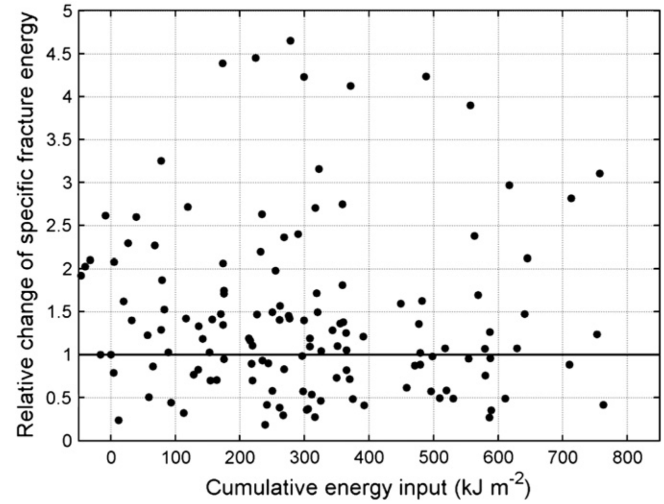

Fig. 5. Relative change of specific fracture energy vs. cumulative energy input at the snow surface ($N=140$, $p=0.8$; eight outliers (>5) not shown).

The critical energy release rate ranged from 0.4 to 2.2 J m^{-2} with a mean of 1.3 J m^{-2} (Table 4) (Schweizer et al., 2011). Linear regression analysis did not reveal any trend in the change of critical energy release rate with warming ($p=0.8$). The observation that the specific fracture energy did not significantly change with surface warming is in agreement with the snow temperature measurements that showed no prominent warming at the depth of the weak layer.

4.3. Cut length in PST experiments

The critical cut lengths recorded in the propagation saw tests in the course of a field day were compared to the first measurements in the morning. The relative change in cut length was then related to the energy input at the snow surface cumulated up to the time of measurement (Fig. 6). For cumulative energy inputs below about 400 kJ m^{-2} the change of critical cut length varied widely; positive and negative changes were observed. Above about 400 kJ m^{-2}, however, most cut lengths were shorter than the initial cut length (reference measurement). A linear regression yielded a high root mean square error of 0.42. Nevertheless, a statistically significant trend ($p=0.02$) was found towards shorter cut lengths in PST experiments under surface warming.

5. Discussion

We used the cumulative energy input to quantify surface warming and its consequences on mechanical properties. This approach does not take into account the initial slab temperature, though it is known that the mechanical properties are not a linear function of snow temperature (e.g. Schweizer and Camponovo, 2002). However,

Table 3
Fit parameters and statistics for trend lines for the relative change of effective modulus in a given range of depth and in the basal layer vs. cumulative energy input (Fig. 4). Exponential fit of the form e^{mx+k} with root mean square (RMS), p-value (p), number of layers (N) and outliers exceeding $E/E_0=10$.

Parameter	Depth of layers				
	0–5 cm	5–10 cm	10–20 cm	>20 cm	Base
m (10^{-3})	−2.2	−2.2	−0.8	0.002	0.02
k	−0.14	0.19	0.05	0.01	0.04
RMS	4.07	4.58	2.34	1.57	2.71
p	$\ll 10^{-4}$	$\ll 10^{-4}$	10^{-4}	0.9	0.3
N	215	218	317	395	194
$E/E_0>10$	4	7	6	1	6

as neither the layer temperatures nor the temperature dependence for the various snow types was known, estimating the energy change with depth for each single layer is not feasible and relating the energy input to changes in effective modulus seems the only practical approach.

The energy input derived from the energy surface fluxes are prone to errors – not least because turbulent fluxes were modeled based on a bulk approach and atmospheric stability assumptions. For each of the energy fluxes contributing to the energy input an uncertainty can be assigned. The error for the outgoing longwave radiation was estimated from the error of snow surface temperature measurement that was assumed to be 1 °C. For shortwave radiation fluxes and incoming longwave radiation the measurement error of the instrument was used. Uncertainties of turbulent fluxes were estimated from model runs with varying atmospheric stability assumptions. The overall uncertainty of the surface energy fluxes was about 12 W m^{-2}, yielding an uncertainty of the energy input per time step (15 min) of about 11 kJ m^{-2}. For a measurement series of 6 h the error of the energy input would then be 53 kJ m^{-2}. Although the energy input may seem to be quite uncertain, field days can be classified into days of low (<200 kJ m^{-2}), medium (200–500 kJ m^{-2}) and high energy input (>500 kJ m^{-2}) according to the maximum observed energy input presented in Table 4.

A reduction of the effective modulus in surface layers was observed for energy inputs exceeding about 400 kJ m^{-2}. Above this value also the majority of PST experiments showed shorter critical cut lengths. So, at least a day of medium energy input due to either insolation on a suitably inclined slope or positive adding of turbulent fluxes and radiative fluxes is required to have a notable effect on the critical cut length, or in other words, to promote instability.

We accepted the values of effective stiffness without any further fitting, as explained above. To quantify the reduction of stiffness in snow layers associated with warming, we considered relative changes of the effective modulus. The absolute values of the effective modulus have an effect on the values of the specific fracture energy of the weak layer, which we do not consider here, but were analyzed by Schweizer et al. (2011).

This study is the first to quantitatively measure the effect of surface warming. Measurements were performed on selected slopes on days when surface warming was anticipated to have an effect on stability. The results show decreasing values of slab stiffness and critical cut length with ongoing warming. Hence, we observed an increase in crack propagation propensity in snowpacks which supported crack propagation, i.e. in snowpacks that contained a potential weakness

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Table 4
Field days with compression test score (CT) including number of taps and fracture type (SC: sudden collapse, RP: resistant planar), meteorological conditions: maximum energy input at the snow surface (H), average depth of the weak layer (h_{WL}), and fracture test results: means of effective modulus of the slab (E) and of the reference measurement (E_0), both with standard deviation, number of PSTs performed (N), means of critical cut length (r_c) with standard deviation and means of specific fracture energy (w_f) with standard deviation.

Date	CT	H (kJ m^{-2})	h_{WL} (cm)	E (MPa)	E_0 (MPa)	N	r_c (cm)	w_f (J m^{-2})
8 Feb 2010	CT 14 SC	290	40	1.7 ± 1.7	2.6 ± 1.6	18	17 ± 5	0.4 ± 0.4
15 Feb 2010	CT 12 SC	270	27	3.2 ± 0.2	3.1 ± 0.3	15	26 ± 7	0.7 ± 0.4
16 Feb 2010	CT 15 -	130	46	2.0 ± 0.7	1.7 ± 0.3	18	24 ± 3	0.6 ± 0.3
25 Feb 2010	CT 13 SC	310	39	3.7 ± 2.7	4.9 ± 1.5	18	29 ± 4	1.7 ± 1.1
3 Mar 2010	CT 14 -	710	46	12.2 ± 5.7	17 ± 6.9	14	43 ± 7	2.2 ± 2.2
8 Mar 2010	CT 16 SC	660	46	4.1 ± 1.2	5.6 ± 1.6	18	36 ± 5	1.8 ± 1.0
12 Mar 2010	CT 19 SC	590	50	3.8 ± 1.3	4.2 ± 0.9	23	35 ± 3	2.1 ± 0.8
18 Mar 2010	CT 14 SC	740	37	2.7 ± 1.1	3.2 ± 1.1	24	27 ± 4	0.8 ± 0.3
6 Apr 2010	CT 13 RP	600	29	0.9 ± 0.7	0.6 ± 0.4	0	–	–
23 Mar 2011	CT 19 SC	430	41	0.9 ± 0.5	1.2 ± 0.6	20	18 ± 6	1.0 ± 0.7

as indicated by the CT score (Table 4). The results are hence not in contrast with former analyses of contributory factors, where it had turned out that warming played a subordinate role.

Wilson et al. (1999) found with FE modeling that a reduction in slab stiffness had an effect on the peak stress and strain in the weak layer. Therefore also fracture initiation should be considered for comprehensive stability assessment. However, this study did not take fracture initiation into account.

6. Conclusions

The energy input as a measure of surface warming – calculated from the partly measured and partly modeled surface energy flux – was related to stiffness observed in near-surface snow layers with 366 measurements and to the critical cut length found in 168 PST experiments.

A decreasing trend of slab stiffness derived from the SMP penetration force signal was observed with increasing cumulative energy input, i.e. in the course of daytime warming. On the other hand, the specific fracture energy of the weak layer did not show a trend despite ongoing surface warming. Eventually, the critical cut length in propagation saw test experiments tended to decrease with increasing energy input into the snowpack, though the effect was less pronounced than for the slab stiffness.

The critical cut length is an integral measure of the crack propagation propensity, i.e. it includes the interaction of slab and weak layer properties. We conclude that the reason for the decreased critical cut length, indicating increased crack propagation propensity, was increased bending of the slab layers, as we measured a reduction of stiffness, but did not observe a trend in the weak layer fracture energy on days with prominent surface warming.

However, observed changes in critical cut length were subtle. A pre-existing weakness and significant energy input are required that surface warming may promote instability.

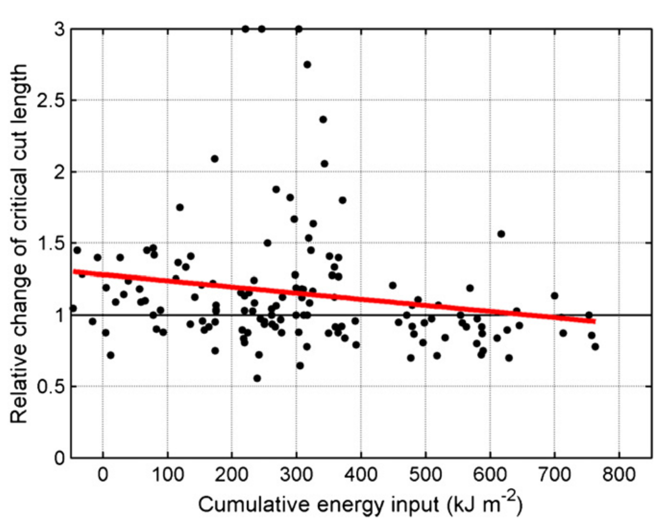

Fig. 6. Relative change of critical cut length with linear trend vs. cumulative energy input at the snow surface ($N = 140$, $p = 0.02$).

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References

Bakermans, L., Jamieson, B., 2009. SWarm: a simple regression model to estimate near-surface snowpack warming for back-country avalanche forecasting. Cold Regions Science and Technology 59 (2–3), 133–142.

Bartelt, P., Lehning, M., 2002. A physical SNOWPACK model for the Swiss avalanche warning; Part I: numerical model. Cold Regions Science and Technology 35 (3), 123–145.

Camponovo, C., Schweizer, J., 2001. Rheological measurements of the viscoelastic properties of snow. Annals of Glaciology 32, 44–50.

Exner, T., Jamieson, B., 2008. The effect of snowpack warming on the stress bulb below a skier. In: Campbell, C., Conger, S., Haegeli, P. (Eds.), Proceedings ISSW 2008, International Snow Science Workshop, Whistler, Canada, 21–27 September 2008, pp. 415–420.

Fierz, C., 2011. Temperature profile of snowpack. In: Singh, V.P., Singh, P., Haritashya, U.K. (Eds.), Encyclopedia of Snow, Ice and Glaciers. : Encyclopedia of Earth Sciences Series. Springer, Netherlands, pp. 1151–1154.

Gauthier, D., Jamieson, B., 2008a. Evaluation of a prototype field test for fracture and failure propagation propensity in weak snowpack layers. Cold Regions Science and Technology 51 (2–3), 87–97.

Gauthier, D., Jamieson, B., 2008b. Fracture propagation propensity in relation to snow slab avalanche release: validating the propagation saw test. Geophysical Research Letters 35 (13), L13501.

Harvey, S., Signorell, C., Genswein, M., 2002. Avalanche incidents in backcountry terrain of the Swiss Alps: new investigations with a 30 years database. In: Stevens, J.R. (Ed.), Proceedings ISSW 2002. International Snow Science Workshop, Penticton BC, Canada, 29 September–4 October 2002: International Snow Science Workshop Canada Inc., BC Ministry of Transportation, Snow Avalanche Programs, Victoria BC, Canada, pp. 449–455.

Jamieson, J.B., 1999. The compression test—after 25 years. The Avalanche Review 18 (1), 10–12.

King, J.C., Pomeroy, J.W., Gray, D.M., Fierz, C., Föhn, P.M.B., Harding, R.J., Jordan, R.E., Martin, E., Plüss, C., 2008. Snow–atmosphere energy and mass balance. In: Armstrong, R.L., Brun, E. (Eds.), Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling. Cambridge University Press, Cambridge, UK, pp. 70–124.

Kronholm, K., Schneebeli, M., Schweizer, J., 2004. Spatial variability of micropenetration resistance in snow layers on a small slope. Annals of Glaciology 38, 202–208.

Landl, B.M., 2007. Investigation of small scale characteristics of the energy ealance over snow covered Alpine terrain. Swiss Federal Institute of Technology Zurich, Zurich, Switzerland. 103 pp.

Marshall, H.-P., Johnson, J.B., 2009. Accurate inversion of high-resolution snow penetrometer signals for microstructural and micromechanical properties. Journal of Geophysical Research 114 (F4), F04016.

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McClung, D.M., 1996. Effects of temperature on fracture in dry slab avalanche release. Journal of Geophysical Research 101 (B10), 21907–21920.
McClung, D.M., Schaerer, P., 2006. The Avalanche Handbook. The Mountaineers Books, Seattle WA, USA. 342 pp.
McClung, D.M., Schweizer, J., 1999. Skier triggering, snow temperatures and the stability index for dry slab avalanche initiation. Journal of Glaciology 45 (150), 190–200.
Perla, R., 1970. On contributory factors in avalanche hazard evaluation. Canadian Geotechnical Journal 7, 414–419.
Schneebeli, M., Johnson, J.B., 1998. A constant-speed penetrometer for high-resolution snow stratigraphy. Annals of Glaciology 26, 107–111.
Schweizer, J., 1993. The influence of the layered character of snow cover on the triggering of slab avalanches. Annals of Glaciology 18, 193–198.
Schweizer, J., 1998. Laboratory experiments on shear failure of snow. Annals of Glaciology 26, 97–102.
Schweizer, J., Camponovo, C., 2001. The skier's zone of influence in triggering slab avalanches. Annals of Glaciology 32, 314–320.
Schweizer, J., Camponovo, C., 2002. The temperature dependence of the effective elastic shear modulus of snow. Cold Regions Science and Technology 35 (1), 55–64.
Schweizer, J., Föhn, P.M.B., 1996. Avalanche forecasting—an expert system approach. Journal of Glaciology 42 (141), 318–332.
Schweizer, J., Jamieson, J.B., Schneebeli, M., 2003. Snow avalanche formation. Reviews of Geophysics 41 (4), 1016, http://dx.doi.org/10.1029/2002RG000123.
Schweizer, J., van Herwijnen, A., Reuter, B., 2011. Measurements of weak layer fracture energy. Cold Regions Science and Technology 69 (2–3), 139–144.
Shapiro, L.H., Johnson, J.B., Sturm, M., Blaisdell, G.L., 1997. Snow Mechanics—Review of the State of Knowledge and Applications. Report 97–3 US Army CRREL, Hanover, NH, USA.
Sigrist, C., Schweizer, J., 2007. Critical energy release rates of weak snowpack layers determined in field experiments. Geophysical Research Letters 34 (3), L03502, http://dx.doi.org/10.1029/2006GL028576.
Simenhois, R., Birkeland, K.W., 2008. Extended column test results during surface warming: does surface warming affect fracture propagation potential? In: Campbell, C., Conger, S., Haegeli, P. (Eds.), Proceedings ISSW 2008, International Snow Science Workshop, Whistler, Canada, 21–27 September 2008, pp. 26–35.
Stössel, F., Guala, M., Fierz, C., Manes, C., Lehning, M., 2010. Micrometeorological and morphological observations of surface hoar dynamics on a mountain snow cover. Water Resources Research 46, W04511, http://dx.doi.org/10.1029/2009WR008198.
van Herwijnen, A., Heierli, J., 2010. A field method for measuring slab stiffness and weak layer fracture energy. International Snow Science Workshop ISSW, Lake Tahoe CA, U.S.A., 17–22 October 2010, pp. 232–237.
Wilson, A., Schweizer, J., Johnston, C.D., Jamieson, J.B., 1999. Effects of surface warming of a dry snowpack. Cold Regions Science and Technology 30 (1–3), 59–65.

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