SNOWPACK PROPERTIES OF UNSTABLE WET SNOW SLOPES: OBSERVATIONS FROM THE SWISS ALPS

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ABSTRACT: Next to meteorological parameters, snowpack properties play a major role in the formation of wet snow avalanches. We investigated profiles observed at wet snow avalanche fracture lines (winter 1992-2009, 20 profiles) and in slopes where signs of instability like cracking or collapsing were noted at the time of observation (2006-2010, 16 profiles). Furthermore, we investigated snowpack properties in southerly aspect start zones before, during and after wet snow avalanche cycles at the regional scale (2002-2010, 156 profiles). Investigated parameters include grain shape and size, hand hardness and wetness of the failure plane, the slab layer and the bed surface. The failure plane of wet snow avalanches was generally at the interface or within a moist, very soft layer consisting of a mix of melt-freeze, faceted or depth hoar grains. The slab tended to be fully moist, soft and was already transformed to melt-freeze grains for the most part. Typically, in unstable slopes the Rutschblock (RB) score was very low (median score 2) and failed within or at the interface to a soft or very soft layer consisting of moist, coarse facet or depth hoar grains. The comparison of snowpack properties before and during wet snow avalanche cycles showed that significant differences exist in snow temperature, the proportion of the snowpack which is wet and in the wetness of the snowpack. To assess the potential of avalanche failure deep in the snowpack, it is important to determine if soft layers containing coarse, facet or depth hoar grains are present.

KEYWORDS: Wet snow, snow stability, fracture line profiles, snowpack properties

1. INTRODUCTION

Wet snow avalanches are a major concern for infrastructure, ski areas and back-country skiers in the Swiss Alps and other alpine regions, particularly in spring. Avalanche forecasters consider the onset of wet snow avalanching and the failure of instabilities deep within the snowpack difficult to forecast (Techel and Pielmeier, 2009). If direct stability information (like avalanche observations) is not available, the assessment of wet snow stability is often based more on meteorological parameters than on snowpack information. However, meteorological information by itself is insufficient to predict the timing and size of avalanching (Armstrong, 1976; Trautmann, 2008). Also, snowpack structure plays a role in the type, formation and size of wet snow avalanches (Baggi and Schweizer, 2009).

One reason for the relatively limited use of snowpack information for wet avalanche forecasting is the fact that only little snowpack information is available without observing snow profiles. However, digging a snow-pit is time-consuming and represents only a point-observation. Additionally, with snowpack properties changing rapidly once water enters the snowpack, any observation must

be temporally and spatially interpreted. A recent survey showed that many avalanche forecasters consider snow stability tests in wet snow conditions of limited use (Techel and Pielmeier, 2009).

Snowpack characteristics during wet snow avalanche activity have been described in several case studies (e.g. Armstrong 1976; Reardon and Lundy 2005; TNZ, 2005). Romig et al. (2005) compared meteorological parameters as well as information on snow depth and new snow to wet snow avlanche activity. Baggi and Schweizer (2009) statistically explored these, but also snowpack parameters in regard to wet snow avalanche activity. In these studies, often cited critical snowpack parameters are: the presence of weak basal layers consisting of facets or depth hoar, capillary barriers or new snow, but also when snowpack temperatures become isothermal and large proportions of the snowpack are wet.

In this study, we focus on the exploration of snowpack characteristics of unstable wet snow slopes (as fracture line profiles). In addition, we compare snowpack properties in southerly aspect start zones prior, during and after wet snow avalanche cycles in similar slopes and aspects in the canton of Grisons. Baggi and Schweizer (2009), who focused on the catchment scale (Dischma valley, NE aspect) explored meteorological information and snowpack observations based on fortnightly profiles. Our study differs to that study as we specifically investigate snowpack observation only and compare these to avalanche occurrences

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(of the same corresponding time). Further, we investigate data on the regional scale, although in a similar climatic region.

2. DATA

2.1. Avalanche data

In Switzerland, the liquid water content of avalanches is recorded as dry, mixed or wet (SLF, 2008). These estimations are based on the observation of the avalanche debris. This procedure differs from the international standard (UNESCO, 1981), which defines a wet avalanche as one where liquid water is present throughout the avalanching layer in the start zone. If this is not the case, avalanches would be classified as dry or mixed.

In this study, where we investigate avalanche fracture line profiles, we define a *wet* avalanche as one where the failure plane is not dry (which is similar to UNESCO, 1981). Since most wet avalanches are observed from below, we cannot be certain about the liquid water content in the start zone. Therefore, we make the assumption that an avalanche recorded as wet was indeed one, where the failure plane was wet in the start zone.

The avalanche recordings of the Swiss observation network are stored in a data-base. Often several avalanches from different aspects and elevations, of different type and size are recorded in one observation form. This facilitates the data entry and thus increases the number of returned observation forms. However, valuable information on elevation- or aspect-specific avalanche characteristics is lost. Thus, the data-base does not allow to derive the exact number of avalanches from a certain aspect or elevation.

Avalanche observations classified as *mixed* avalanches may either have released as a dry avalanche and entrained wet snow on the descent or they may be avalanches with low liquid water content in the start zone. If several avalanches with different wetness were recorded, they are classified as *dry/wet*. This might indicate a combination of dry and wet avalanches from different aspects and elevations or *mixed* avalanches as described before. All these *mixed* and *dry/wet* avalanche recordings will hereafter be treated as 'mixed' avalanches. Due to these limitations, we are mindful on the interpretation of these '*mixed*' avalanches.

Avalanche activity is explored for the spring season (February - May) for two regions in the eastern Swiss Alps: Davos and surrounding area (years 2002-2005, 2009-2010) and the region Southern Grisons (2002-2005, 2009, see colored regions in Fig. 1). Avalanche observations are included in the analysis when the avalanches were classified as 'mixed' or wet and when at least one avalanche failed in a southerly aspect start zone (SE-S-SW). Avalanche activity is described using the avalanche activity index (AAI, Schweizer et al., 2003), which is determined by the number and size of avalanches.

Avalanche activity (AAI≥1) was observed on average on 19 days each spring with a total of more than 5000 mixed and wet snow avalanches recorded. High activity of 'mixed' and wet snow avalanches (AAI≥10) was observed on average on 7 days each spring. Most often, the peak of wet snow avalanche activity in southerly aspect slopes occurred in the second half of March or early April.
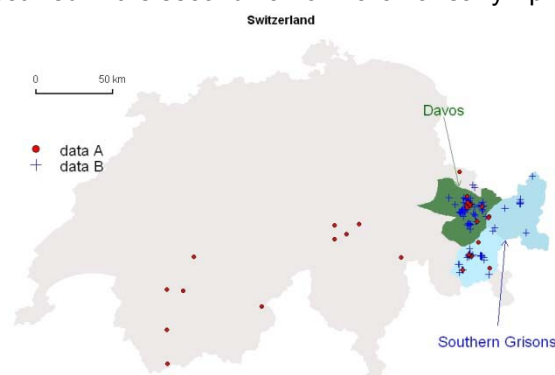

Fig. 1: Profile locations shown on a map of Switzerland: data A (red circles): profiles observed at wet snow avalanche fracture lines or in unstable slopes, data B (blue crosses): slope profiles in southerly aspect start zones for the two regions Davos (green) and Southern Grisons (Südbünden, light blue).

2.2. Snow profile data

The Swiss snow profile data-base was searched for
- unstable wet snow profiles (Data A, n=36, section 3.1) and
- snow profiles observed in southerly aspect start zones during spring (Data B, n=156, section 3.2)

The first group includes profiles from the whole Swiss Alps, although most were observed in southerly aspect start zones (53%) and in the above-mentioned two regions Davos and Southern Grison (77%). The second group includes only profiles observed in either the Davos or the Southern Grisons region during the months February to May in southerly aspect start zones at elevations of 2000 to 3000 m a.s.l. (Fig. 1).

3.   METHODS

3.1.   Definition of unstable profiles (Data A)

For this analysis, profiles are classified as *unstable* when at least one of the following criteria was fulfilled:

- *Signs of instability*, like triggering of avalanches, collapsing of snowpack (Fig. 2), whoompf-sounds or crack formation, were observed in the same slope as the profile and at the time of profile observation (n=16) and the failure plane of a Rutschblock (RB) test had to be at least moist.
- The profile was observed at a *wet snow avalanche fracture line*, where the failure occurred within the snowpack and where the failure plane was at least moist (n=20).

Fig. 2: Collapse-type failures were repeatedly observed in slopes, where soft, moist layers consisting of facets or depth hoar were present. As in dry snow, we consider such snowpack collapses as a sign of instability in wet snow.

3.2.   Evolution of snowpack properties in relation to avalanche activity (Data B)

Snow profiles observed between 2002 and 2010 (n=156) are classified in relation to regional wet snow avalanche activity in similar slopes and aspects into four groups (see also Fig. 3). For this, the main wet snow avalanche cycle is qualitatively defined for each spring. In very few cases, a second peak occurred, although this often included also northerly aspects (Fig. 3). In these cases, the peak with the higher AAI is used.

- *wet*: days when AAI≥1 for wet avalanches (n=22)
- *'mixed'*: days when AAI≥1 for mixed avalanches (n=20), 80% of these '*mixed*' situations were observed before the peak of wet snow avalanche activity
- *before*: prior to wet snow avalanche activity peak (n=106), AAI<1
- *after*: after peak of wet snow avalanche activity (n=8), AAI<1

Days when both, wet and 'mixed' avalanches were recorded were classified as wet. The profiles in each group were observed in similar aspects and elevations.
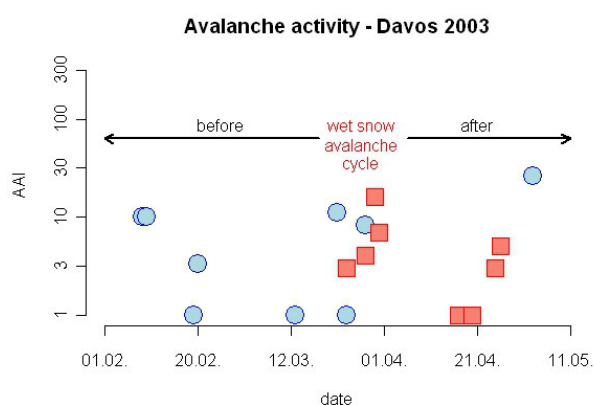

Fig. 3: Description of snowpack situation in regard to wet snow avalanche activity (avalanche activity index, AAI). For each spring, the main wet snow avalanche cycle is qualitatively defined. Profiles were grouped: first - according to avalanche activity observed on the same day and secondly in temporal relation to the wet snow avalanche cycle (before or after). An example is shown for one spring only.

3.3.   Investigated variables and statistical methods

Investigated variables include snowpack parameters observed in manual snow profiles (Tab. 1; SLF, 2008). Weighted means are calculated for the wetness, hardness and grain size of the *slab*, incorporating all layers above the failure plane, and for the full snow profile (*snpk*). These calculations are based on the respective index values given in the standard observational guidelines (e.g. SLF, 2008, Fierz et al., 2009). The only exception was the wetness of ice-layers (index 8). For these, we used a wetness-index of 1. The failure plane (*fail.plane*) is either: (1) the avalanche failure plane or (2) the RB failure plane. Failure plane properties are described by snow properties immediately above and below the failure interface.

Grain shape is considered by calculating a grain shape index expressing the metamorphic state of the snowpack (Tab. 2). For this index, the

Tab. 1: Investigated parameters for three parts of the snowpack (*snpk* - full snowpack, *slab* - layers which are above the failure plane (*fail.plane*) of an avalanche or Rutschblock). Calculated are the weighted mean (*mean*) or the actual value for the fail.plane (*x*). Flags are assigned for the presence of a dry or wet weak layer.

variable	snpk	slab	fail.plane
snow temperature (ts)	mean		
wetness (*W*)	mean	mean	x
hardness (hand test, *H*)	mean	mean	x
ram hardness (*R*)	mean		
grain shape (Tab. 2)	mean	mean	x
grain size (*size*)	mean	mean	x
wet proportion of snowpack (*W.prop*)	%		
dry weak layer (dry.*wL*: $H \leq 1.5$, $W = 1$, FC.index≥ 0.7)	yes/no		yes/no
wet weak layer (*wet.wL*: $H \leq 1.5$, FC.index≥ 0.3, $W \geq 1.5$)	yes/no		yes/no

Tab. 2: Grain shape according to observational guidelines (Fierz et.al., 2009) and classification in one of three grain shape groups. Indices were calculated for each group (FC → FC.index, PP/RG.index, MF.index, see section 3.3 for details).

Grain shape	Grain shape group	Groups
FCxr, DH, SH, FC	'faceted' forms	FC
PP, DF, RG	precipitation and round particles	PP/RG
WG, MF, ICil	melt-freeze forms	MF

observed primary and secondary grain shape of each layer are assigned with weights of 0.7 and 0.3, respectively. Then the sum is calculated for each layer and the weighted mean is calculated for the *snpk* and the *slab*. As an example: if a layer consists of FC(DH) this results in a *FC.index* of 1, while a layer consisting of MF(RG) has a *MF.index* of 0.7 and *PP/RG.index* of 0.3. An *MF.index* of 1 for a full profile indicates a profile which has completely transformed to melt-freeze-forms.

The role of very soft, FC-layers is explored by combining information on hardness (H<4F), wetness and grain shape of these layers resulting in a dry and a wet 'weak' layer index (*dry.wL*, *wet.wL*, definition see Tab. 1).

RB failure planes are considered relevant if the failure occurred: (1) not immediately below the surface melt-freeze crust or (2) at least 15 cm below the snow surface. If a test failed at several depths, the weakest score and the best release type/fracture potential were considered for further analysis.

Variables were compared using the Mann Whitney U-test or Fisher Exact test for count data (Ross, 2006; Agresti, 2007). The level of significance was $\alpha \leq 0.05$.

4. RESULTS

4.1. *Unstable snow profiles*

The data-set of unstable profiles (data A) was observed mostly above tree line (median elevation 2370 m) in steep slopes (median slope angle 33°).

Typically, avalanches failed within or at the upper interface to moist layers, where the failure layer was very soft and composed of a mix of coarse-grained MF and FC (43%). The failure often occurred in the lower half of the snowpack (65%). The slab overlying the failure plane was moist or wet, relatively soft and consisted of coarse MF-forms, although precipitation and round particles were also observed (Tab. 3).

Typical for all unstable profiles were a 0°C-isothermal snowpack and that large parts of the snowpack were moist or wet. Often the upper part of the snowpack had undergone considerable wet snow metamorphism, consequently melt-freeze forms dominated. The most frequent profile type was profile type 1 (26%, according to the profile classification by Schweizer and Wiesinger, 2001), while 63% of the profiles had a weak base (profile type 1-5).

In slopes, where signs of instability were observed, moist, soft coarse-grained facet and depth hoar layers were present in 80% of the profiles. Layers with these properties were often the failure layer or

Tab. 3: Characteristics of the snowpack (snpk), all layers above the failure plane (slab), the layers immediately above and below the failure plane (failure plane of an avalanche or as detected with the Rutschblock test) of unstable snow profiles (Data A). Median values or the most frequent observation is shown. HS – snow depth; ts – snow temperature; wetness (W): m-moist, w-wet; hardness (H): F-fist, 4F-four finger (all according to standard observational guidelines, e.g. Fierz et.al., 2009), grain shape: see Tab. 2.

parameter	snpk	slab	above failure plane	below failure plane
thickness [cm]	108	55		
t_s [°C]	0.0			
W	m-w	m-w	m	m
H	F-4F	4F	4F	F
shape	MF(FC)	MF	MF(FC)	MF(FC)
size [mm]	1-2	1-1.5	1-1.5	1-2.5

interface of RB failures (69%). In these slopes, the RB score was low (median RB score 2, Tab. 3). Collapse-type RB-failures were noted.

Unstable profiles also include several cases where new snow fell onto an isothermal wet snowpack, both in spring and in winter. In all these cases, the snowpack base was weak, moist and consisted of facets and depth hoar grains.

4.2. *Evolution of snowpack characteristics in relation to wet snow avalanche activity*

Before the onset of wet snow avalanche activity in southerly aspect start zones (*before*), the snowpack is generally cold and dry (Fig. 4a-c). The snowpack structure varies depending on the winter's meteorological conditions: isolated melt-freeze crusts may be present in the snowpack, which consists mostly of facets and depth hoar layers (Fig. 5a-c). Dry, weak layers (*dry.wL*) exist in the vast majority of the profiles (76%, Fig. 5d).

Wet snow avalanche days typically occur when the snowpack temperature is 0°C-isothermal and mostly wet (wet proportion more than 75%). At the same time, facet and depth hoar layers are still present in the lower part of the snowpack. Dry or wet weak layers are observed (~40%, Fig. 4, Fig. 5d). W, $W.prop$ and t_s, but also the grain shape

indices differ significantly between days when no avalanche were observed (*before*) and *wet* avalanche days (Tab. 4). Neither ram hardness nor the RB test (score and release type) differ significantly between the *before* and *wet* groups.

The few profiles (n=8) observed after the large spring wet snow avalanche cycle consist almost entirely of MF-forms, wet or frozen. The snowpack can be characterized by the absence of dry weak layers (dry.wL, Fig. 5d), although wet weak layers (*wet.wL*) are still observed (facets or depth hoar as secondary grain shape; Fig. 4, Fig. 5). None of the other parameters deviate significantly between the groups *wet* and *after*.

The particular case of *the 'mixed'* group (see section 2.1 for details), which was mostly observed prior the wet snow avalanche activity, coincides with snowpack warming (where at least the snow surface is 0°C) and subsequent infiltration of liquid water. At this stage, both dry and wet very soft FC-layers are present (*dry.wL 65%, wet.wL* 20%, Fig. 5). Recorded snow temperature (t_s), the wetness (W) and the proportion of the snowpack which has been wetted (*W.prop*) is significantly higher on *'mixed'* avalanche days than on days with no activity (group *before*, Tab. 4) and lower than on days with *wet* snow avalanches.
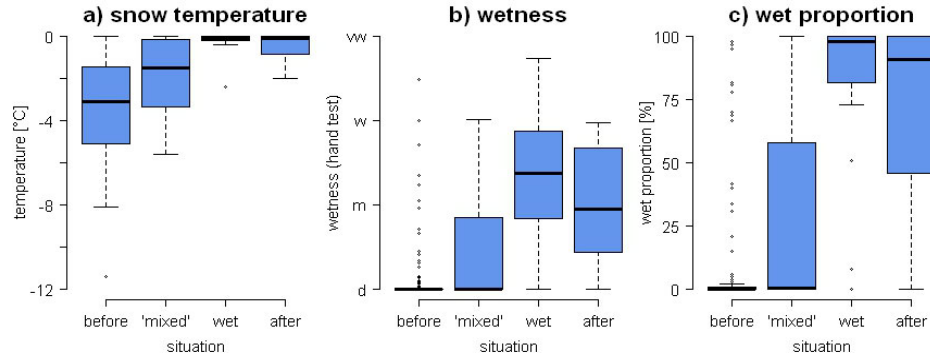

Fig. 4: Evolution of mean snow temperature (a), mean wetness (hand test, b) and proportion of snowpack which was not dry (c) correlated to snowpack situation. Snowpack situation as defined in section 3.2.
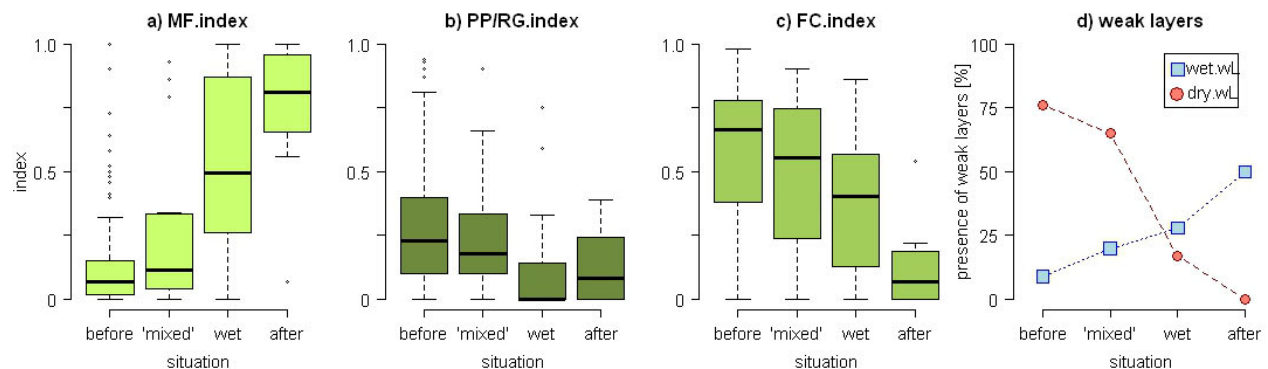

Fig. 5: Evolution of grain shape (a-c) and presence of weak layers (d) observed in the snowpack, expressed as index-variables in correlation to the situation of the snowpack (index variables defined in section 3.3, Tab. 1, Tab. 2).

Tab. 4: Significant differences (∆) in snowpack properties between different snowpack situations (section 3.2) (Tab. 1, Fig. 4, Fig. 5). p-values: p≤0.001: ***, p≤0.01: **, p≤0.05: *, p≤0.1: (*), not significant p>0.05: - (Mann-Whitney test, Fisher-test)

Variable	$\Delta_{before/'mixed'}$	$\Delta_{before/wet}$	$\Delta_{wet/after}$
snow temp. (t_s)	**	***	-
wetness (W)	*	***	-
hand hardness (H)	-	*	-
ram hardness (R)	-	-	-
wet proportion	*	***	-
MF.index	-	***	-
PP/RG.index	-	***	-
FC.index	-	***	(*)
dry.wL	-	**	*
wet.wL	***	***	***
RB score	-	-	-
RB release type	-	-	-

5. DISCUSSION

5.1. Avalanche fracture line profiles

Relatively few profiles at wet snow avalanche fracture lines were available (n = 20), despite exploring a large data-base and going back 18 years. It seems that observers are biased to the observation of avalanche fracture lines where the failure occurred 'deep' within the snowpack. This is not too surprising, as these large avalanches may be a threat to roads and villages and may therefore be of prime interest. However, there are many different types of wet snow avalanches (loose, slab, glide) and avalanches may occur before the failure plane is wet. Thus, the presented avalanche data-set must be regarded as one which describes only the failure of 'deep', wet instabilities.

5.2. Unstable snowpack criteria

Although the data-set is relatively small and unbalanced between the number of profiles in each snowpack situation (Data B), the results provide some indication of the snowpack parameters to observe when assessing wet snow stability.

Snowpack properties observed in slopes considered rather unstable are (Data A, Tab. 3):

- presence of moist or wet, very soft layers consisting of coarse-grained facets or depth hoar
- a RB score ≤ 3
- new snow on a snowpack with a very soft, moist snowpack base consisting of facets and depth hoar
- an isothermal snowpack where a large proportion of the snowpack is wet.

The presence of very soft, coarse grained facet or depth hoar layers has been observed in many of the unstable failure planes (Data A, Tab. 3). At the regional scale (Data B), the presence of moist or wet, very soft layers consisting of coarse-grained facets or depth hoar is a suitable discriminator between periods with high wet snow avalanche activity and those without (group before, Tab. 4). However, as the snowpack almost always contains such layers prior to wetting (Data B, Fig. 5d) and in some cases even after the main avalanche cycle, the presence of these layers is a poor, sole criterion for the assessment of snow stability undergoing wetting. This supports previous results (Baggi and Schweizer, 2009) that the presence of basal weak layers is not a significant snowpack indicator.

The RB score tended to be very low in slopes where signs of instability were observed. Often a collapse-type failure occurred in very soft, moist facet and depth hoar layers. Thus, if a RB is performed and the score is 3 or less, we propose this as an indicator of instability. On the other hand, we want to emphasize that high RB scores may not necessarily indicate stable snowpack conditions, particularly in wet snow. In the majority of cases (67%), the RB score was 4 or higher on days when wet snow avalanches were observed.

The comparison between profiles before and during the spring wet snow avalanche cycle indicated that in particular snowpack temperature and the proportion of the snow which is wet, might be suitable indicators of wet snow stability at the regional scale. This was also shown on the catchment scale (Baggi and Schweizer, 2009).

The number of profile observations after the major spring wet snow avalanche cycle is very limited. It is of note, that hardly any of the snowpack parameters differed significantly between observations on days with wet snow avalanche activity and those without (group after). Still, the observed snowpack properties are similar to observations from maritime climates, where a well-drained snowpack consisting entirely of melt-freeze grains can be considered as relatively stable (Conway et al., 1988).

These results may help to assess wet snow stability for the transitional and inner-Alpine climate of the Swiss Alps. However, we caution that our study does not allow the contraposition if the above-mentioned parameters are not fulfilled. Also, these results will likely not be applicable to surficial avalanche activity or full-depth glide avalanches.

6. CONCLUSION

Based on a wet snow avalanche and snow-profile data-set from the Swiss Alps, we found snowpack parameters correlating to unstable wet snow conditions at the slope and regional scale. These are: snow temperature, the proportion of the snowpack which is wet and the presence of moist and very soft layers containing facets and depth hoar.

Further research should focus on expanding the data-set with data from other snow-climatic regions. The combination of snowpack and meteorological variables would facilitate the establishment of expert rules to assess wet snow stability. The exploration of this data-set has shown the strong emphasis on dry snow observations resulting in relatively limited snowpack data observed in wet snow conditions in Switzerland. The current way of recording avalanches in Switzerland could be improved to facilitate research.

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