Avalanche danger level characteristics from field observations of snow instability

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Abstract. Avalanche danger levels are described in qualitative terms that mostly are not amenable to measurements or observations. However, estimating and improving forecast consistency and accuracy requires descriptors that can be observed
10 or measured. Therefore, we aim to characterize the avalanche danger levels based on expert field observations of snow instability. We analyzed 589 field observations by experienced researchers and forecasters recorded mostly in the region of Davos (Switzerland) during 18 winter seasons (2001-2002 to 2018-2019). The data include a snow profile with a stability test (rutschblock, RB) and observations on snow surface quality, drifting snow, signs of instability and avalanche activity. In addition, observers provided their estimate of the local avalanche danger level. A snow stability class (*very poor*, *poor*, *fair*,
15 *good*, *very good*) was assigned to each profile based on RB score, RB release type and snowpack characteristics. First, we describe some of the key snowpack characteristics of the data set. In most cases, the failure layer included persistent grain types, even after a recent snowfall. We then related snow instability data to the local avalanche danger level. For the danger levels *1–Low* to *4–High*, we derived typical stability distributions. The proportions of profiles rated *poor* and *very poor* clearly increased with increasing danger level. For our data set, the proportions were 5 %, 13 %, 49 % and 63 % for the danger levels
20 *1–Low* to *4–High*, respectively. Furthermore, we related the local avalanche danger level to the occurrence of signs of instability such as whumpfs, shooting cracks and recent avalanches. The absence of signs of instability was most closely related to *1–Low*, the presence to *3–Considerable.* Adding the snow stability class and the 3-day sum of new snow depth improved the discrimination between the lower three danger levels. Still, *2–Moderate* was not well described. Nevertheless, we propose some typical situations that approximately characterize each of the danger levels. Obviously, there is no single easily
25 observable set of parameters that would allow fully characterizing the avalanche danger levels. One reason for this shortcoming is the fact that the snow instability data we analyzed usually lack information on spatial frequency, which is needed to reliably assess the danger level.

1   Introduction

Snow avalanches in populated snow-covered mountain regions may at times threaten people and infrastructure. To mitigate the effects of avalanches, among other things, warnings are issued by avalanche forecasting services that inform the public about when and where the danger is most imminent. The danger is described with the help of a danger scale including five levels: *1–Low, 2–Moderate, 3–Considerable, 4–High* and *5–Very High* (or Extreme) (e.g., EAWS, 2019; Statham et al., 2018). The danger levels were originally characterized by the avalanche release probability (which increases if stability decreases), the spatial distribution of snow instability and the avalanche size (Meister, 1995). These three components are supposed to increase with increasing avalanche danger (level). Forecasts are issued for areas typically larger than 100 km², i.e. they do not refer to single slopes. Hence, the danger level describes the probability of natural or skier-triggered avalanches and the possible extent of avalanches in a particular region (Föhn, 1994; Meister, 1995).

However, the avalanche danger that exists in an area cannot be measured – at best, it can be estimated (Föhn and Schweizer, 1995; Giraud et al., 1987). Even in hindsight indicators of the past danger may be lacking, such as released avalanches. Nevertheless, avalanche activity, or indices describing it, were used to verify the forecast (Giraud et al., 1987). However, as several verification studies pointed out, this approach is not feasible for the danger levels *1–Low, 2–Moderate* and *3–Considerable* (e.g., Föhn and Schweizer, 1995). Schweizer et al. (2003) therefore used point snow instability data instead and characterized the lower three danger levels by stability distributions. On the other hand, the higher two danger levels are clearly characterized by numerous natural avalanches (e.g., Schweizer et al., 2020).

Alternatively, estimates of local avalanche danger (local nowcasts) by experienced experts can be used to assess the accuracy of regional forecasts (e.g., Harvey et al., 1998; Jamieson et al., 2009; Techel and Schweizer, 2017). These local nowcasts are typically based on observations recorded during a day travelling in the backcountry. Among the most indicative observations to assess snow instability and hence the local danger are signs of instability such as whumpf sounds, shooting cracks and recent avalanching as well as snow stratigraphy observations and snow instability tests (e.g., Schweizer and Jamieson, 2010).

However, there is no specific set of observations that unequivocally relates local observations to one of the lower three danger levels. Simple field observations help to downscale from a regional to a local danger level (Jamieson et al., 2009). Their classification tree analysis suggests that on a particular day with regional forecast *3–Considerable* and at least one sign of instability observed, either recent slab avalanching, shooting cracks or whumpfs, the local danger estimate was in fact *3–Considerable* – otherwise it was *2–Moderate*. A similar study by Bakermans et al. (2010) using snowpack observations revealed the usefulness of the avalanche bulletin. Stability test variables were correlated with the local danger level estimate, yet the strongest correlation they found was still between the regional forecast and the local danger estimate. Schweizer (2010) preliminarily analyzed whether the danger level could be inferred from signs of instability. Shooting cracks were mostly associated with the danger level *3–Considerable*, whereas in the absence of any signs of instability the danger level was lower,

whether *2–Moderate* or *1–Low*, remained unclear. Two more recent studies tried to quantify the danger levels based on stability
test data and observed avalanche activity. Techel et al. (2020) related snowpack stability, the frequency distribution of
snowpack stability and avalanche size to the avalanche danger levels *1–Low* to *4–High*. The best predictor was the frequency
of profiles rated as very poor, followed by the maximum avalanche size. Avalanche activity and avalanche size were related
to the danger levels by Schweizer et al. (2020). With increasing danger level, avalanche activity strongly increased, while
avalanche size did not generally increase, in particular not at the lower danger levels (*1–Low* to *3–Considerable*). Only at
danger levels *4–High* and *5–Very High*, the proportion of large and very large avalanches clearly increased.

While avalanche danger is obviously best described in terms of snow stability, the frequency distribution of snow
stability and avalanche size (Techel et al., 2020), comprehensive measurements of this set of quantities are virtually inexistent.
Instead proxies are used such as signs of instability to assess the avalanche danger – though it is presently unclear how useful
these proxies are. Hence, the aim of the present study is to further foster the quantitative description of the avalanche danger
levels, by characterizing the danger levels based on proxies, namely field observations of snow instability. To this end, we
analyze a data set of 589 snow profiles with a snow instability test (rutschblock) and additional information. These data include
observations on signs of instability and an estimate of avalanche danger (local nowcast) for the date and area of the profile.

2   Data and methods

We analyzed a data set of 589 snow profiles that were almost exclusively (95 %) observed in the region of Davos (Eastern
Swiss Alps) during the winter seasons of 2001-2002 to 2018-2019 (18 winters). As of winter 2001-2002 observers were asked
to complement snow profile records with field observations to support their interpretation in operational forecasting. These
observations include specific, additional information related to the snow profile, namely (1) profile site, (2) snow cover
characteristics, (3) stability test results, as well as other relevant observations made while travelling the backcountry, on (4)
snow surface properties, (5) drifting snow, (6) whumpfs and shooting cracks, and (7) recent avalanche activity; these
observations are completed with (8) an estimate of the local avalanche danger (local nowcast, LN). Two observation examples
are shown in Table 1.

We selected 589 profiles from SLF's snow profile database based on whether (a) all text fields had complete information
(Tab. 1), (b) an experienced observer had done the pit and (c) snow conditions were dry. We considered information to be
complete if, for instance, in the category "signs of instability and recent avalanching" not only the presence but also the absence
of these observations was explicitly stated.

All profiles were recorded on slopes. The most frequent aspect was north; almost 60 % of all profiles were observed in
slopes facing northwest, north or northeast. Slope angle varied between 14 and 43°; 75 % of the profile slopes were steeper
than 30°, with a median of 33°. Median elevation was 2470 m a.s.l.; less than 10 % of the profiles were observed below tree
line. Snow profile records included snow stratigraphy (grain type and size, snow hardness index; Fierz et al., 2009), snow

temperature and a rutschblock test (RB; Föhn, 1987). For the rutschblock test the score (1 to 7), release type (whole block, partial release below skis or only an edge) and quality of fracture plane (smooth, rough, irregular) were recorded (Schweizer and Jamieson, 2010).

Table 1: Two examples of field data collected in the course of a snow profile observation.

Data entry	Example 1: Salezer Mäder, 24 Feb 2015	Example 2: Latschüel, 23 Feb 2017
(1) Profile site	On a small roll, lee slope. Snow depth above average.	In the lower half of medium-sized slope. Snow depth below average. Rocky ground. Representative for slopes of this aspect and elevation.
(2) Snow cover characteristics	Thick layer of new snow on hard thick crust, well consolidated due to sun. Basal layers seem slightly moist.	In general, poorly consolidated. Early winter depth layers are down about 70 cm. No prominent weak layers in the more recent layers.
(3) Stability test results	RB released when stepping onto it, but only below skis. CT and ECT show several failures in the new snow layers.	RB: only after several jumps one edge did break away: failure below the crust in depth hoar layer, down 70 cm. Other snow stability tests (ECT) showed similar results.
(4) Snow surface properties	About 20 cm of new snow, smooth. No new snow in wind exposed areas at all, but hard surface (crust on sunny aspects) or strongly faceted surface layers in shady aspects.	Mainly smooth, crusty on sunny slopes.
(5) Drifting snow	New small to medium-sized wind slabs are forming.	No recent snow drift accumulations observed, though occasionally some drifting snow in the morning.
(6) Signs of instability: whumpfs and shooting cracks	None observed.	No signs of instability observed.
(7) Recent avalanching	Small wind slab observed at Salezerhorn east ridge, 2100 m a.s.l.; triggered a small wind slab near Damm.	No recent slab avalanches observed. Many sluffs in steep sunny slopes.
(8) Local danger estimate (local nowcast)	Considerable above treeline. New snow drifts can be easily triggered, in all aspects, but fairly localized.	Moderate, above 2200 m a.s.l., in western, northern and eastern aspects.

For the analysis, all profiles were classified into 10 hardness profile types (1 to 10) and five stability classes (1: *very*
95 *poor*, 2: *poor*, 3: *fair*, 4: *good* and 5: *very good*) according to Schweizer and Wiesinger (2001). This 5-class stability scheme
considers the RB test result (score and release type), failure layer properties, snow stratigraphy and snowpack structure.

For the layer and height where the RB failed, we calculated the stratigraphy-based threshold sum using six unweighted
variables: difference in grain size, failure layer grain size, difference in hardness, failure layer hardness, failure layer grain
type and failure layer depth. The threshold values (or critical ranges) we used were those suggested by Schweizer and Jamieson
100 (2007). In case the RB failed at several locations in the profile, we selected the most relevant failure layer based on depth, RB
score and RB release type. In general, we chose the failure layer that had the lowest score. In case there were two failure layers
with the same score, but different depth, we opted for the failure layer where the whole block released, otherwise for the one
closer to the surface. Once the primary failure layer was found, the layer across the failure interface, either above or below the
failure layer, the so-called adjacent layer was also known (Schweizer and Jamieson, 2007). Differences in grain size and hand
105 hardness index were calculated across the failure interface, i.e. between failure layer and adjacent layer.

We then combined the threshold sum, the RB score and RB release type to obtain a simple alternative stability
classification (A: *POOR*, B: *FAIR*, C: *GOOD*) as suggested by Schweizer et al. (2008). We refer to this classification as the 3-
class stability scheme.

In addition, for each profile, the snowpack structure was classified by calculating the snowpack index $SNPK_{index}$ as
110 suggested by Techel and Pielmeier (2014). This index includes three elements: properties of (1) the slab (thickness), (2)
weakest layer interface and (3) the proportion of the snowpack that is soft, coarse-grained and consists of persistent grain types.

When analyzing the text fields, we simply considered the presence (1) or absence (0) of whumpfs, shooting cracks and
recent avalanching. For recent avalanching, we did not consider sluffs, wet-snow or glide-snow avalanches, but only dry-snow
slab avalanches. For the local nowcast, observers occasionally provided intermediate values of the danger level, which for
115 analysis were assigned to the next full danger level (e.g. 2- to *2–Moderate*, 2-3 as well as 3+ to *3–Considerable*).

We also considered new snow depth for analysis. As these data were not recorded by the observers, we compiled snow
depth data from measurement stations in the surroundings of the snow profile locations. We considered the median snow depth
from all new snow measurements, either manually observed or calculated from automatic snow depth recordings at automatic
weather stations (Lehning et al., 1999), within a radius of 10 km of the profile location. Measurement locations had to be
120 within ± 300 m in elevation from the elevation of the profile location. Occasionally, in about 3 % of the cases, the radius had
to be increased to 20 km.

Finally, the data set was completed with the most recent regional danger level as forecast in the public bulletin for the
day of observation (*N* = 583). Hence in a few cases in early winter, the danger forecast was not available since operational
forecasting had not started yet.

125   When analyzing the occurrence of signs of instability, we compare the relative frequency of e.g. whumpfs at danger level *1–Low* to the base rate, i.e. how often whumpfs were reported at all. Moreover, we provide the odds ratio. The calculation of the odds, which is the ratio of a probability to its complementary probability, $P/(1 – P)$ is based on the usual 2×2 contingency table used in forecast verification (Wilks, 2011; p. 307). The odds ratio θ is defined as the ratio of the conditional odds of a hit *a*, given that the events occurs $\frac{a}{b}$, to the conditional odds of a false alarm *b*, given that the event does not occur $\frac{c}{d}$:

130     $$\theta = \frac{a}{b} : \frac{c}{d} = \frac{a\,d}{b\,c}$$ (1)

with *c* the misses and *d* the correct non–events. As we have four different danger levels we provide the odds ratio for each danger level compared to either the rest, e.g. *1–Low* vs. the group of *2–Moderate*, *3–Considerable* and *4–High*, or compared to the higher (or lower danger levels), e.g. *2–Moderate* vs. the group of *3–Considerable* and *4–High*. Also, we compare the odds between the lower two to the higher two danger levels: *1–Low* and *2–Moderate* vs. *3–Considerable* and *4–High*.

135   To assess the uncertainty of the observed stability distributions, we sampled 50 times from the observed distributions (bootstrap) and calculated the mean frequency and its standard deviation for each stability class. To compare distributions, we applied the non-parametric Mann-Whitney *U*-Test. We selected a level of significance $p = 0.05$ to judge whether the observed differences were significant. We also checked for equality of proportions in 2×2 contingency tables. Relations between variables were described with the Spearman rank-order correlation coefficient r_{sp}. To compare distributions of categorical

140   variables data were cross-tabulated and the Pearson χ^2 statistic was calculated (Spiegel and Stephens, 1999). Finally, we evaluated whether we can relate the observed signs of instability to the danger levels with the help of a classification tree (Breiman et al., 1998).

     Our data set was unbalanced with regard to the danger levels. Hence, for the classification tree analysis, we randomly sampled 131 cases for the danger levels *2–Moderate* and *3–Considerable* to create 10 balanced data sets with each 131 cases

145   of the three lower danger levels.

3   Results

We will first present relevant results on the snowpack characteristics of our data set, then report on the frequency of snow stability classes in relation to the avalanche danger level and finally present the results on characterizing the danger levels based on the signs of instability, the snow stability class and new snow depth.

150 ## 3.1   Snowpack characteristics

In the following, we present the characteristics of the snow profile data, the stability test results and thereof derived stability, and selected relations between these data.

3.1.1 Snow depth

Snow depth at profile sites varied between 42 and 260 cm with a median of 108 cm, which is less than the mean snow depth
155   at Weissfluhjoch (2540 m a.s.l.) considering the period mid November to mid March: 133 cm. Hence, snow depth at the profile
sites was below average compared to the Weissfluhjoch site. The latter we consider as reference, since most profiles were from
the region of Davos: 90 % of the profile locations were less than 13 km from the Weissfluhjoch site.

3.1.2 Failure layer characteristics

Characteristics of the failure interface, which are relevant for calculating the threshold sum, are summarized in Table 2. The
160   median failure layer depth (or slab depth) was 38 cm, with the lower quartile at 25 cm and the upper at 52 cm. In 87 % of the
profiles the failure layer depth was within the so-called critical range [18 cm, 94 cm] as defined in the threshold sum approach.
The median failure layer thickness was 7.7 cm with the middle 50 % ranging from 3 to 15 cm.

**Table 2: Characteristics of failure interface (FI) with properties of failure layer (FL) and adjacent layer (AL); FL grain types:
faceted crystals (FC), rounded grains (RG), rounding faceted particles (FCxr); Failure layer hardness is shown as hand hardness**
165   **index: 1 (Fist), 2 (4 Fingers), 3 (1 Finger), 4 (Pencil); N = 589.**

Property	Median or modus	1st and 3rd quartile; 2nd and 3rd most frequent
Snow depth	108 cm	82 – 137 cm
FL depth	38 cm	25 – 52 cm
FL thickness	7.7 cm	3 – 15 cm
FL hardness index	1	1 – (1 to 2)
FL grain type	FC	RG, FCxr
FL grain size	1 – 1.5 mm	(0.5-1.5) – (1.0-2.5) mm
AL thickness	5 cm	1 – 13 cm
AL hardness index	2 to 3	2 – (3 to 4)
AL grain size	0.75 – 1 mm	(0.5-1.0) – (0.75-2.0) mm
Hardness difference across FI	1	0.5 – 2
Grain size difference across FI	0.5 mm	0.25 – 1 mm
FL above/below AL	276 above, 313 below	-
Threshold sum (number of "lemons")	modus: 5 (median: 4)	4, 3

Most failure layers, 484 out of 589, were very soft or soft with a hand hardness index of 1 (Fist) or 1 to 2 (Fist to 4
Fingers). In about three quarters of the cases the mean failure layer grain size was 1 mm or less.

In 417 out of 589 cases (71 %) the failure layer consisted of persistent grain types, with faceted crystals (FC) the most

170   common type. In the remaining 172 cases, where the grain type was non-persistent, most failure layers included small rounded

grains (RG). Failure layers with non-persistent grain types were mostly above the failure interface (in 129 out of 172 cases;

75 %), whereas for failure layers with persistent grain types, the failure layer was usually below the failure interface (in 270

out of 417 cases, 65 %) i.e. the failure occurred at the upper failure layer boundary, or in other words, the failure layer was

below the adjacent layer.

175   Failure layers with persistent grains (median: 40 cm) were deeper in the snowpack than failure layers with non-

persistent grains (median: 30 cm; Mann-Whitney U-Test, $p < 0.001$; Figure 1). Moreover, snow depth was lower in cases with

failure layers consisting of persistent grain types (median: 102 cm) than of non-persistent grain types (median: 122 cm; Mann-

Whitney U-Test, $p < 0.001$).

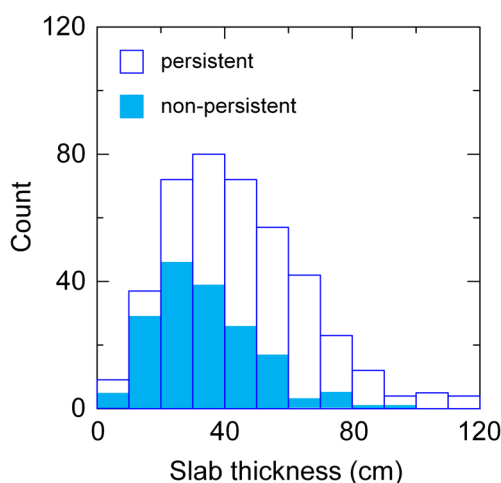



Figure 1: Frequency of slab thickness for failure layers with non-persistent grains (light blue; $N = 172$) and with persistent grains
180   **(white; $N = 417$).**

3.1.3 New snow

In 29 % of the cases no new snow was recorded the day the profile was observed nor on the two preceding days (HN3d $\leq$ 1 cm;

$N = 172$). In the other cases, the median 3-day sum of new snow depth was 13 cm ($N = 417$). In less than 10 % of these cases

a major snowfall (HN3d $\geq$ 50 cm) preceded the day of observation.

185   With regard to failure layer depth and grain type in the failure layer (non-persistent vs. persistent) differences for days

with and without new snow were small. Considering the cases without new snow (HN3d $\leq$ 1 cm), the failure layer depth was

again larger for the failure layers with persistent grain types (median: 39 cm) than for the layers with non-persistent grains

types (median: 26 cm; Mann-Whitney U-Test, $p = 0.01$). For the cases with new snow, the median 3-day sum of new snow

depth was 13 cm for the cases with persistent grain types in the failure layer and slightly larger, namely 16 cm, for the cases
190 with non-persistent grain types in the failure layer; the difference was significant (Mann-Whitney U-test, $p = 0.018$).

For cases with HN3d ≤ 10 cm ($N = 349$) the proportion of cases with persistent failure layers was significantly larger
(74 %) compared to 66 % for cases with HN3d > 10 cm ($p = 0.028$). In the 41 cases with a substantial amount of new snow
(HN3d ≥ 50 cm) the proportion of failure layers with persistent grain types was still 49 %, though significantly lower than the
base rate of 71 % (proportion test, $p = 0.005$). Overall, persistent grain types were dominant in failure layers almost regardless
195 of the amount of new snow.

3.1.4 Rutschblock test results

The RB scores 3 to 6 were all similarly frequent in the data set; the median RB score was 4. RB score increased with increasing
failure layer depth ($r_{sp} = 0.28$, $p > 0.001$). The frequency of the release type *whole block* decreased with increasing RB score
(Figure 2). Its relative frequency at RB score 2 was 74 %, whereas it was only 5 % at RB score 6. This finding suggests that
200 with increasing load needed for failure initiation also the propensity for crack propagation decreases.

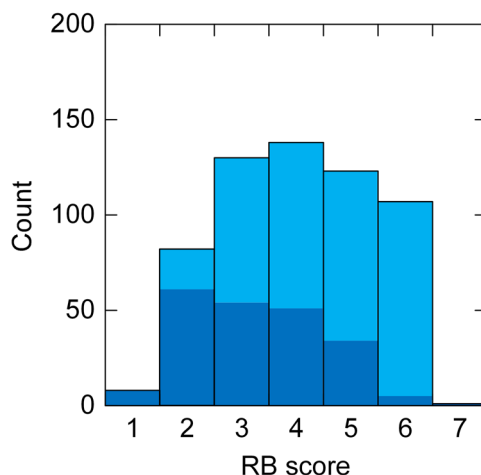



Figure 2: Frequency of rutschblock scores (1 to 7; light blue; $N = 589$); dark blue bars highlight cases with release type *whole block*.

3.1.5 Snow instability ratings

The distribution of point snow stability estimated with the five class scheme according to Schweizer and Wiesinger (2001)
205 was centered at 3: *fair* (Figure 3). More profiles were rated as *good* and *very good* (32 %) than *poor* and *very poor* (25 %;
proportion test: $p = 0.003$). The proportion of profiles rated as *very poor* and *poor* was larger for failure layers with persistent
grain types than for failure layers with non-persistent grain types (29 % vs. 15 %, $p = 0.001$). Among the *poor* and *very poor*
profiles, the majority (86 %) were cases with RB score ≤ 3, *whole block* release and failure layer threshold sum ≥ 5.

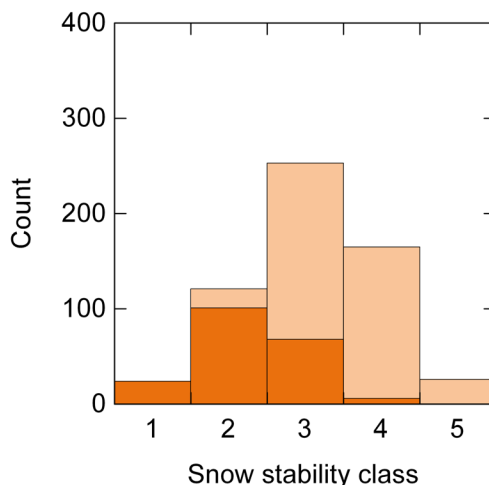



Figure 3: Frequency of snow stability class (1: *very poor*, 2: *poor*, 3: *fair*, 4: *good*, 5: *very good*; light orange). For each class the
210 **number of cases with RB score ≤ 3, whole block release and threshold sum ≥ 5 are shown in orange (which corresponds to class A:**
POOR of the 3-level stability class scheme); *N* = 589.

Median snow depth increased from 92 cm for the profiles rated as *very poor* to 144 cm for the profiles rated as *very good* (Figure 4) (Mann-Whitney *U*-test, $p < 0.001$). Still, there was substantial scatter, so that the correlation of stability with snow depth was rather weak ($r_{sp} = 0.24$), though statistically significant ($p < 0.001$).

215 Considering the 3-class stability rating scheme that combines the threshold sum, the RB score and RB release type as suggested by Schweizer et al. (2008), the three stability classes were almost equally frequent (*POOR*: 199, *FAIR*: 192, *GOOD*: 198). For the failure layers with persistent grain types, the 3-class stability was significantly lower, with *POOR* the most frequent class (41 %; 173 out of 417 cases), whereas for failure layers with non-persistent grain types the most frequent stability class was *GOOD* (54 %; χ^2-test, $p < 0.001$). Likewise, with persistent grains in the failure layer *whole block* releases in the 220 rutschblock test were observed in 172 out of 417 the cases (41 %), whereas with non-persistent grains the proportion was only 24 %, thus significantly lower (proportion test, $p < 0.001$).

Hence, both stability classifications revealed that profiles with non-persistent failure layers had better overall snow stability ratings than profiles with persistent failure layers. This finding is in line with the fact that few profiles were recorded immediately after a major snowfall, when failure layers with non-persistent grain types may actually be as weak as failure 225 layers with persistent grain types (Reuter et al., 2019).

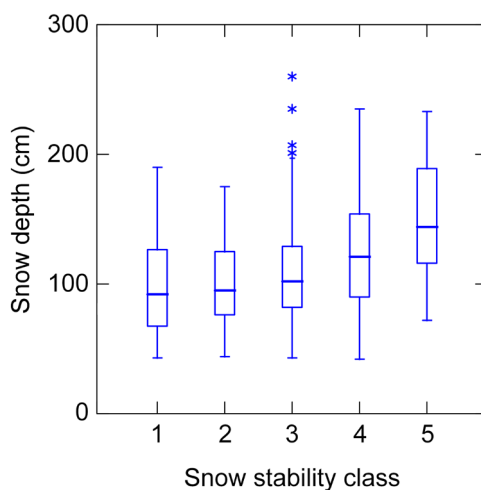



Figure 4: Snow depth by snow stability class (1: *very poor*, 2: *poor*, 3: *fair*, 4: *good*, 5: *very good*). Boxes span the interquartile range from 1st to 3rd quartile with a horizontal line showing the median. Whiskers show the range of observed values that fall within 1.5 times the interquartile range above the 3rd and below the 1st quartile. Asterisks refer to outliers beyond the fences. $N = 589$.

3.1.6 Snowpack structure index

We finally considered the snowpack structure index as introduced by Techel and Pielmeier (2014). The median value of $SNPK_{index}$ was 1.7 indicating that for about half of the profiles (52 %) the $SNPK_{index}$ class was 1 or 2 (with 1 suggesting an unfavorable snowpack structure).

With regard to profile type (Schweizer and Wiesinger, 2001), the snowpack structure index $SNPK_{index}$ was significantly higher (*U*-test; $p < 0.001$) for profiles with soft basal layers (profile types: 1 to 5) compared to profiles with profile types: 6 to 10; less than half of the profiles (46 %) had soft basal layers.

3.2 Danger level and stability distributions

We first present the frequency distributions for the regional forecast and the local nowcast, and the deviation between these two danger ratings. Then, we consider the 5-class stability distribution per danger level (local nowcast).

3.2.1 Regional forecast and local nowcast

The regional danger level as forecast in the public bulletin on the day of observation was in most cases (85 %) either *2– Moderate* or *3–Considerable* (RF; Figure 5a). This agrees with the long-term mean distribution in the region of Davos for dry-snow conditions, which is 14 %, 51 %, 34 %, 1.3 % for the forecast regional danger levels *1–Low* to *4–High*.

Observers rated the local danger level (local nowcast: LN; Figure 5a) in 22 % as *1–Low*, in 41 % as *2–Moderate*, in

245   35 % as *3–Considerable* and in 1.7 % as *4–High*. They agreed with the regional forecast in 70 % of the cases; in 25 % of the

cases they estimated the local danger lower than forecast, in the remaining 5 % higher (Figure 5b).

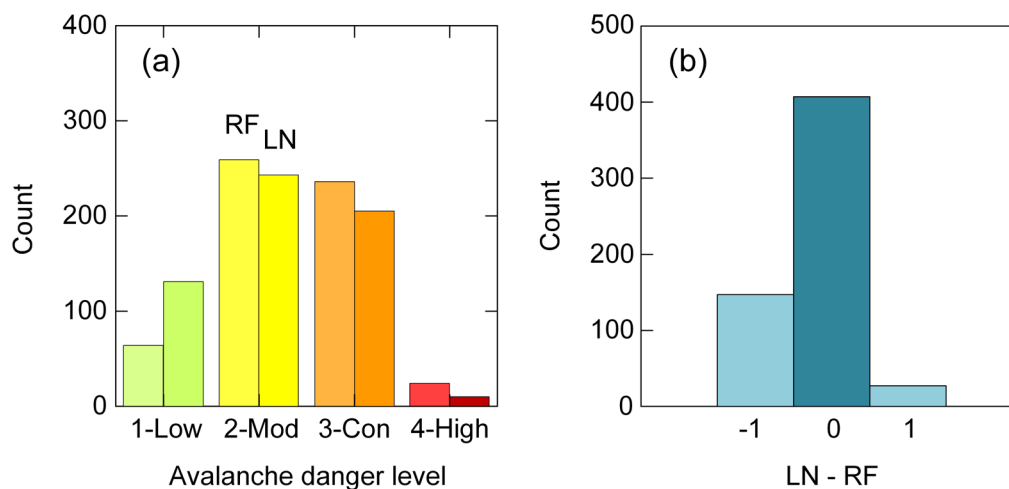



Figure 5: (a) Frequency of avalanche danger levels (*1–Low* to *4–High*). For each danger level, on the left the regional forecast (RF;
250   **N = 583), on the right the local nowcast (LN, N = 589) is shown, for the day when the snow profile was recorded. (b) Deviation of**
regional forecast from local nowcast (N = 583).

3.2.2 Frequency of snow instability classes

Figure 6 shows the frequency distributions for the 5-class stability rating, resampled to indicate the uncertainty. The

distributions of the four danger levels (LN) rated by the observers were significantly different (Mann-Whitney *U*-Test,

255    $p < 0.001$). At danger level *1–Low*, more than 50 % of the profiles were rated as *good* or *very good*. The clear majority, almost

84 % of the profiles were rated *fair* or *good* at danger level *2–Moderate*. At the danger level *3–Considerable* about half of the

profiles (49 %) were rated *poor* or *very poor*, with a very large portion of *fair* profiles. Finally, at *4–High*, the distribution is

uncertain due to the low number of cases ($N = 10$) with a majority of profiles (63 %) rated as *poor* and *very poor*. Even though

the stability distributions were statistically significantly different, they showed substantial overlap, in particular, for *2–*

260   *Moderate* and *3–Considerable*. In both cases, the modus and median was 3, i.e. *fair*. Yet, looking at their tails on the low

stability end, differences were clearly more prominent and better suited to distinguish between the different distributions.

The median sum of new snow depth in the 10 cases with *4–High* was 52 cm. In general, the sum of new snow depth

(HN3d) was positively correlated with the danger level ($r_{sp} = 0.51$) and negatively with the 5-class stability rating ($r_{sp} = -0.30$).

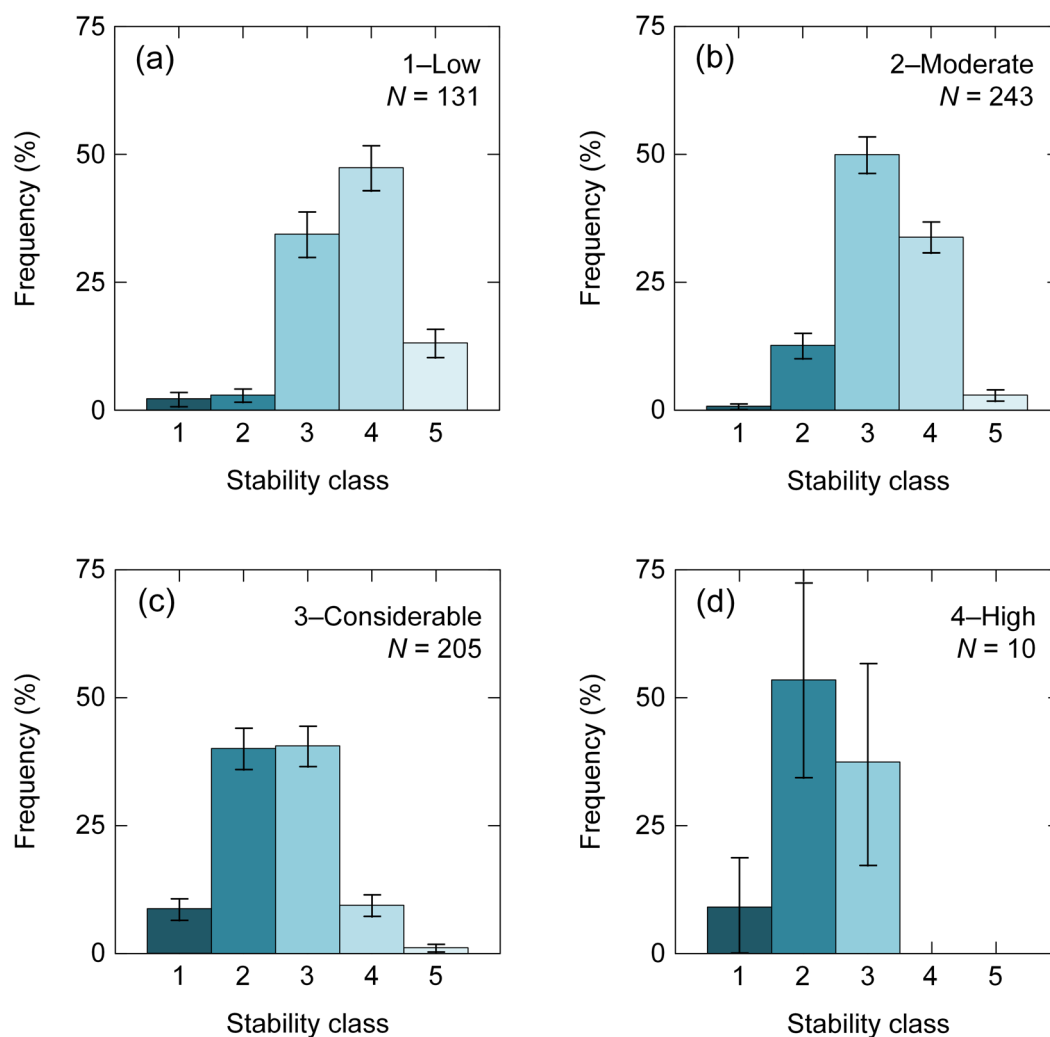



Figure 6: Frequency distributions for the 5-class stability at the four local danger levels (a-d) from *1–Low* to *4–High* (LN, as rated by observers). Mean frequency and standard deviation (whiskers) are shown for 50 times resampling from the observed distributions.

3.3 Signs of instability

In the following, we first present some general findings on the observations of signs of instability, then relate the single signs to the avalanche danger and finally, explore whether the danger levels can be characterized by signs of instability.

Either whumpfs, shooting cracks or recent avalanches were observed in 267 out of 589 cases. Whumpfs were most frequently (32 %), shooting cracks least frequently (17 %) reported. The frequency of whumpfs, shooting cracks and recent avalanching increased with increasing danger level ($r_{sp} > 0.99$; Table 3); the increases in frequency from one danger level to

the next were almost all statistically significant (proportion test, *p* < 0.023); the only two exceptions were the proportions of shooting cracks at *1–Low* vs. *2–Moderate*, and *3–Considerable* vs. *4–High*.

275   The strongest increase, more than 8 times, was observed for shooting cracks from *2–Moderate* to *3–Considerable*. Also, the odds ratio was 15, i.e. with shooting cracks it was 15 times more likely that the danger level was *3–Considerable* than *1–Low* or *2–Moderate* (Table 4). For *3–Considerable* or higher the odds ratio was even 16.

At the danger level *1–Low* signs of instability were rare; overall on 16 out of 131 days (12 %) either whumpfs, shooting cracks or recent avalanches were reported. For the danger levels *2–Moderate* to *4–High*, this proportion was 31 %, 81 % and
280   100 %, respectively. The seemingly inconsistent assessment of *1–Low* while signs of instability were present, were in most cases related to a low frequency of these signs and in general of triggering spots, as e.g. found in early-winter situations.

Table 3: Frequency and relative frequency (in percent) of signs of instability per danger level (LN: local nowcast). Also given is the ratio of relative frequencies, i.e. the relative frequency of a sign of instability at a given danger level to the base rate of that sign of instability, which is given in the bottom row; total number of observations: *N* = 589.

Danger level	*N*	Whumpfs			Shooting cracks			Recent avalanching		
		Frequency		Ratio	Frequency		Ratio	Frequency		Ratio
1–Low	131	13	9.9 %	0.31	4	3.1 %	0.18	4	3.1 %	0.13
2–Moderate	243	46	19 %	0.59	11	4.5 %	0.26	35	14 %	0.62
3–Considerable	205	122	60 %	1.8	80	39 %	2.3	88	43 %	1.8
4–High	10	9	90 %	2.8	7	70 %	4.0	10	100 %	4.3
Total	589	190	32 %		102	17 %		137	23 %	

3.3.1 Whumpfs

Whumpfs were observed in 190 out of 589 cases, i.e. the base rate was 32 % (Table 3). In 131 out of these 190 cases (69 %)
285   the local danger estimate was *3–Considerable* or higher; in 46 out of 190 cases it was *2–Moderate*, and in about 7 % of the cases it was *1–Low*. On the other hand, when no whumpfs were observed, the local danger estimate was in 79 % of the cases *2–Moderate* or lower.

3.3.2 Shooting cracks

Shooting cracks were reported in 102 out of 589 cases (17 %; Table 3). When shooting cracks were recorded, observers rated
290   the avalanche danger as *3–Considerable* or higher in 85 % of the cases; on 11 days they rated the local danger as *2–Moderate*, at four days as *1–Low*. For shooting cracks, the odds ratio increased by a factor of more than 200 from *2–Moderate* to *3–Considerable* (Table 4); this is the largest increase and suggests that shooting cracks may have particular discrimination power.

Table 4: Odds ratios for signs of instability and a given danger level vs. other danger levels. The odds ratio describes how much more likely a certain danger level is compared to a group of other danger levels given the observation of a sign of instability.

Grouping of danger levels	Odds ratio		
	Whumpfs	Shooting cracks	Recent avalanching
1–Low vs. rest	0.17	0.12	0.077
2–Mod vs. *3–Con, 4–High*	0.15	0.07	0.20
3–Con vs. *1–Low, 2–Mod*	7.9	15	6.4
4–High vs. rest	20	12	-
3–Con, 4–High vs. 1–Low, 2–Mod	8.3	16	7.2

3.3.3 Recent avalanching

Recent dry-snow slab avalanches were reported on 137 out of 589 days (23 %) (Table 3). The local danger level estimate on those days was *1–Low* on four days, *2–Moderate* on 35 days (26 %), and *3–Considerable* or higher on the remaining 98 days (73 %). In 44 % of the days with avalanche activity, no other signs of instability were observed; this was particularly common at the lower danger levels *1–Low* (3 out 4: 75 %) and *2–Moderate* (26 out of 35: 74 %).

3.3.4 Whumpfs, cracks, avalanching

When all three signs of instability were observed, which was rare (in only 41 out of 589 cases: 8 %), the local danger estimate was nearly always (98 %) *3–Considerable* or higher. In cases when none of the three signs of instability were observed ($N = 322$), there were only 39 cases when the local danger level estimate was *3–Considerable*, and in most of these cases the snow stability was *fair* or lower (85 %) or HN3d > 10 cm (49 %).

On the other hand, when the local nowcast was *3–Considerable* (or higher) signs of instability were frequently observed, namely whumpfs in 60 %, shooting cracks in 39 %, and avalanches in 43 % of the cases (Table 3). For days with *2–Moderate* signs of instability were less frequent: whumpfs were triggered on 19 % of the days, shooting cracks were rare (< 5 %), and recent avalanches were observed on about every seventh day (14 %). Even though observers estimated the local danger as *1–Low*, they occasionally reported whumpfs (in 13 out of 131 cases) and on very few days even shooting cracks or recent avalanches.

3.3.5 Characterizing danger levels with signs of instability

For all three signs of instability, the odds ratios for *1–Low* and *2–Moderate* were < 1 (Table 4) indicating that these danger levels and the signs of instability were negatively correlated. In other words, the presence of signs of instability implied that the danger level was rather not *1–Low* or *2–Moderate*. On the other hand, the odds ratios were clearly > 1 for the danger levels

3–Considerable and *4–High* suggesting a positive correlation between signs of instability and these two danger levels. Even though signs of instability were more frequently associated with the danger level *3–Considerable* and *4–High* than with *1–Low* or *2–Moderate*. Still, assessing the danger level is not conclusive if based on signs of instability only.

320   Hence, in the following, we first relate the local nowcast to signs of instability with the help of a classification tree. Then we add the stability class and subsequently the 3-day sum of new snow depth as additional independent variables to ease classification.

The first classification tree with signs of instability only (Figure 7) showed that it was not possible to clearly discriminate between danger levels based on observed signs of instability. Based on the presence or absence of shooting cracks

325   and whumpfs the tree suggested a classification into either *2–Moderate* and *3–Considerable* danger; *1–Low* and *4–High* could not be classified. However, in the lower left box (terminal node) of the tree in Figure 7, 115 out of 131 cases of *1–Low* were found. Considering the base rate, this proportion was higher than for *2–Moderate*. The fact that *4–High* was not classified is simply due to the low number of cases, i.e. the unbalanced nature of our data set. Still, 7 out of 10 cases were found in the uppermost terminal node.

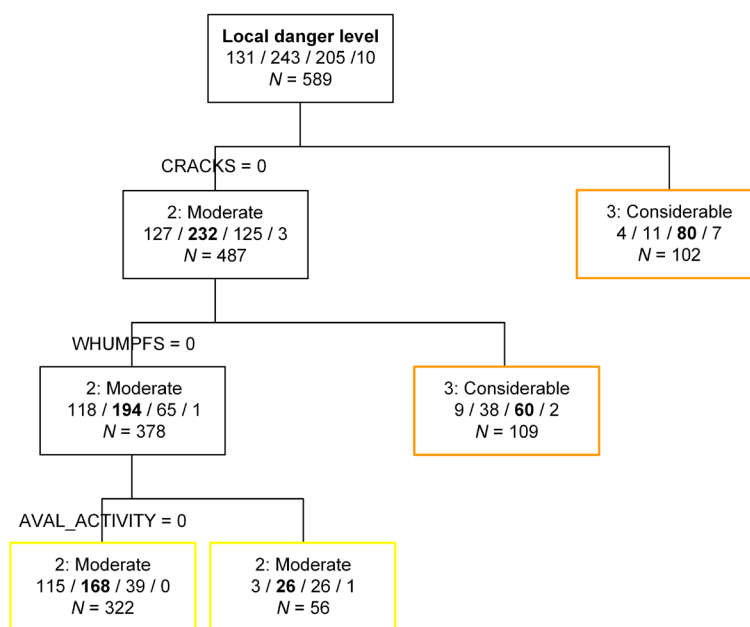



Figure 7: Classification tree for local danger estimate (LN) based on signs of instability (whumpfs, shooting cracks and recent avalanching). The numbers indicate the frequency of the four danger levels, with the number of cases for the predicted danger level given in bold.

330   Considering the classification trees obtained with the 10 balanced resampled data sets for the danger levels *1–Low, 2–Moderate* and *3–Considerable* revealed that in 3 out of the 10 trees, the order of splits was the same as in Figure 7, namely

first cracks, then whumpfs and then avalanche activity. However, in 6 out of 10 cases the first split was the presence or absence of whumpfs. The average classification accuracy of the 10 classification trees was 56 %. In all trees there was one terminal node where the most frequent danger level was *1–Low* when no signs of instability were observed; on average 115 out 131

335 cases of *1–Low* were correctly classified. Also, there were always at least two terminal nodes classified as *3–Considerable*. On the other hand, in only 3 out of the 10 trees a terminal node with *2–Moderate* as most frequent end-member class existed, typically including less than 20 cases. In other words, *2–Moderate* was poorly classified, in contrast to *1–Low* and *3–Considerable*. Essentially, the trees suggested that the presence of signs of instability implies *3–Considerable*, and their absence *1–Low*. In the few cases that were correctly classified as *2–Moderate* recent avalanching was observed, but no

340 whumpfs or cracks.

3.3.6 Characterizing danger levels with signs of instability and snow stability class

Using the original (unbalanced) data set and adding the 5-class stability rating as independent variable, the danger level *1–Low* could be classified (Figure 8; lower left box/end member). The danger level was *1–Low*, when there were no signs of instability and snow stability rated as *good* or *very good*, which is essentially equivalent to the absence of a critical weakness. In fact, in

345 almost 80 % of these cases the threshold sum for the failure layer interface was ≤ 4.

Using the 10 balanced data sets instead for classification revealed that in 6 out of 10 classification trees the first split variable was the presence or absence of whumpfs, whereas the stability class only showed up once as first split variable and 4 times in the second split. Nevertheless, in all 10 classification trees all three danger levels could be classified by introducing the stability variable, a clear improvement compared to the classification trees that only included the three signs of instability.

350 The danger level *2–Moderate* was often classified when no signs of instability were observed but the stability class was *fair* or lower, which indicates that a persistent weak layer showing intermediate stability test results existed. On the other hand, when the stability was at least *good* and no signs of instability were observed, the danger level was clearly *1–Low*. *Good* stability with either a whumpf or recent avalanching hinted toward *2–Moderate*. Clearly, cases with cracks or whumpfs plus *fair* or lower stability were classified as *3–Considerable*. The average classification accuracy of the 10 classification trees was

355 61 %. The best classification was obtained for *3–Considerable* (77 ± 5 %), followed by *1–Low* (58 ± 9 %) and *2–Moderate* (47 ± 14 %).

Alternatively, we also tested other stability variables, but with those not all three of the lower danger levels were classified and in general classification power in tree analysis compared to the 5-class stability variable was lower. Still, all stability related variables, the 5- and 3-class stability rating, RB score as well as the snowpack structure index were all four

360 negatively correlated with the local danger level estimate: r_{sp} = -0.50, -0.36, -0.37, -0.11; the correlation was highly significant for the two stability class variables and the RB score ($p < 0.001$).

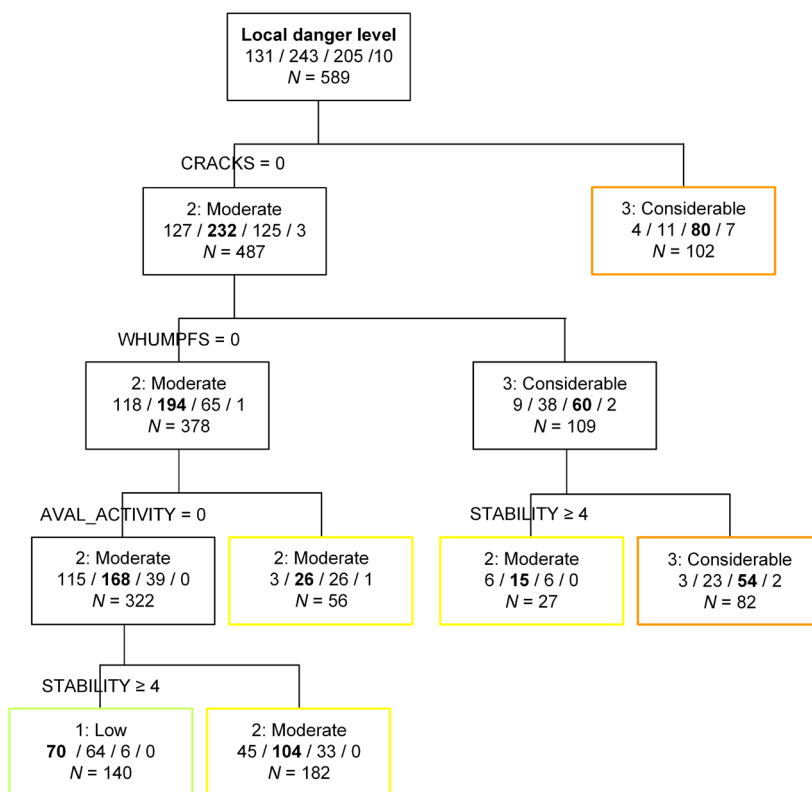



Figure 8: Classification tree for local danger estimate (LN) based on signs of instability (whumpfs, shooting cracks and recent avalanching) and snow stability class.

3.3.7 Characterizing danger levels with signs of instability, snow stability class and new snow

365 Finally, we added a further easily observable variable, the 3-day sum of new snow depth, as independent variable. Figure 9 shows the resulting classification tree using the original (unbalanced) data set. As with the stability class the three lower danger levels could be classified and the split variables and values were plausible. The 3-day sum of new snow depth showed up twice as split value, once discriminating early on between days with and without new snow.

Using the 10 balanced data sets confirmed these findings. In 7 out of the 10 trees the new snow depth was the second
370 split variable, in 3 trees it was even the first. In these 3 cases the split value was typically about 10 cm. In the other 7 trees, the first split variable was 6 times either the presence or absence of whumpfs or cracks, and once the snow stability class. Overall, the classification accuracy slightly improved, increasing to 64 %. In particular, *1–Low* was significantly better classified (77 ± 5 %), whereas the classification accuracy for the other two danger levels slightly decreased (*2–Moderate*: 44 ± 16 %; *3–Considerable*: 72 ± 5 %). Cases with danger level *1–Low* were those, as found above, with no signs of instability and *good* or
375 higher stability, and now, in addition, no or an insignificant amount of new snow.

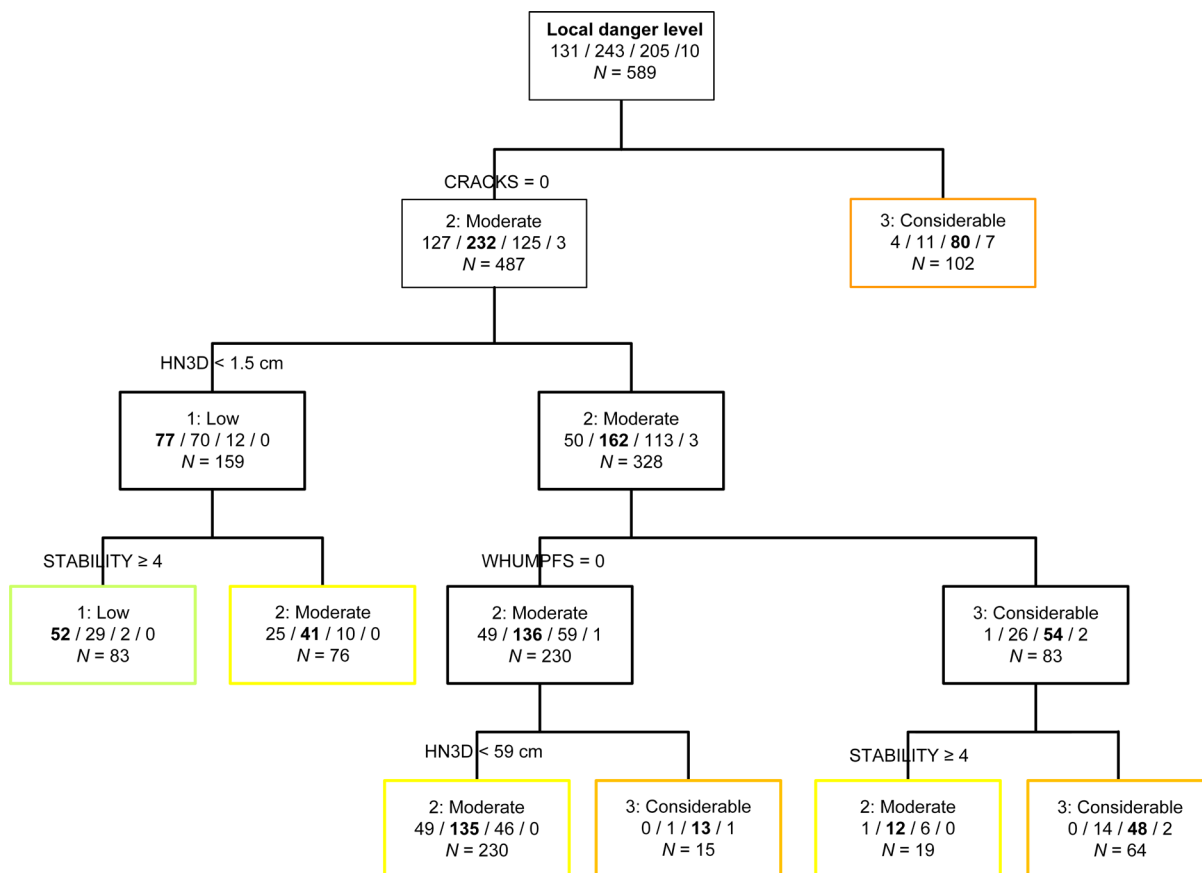



Figure 9: Classification tree for local danger estimate (LN) based on signs of instability (whumpfs, shooting cracks and recent avalanching), snow stability class and 3d-sum of new snow depth.

Incidentally, using the 3-day sum of new snow depth as single independent variable the median split value of the 10 trees obtained with the balanced data sets was < 11 cm. With this split value 91 % of the cases with *1–Low* were correctly classified, and 64 % of the cases with *3–Considerable*.

3.3.8 Characteristics of danger levels: summary

Based on the above findings we provide some typical situations that characterize the danger levels (Table 5). They are based on selected complete branches from the 30 classification trees and have to be considered as approximate description. For the danger level *4–High* we did not have enough cases for a quantitative classification analysis, but the few cases included in our data set suggest that one can discriminate between *3–Considerable* and *4–High* based on the amount of new snow in combination with presence of signs of instability. The odds ratios given in Table 5 indicate how well the situation is related to

the corresponding danger level. For the danger level *2–Moderate*, the odds ratios were relatively low, lower than for the other danger levels – in line with the findings described above.

390 **Table 5: Rough characterization of avalanche danger levels based on signs of instability, stability class and 3-day sum of new snow depth, with corresponding odds ratio for the corresponding danger level.**

Danger level	Typical situation	Odds ratio
1–Low	No signs of instability	8.7
	No signs of instability and at least *good* stability	6.4
	No signs of instability and no new snow	7.4
	No signs of instability and at least *good* stability and no new snow	9.7
2–Moderate	No signs of instability, but 10-30 cm of new snow	3.4
	No signs of instability, but >10 cm new snow	2.9
	No signs of instability and *fair* stability	2.7
	No signs of instability, *fair* stability and new snow > 10 cm	2.9
3–Considerable	Shooting cracks	10.5
	Whumpfs plus *fair* or lower stability	9.9
	All three signs of instability are present.	9.0
	At least one sign of instability is present.	11.9
(4–High)	All three signs of instability are present and more than 35 cm of new snow.	120
	At least one sign of instability present and more than 35 cm of new snow	89

4   Discussion

We analyzed a data set of 589 snow profiles with associated RB test and field observations that were selected from a large database of snow profiles observed in the Swiss Alps. Whereas the selection procedure resulted in some biases, it also ensured a high quality, completeness and consistency of the data. Biases include, for instance, a focus on the region of Davos likely 395 resulting in a high proportion of persistent weak layers since the region belongs to an inner-alpine area where persistent weak layers are common (Techel et al., 2015). On the other hand, the limited number of profiles, allowed for quality control. This included, for each profile, to revisit the snow stability class, correcting it if inconsistently assigned, reviewing the rutschblock

test results and checking failure layer depth and characteristics. Still, with 589 profiles we cover a large variety of snowpack and stability conditions from 18 winter seasons.

400   Almost all data represent observations that are essentially qualitative, though highly standardized. Hence, some data may be subjective and not independent. However, all observers were experienced and trained yearly according to international standards such as ICSSG (Fierz et al., 2009). In addition, during quality control any records with implausible data were discarded. On the other hand, observations of signs of instability are rather objective, but still depend on terrain travelled and the attentiveness of the field team (Jamieson et al., 2009). Finally, the local avalanche danger estimate, a key element of this

405   study, is inherently subjective, since there is no objective measure of avalanche danger (Techel and Schweizer, 2017). Moreover, any observation made during a field day may have influenced the danger assessment.

      Our data do not include any information on the spatial frequency of the stability information – that is essential for assessing the danger level (e.g., Techel et al., 2020). We do not know whether a single whumpf or many whumpfs were observed, or whether the weak layer found was frequently observed and known to be a problem in the area – or whether the

410   profile was considered as not representative, i.e. was rather an outlier. The lack of spatial information may lead to seemingly inconsistent assignment of the danger level. For instance, several whumpfs, but a thin and discontinuous snow cover, may well justify the danger level *1–Low*, despite the observed signs of instability. In general, the danger assessment is based on point observations; they may be insufficient for estimating the spatial frequency of instability needed for reliable danger assessment. Apart from this general scale mismatch, conditions may limit the terrain that can be travelled, e.g. at times when the avalanche

415   situation is critical.

      As we relate the local danger estimate to snowpack stability and signs of instability, there is potential for a circular argument. Given that signs of instability were recorded and at the same time the danger level estimated as *2–Moderate* and sometimes even a *1–Low* (in 12 % of the cases with *1–Low* at least one of the three signs of instability was observed), clearly indicates that observers were capable of differentiating between situations and not simply opted for *3–Considerable* as soon

420   as they observed any sign of instability. For instance, they may have implicitly considered the spatial frequency. Moreover, we are not aware of any practical method that would ensure full independence of these observational data and allow capturing characteristics of the danger levels based on observations in the field, which is the very purpose of this study.

      Many snowpack characteristics we found were similar to other studies (e.g., Schweizer and Jamieson, 2003; van Herwijnen and Jamieson, 2007). For instance, the median slab depth as identified with the rutschblock test was 38 cm in our

425   data set (Fig. 2), close to 39 cm reported by Schweizer and Jamieson (2003). Most failure layers (71 %) were ≤ 50 cm from the surface and in very few cases (1 %) the slab thickness was > 1 m. This distribution of failure layer depth or slab thickness reflects the fact that skier stress decreases with depth and agrees with the critical range (18-94 cm) suggested in the threshold sum approach (Schweizer and Jamieson, 2007). The high percentage (71 %) of persistent grain types in failure layers confirms the prevalence of the avalanche problem *persistent weak layer* in the inner-alpine region of Davos. Even when there was a

430 substantial amount of new snow (HN3d > 30 cm), which we argue implies the avalanche problem *new snow*, the majority of the failure layers included persistent grain types. This finding suggests that in case of snowfall the *new snow* problem is commonly accompanied by the *persistent weak layer* problem.

The stability ratings were higher when the failure layer consisted of non-persistent grains. Also, stability increased with increasing snow depth in line with some previous studies (e.g., Schweizer et al., 2003; Zeidler and Jamieson, 2004) and

435 supporting the approach of selecting profile locations with below average snow depth. However, Reuter et al. (2015) reported that on a particular day, only in 1 out 5 cases differences in snow depth were indicative of snow instability. On the other hand, they also confirmed the long-term trend across many days towards higher stability with increasing snow depth.

The frequency of forecast danger levels was typical compared to the long-term statistics. The agreement of 70 % between regional forecast and local nowcast is rather low but in the range reported in previous verification studies (e.g., Techel

440 and Schweizer, 2017). Overall, the data set seems rather representative with regard to snow properties and avalanche conditions and does not indicate any particular biases – apart from the obvious influence of snow climate and less obvious potential peculiarities of the avalanche forecasting practice in Switzerland (e.g., Techel et al., 2018). Hence, in snow climates with similar types of dry-snow avalanche problems, we expect our findings to be applicable, yet corroborating them with similar analyses from other regions would certainly be beneficial for further fostering the quantitative description of danger levels.

445 Comparing observed signs of instability to the local danger level estimate confirmed that their occurrence increases with increasing danger level and that they are typical at danger level *3–Considerable*. On the other hand, if no signs of instability were observed, the danger level was likely (88%) not *3–Considerable* (or higher). This finding agrees with a table characterizing the danger levels based on typical observations that was suggested based on expert judgment by Schweizer (2003), but also with the classification tree derived by Jamieson et al. (2009) for the Columbia Mountains in Canada. Their

450 tree predicted the danger level *3–Considerable* when whumpfs were observed – comparably to our tree (Fig. 7) – and supported by the high value of the corresponding odds ratio (Tab. 4). Adding the stability class and the 3-day sum of new snow depth improved the classification, in particular with regard to the discrimination between the lower three danger levels. Still, the danger level *2–Moderate* was not well characterized, compared to *1–Low* and *3–Considerable* that can be described by either the absence and presence of signs of instability.

455 We then made an attempt to extract from the classification trees some typical situations (Table 5). Again, the odds ratios illustrate that *2–Moderate* is not well defined by the simple observations we used in our analyses. At best, *2–Moderate* means that no signs of instability were observed, but there was recently some new snow or the snow stability is *fair,* i.e. there is still a persistent weak layer in the snowpack, but showing intermediate stability test results. Whereas this description is far from conclusive it indicates that in the absence of signs of instability, digging a snowpit and performing a stability test may be

460 needed to discriminate between the lower danger levels. This interpretation is in line with the procedure suggested by, e.g., Bellaire et al. (2010).

The finding that the lower danger levels cannot easily be characterized by simple observations supports the view that only with extensive snow stability sampling the lower danger levels can be verified (Schweizer et al., 2003). Also, locations with poor stability are less frequent with lower danger levels and hence single point observations are naturally less indicative.

465 Whereas we did not have many stability ratings on a given day, we still attempted to derive stability distributions for the four danger levels. To this end, we assumed that on different days with the same danger level, the stability distributions are similar, so that we could combine the single stabilities from many different days into one distribution (Techel et al., 2020). This assumption is probably not fully valid as was shown by Schweizer et al. (2003) who reported slightly different stability distributions for days with the same danger level. Still, Techel et al. (2020) showed that on different days with the same danger

470 level the stability distributions were indeed similar, within a certain range. Nevertheless, Schweizer et al. (2003) also provided typical stability distributions for *1–Low*, *2–Moderate* and *3–Considerable*. We revisited their analysis and added their data from the winter 2002-2003 as described in Schweizer (2007). All these data are compiled in Figure 10 and allow to compare the stability distributions from this study (Fig. 6) to these previous results where up to almost 100 profiles were recorded within a few days with the same avalanche conditions and danger level in the region of Davos. Schweizer et al. (2003) also provided

475 two stability distributions for situations that were found to be rather in-between two danger levels, which for comparison are also shown in Figure 10.

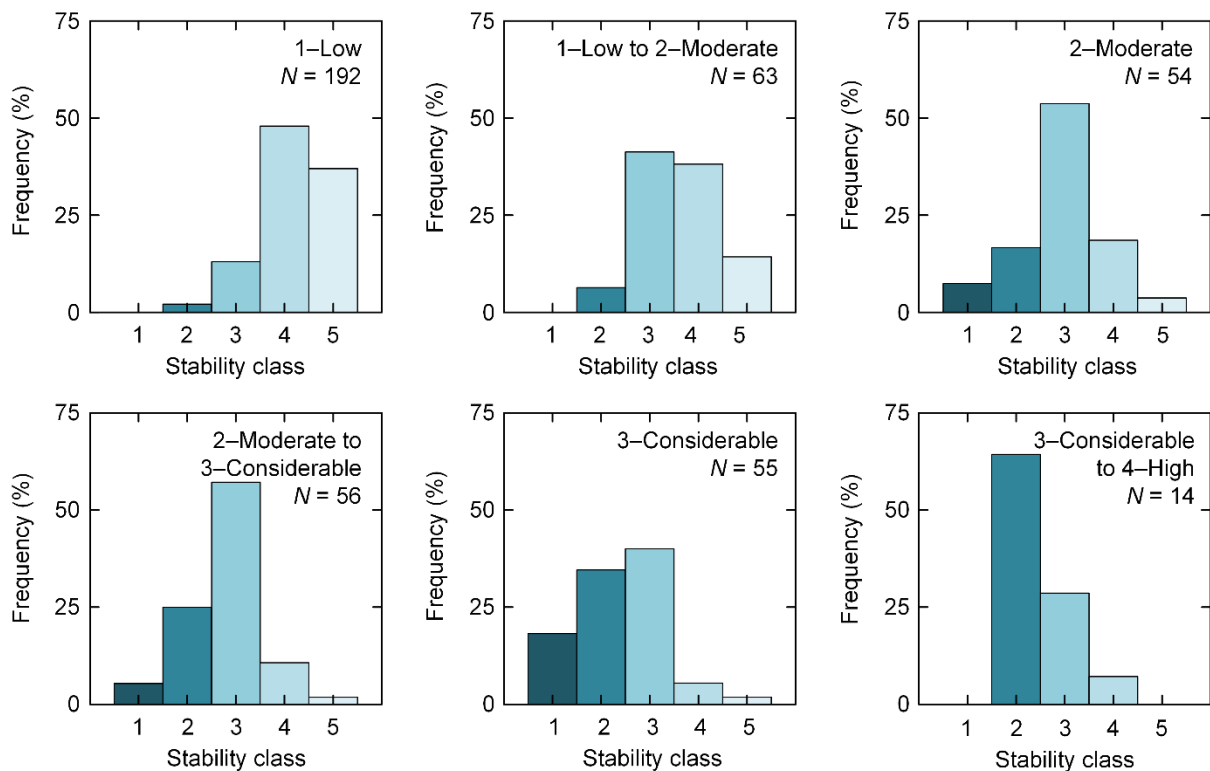
The stability distribution for *1–Low* we found, is slightly more inclined to the unstable classes compared to the distribution from the verification campaigns. There were even a few profiles rated as *very poor* and clearly more profiles rated as *fair* and less as *very good* (proportion test, $p < 0.001$). For *2–Moderate*, the trend was opposite as our distribution was

480 somewhat more inclined towards the stable classes: there were less profiles rated as *very poor*, and more rated as *good* compared to the distribution from the verification campaigns (proportion test, $p < 0.017$). The distributions for *3–Considerable* were similar (*U*-test, $p = 0.25$), again with a slight trend to more stable conditions as the proportion of *very poor* profiles was lower, though the difference was not significant (proportion test, $p = 0.06$). For *4–High*, both analyses suffer from the fact that the number of cases is too low and likely include a substantial observation bias, since observers had, first of all, to consider

485 their own safety while sampling.

The proportions of *poor* and *very poor* rated profiles clearly increased with increasing danger level. For our data set, the proportion were 5 %, 13 %, 49 % and 63 % for the danger levels *1–Low* to *4–High*, respectively. For comparison, the data from the verification campaigns revealed proportions of 2 %, 24 %, 53 % and 64 %. Hence, for *2–Moderate* the proportion was twice as high (proportion test, $p = 0.05$).

490 Recently, Techel et al. (2020) analyzed a large data set of 4439 profiles with RB tests and established stability distributions for the danger levels *1–Low* to *4–High*. They automatically classified stability based on the RB test results into four stability classes (very poor, poor, fair, good). Hence their stability classification approach is slightly different. Still, we can also calculate the stability classes following their approach for our data set. The resulting stability distributions using their

stability classification approach are shown in the Appendix (Figure A1). Again some differences exist, but the main features
495 were reproduced, except for the prominent increase of the proportion of *very poor* stability test results reported by Techel et
al. (2020): 2 %, 4 %, 17 % and 38 % for the danger levels *1–Low* to *4–High*; in our data set the respective proportions were
5 %, 8 %, 20 % and 10 %. The differences exemplify that any stability distribution in part depends on the data set used and
the stability scheme employed.

500 **Figure 10: Frequency distributions for the 5-class stability per danger level from the 8 verification campaigns in the winters 2001-
2002 and 2002-2003; *N* = 434 (updated and adapted from Schweizer et al., 2003).**

Obviously, for the danger level *4–High* it is not feasible to derive stability distributions based on snow stability sampling
by conducting snow profiles with stability tests. The increase of instability, as for instance, expressed with the proportion of
very poor profiles is too low compared to the increases between the lower danger levels. The increase should rather be derived
505 based on avalanche activity. For instance, Schweizer et al. (2020) reported the increase of the average number of dry-snow
natural avalanches per day with danger rating *1–Low* to *4–High* as 1.3, 2.2, 4.8 and 22. This very prominent, well-known
increase from *3–Considerable* to *4–High* cannot be reproduced with stability sampling. Nevertheless, it seems not

straightforward to merge the different data sets to provide a clear answer on how the frequency of locations with very poor stability increases with increasing danger level. Still, the factor is likely larger than 2, rather 3 to 5.

510   The ambiguities found in classification make it clear that "objective" data such as the signs of instability are not sufficient for deriving the danger level. Obviously, even after travelling a day in the field assessing the danger level includes subjectivity. This finding supports the view that any local estimate of the avalanche danger level, even by an experienced forecaster, has to be considered as an informed best guess. In fact, Techel (2020) estimated the reliability of a local nowcast to 0.88, indicating that some variation in local danger estimates exists already at the scale of a warning region (about 100 km^2).

515   A similar agreement rate between different observers was reported by Haladuick (2014). This uncertainty is inherent to "expert verification". In other words, the lack of a quantitative approach not only illustrates that forecasting is by large empirical, it also hampers the development of numerical models and the verification of forecasts.

5   Conclusions

We analyzed a large data set of snow profiles including a rutschblock test (RB), concurrent observations of signs of instability

520   and local danger estimates – to explore relations between snow instability data and avalanche danger.

With a median snow depth of 108 cm and the middle 50 % of the slab thicknesses ranging between 25 and 52 cm the snowpack exhibited characteristics related to an inner-alpine snow climate with frequent persistent weak layers – which often pose a challenge to forecasting. Even with recent snowfall, the majority of the failure layers included persistent grain types – suggesting that the *new snow* problem is commonly accompanied by the *persistent weak layer* problem, at least in the snow

525   climate our data were collected. *Whole block* releases in rutschblock tests were frequently observed with low scores – suggesting that propensity of failure initiation and crack propagation do not decrease independently.

Snowpack observations were classified into five classes of snow stability considering RB score, RB release type and snowpack structure. Snow stability increased with increasing snow depth and was correlated with avalanche danger level. The local estimate of avalanche danger level agreed in 70 % with the forecast regional danger level. The snow stability frequency

530   distributions per danger level, which we established assuming that aggregating the single observations can represent the typical stability distribution, agreed reasonably well with the stability distributions found in previous verification studies. The proportions of *poor* and *very poor* rated profiles clearly increased with increasing danger level. For our data set, the proportion were 5 %, 13 %, 49 % and 63 % for the danger levels *1–Low* to *4–High*, respectively. However, the increase from *3–Considerable* to *4–High* cannot reliably be estimated by stability sampling and should be assessed by the increase in natural

535   avalanche activity, which increases by about a factor of 3 to 5.

Relating signs of instability (whumpfs, shooting cracks and recent avalanches) to the local danger estimate suggests that the presence of shooting cracks, though rarely observed, is most indicative of the danger level *3–Considerable* (or higher)

as the odds ratio was highest. The presence of shooting cracks was also selected as first split in a classification tree. The most frequently observed sign of instability were whumpfs. Their presence was typical at *3–Considerable*. Still, 31 % of the whumpfs were observed when observers rated the danger as *2–Moderate* or even *1–Low*. In the absence of signs of instability the danger level was likely *1–Low*, provided sufficient terrain in the avalanche prone aspects and elevation band is travelled. The discrimination between the three lower danger levels *1–Low* to *3–Considerable* improved when the snow stability class and the 3-day sum of new depth were included into the tree analysis. Still, the danger level *2–Moderate* was not well characterized. Nevertheless, we made an attempt to characterize the danger levels based on the results of the tree analysis by providing some illustrative situations.

Whereas the frequency of signs of instability increases – as does snow instability – with increasing avalanche danger level, the characterization of danger levels with signs instability only is illustrative, but not conclusive. A quantitative description of the danger characteristics is, however, a prerequisite for applying the avalanche danger scale in forecasting and eventually providing consistent forecasts. Our findings and other recent studies suggest that a combination of data on avalanche activity, snow instability (including its frequency distribution) and other field observations are needed to quantitively describe the wide range of snow and avalanche conditions covered by the five avalanche danger levels. In other words, for expert verification or downscaling to a local danger estimate a single set of well-defined observations is presently not available. This lack of objective verification also challenges the development of numerical forecast models.

Data availability

The data set of field observations will become available at www.envidat.ch.

Author contributions

JS designed the study with contributions from CM, BR und FT. CM and FT extracted the data. JS curated and analyzed the data and prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no competing interests.

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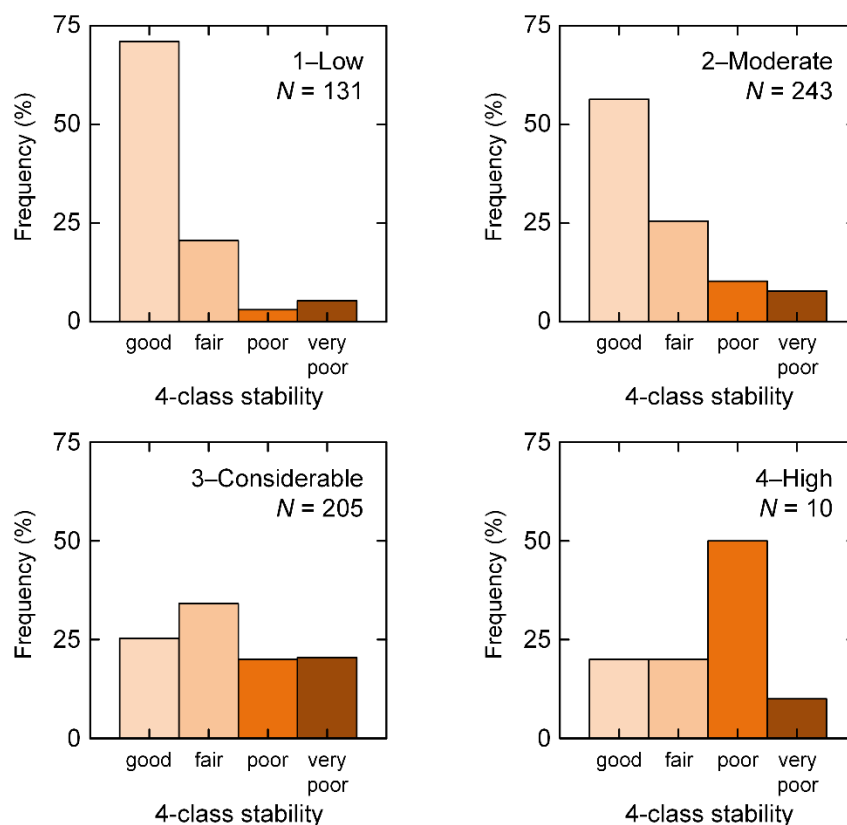
Appendix

For comparison, the distributions for the 4-class stability per danger level is shown (Figure A1). The stability classification into four classes (very poor, poor, fair, good) was introduced by Techel et al. (2020) and solely based on RB score and RB release type, which allows for automated classification.

650 **Figure A1: Frequency distributions for the 4-class stability rating (Techel et al., 2020) at the four local danger levels from *1–Low* to *4–High* (LN, as rated by observers); *N* = 589.**