QUANTIFYING THE OBVIOUS: THE AVALANCHE DANGER LEVEL

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ABSTRACT: The avalanche danger level is the key communication vehicle when it comes to describing the avalanche situation and issuing public warnings. Yet the foundations of the avalanche danger scale are fragile at best – not only from a scientific point of view, but also from an operational point of view they are rather indicative. Still, the avalanche danger level nicely summarizes key elements of avalanche danger: the release probability, the frequency and location of triggering spots and the potential avalanche size. However, none of these three elements is well defined and it is not fully clear how they are finally combined into one number – the danger level. Moreover, temporal and spatial scale issues further complicate the concept. For example, at the danger level *3-Considerable* the release probability is described as possible, which translates into a probability of at least 33-66%. Combined with probabilities for frequency and location of triggering spots, assuming 33-66% corresponds to 'many steep slopes', we obtain a probability of 11-44% of triggering an avalanche. Is the forecast wrong if we ski ten very steep slopes and nothing happens? Obviously, the forecast is valid for a region, not a slope. Still, what does the release probability mean at the regional scale? We attempt to quantify the three key elements that define the danger level by evaluating a large data set of manually observed avalanches. The frequency of natural avalanches strongly increases with increasing danger level confirming that not only the release probability but likely also the number of triggering spots increases – non-linearly. However, no clear increase of avalanche size with avalanche danger level was observed, which suggests that the definitions of the danger levels should be revisited. Moreover, the frequency of wet-snow avalanches was found to be higher at some danger levels than the frequency of dry-snow avalanches, which may hint at inconsistent usage. With regard to proportional quantifiers such 'many', conclusions are not straightforward, but we suggest that 'many avalanches' means on the order of 10 avalanches per 100 km^2. Data sets of manually observed avalanches are known to be inherently incomplete so that our results need to be confirmed using other similarly comprehensive data sets.

KEYWORDS: avalanche forecasting, snow instability, avalanche triggering, avalanche size.

1. INTRODUCTION

Avalanche forecasting is traditionally defined as the prediction of current and future snow instability in space and time relative to a given triggering level (McClung, 2002). The main source of uncertainty in forecasting is the usually unknown temporal evolution and spatial variations of instability in the snow cover including their links to terrain. For these reasons predictability is limited – inversely related to scale (Schweizer, 2008). In forecasting of natural systems, in which variations may or may not be random, a distinction is often made between forecasting and prediction. In our case, prediction means precisely defining when and where an avalanche occurs. Forecasting, on the other hand, implies describing the probability of avalanche occurrence within a certain time frame and area. Given these definitions it is obvious that prediction is not possible – no matter how much we would like it to be – whereas forecasting is certainly possible but inherently includes uncertainty as the forecast is probabilistic (Silver, 2012).

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Even if avalanche forecasting is probabilistic and includes uncertainty, it should be grounded in clear definitions and uncertainty should not stem from nebulous terms but the nature of the problem. In public forecasting, i.e. issuing bulletins describing the avalanche situation, avalanche hazard is described by one of five avalanche danger levels. The danger levels (*1-Low* to *5-Very High*) are defined in the avalanche danger scale originally agreed by the European avalanche warning services in 1993 (EAWS, 2017; Meister, 1995); subsequently a very similar scale was adopted in North America (Dennis and Moore, 1997; Statham et al., 2010).

The avalanche danger levels are defined in terms of the release (or triggering) probability, the frequency and location of triggering spots and the potential avalanche size. All three elements are supposed to increase with increasing avalanche hazard. However, the definitions are short, qualitative description and leave room for widely varying interpretations.

For example, the danger level *3-Considerable* is defined as: "*The snowpack is moderately to poorly bonded on many steep [>30°] slopes. Triggering is possible even by low additional loads particularly on (the indicated) steep slopes [as specified in the bulletin]. In some cases medium-sized [size 3], in isolated cases large [size 4] natural avalanches are possible.*" The definitions include many terms that have a clear meaning in either everyday life or science. For example, '*many*' clearly means that such slopes are frequent, but not abundant, say in the range of 20-50%. However, this percentage range is fully arbitrary, and some people associate many with a percentage >50%. Other proportional quantifiers include *'isolated'*, *'some'*, and *'most'*. A common complete set of quantifiers is actually as follows: *'nearly none'*, *'a few'*, *'several'*, *'many'*, *'nearly all* (Shikhare et al., 2015). How can these proportional quantifiers (imprecise verbal information) be translated into numerical estimates? How many are '*many mosquitos*', perhaps several thousands? We saw '*many bears*', perhaps a dozen? So which number do we relate with '*many avalanches*'?

According to Morgan (2017) such qualitative uncertainty language is inadequate because (among other reasons): (1) the same words can mean very different things to different people; (2) the same words can mean very different things to the same person in different contexts [see above mosquitos vs. bears]. In our case, these proportional quantifiers are obviously linked to scale (i.e. the context). This is even more true for the words expressing likelihood such as '*possible*' or '*probable*'. According to the terminology used by IPCC (IPCC, 2014) '*possible*' corresponds to a likelihood of occurrence of 33-66% probability; likewise '*probable*' corresponds to >66% probability. When the danger level is *3-Considerable*, triggering is '*possible*', hence the probability is 33-66%. Would you ski a slope when the triggering probability is as high? Certainly not. So, is the definition wrong? No, not, if we assume that this probability describes the likelihood that on a sunny day in a given region when the danger level is *3-Considerable*, at least one human-triggered avalanche occurs. But, is this really meant? In any case, the individual triggering probability when you ski a slope is much lower, rather on the order of 0.1% (Jamieson et al., 2009). Still, what does the release probability mean at the regional scale?

Guidance on how to use the scale and assign a certain danger level to a given situation is facilitated by the originally so-called Bavarian matrix (now called EAWS matrix) that shows the various avalanche situations that can be described with a given danger level (Müller et al., 2016). For example, for *2-Moderate* 11 different situations with regard to release probability and frequency of triggering spots exist, 8 situations in case of *3-Considerable*. A recent study that looked at forecast differences across borders of contiguous forecast areas suggests remarkable inconsistencies in the application of the danger levels exist (Techel et al., 2018). This finding is not too surprising given the vague, qualitative definitions of the danger levels. There is definitely a lack of quantification with regard to the three key elements and their links in the avalanche danger scale.

Our aim is therefore to explore a data set of avalanche observations from the region of Davos, Switzerland. We will focus on quantifying the relations between the danger level and the three key elements: release probability (or ease of triggering), frequency of triggering spots and avalanche size.

2. DATA

We analyzed a data set of manually observed avalanche occurrences from the region of Davos (about 360 km^2). Data cover the winters from 1998-1999 to 2016-2017 and include 11,339 individual avalanches, which were all mapped. For each avalanche, we derived avalanche length and width from a rectangle enclosing the mapped perimeter ('minimum bounding geometry'). Based on avalanche length and width we assigned the avalanche size class (1 to 4, according to the Canadian size classification). The number of avalanches per size class were 547, 7992, 2576, 224 for sizes 1 to 4, respectively. In addition, the avalanche records included information on the type of triggering (natural, person, explosives/snow grooming machine, unknown) and the type of snow conditions, i.e. the liquid water content in the starting zone (dry, wet, mixed, unknown); dry and wet refer to dry-snow and wet-snow avalanches, respectively, whereas mixed is less well defined and typically refers to avalanches with dry-snow conditions in the starting zone, but wet-snow conditions in the track or runout zone. The avalanche observations were recorded for 1112 individual days.

We calculated the avalanche activity index for each day using the usual weights for size classes 1 to 4, namely 0.01, 0.1, 1, and 10 respectively (Schweizer et al., 2003). Moreover, we considered the type of triggering again using weights of 1 for natural avalanches, 0.5 for human-triggered avalanches, and 0.2 for the other artificially triggered avalanches (Föhn and Schweizer, 1995). For the avalanches with unknown trigger we assigned a weight of 0.84 since this was the weighted average of the triggering weight considering the frequency of avalanches for the three known triggering classes. In fact, almost all of the avalanches in the unknown triggering class are likely natural avalanches. We also calculated individual AAI's for the combinations of the various types of triggering and types of snow conditions, resulting in 16 different indices for avalanche activity.

We then merged the data set of avalanche observations with the avalanche danger as forecast in the public bulletin for that day and the region of Davos. For a total of 3172 days a danger rating for either dry-snow avalanches, wet-snow avalanche or both types was available. In other words, on every third day with a danger rating at least one avalanche was observed for the 19-year period we analyzed.

An initial quality control showed that on 12 out of 39 days with a danger rating of either *4-High* or *5-Very High* the avalanche activity was zero. For each of these days, we revisited the weather, snow and avalanche conditions in the relevant period and either down-rated the danger or changed the date of avalanche observation when, for example, all avalanche observations from a 3-day storm were assigned to the first or last day of the storm. The latter changes were rare (6 cases) and were only done when the records were obviously erroneous. This procedure reduced the number of days with rating *4-High* from 36 to 21, and with rating *5-Very High* from 3 to 2. On only one day with danger rating *4-High* no avalanches were observed; this seems unlikely, but it was not possible to reconstruct the likely date of occurrence in that well-known storm period in February 1999. Unfortunately, records were in general inconsistent during the major storms in January and February 1999.

The median AAI considering natural avalanches only was 13.6, hence not very high. Further quality checking revealed that there were a number of days with higher avalanche activity but lower danger levels. In total on 51 days the avalanche danger was rated *3-Considerable*, but many natural avalanches occurred. Moreover, there were also days, 16 in total, when danger *2-Moderate* was forecast. Again, we checked all these cases. For 49 of 51 days we increased the rating from *3-Considerable* to *4-High* since the AAI clearly indicated that the avalanche activity had been underestimated at the time of the forecast. On the remaining two days the number of natural avalanches was too low (<10) to justify a change. For 12 out of 16 days with forecast danger *2-Moderate*, we changed the danger level to *4-High* as many avalanches were observed and the AAI was high. For the remaining 4 we changed the danger level to *3-Considerable* as the total number of natural avalanches was too low (<10).

Subsequently, we considered the number of cases with *2-Moderate* danger, but an avalanche activity (only naturals) higher than the median index (1.0) for days with *3-Considerable* danger. There were 77 days with AAI>1.0. In 20 of these cases, the number of avalanches (size 2 and larger) was larger than 10. For these 20 days we changed the danger rating to *3-Considerable*. In 15 out of these 20 cases the avalanches were wet-snow avalanches.

Overall, we changed 105 danger ratings, mostly by one danger level, occasionally by two danger levels (12%); in most cases (88 out of 105: 84%) we increased the danger rating since there was clearly a rather high activity of natural avalanches. In total there were finally 82 days with danger rating *4-High*, still fairly few for 19 winter seasons.

3. RESULTS

3.1 Avalanche activity index

Figure 1 shows the avalanche activity index and Table 1 summarizes some key figures on the avalanche activity with respect to the danger level. The proportion of days when avalanches were observed at a given danger level, increased from 8.3% at *1-Low* to almost 99% for *4-High*. If only natural avalanches were considered, these proportions were 6%, 15%, 33% and 95%. Hence, the increase was far from linear. At *1-Low* and *2-Moderate* natural avalanches were observed at only 1 out of 8 days when these danger levels were forecast. At *3-Considerable*, natural avalanches were recorded every third day and at 4-High at almost all days. The number of avalanches observed increased clearly: at the lower danger levels *1-Low* to *3-Considerable*, the median number of avalanches on a day with avalanche activity was 1, whereas the number was more than 10 times higher at *4-High*, with a median number of natural avalanches of 22. Below we will consider avalanche activity with regard to snow conditions and type of triggering in more detail.

Table 1: Avalanche activity and avalanche size per danger level. The AAI considers all types of avalanches independent of snow conditions and trigger type. Moreover the median number of avalanches per day (natural or artificially triggered) is given, and the total number of avalanches per size class.

Danger level	Number of days	Number of days with AAI>0 (Proportion in %)	AAI Median	Number of natural avalanches (≥size2)	Number of artificially triggered aval. (≥size2)	Avalanche size 1	2	3	4
1	288	24 (8.3%)	0.15	1	0	3	36	8	3
2	1585	371 (23%)	0.22	1	0	65	856	218	14
3	1215	634 (52%)	1.0	1	1	266	3558	975	54
4	82	81 (99%)	22	22	1	213	3542	1371	147
5	2	2 (100%)	32	5	0	0	0	4	6

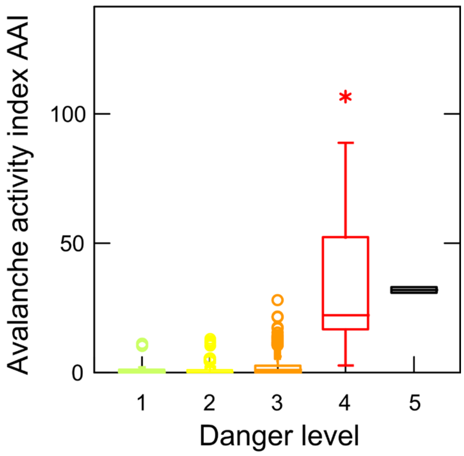

Figure 1: Avalanche activity index AAI per danger level (*1-Low* to *5-Very High*). Only days with AAI > 0 are included; two outliers with AAI > 140 not shown; N = 1112.

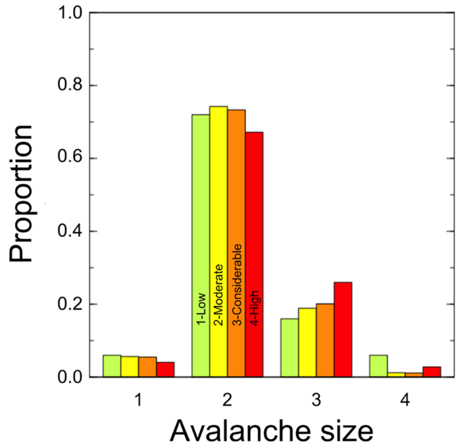

Figure 2: Frequency of observed avalanche sizes (1 to 4) at the danger levels *1-Low* to *4-High*. The overall frequency is 5%, 70%, 23% and 2% for the sizes 1 to 4, respectively.

3.2 Avalanche size

The majority of avalanches recorded were size 2 avalanches (Figure 2). This size was the most frequent at all danger levels, except at *5-Very High* where, however, the records are most likely incomplete. Interestingly, the size distribution was almost independent of the danger level (if *5-Very High* was not considered). At any danger level, 70-80% of the avalanches were size 1 or 2, whereas size 3 and size 4 avalanches were reported in about 20-30% of the days. Size 4 avalanches were most frequent at danger level *4-High*, and about 3 times more frequent than at *3-Considerable*, yet surprisingly there is no remarkable increase of avalanche size with avalanche danger – except that there are slightly more avalanches of size 3 and 4 at danger level *4-High* (Figure 2). On the other hand, at danger level *1-Low* and *2-Moderate* avalanches were not generally smaller, simply avalanches were less frequently observed (Table 1). We will below consider avalanche size in more detail with regard to snow conditions and type of triggering.

3.3 Snow conditions

Considering snow conditions as reported, about half (52%) of all avalanche were recorded as dry, 32% as wet and the remaining 16% as either mixed or unknown, i.e. no type of snow was recorded. The distribution of avalanche sizes within these three classes of snow conditions was similar to the overall distribution (Figure 2). Some differences though existed. Wet-snow avalanches of size 3 and 4 were slightly more frequent (12 and 17%) than dry-snow avalanches; also relatively less wet- than dry-snow avalanches were recorded. Overall a slight trend to smaller avalanches for dry than for wet-snow conditions was observed. Most size 4 avalanches were recorded for mixed or unknown conditions, relatively twice as many as for dry-snow or wet-snow conditions.

Considering the danger ratings shows that there were clearly relatively more wet- than dry-snow avalanches recorded at *1-Low*. Accordingly, the avalanche activity index was ten times larger for wet-snow than for dry-snow avalanches. At danger levels *2-Moderate* and *4-High* the median AAI was similar for dry- and wet-snow avalanches, but the highest values were associated with wet-snow avalanche activity. At danger level *3-Considerable* no differences were observed with regard to avalanche activity and snow conditions, except a slight tendency to somewhat higher activity with dry-snow conditions.

3.4 Type of triggering

Comparing natural to human-triggered dry-snow avalanches showed that overall, i.e. not considering the danger level, the frequency of avalanche sizes again was similar. For both natural and human-triggered avalanches, size 2 avalanches were most frequently observed, in 73 and 70% respectively. However, there were relatively more human-triggered avalanches of size 2 and 3, yet more natural avalanches of size 3 and 4. In other words, there was a clear tendency for larger dry-snow avalanches with natural release, and smaller avalanches with human-triggered dry-snow avalanches.

Considering the danger level revealed that human-triggered as well as natural dry-snow avalanches were rare when the danger was rated as *1-Low*. Only in 5 out of 332 days (1.5%) a human-triggered avalanche was recorded, and in another 5 days a natural avalanche. In total there were 5 human-triggered and 6 natural avalanches, i.e. typically there was one avalanche per day when there were avalanches at all at *1-Low*. The number of recorded avalanches clearly increased with increasing danger level. For the human-triggered avalanches at *2-Moderate* the average number per day is 1.5, at *3-Considerable* 2.6, but at *4-High* it slightly decreases to 2.4. For the natural avalanches, which are more closely related to the release probability, the increase is more prominent: 1.2, 2.3, 4.5, 21 naturals per day with danger rating *1-Low* to *4-High*, respectively. This corresponds to about a 2, 4 and 17 times increase from *1-Low* to the higher levels.

This strong non-linear increase is similar for the number of days that either human-triggered or natural avalanches are observed at a given danger level. As mentioned, human-triggered avalanches at *1-Low* are rare, at only 1.5% of the days with this danger level forecast. The portion increases to 6.9, 22 and 32% for days with forecast danger level of *2-Moderate* to *4-High*, respectively. For natural dry-snow avalanches, the corresponding percentage values are 1.5, 5.7, 18 and 57%.

For comparison, we also analyzed the occurrence of wet-snow avalanches; we assume that all wet-snow avalanches are natural releases and compare them to the natural dry-snow avalanches. Some striking differences emerge. The number of avalanches per day with a given danger level is clearly larger with wet-snow than with dry-snow avalanches. For wet-snow avalanches the numbers are: 1.9, 2.5, 7 and 63 for danger levels *1-Low* to *4-High*. Hence, for example, 3 times more avalanches were recorded under wet-snow than under dry-snow conditions when the danger was *4-High*. Already, at *1-Low* almost three times more wet-snow avalanches were recorded than natural dry-snow avalanches, and as mentioned above the AAI was about 10 times larger.

4. DISCUSSION

We analyzed a data set of visually observed avalanches from the region of Davos (Switzerland). Obviously, visual observations are often biased since during times of poor visibility it is often difficult, and sometimes even impossible, to accurately outline the avalanche extent or record the release date. Hence, our data set certainly does not provide the full picture of avalanche activity. Moreover, there may be other biases as it is, for instance, easier to record wet-snow than dry-snow avalanches. Also the level of reporting varied during the 19 winter seasons with a trend to more observations in the second half of the period. However, this did not change key characteristics such as the size distribution. On the other hand, the data set is very extensive and covers many different avalanche situations.

We then compared avalanche activity to forecast danger level. Again this is far from perfect as one would need the verified danger level to compare with. Whereas we have removed obvious outliers, in other words false forecasts, the comparison may still be biased due to a generally known trend of over-forecasting (Techel and Schweizer, 2017). The analysis also mirrors past and recent practice of applying the danger levels. For example, the danger level *4-High* was relatively rarely forecast. This may partly be explained by the location of Davos, which is somewhat protected from major storms. However, it is also remarkable that similar avalanche activity was often differently rated for dry-snow and wet-snow conditions – at all danger levels.

The avalanche size distribution we found was remarkably robust with regard to different data stratifications. In particular, the size distribution did not depend on the danger level (Figure 2), in other words for our data set, avalanche size did not increase with increasing danger level. However, the number of avalanches increased (Table 1).

The number of natural avalanches can be considered as a surrogate for the frequency of triggering spots. We found a strong non-linear increase in frequency of avalanches with increasing danger level. This finding can be compared to spatial analyses (e.g., Reuter et al., 2016), which are most appropriate to determine the distribution of instabilities. For example, Schweizer et al. (2003) reported an increase of poorly rated profiles from virtually 0% to 24% to 53% for the danger levels *1-Low* to *3-Considerable*, respectively. This corresponds to our finding that the number of natural dry-snow avalanches doubled from *2-Moderate* to *3-Considerable*, and even increased almost three times for wet-snow avalanches.

Whereas natural dry-snow avalanches consistently increased with increasing danger levels, this was not the case for the human-triggered avalanches. The frequency of human-triggered avalanches did not increase from *3-Considerable* to *4-High*. This finding does not mean that triggering becomes less likely but rather reflects terrain usage and the effect of avalanche warnings.

Quantifying verbal descriptors such as '*many*' proved to be rather difficult. If we assume that many natural avalanches are typically observed at the danger level *4-High*, we may conclude that about 10 avalanches per 100 km^2 have to be expected, since in our data set in half of the days when *4-High* was forecast more than 22 natural avalanches were recorded. Moreover, when the definition for *2-Moderate* danger states that "*Large natural avalanche are unlikely*", this definition could as well be modified to "*natural avalanche avalanches are unlikely*" since the probability for any size of natural avalanche at *2-Moderate* is less than 5%.

Whereas our analyses are preliminary and the data set may be partly biased (see above), our findings will allow revisiting the definitions of the avalanche danger scale and potentially suggesting modifications.

5. CONCLUSIONS

We made an attempt to quantify some of the key characteristics such as the release probability and the frequency and size of avalanches at a given danger level. To this end, we analyzed a unique data set of 19 years of visually observed avalanche records, all including mapped outlines and compared avalanche characteristics to the forecast regional danger level.

We found the release probability, expressed as the proportion of days with natural avalanches at a given danger level, to strongly increase with increasing danger level. Remarkably, avalanche size did not increase with increasing danger level, neither for human-triggered nor for natural avalanches. Still, the frequency of avalanches increased, again non-linearly with increasing danger level. At a given danger level the frequency of natural avalanches was typically larger for wet-snow conditions than for dry-snow conditions – potentially reflecting inconsistence usage of the danger scale. Our findings, though preliminary, allow revisiting the definitions of the danger scale and possibly quantifying some of the descriptions. For example, we suggest that '*many avalanches*' may mean on the order of 10 avalanches per 100 km^2.

We are aware that visual observations are notoriously incomplete. Hence, our results should be challenged by similar analyzes with similarly extensive data sets. In future, more comprehensive data sets based on remotely-sensed data and results from avalanche detection systems may allow better founded analyses.

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