TOWARDS A DICTIONARY OF AVALANCHE FORECASTING – DESCRIBING SOME KEY TERMS

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ABSTRACT: Avalanche forecasting is to a large extent a communication challenge. To this end, a good mutual understanding of the underlying concepts and their scientific basis is important. While recent work has paved the way to a more evidenced-based approach, many of the terms used in forecasting still are either loosely defined, not used consistently or clash with colloquial use. While effective communication to the public may need compromises, those should not jeopardize consistency with the scientific basis nor with educational practice. For instance, risk, danger and hazard are often used interchangeably, but are not all the same. Snow stability and avalanche release probability (or likelihood of triggering) are key terms in the description of the avalanche danger scale and often are used intertwined, although they do not refer to the same spatial scale. Spatial scales are indeed another pitfall. While we are finally interested whether an avalanche will occur on a specific slope, avalanche forecasting cannot provide the information at that scale. That would mean prediction of timing and location of a single avalanche event. Instead, we actually forecast avalanche activity at the regional scale. Snow stability is a local property at the point scale, yet its frequency distribution is fundamental for characterizing the avalanche danger level. We describe some of the key terms with a particular focus on scale, relate them to research if available, point out some inconsistencies and suggest further clarifications. With this contribution, we aim to stimulate the discussion on consistent definitions and usage of key terms in avalanche forecasting.

KEYWORDS: Avalanche forecasting, snow stability, avalanche release probability, avalanche danger level

1. INTRODUCTION

Avalanche forecasting is about communicating information on snow and avalanche conditions to the public and regional or local authorities. Typically, a so-called avalanche bulletin is issued, which essentially has the character of a warning to the public. Hence, concise language is key to transfer the message. With the agreement in the 1990s on the standard 5-level danger scale (EAWS, 2022) effective communication could be achieved across countries (Greene et al., 2006). The danger levels had been adapted in North America, after considerable discussion, in particular on the “infamous transition category” between moderate and high (e.g., Dennis and Moore, 1997). To increase effectiveness, the danger description includes information on reasoning and impact (e.g., Golding, 2022). Moreover, the information is often structured with regard to relevance, for instance, by following the so-called information pyramid (EAWS, 2023). Not only while communicating, but also when assessing avalanche danger, consistency within and across forecast services (Techel et al., 2018), for instance in the European Alps, is only achieved, if the usage of the danger scale is based on a common, science-based understanding of the key terms, such as avalanche probability or snow stability distribution.

During the past decade much progress has been made by better defining the terms and the workflow in the forecasting process (Müller et al., 2023; Statham et al., 2018). The main objective was to derive the danger level from snow stability (or avalanche probability) and avalanche size. At the same time, several studies contributed to a science-based characterization of the danger levels (Schweizer et al., 2020; Schweizer et al., 2021; Techel et al., 2020). Not surprisingly, these developments also added confusion since the same or similar terms were used in a different context. Moreover, many of the terms are also used in every-day language with again a different meaning. Some of the difficulties in terminology stem from the fact that certain terms in one language have no direct translation in another language.

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For instance, hazard and danger, often used interchangeably despite subtle differences in usage, only have one equivalent in German ('Gefahr'). Finally, the spatial scale we consider, a single slope (or avalanche path) or an entire (forecast) region, has important implications on the meaning of some terms, e.g., avalanche probability. In the following, we will describe some of the key terms, relate them to research if available, point out some inconsistencies and suggest further clarifications. With this contribution, we aim to foster the discussion on consistent definitions and usage of key terms in avalanche forecasting. Ideally, the terms are self-explanatory and clearly imply the scale they refer to.

2. DESCRIPTION OF SOME KEY TERMS

Given the importance of scale, we will consider two scenarios. In the first, a guide assesses a specific slope while climbing up a basin to a peak in the backcountry. She needs to assess the probability of an avalanche occurring on a specific slope below the peak. This reasoning has often been called **slope stability evaluation**. In the second scenario, we focus on **avalanche forecasting** where the (future) potential avalanche activity (occurrences of avalanches, their likelihood and sizes) in a specific region (≳100 km^2) needs to be assessed by a forecaster (or team of forecasters). Figure 1 illustrates the scales we consider: point, slope, local and regional.

2.1 *Slope stability evaluation*

Slope stability evaluation means assessing the probability of an avalanche occurring on a specific slope. That's the scenario where we are concerned about the probability of an avalanche to be triggered (or releasing naturally) on a given slope and the consequences of this avalanche (potential damage) if we get caught. The **avalanche release probability** and the potential **consequences** (damage) determine the **risk** we face when skiing/climbing the slope (Table 1). The probability to trigger an avalanche will depend on slope stability. Slope stability depends on the spatial distribution of point **snow stability** on that particular slope. In the case of dry-snow slab avalanches, point snow stability refers to failure initiation and crack propagation, and slab strength (Reuter and Schweizer, 2018). Point snow stability can be estimated from a snow pit observation, i.e., combining a snow profile with stability tests such as a rutschblock test (RB) or an extended column test (ECT). Snow stability tests should provide information on critical layering (weak layer and slab), failure initiation and crack propagation. If weak layer strength is low, the weak layer not too deeply buried and the snow in the slab not too loose, a skier can initiate a failure that may start to propagate. Whether the crack will propagate across the slope, in self-sustained manner, will depend on the spatial distribution of point stability on that slope, i.e. whether weak layer and slab properties are similar on the slope. If point stability is variable, the initial crack may arrest or in case of high spatial variability (on the order of ~1 m) will not even start to propagate.

Obviously, we cannot know the spatial distribution of point snow stability on a specific slope. If we have some knowledge on snowpack layering in the basin we travel, for instance on the presence of a persistent weak layer, we can guess whether that very layer may exist on the slope we need to assess. In any case, we can consider the information provided by the avalanche bulletin, although it is targeted at the regional scale, as a base value (or prior) and then refine that estimate. Obviously, it is on average more likely to trigger an avalanche when the danger level is

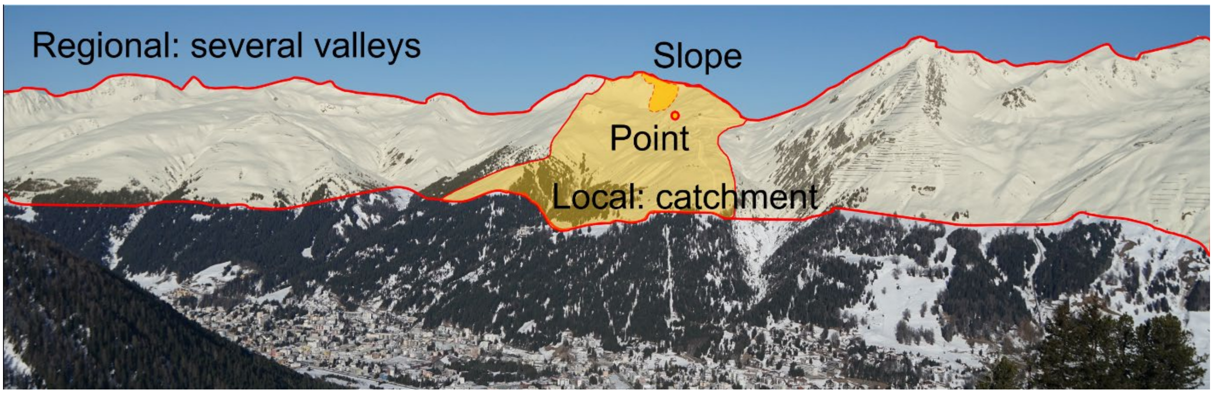

Figure 1: The scales we consider are point, slope, local and regional. The point scale is where we perform stability tests. The slope scale is the starting zone of an avalanche where we assess avalanche release probability (or triggering probability; also called slope stability). The local scale is the basin or catchment we travel in a day and make observations and the regional scale includes several valleys and many basins and is the scale the avalanche forecast is covering, for which the avalanche danger is described in terms of snow stability, its frequency distribution and avalanche size.

3-Considerable than when it is 2-Moderate. However, when assessing a specific slope, we must include local factors such as terrain, snow distribution, prior skiing and any other relevant information that helps us to extrapolate snow stability from snow pit observations or previously observed signs of instability. These data should help to adjust the prior and also to differentiate between slopes of similar aspect and elevation, if we have a choice where to climb or ski. In fact, if we consider several slopes with similar characteristics in a basin, the danger level does not help in selecting which one of these slopes to ski. This will depend on the very local conditions and assessing those becomes key. To do so, we can ask the following questions:

- How likely is an avalanche here and now?
- What are the consequences if I get caught?
- How can we reduce the risk?

Guidance for answering the questions can, for instance, be found in Reuter et al. (2021) or Harvey et al. (2023).

In the present scenario, the (avalanche) risk refers to a single person, or a group, traveling a specific slope. Fortunately, the risk of death due to an avalanche on a single slope is typically very low, on the order of 10^{-3} to 10^{-4} or even lower, obviously depending on conditions and behavior (Jamieson et al., 2009). Accordingly, probability qualifiers such as 'likely' ($\gtrsim 0.66$) (IPCC; Mastrandrea et al., 2010) or even 'certain' are inappropriate when describing avalanche release probability (with consequences ≤ 1). Even in a situation of 4-High or 5-Very high/extreme avalanche danger the natural release probability in a specific avalanche path is often 0.1 or even less, i.e. unlikely (0.33-0.1) or even very unlikely (<0.1) (e.g., Bühler et al., 2019; Schaer, 1995; SLF, 2000). Still, if consequences are high, e.g., if the avalanche path crosses a highway the unlikely event requires closing the highway since the risk to travelers is higher than accepted. In any case, if we consider risk, it always includes consequences (or more formally exposure and vulnerability). This is the technical (engineering) definition: probability of a potentially harmful event to occur (danger or hazard) times exposure (presence of people or values) times vulnerability of those. There is an alternative definition as adopted in ISO 31000:2018. There, risk refers in more general terms to the effect of uncertainty on objectives in the business world (ISO, 2018). Of course, risk can also be determined for larger areas and time scales, for instance, countries and year(s), respectively. However, often the exposure is not sufficiently known and/or additional assumptions are needed to determine risk (e.g., Winkler et al., 2021).

2.2 Avalanche forecasting

In the second scenario, an avalanche center (or service) forecasts the **avalanche danger level** for a region within their forecast area. We start with one of the common definitions of avalanche danger. Greene et al. (2022) describe avalanche danger as *"The potential for an avalanche(s) to cause damage to something of value. It is a combination of the likelihood of triggering and the destructive size of the avalanche(s). It implies the potential to affect people, facilities, or other things of value, but does not incorporate vulnerability or exposure to avalanches. Avalanche danger … is commonly expressed using relative terms such as high, moderate and low."* Greene et al. (2022) also state that danger and hazard are synonymous. In fact, they are often used interchangeably.

The above wording suggests that the definition applies for a single avalanche as well as for multiple avalanches – as also suggested in the conceptual model of avalanche hazard (CMAH; Statham et al., 2018). While it is clear that the local hazard due to a single avalanche also depends on the release probability and the avalanche size, it has the potential for confusion since in general the terms are not scale-independent, as is exemplified by the qualifiers describing the likelihood of triggering. If we consider the likelihood of triggering for a single avalanche, the suggested terms such as 'likely', 'very likely', 'almost certain' (Statham et al., 2018) cannot be correct. This mismatch is known and results from the fact that the definition for likelihood of avalanche(s) in the CMAH is dependent on the forecast's spatial scale (Thumlert et al., 2020). To overcome the scale mismatch, which is explicitly acknowledged in the CMAH, Thumlert et al. (2020) suggested an alternative definition and using frequency descriptions such as *"on average 10-30 out of 100 potential paths will release"* and calling this frequency *"good chance"*.

Given our objective of scale-specific terminology, we assume in the following that avalanche forecasting and so the avalanche danger level always refers to a specific forecast region, i.e. a multitude of potential avalanche starting zones – not a single starting zone. At this regional scale, prediction is feasible, i.e. the uncertainty is not too large, since sufficiently reliable precursory information is available; moreover, verification is possible (McClung, 2000; Schweizer, 2008).

Table 1: Suggested definitions and usage of some key terms

Term	Scale	Definition	How to assess
Snow stability	Point	Point snow stability refers to snowpack layering, propensity for failure initiation and onset of crack propagation.	Snow pit with stability tests (CT, ECT, RB)
Avalanche release probability (or triggering probability, or likelihood of occurrence)	Slope	The probability of an avalanche occurring on a specific slope, either naturally or (human-)triggered. Also called triggering probability in the case of human-triggering.	Reasoning to extrapolate from the point scale to the slope scale by weighing in local observations (from the slope and catchment scale) with regard to the prior, the regional forecast.
Consequences	Slope	The potential damage if being caught.	Anticipate damage based on assessing, e.g., slope size, avalanche volume and terrain in path and runout.
Risk	Slope	The result of combining the avalanche release probability and the consequences.	Reasoning, supported by tools such as DCMR (Reuter et al., 2021).
Slope stability	Slope	The probability of an avalanche occurring on a specific slope (see above). Depends on the distribution of point snow stability on the specific slope.	Extrapolation from the point scale by considering local observations and regional forecast, essentially guessing existence and spatial variations of weak layer and slab properties across the slope.
Avalanche danger level	Regional	Function of snowpack stability, the frequency distribution of snowpack stability and avalanche size.	Traditional experienced-based approach of integrating diverse data, supplement by model results, and supported by tools such as the EAWS matrix or the CMAH.
Snowpack stability	Regional	The lowest relevant stability class in the frequency distribution obtained by virtual sampling of point snow stability in the forecast region.	Reasoning to extrapolate based on diverse stability data from the forecast region. In the future, numerical modeling may provide the necessary statistics.
Frequency distribution of snow stability	Regional	The frequency of the various stability classes obtained by virtual sampling of point snow stability in the forecast region. For assigning the avalanche danger level, only the frequency of the lowest stability class is relevant.	Assessing the frequency of hazard locations where avalanche release is most likely according to the snowpack stability at the regional scale.
Avalanche activity	Regional	Potential frequency, type and size of avalanches occurring in the forecast region within the forecast period, typically the next 24 hours.	Anticipate future activity based on current knowledge on snowpack stability and its frequency distribution, potential avalanche fracture depth, propagation propensity and meteorological drivers.

We suggest the avalanche danger levels are characterized by **avalanche activity** at the regional scale, i.e. the potential frequency, type and size of avalanches occurring in the forecast region within the forecast period, typically the next 24 hours. As the frequency of human-triggering depends on terrain use, foremost at the lower danger levels, it is better to focus on stability (see below).

This characterization is actually rather close to the original formulation as for instance given by Meister (1995). After the introduction of the 5-level danger scale the danger was described as *"the probability of occurrence and the possible extent of avalanches in a particular region, whereby the precise time of triggering and the areas the avalanche will affect are determined by chance."* Another common wording at that time was to describe the danger as function of *"the release probability (the natural stability of the snow cover and the effects of human activities), the distribution and frequency of dangerous slopes, the size and type of avalanches, and the thickness of the sliding snow layers"* (SLF, 1993).

So far, all definitions were qualitative. Only recently, a few attempts were made to characterize the danger levels quantitatively (e.g., Clark and Haegeli, 2018; Schweizer et al., 2020). In particular, Techel et al. (2020) demonstrated that the avalanche danger level is related to snowpack stability, the frequency distribution of snowpack stability and avalanche size. The EAWS has recently adopted this definition (EAWS, 2022).

Snowpack stability

Snowpack stability at the regional scale is the first of the three elements that define the avalanche danger level. As discussed before snow stability is a local property referring to the point scale. Therefore, in the context of avalanche forecasting, which relates to snowpack stability in the forecast domain, i.e. at the regional scale, the term snow*pack* stability becomes a statistical property of the snow stability distribution. This distribution can be estimated, for instance, by many snow stability tests in the forecast region or in the near future by grid-based distributed numerical snow cover and stability modeling (e.g., Herla et al., 2023; Mayer et al., 2023), or possibly in hindsight from avalanche activity observed with remote sensing techniques (e.g., Hafner et al., 2021). Hence, the stability distribution is at best a sample of snow stability in the region – the larger the sample the better.

So far, snow stability, as estimated from stability tests in snow pits, is not a continuous property but an ordinal variable that has ordered categories with unknown distances between categories – just as the danger level. The commonly used categories used are *very poor*, *poor*, *fair*, *good*, and *very good*. These classes primarily describe the artificial triggering part, so that we may well underestimate the frequency in the very poor end of the tail (natural avalanches). Very poor means very easy triggering by a skier or natural release. Very good means triggering is very hard to nearly impossible, since there is no critical weak layer-slab configuration (e.g., Schweizer and Wiesinger, 2001). These stability classes refer to the very test location, the point scale.

Since, in the context of avalanche forecasting, snowpack stability refers to the stability distribution in the region, we need to specify the statistical property that links the point-scale stability estimates to the regional stability: the mean, the median, the modus or the minimum stability? As we focus on instability, the probability of avalanche release, we are concerned about the lowest values in the stability distribution. In other words, we look at the poor end or the tail of the stability distribution. In fact, Techel et al. (2020) showed that the minimum stability class in the stability distribution is decisive to assess snowpack stability, or in other words how easy it is to trigger an avalanche. In most situations there will be at least a few locations with very poor stability, occasionally the lowest class does not exist, and the minimum class is poor. If stability were a continuous variable (modeled or measured), we could focus on something like the 10% percentile.

Frequency distribution of snowpack stability

The second element is the frequency distribution of snowpack stability, so the very same distribution we already considered above. As we have seen above, the minimum stability class is decisive. Now the question is, what is the frequency of the minimum stability class. In other words, how many locations with low stability (hazard locations) exist where an avalanche may occur (aka "triggering spots" in case of artificial release)?

From the frequency distribution of snowpack stability in the region we have estimated above, the ease of triggering, i.e. the minimum stability class. Now we need to estimate the frequency of the minimum stability class, or of the hazard locations. The frequency of the minimum class can be expressed with qualifiers such as "nearly none", "a few", "some", and "many" (Techel et al., 2020). Combining both, the minimum stability class and its frequency, we obtain an estimate of the potential avalanche activity, the property we are aiming for when forecasting regional avalanche danger.

Schweizer et al. (2020) suggested to call the combination of snowpack stability and its frequency distribution the probability of avalanche occurrences (aka likelihood of avalanches). Avalanche occurrence probability refers to the potential avalanche activity in a region, in contrast to probability of avalanche release (or probability of triggering) that refers to a slope or avalanche path (see above).

In the past, the snowpack stability distribution was often interpreted as a *spatial* distribution, i.e. referring to where the triggering spots are located. However, as was already pointed out by Schweizer et al. (2020), the stability distribution does only refer to the frequency of locations with very poor (or poor) snow stability where avalanches can initiate from. In other words, where exactly the points with very poor snow stability are located in the terrain is irrelevant, only their frequency counts, when deciding on a certain danger level. Of course, for backcountry recreationists it would be nice to know where the potential triggering spots are. Sometimes they can be supposed, for example at the transition from a thick to a rather thin snowpack, i.e. at the border of a bowl towards a ridge. This kind information is often provided in the descriptive part of public bulletins.

Spatial aspects

Obviously, there are spatial variations of stability in avalanche terrain. In other words, in some parts of the forecast area, or in some aspects, the hazard locations are more frequent than in others. However, when deciding on a given danger level, we consider the largest possible unit where the frequency distribution does not change significantly when we subdivide the unit, typically described in terms of elevations and aspects. In this unit, the danger level is assessed from the stability distribution. In other aspects, for instance, the stability distribution is different, i.e. the frequency of the minimum stability class is different; for instance, there are only some instead of many locations with very poor stability. In other words, in the slope sectors and elevation band indicated for a given danger level, the frequency of hazard locations cannot further be differentiated. However, in other sectors and elevation ranges avalanches can occur as well, the frequency distribution of snow stability is simply different. The concept of subdividing a region and/or aspect sectors and elevations until the stability distributions do no longer differ was applied by Schweizer et al. (2003) who first provided exemplary stability distributions at a given danger level.

Avalanche size

Finally, the third element is avalanche size. In general, avalanche size is in many situations less decisive than snowpack stability and its frequency distribution – unlike common perception that assumes continuously increasing avalanche size with increasing danger level. In fact, the avalanche size distribution at the lower three danger levels does not vary much (Schweizer et al., 2020; Techel et al., 2020). For deciding on the danger level, given a certain frequency of the minimum stability class, the largest potential avalanche size is considered, since the largest size allows for a better discrimination than, for instance, the typical size (Techel et al., 2020). Again, as in the case of the stability distribution, we focus on the tail of the avalanche size distribution, on the larger end. In general, it is assumed that avalanche sizes follow the Gutenberg-Richter law, i.e. small avalanches are much more frequent than large ones. However, the small ones are often underreported, even more so when very large avalanches are observed. By focusing on the largest size class, this bias becomes less relevant.

Use in forecasting

Analyses based on over 15’000 assessments in Canada following the CMAH revealed that forecasters tended to rate the danger level differently for different avalanche problem types even though the decisive factors likelihood of avalanches and the destructive size were identical (Clark, 2019). These findings highlight that it would be useful to have a reference or lookup table in order to assure consistency when assigning the avalanche danger level. While in Europe, there has long been a matrix supporting consistent usage (EAWS adopted the Bavarian matrix in 2005; Müller et al., 2016), the reality also showed significant differences in danger level usage between forecast centers (Techel et al., 2018). Based on the findings by Techel et al. (2020), the EAWS has developed a lookup table reflecting the refined danger level definitions so that the three elements described above can be assessed individually and then the most appropriate hazard level derived from the combination (Müller et al., 2023).

Risk and danger

Needless to say that in public forecasting we do not forecast risk but danger, even though, impact-oriented warnings are promoted these days in the weather forecasting community and are often called risk-based warnings (e.g., Mu et al., 2018). While it is important to provide information on the potential impact, the risk will depend on the presence of people or values that are typically not known in the often remote areas public forecasts apply to. In case of a thunderstorm warning for a large city, exposure and vulnerability are much better known, and warnings tailored on the risk may be feasible. In the future, we may be able to forecast the risk due to natural avalanches for infrastructure, which is stable/invariable in time and space, provided we can successfully couple snow cover and avalanche dynamics models (aka real-time hazard mapping).

3. SUMMARY

We made an attempt to revisit the definitions of some key terms in slope stability evaluation and avalanche forecasting, taking into account some recent developments and with a particular focus on differentiating between the spatial scales. While some terms can clearly be located, others cannot as easily be assigned to one of the scales we considered: point, slope or regional. Scale issues have traditionally plagued avalanche forecasting and model development. While the CMAH aims at a scale-invariant concept, we suggest that communication among avalanche professionals with different backgrounds may profit from consistent use of certain terms at certain scales. For instance, avalanche release probability clearly refers to a specific location, thus the slope scale; snow stability as assessed from snow pits belongs to the point scale, and in avalanche forecasting the potential avalanche activity at the regional scale is predicted. Overall, terminology is a difficult topic, and we were far from successful in finding clear definitions and usage for all key terms. However, we primarily wanted to provide food for thought, stimulate discussion, and promote international cooperation.

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