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How is avalanche danger described in public avalanche forecasts? Analyzing textual descriptions of avalanche forecasts in Switzerland

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Abstract. Efficient communication in public avalanche forecasts is of great importance to clearly inform and warn the public about expected avalanche conditions. In Europe, avalanche danger is communicated using a pyramid, starting with ordinal categories of avalanche danger, and progressing through avalanche-prone locations and avalanche problems to a danger description. In many forecast products, information relating to the trigger required to release an avalanche, the frequency or number of potential triggering locations, and the expected avalanche size, are described exclusively in the danger description. These danger descriptions are, however, the least standardized part of avalanche forecasts. Taking the perspective of the avalanche forecaster, and focusing particularly on terms describing these three characterizing elements of avalanche danger, we investigate firstly which text symbols are used to describe these elements, and secondly how these descriptions relate to the forecast danger level. We do so through the perspective of the semiotic triangle, relating a referent (the avalanche situation) through thought (the processing process) to symbols (the textual danger description). We analysed almost 6000 danger descriptions in avalanche forecasts published in Switzerland, and written using a structured catalogue of phrases with a limited number of words. Text symbols representing information describing these three elements were labeled and assigned to ordinal classes by Swiss avalanche forecasters. These classes were then related to avalanche danger. Forecasters were relatively consistent in assigning labels to words and phrases with Cohen's Kappa values ranging from 0.67 to 0.87. Nonetheless, even experts were not in complete agreement about the labelling of terms, and were less likely to agree on terms not used in official definitions. Avalanche danger levels were categorised relatively consistently using words and phrases, with for example avalanche size classes increasingly monotonically with avalanche danger. However, especially for danger level 2-Moderate, information about key elements was often missing in danger descriptions. In general, the analysis of the danger descriptions showed that extreme conditions are more frequently described in detail than intermediate values, highlighting the difficulty of communicating conditions that are neither rare nor frequent, or neither small nor large. Our results provide data-driven insights that could be used to refine the ways in which avalanche danger could and should be communicated, especially to recreationalists, and provide a starting point for future studies of how users interpret avalanche forecasts.

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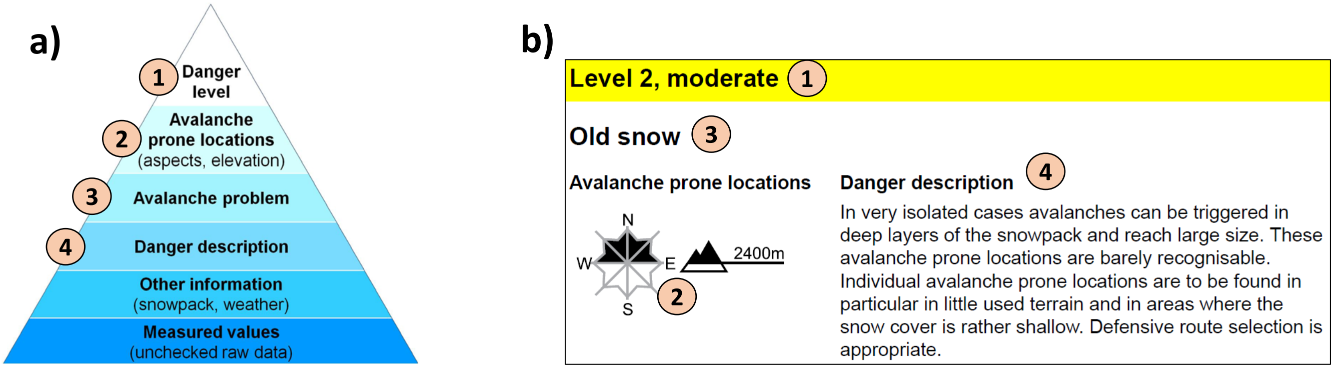

Figure 1. (a) In Europe, avalanche forecasts are structured according to an information pyramid (EAWS, 2017) with the danger level at the top (1), followed by the avalanche-prone locations and the avalanche problem (2 and 3), and a danger description (4) providing further details. (b) Exemplary description of a danger region in the Swiss avalanche forecast (forecast published on 2021/02/26 at 8 am). Even though the danger description is written in present tense, it describes the expected conditions for the 24 hours following publication.

1 Introduction

Avalanche forecasts, as provided in many mountainous regions inform the public about snow and avalanche conditions at a regional scale. To express the complexity of the avalanche situation, forecasts often describe expected conditions systematically, using a hierarchical information pyramid communicating the current regional danger level, the most avalanche-prone locations (*aspects* and *elevation range*, also called the *core zone*), the dominant *avalanche problem*, and a *danger description* (Fig. 1a and b; Engeset et al., 2018; SLF, 2020). Although the communication of the danger level, the corresponding core zone and the dominant avalanche problems are often standardized using common terms or symbols (e.g. in Europe: five danger levels (EAWS, 2018), five avalanche problems (EAWS, 2021), compare also with the example shown in Fig. 1b), the degree of detail and the use of text and graphics varies considerably between forecast products (Burkeljca, 2013; Engeset et al., 2018; Techel et al., 2018). Important information such as the likely triggers required to release an avalanche, the frequency with which such triggering locations will be found in a region, the specifics of the likely locations of these triggering spots, and the expected avalanche sizes are all communicated in the danger description. Even though this information defines the avalanche danger level, its communication is much less standardized and in most European avalanche forecasts (with some exceptions, e.g. in Norway information regarding these values is provided in tabular format (Engeset et al., 2018)) it is communicated as part of a written danger description (cf. Fig. 1b).

Our starting point is an acknowledgement of the semiotic triangle (Ogden and Richards, 1925; MacEachren, 2004), a concept commonly used in linguistics and cartography to explain the relationship between a referent (in our case a current avalanche situation which can be (partially) observed), thought (all of the information that a forecaster or forecasting team assimilates and uses to form a judgement about a situation) and a symbol (the avalanche forecast as communicated). This triangle is helpful as, in contrast to other ways of thinking about avalanche forecasts, it acknowledges that the process of moving from a referent (the avalanche situation) to a symbol (the avalanche forecast) is influenced by those observing and communicating that situation and that this process is not completely knowable. Perhaps the most important aspect of the semiotic triangle with respect to forecasting is that it makes explicit the obvious, but often forgotten, reality that a forecast is an abstraction of a reality, understood by individuals, and communicated through symbols in a particular way.

Taking the semiotic triangle as our basis, we can study danger descriptions from different perspectives. The most important of these is how users of a forecast interpret the symbols used by forecasters to communicate a particular situation. However, this presupposes that these symbols actually communicate useful and consistent information, and that individual forecasters interpret and communicate similar avalanche situations in similar ways. This is essentially a question of forecast quality, and in this paper we address it by exploring the use of textual danger descriptions, as used in Switzerland.

To date, most effort exploring quality and consistency of avalanche forecasts has focused on the forecast danger level (e.g. Elder and Armstrong, 1987; Giraud et al., 1987; Brabec and Stucki, 1998; Techel and Schweizer, 2017; Techel et al., 2018). In comparison, little research has explored either consistency or quality of the symbols and text elements used by forecasters. Most studies have treated the forecast as a product and, for example explored usability by testing whether users were aware of different elements of the bulletin (Winkler and Techel, 2014) or whether users understood the information presented (LWD Steiermark, 2015). Engeset et al. (2018, in Norway) tested the comprehension of text, symbols and pictures, and noted that the ability to comprehend the information provided in the forecast depends on the competency of the user and the complexity of the avalanche scenario. Based on interviews, St. Clair (2019) developed a typology of avalanche bulletin users reflecting the competency of the users to grasp the information provided in the bulletin. Recently, based on a survey, Finn (2020) explored the literacy of bulletin readers of the standardized terms and icons used in the avalanche bulletins in North America (such as listing or ordering the danger levels, identifying avalanche problem icons, or applying information in a slope-choice experiment). Perhaps most relevant to our work is a study by Clark (2019) who explored how forecasters describe the nature of the forecast avalanche problem, with an emphasis on the likelihood of avalanches (which compares to the combination of snowpack stability and the frequency distribution of snowpack stability in Europe) and avalanche size for Canadian avalanche forecast, where this information is provided in graphical format. To our knowledge, there has been no exploration of how forecasters actually describe the avalanche conditions in the danger description, which is formally the least structured yet important element in avalanche forecasts.

Standards used in avalanche forecasting, including the danger scale (EAWS, 2018), the avalanche problems (EAWS, 2021), the avalanche size classification (EAWS, 2019), or the conceptual model of avalanche hazard (Statham et al., 2018), make use of rather specific terms to describe the stability of the snowpack (or what it takes to trigger an avalanche), the frequency distribution of snowpack stability (or how frequent triggering spots are), and what the expected avalanche size and hence the damage potential is. However, there is no official translation of terms characterizing these three elements to the much more varied language used in the text part of avalanche forecasts. Thus, and focusing on the perspective of the forecaster, this leads to our first research question: (1) How do forecasters use language to characterize the trigger required to release avalanches, the frequency of triggering locations or avalanches, and the expected avalanche size, and how consistent are they in doing so? Our second research question builds on this characterisation, and given a consistent use of language asks: (2) How does the use of

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Table 1. Data overview: avalanche forecasts.

type	1-Low	2-Mod	3-Cons	4-High	5-vHigh	all
dry-snow	1031	2245	1836	158	4	5274
wet-snow	177	300	133	13	0	623
all	1208	2545	1969	171	4	5897

2-Mod: 2-Moderate; 3-Cons: 3-Considerable; 5-vHigh: 5-very High

language in danger descriptions relate to avalanche danger? To address these questions, we explored danger descriptions and avalanche danger published in more than 1,000 avalanche forecasts by the national avalanche warning service in Switzerland during eight forecast seasons.

2 Data

2.1 Avalanche forecast

In Switzerland, the national avalanche warning service at WSL Institute for Snow and Avalanche Research SLF, Davos publishes a forecast for the Swiss Alps and the Jura mountains in the evening at 1700 CET[1], valid until the following day at 1700 CET. During the main winter season, the forecasts are updated at 0800 CET, valid until 1700 CET on the same day.

Each forecast describes expected regional avalanche conditions. To communicate spatial variations in avalanche conditions, the forecast area is divided into more than 130 *warning regions*, the smallest spatial units used in the forecast. Depending on conditions, these warning regions can be aggregated flexibly to *danger regions*.

Here, we analyze the 1,286 map-based avalanche forecasts published at 1700 CET during eight winter seasons between 27 Nov 2012 and 13 Feb 2020. 5,897 danger regions were described using the information pyramid by a danger level, an avalanche problem, aspects and elevations where the danger prevails, and a danger description (SLF, 2020, see also example shown in Fig. 1b). Sometimes, if the avalanche situation is complex, a secondary avalanche problem was also described.

For this study, we extracted the forecast danger level (element 1 in Fig. 1), and the respective danger description related to the major problem being either dry-snow conditions or wet-snow/gliding avalanches (elements 4 and 3 in Fig. 1), Tab. 1).

2.1.1 Danger level

The forecast danger level summarizes avalanche conditions at a regional scale using one of five levels (1-Low, 2-Moderate, 3-Considerable, 4-High, 5-Very High) according to the European Avalanche Danger Scale (EADS, EAWS, 2018).

[1]CET or CEST, respectively

2.1.2 Danger descriptions

Each danger region contains a textual description of avalanche conditions. Since November 2012, this text is written using a controlled-language environment, relying on a so-called *catalogue of phrases* (Winkler et al., 2013; Winkler and Kuhn, 2017). In the software used to produce the bulletin, a search-engine module permits sentences or textual elements to be found and selected (Ruesch et al., 2013).

The way these danger descriptions are composed, with a defined number of textual elements, makes these highly suitable to explore the textual content in detail, since the vocabulary to be annotated is constrained.

2.2 Catalogue of phrases

At the core of the danger descriptions lies a catalogue-based translation system, a collection of predefined sentence templates (Winkler and Kuhn, 2017). In the following, we present key factors of the catalogue of phrases.

The application of the catalogue of phrases permits a real-time translation of the German text, the operating language of the forecasters at the national avalanche warning service, into French, Italian and English. In our analysis, we therefore worked with the German danger description. Since its introduction in Switzerland in 2012, the catalogue of phrases has been extended and now also permits Italian as an operating language (Mitterer et al., 2018), and from the beginning of the winter 2020/21 it has been expanded to include further languages.

The catalogue of phrases consists of a number of *sentences*, each with a unique *sentence_name* and *sentence_id*. Each sentence then also consists of a number of *phrase_options*. Finally, phrase_options contain either *values*, the actual textual content, or up to two additional levels of phrase_options, thus allowing an enormous number of possible combinations. An example, illustrating the creation of a single sentence, is shown and explained in Figure 2.

The number of sentences increased from 2012 to 2018 (from 107 to 125) as a result of feedback from the forecasting team, allowing a more varied way of combining phrases and greater variability in describing snowpack structure. However, the most relevant change to our research was introduced in 2018 – following a relabeling of the avalanche size classes by the European avalanche Warning Services (EAWS) in 2018, labels assigned to avalanche size classes 1 to 5 were shifted (Appendix Tab. A1, EAWS, 2019). We accounted for this shift in our analysis.

3 Methods

The catalogue of phrases, the text base for the danger descriptions, contains 9'989 unique values, each clearly linked to a context within a phrase_option and a sentence. As only some values contain information related to the three key factors characterizing avalanche danger - trigger, triggering spots and avalanche size, a two-step approach was used to annotate the text.

First, (step 1 in Fig. 3), individual values in the catalogue of phrases were assigned to one of the three key factors in an iterative annotation process (Sect. 3.1). This step allowed us to retain only the values contained in the catalogue of phrases that describe one of the three key factors, considerably reducing the amount of labeling to be done in the following step. Second,

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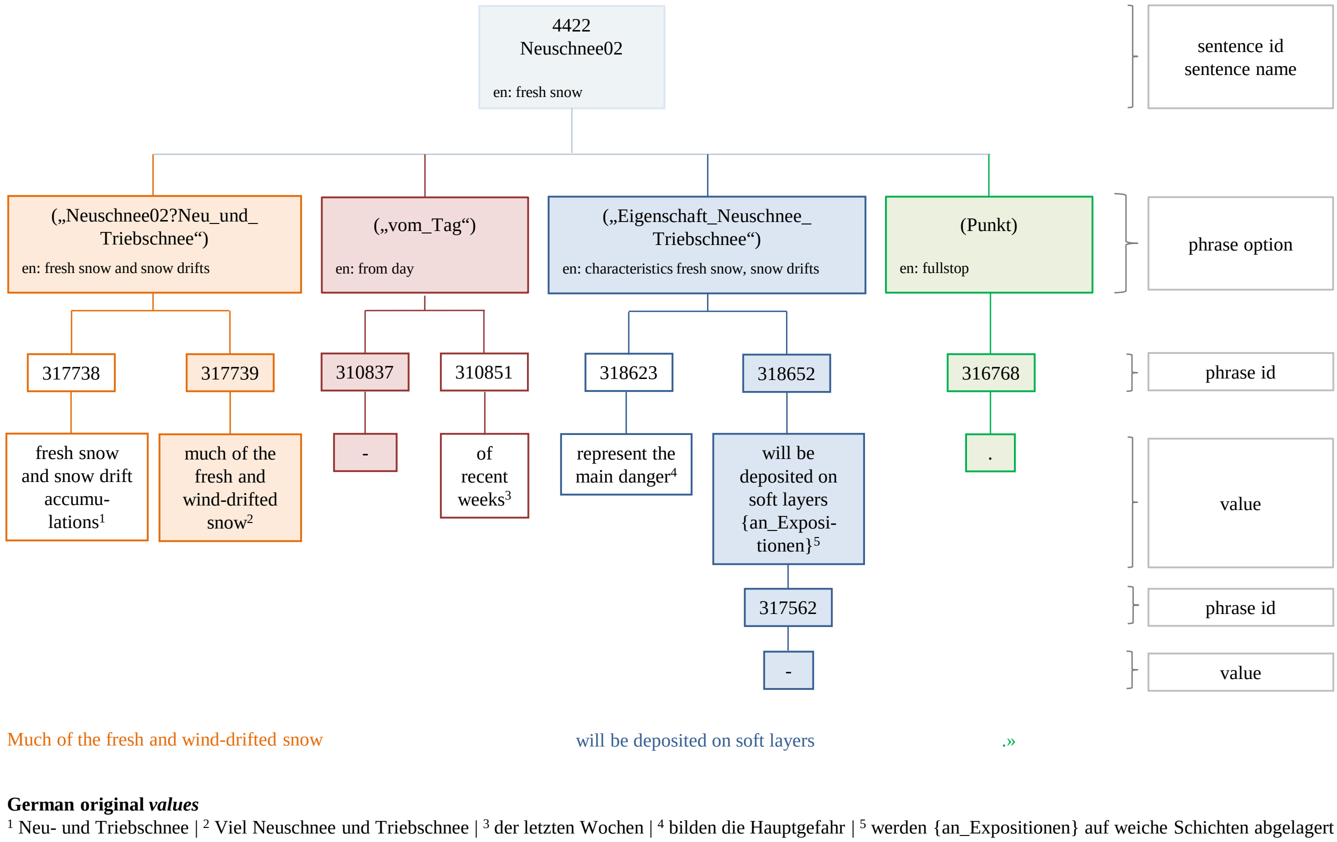

Figure 2. Structure of the catalogue of phrases. A *sentence* consists of *phrase_options*. These must be filled with *values*. In this example, the sentence labeled *Neuschnee02* (sentence id 4422) is selected. This sentence contains four phrase_options, each providing a set of values (text modules). In this example, only two of the possible values are shown. The operational language in the Swiss catalogue of phrases is German.

(step 2 in Fig. 3), the values which characterize the key factors were assigned ordinally-ranked thematic labels according to current practice and/or suggested labeling used in avalanche forecasting or recent research (Sect. 3.2). These two steps allowed to answer research question 1: «How do forecasters use language to characterize the trigger required to release avalanches, the frequency of triggering locations or avalanches, and the expected avalanche size, and how consistent are they in doing so?»

Finally, danger descriptions and the labels assigned to them were analysed with respect to avalanche danger (step 3 in Fig. 3, Sect. 3.3) permitting the exploration of research question 2: «How does the use of language in danger descriptions relate to avalanche danger?»

3.1 Catalogue of phrases: annotation and extraction of values describing key factors

The values in the catalogue of phrases were labeled in an iterative process, described in detail in the MSc thesis by Hutter (2020). Here, we summarize this process (see also Fig. 3 - step 1):

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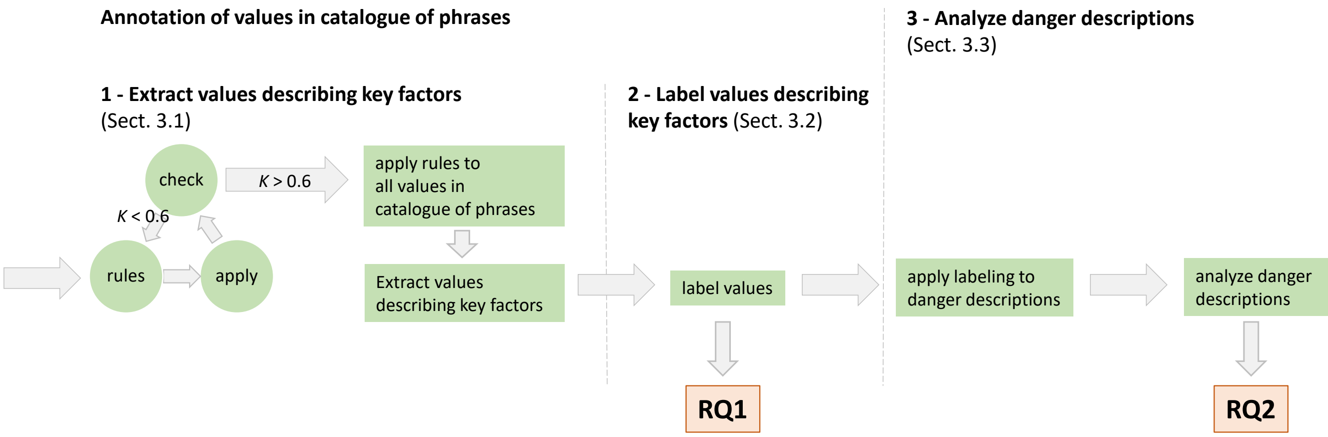

Figure 3. Workflow describing the annotation of values in the catalogue of phrases and the analysis of the danger descriptions. The annotation (step 1) and labeling (step 2) of the values allowed to answer research question 1 (RQ1: «How do forecasters use language to characterize the trigger required to release avalanches, the frequency of triggering locations or avalanches, and the expected avalanche size, and how consistent are they in doing so?»), while the application of the labeling to the danger descriptions (step 3) permitted to answer RQ2 («How does the use of language in danger descriptions relate to avalanche danger?»). For details refer to text.

- (a) Annotation rules were developed based on the definitions or descriptions of key factors in scientific literature and operational guidelines (VH[2]). A short version of the annotation rules is provided as a supplement in the Appendix A2.
- (b) Relying on these rules, all the values in a set of ten randomly selected danger descriptions (two for each danger level) were annotated with regard to which of the key factors they belonged to (VH, FT, RP).
- (c) Following annotation, the inter-annotator agreement score κ (Landis and Koch, 1977) was calculated.
- (d) Steps (a) to (c) were repeated until sufficient agreement in labeling was achieved. We considered a sufficient agreement if the minimal agreement between any of the annotators was $\kappa > 0.6$, which is considered *substantial* agreement according to Landis and Koch (1977). To achieve this level of agreement, three annotation rounds, after each of which the annotation rules were discussed and revised, were carried out. In each of these rounds, ten new danger descriptions were annotated. The agreement between annotators increased from $\kappa > 0.54$ (round 1) to $\kappa > 0.7$ (round 3).
- (e) Applying the annotation rules, the values contained in the catalogue of phrases were assigned to a key factor (VH). As only a small subset was annotated in the three annotation rounds (5% of the values), the assigned labels were quality-checked resulting in the inclusion of two additional values (FT). About 1200 values contained information characterizing one of the three key factors.

[2]two-letter abbreviations indicate who performed the task. Authors: VH - Veronika Hutter, FT - Frank Techel, RP - Ross Purves. Seven other avalanche forecasters are not specified

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3.2 Catalogue of phrases: labeling of values

Once the values were assigned to key factors, the second step was the labeling of the individual values (see also Fig. 3 - step 2).

A first step involved the grouping of values, which were very similar in its meaning (VH). Values considered similar included variations which we judged to be synonymous such as «even in places that are not usually affected» [3] and «even in places that are usually less vulnerable» [4], or singular and plural forms. This reduced the original 1200 values to 109.

To label the values, no further annotation rules were defined as we were interested in how the forecasters (our annotators) understood these values. The number and labels of classes was based on definitions used in avalanche forecasting in Europe (five avalanche size classes and their official labels, EAWS, 2019), or current practice and recent developments or research (natural or artificial triggers as described in the EADS (EAWS, 2018), three classes for the frequency or number of triggering points (e.g. Statham et al., 2018; Techel et al., 2020)) (Tab. 2).

- (i) Three annotators (VH and two forecasters) assigned a single class to the 109 groups of values, including the option to choose that a class could not be assigned. The inter-rater agreement rates ranged from 0.53 (considered *moderate*) and 0.63 (considered *substantial*). 53% of the groups of values were rated the same by all three annotators. More than 20 of the values could not be assigned to a class by at least two of the three annotators.

- (ii) Removing the values which could not be assigned to a class in the first round (i), the eight avalanche forecasters working at SLF assigned one or two classes to values. The inter-rater agreement rate κ was on average 0.74 (considered *substantial*, Landis and Koch, 1977) between any two annotators, but ranged between 0.64 (considered *substantial*) and 0.87 (considered *almost perfect*, Fig. 4). 53% of the values were assigned the same class by all eight forecasters.

If five annotators (a majority) indicated the same class, the value was assigned to this class. If there was no clear majority vote, the value was assigned to the two most frequent classes chosen. The values and their assignment to classes are shown in the Appendix (Tab.s A3 and A4), with their German original, their corresponding English translation, and the assigned class labels. For the remainder of this manuscript, we refer purely to the class labels shown in Tab. 2.

Values which described the location of potential trigger locations were not categorised. An overview of the values is given in the Appendix (Tab. A5).

3.3 Danger description: analysis

Applying the annotated catalogue of phrases to the actual danger descriptions (Fig. 3 - step 3), we were able to analyze the content of the danger descriptions (see also example in Fig. 5). Labels were assigned to values according to Tab.s A3 and A4. Where a value was not clearly linked to a single class, we randomly selected one of the two most frequent labels rather than removing these cases or for always opting for a more unfavorable label. This random assignment was required only for values referring to avalanche sizes (cf. Tab. A4).

[3] original: an sonst wenig gefährdeten Orten
[4] original: an sonst weniger gefährdeten Orten

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Table 2. Number and labels used to describe the key factors. Additionally to the labels shown, a value could also be labeled *not assignable*. The order of the labels corresponds to the rank order used in this analysis with the left-most labels representing the most unfavorable conditions and the right-most label the most favorable conditions.

key factor	categories	labels
trigger	2	natural (expected, possible), additional load (low, high)
frequency	3	many, several, a few
avalanche size	5	5 - extremely large, 4 - very large, 3 - large, 2 - medium, 1 - small

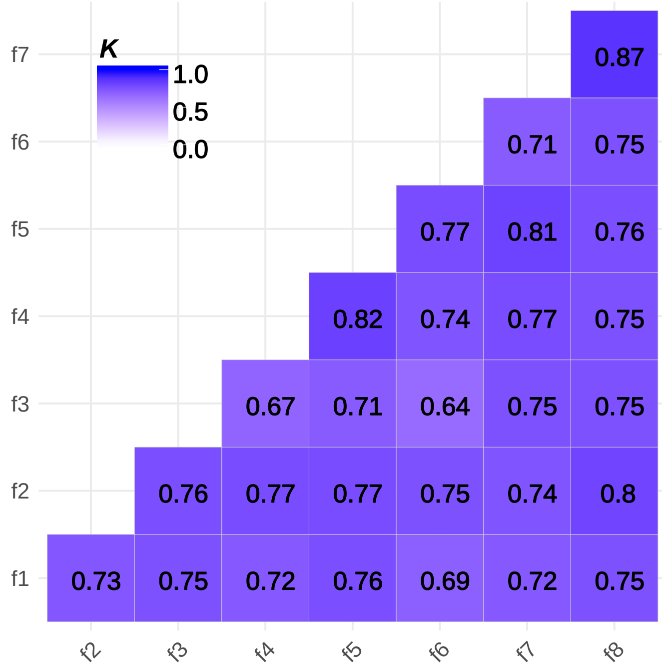

Figure 4. Kappa scores for the eight forecasters (f1-f8). $\kappa > 0.6$ is considered *substantial*, $\kappa > 0.8$ *almost perfect* (Landis and Koch, 1977).

We conducted the analysis in two steps: First, we explored whether information describing the key factors was present in the danger descriptions, regardless of their label. Second, we analyzed the frequency that a certain class was mentioned, considering all danger descriptions of a specific data subset (e.g. a specific danger level). To do so, we searched for the most unfavorable piece of information describing a specific element within a danger description. As shown in Tab. 2, classes are rank-ordered from most unfavorable to most favorable as follows:

- trigger required to initiate an avalanche: *natural release* (with likelihood descriptors *expected* and *possible*), *additional load* (with sub-classes *low* and *high*)
- frequency of triggering locations: *many*, *several*, *a few*

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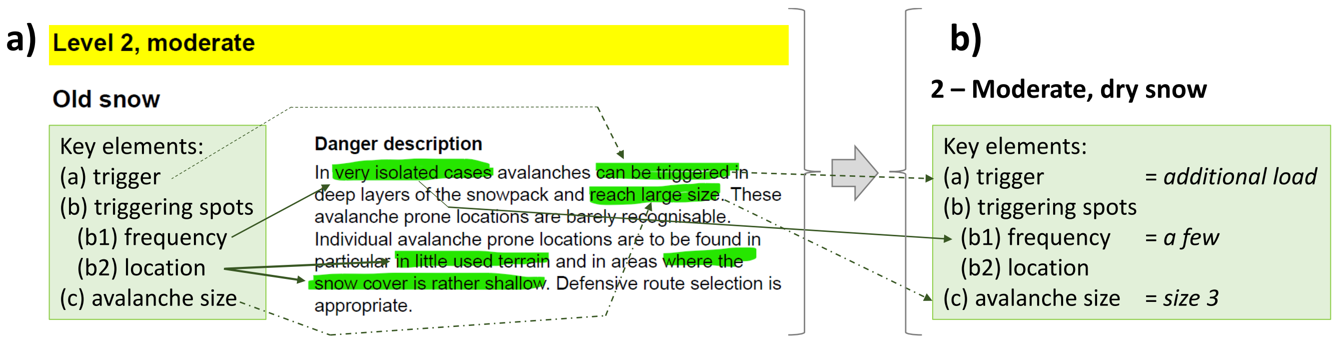

Figure 5. Following the annotation and labeling (Sect.s 3.1 and 3.2), the key factors and their labels were extracted from each danger description. Here, the same example as used in Fig. 1b is shown.

– avalanche size: *size 5* to *size 1*

To compare two proportions, we relied on a one-sided proportion test, testing the hypothesis as to whether the proportion in one subgroup was significantly lower (or higher) than in another subgroup. We refer to results as statistically significant if $p < 0.05$. We show p-values in three classes: $p < 0.05$, $p < 0.01$, $p < 0.001$. All analysis was conducted using *R* (R Core Team, 2020).

4 Results

4.1 Description of dry-snow avalanche conditions

5'274 danger descriptions referred to dry-snow conditions (Tab. 1).

4.1.1 Description of key factors

In the description referring to dry-snow avalanche conditions, avalanche size (68% of cases; example in Fig. 5: *reach large size* = size 3) and the frequency of potential triggering locations (76%; example *very isolated cases* = a few) were described most of the time, while information on the trigger required was provided as often as not (53%; example: *can be triggered* = additional load). Additionally to describing the frequency of triggering locations, 72% of the danger descriptions provided an indication of potential triggering locations (example: *in little used terrain* and *where the snow cover is rather shallow*). A text value indicating either a frequency or a specific location of trigger spots was indicated in 90% of the danger descriptions.

The proportion of danger descriptions providing information on all three elements characterizing avalanche danger decreased from one danger level to the next (Tab. 3). Differences were significant ($p < 0.001$) for all comparisons, except when comparing 5-Very High (75%) and 4-High (52%). The description of 2-Moderate was the most incomplete in this regard: 34% of the danger descriptions described only one (30%) or none of the three key factors (4%, Tab. 3). This proportion is significantly larger than for any of the other danger levels ($p < 0.001$).

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Table 3. Proportion of dry-snow danger descriptions which contained information on the key factors (trigger, triggering spots, avalanche size) for the factors characterized with an *, and for each individual combination of factors. 1 - key factor described, 0 - key factor not described.

factors*	trigger*	triggering spots frequency*	triggering spots location	avalanche size*	1-Low $N = 1031$	2-Mod $N = 2245$	3-Cons $N = 1836$	4-High $N = 158$	5-vHigh $N = 4$
all 3*					0.03	0.21	0.36	0.52	0.75
	1	1	0	1	0	0.05	0.15	0.28	0.50
	1	1	1	1	0.03	0.16	0.20	0.23	0.25
2 of 3*					0.82	0.45	0.46	0.47	0.25
	0	1	1	1	0.78	0.20	0.03	0	0
	1	0	0	1	0	0.01	0.18	0.19	0.25
	1	0	1	1	0	0.04	0.14	0.28	0
	1	1	1	0	0	0.11	0.06	0	0
	0	1	0	1	0.03	0.05	0.01	0	0
	1	1	0	0	0	0.04	0.04	0	0
1 of 3*					0.14	0.30	0.15	0.01	0.00
	0	1	1	0	0.11	0.19	0.02	0	0
	1	0	0	1	0	0.02	0.06	0	0
	0	1	0	0	0	0.06	0.01	0	0
	0	0	1	1	0.02	0.02	0.01	0	0
	1	0	0	0	0	0	0.05	0	0
	0	0	0	1	0.01	0	0	0	0
none*					0.01	0.04	0.04	0	0
	0	0	1	0	0	0.03	0.02	0	0
	0	0	0	0	0	0.01	0.01	0	0

4.1.2 Descriptions of key factors at different danger levels

The trigger required to release an avalanche is either described as natural avalanches or indicating a trigger or additional load (i.e. a person). Potential triggers were rarely specified at 1-Low (3% of cases), more often at 2-Moderate (43%), and most of the time or always at the other danger levels ($\geq$ 88%, Tab. 3). All the danger descriptions at 4-High and 5-Very High (100%) indicated natural avalanches, compared to 33% at 3-Considerable, 2% at 2-Moderate, and 0.5% at 1-Low (Fig. 6a). The proportion of danger descriptions which mentioned natural avalanche occurrence increased significantly from one danger level to the next higher (1-Low to 4-High, $p < 0.001$). Terms used to describe the probability of natural release were *expected* or *probable* indicating a high probability, and *possible* indicating a lower probability. For cases, when either of these terms was indicated, it was generally *expected* or *probable* at 4-High and 5-Very High (88% and 100%, respectively), and mostly *possible* at the other danger levels (1-Low 96%, 2-Moderate 90%, 3-Considerable 76%). An additional load was rarely indicated at 1-Low (3% of the time), and about as often as not at 2-Moderate (41%) and 3-Considerable (55%). If an additional load was specified, it was mostly described as a low additional load at 3-Considerable (98%) and at 2-Moderate (68%), and a high additional load for the few cases which contained this information at 1-Low (72%).

The frequency of potential triggering locations or of the number of avalanches was described about 50% of the time at 3-Considerable and 4-High, and more frequently at the other danger levels ($\geq$ 75%, Tab. 3). When the frequency of triggering locations was described, most frequently it was class *a few* at 1-Low, *several* at 2-Moderate and 3-Considerable, and *many* at 4-High and 5-Very High (Fig. 6c). The proportion of danger descriptions which indicated *a few* locations decreased significantly from 1-Low (87%) to 2-Moderate (33%), from 2-Moderate to 3-Considerable (19%), and from 3-Considerable to 4-High (9%; $p < 0.001$). Similarly, the proportion of forecasts which mentioned *many* locations, increased significantly from 2-Moderate ($<$ 0.3%) to 3-Considerable (3%), and from 3-Considerable to 4-High (36%; $p < 0.001$).

Beside simply describing the frequency of potential triggering locations, a more specific description of where in the terrain these spots were likely to be was provided often at 1-Low (95%) and 2-Moderate (80%), less frequently at 3-Considerable (57%) and 4-High (54%), and rather seldom at 5-Very High (25%). In other words, pointing out specific locations of trigger spots was more often the case at danger levels when the frequency is rather low (*a few* or *several*).

Avalanche size was comparably rarely indicated at 2-Moderate (53% of cases). There was a perfect monotonic correlation between the most frequently indicated avalanche size and the danger level, with, for instance, size 1 being most frequently indicated at 1-Low and size 5 at 5-Very High (Fig. 6e).

In summary, for dry-snow conditions the five danger levels were typically described as:

- 1-Low: additional load, a few, avalanche size 1
- 2-Moderate: additional load, several, avalanche size 2
- 3-Considerable: additional load, several, avalanche size 3
- 4-High: natural avalanches expected, many, avalanche size 4
- 5-Very High: natural avalanches expected, many, avalanche size 5

4.2 Description of wet-snow or gliding avalanche conditions

623 danger descriptions described wet-snow or gliding avalanches as the primary danger (Tab. 1). These were almost always described as natural avalanches ($>$ 96%, Fig. 6b). Natural avalanche activity was described predominantly *possible* at 1-Low (94%), about as often with *possible* (49%) or *expected* (51%) at 2-Moderate, while at 3-Considerable and 4-High natural avalanches were typically *expected* (93% and 100%, respectively).

The description of the frequency of expected avalanches showed a bi-modal distribution with the middle class *several* rarely being used (5%). Furthermore, frequency information was missing in 70% of the cases at 2-Moderate, and 45% of the time

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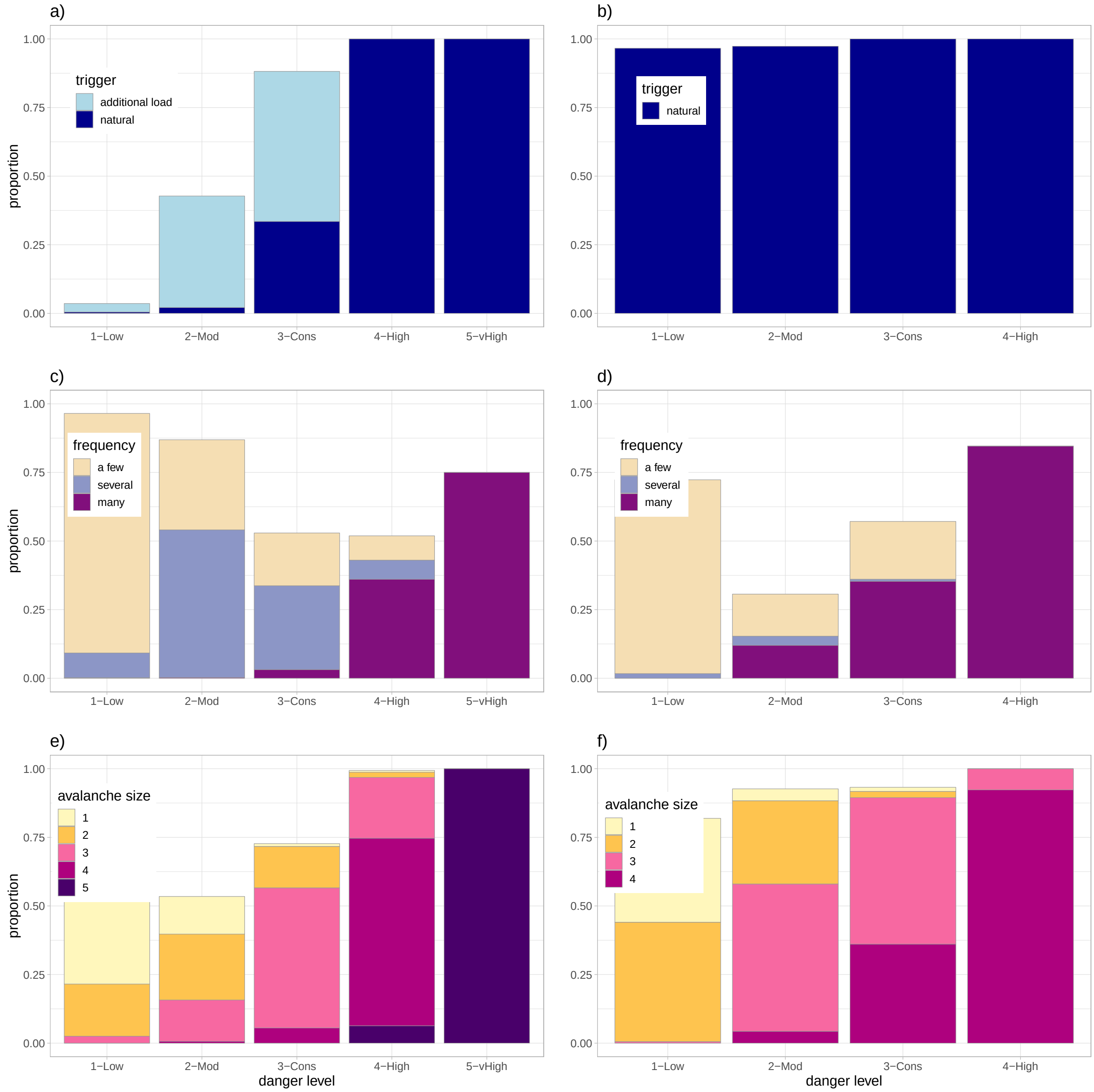

Figure 6. Proportions shown for the values describing the three key factors by danger level. The left column (a, c, e) shows the distributions for dry-snow conditions, and the right column (b, d, f) for wet-snow conditions. The upper row (a, b) shows the trigger, the middle row (c, d) the frequency of triggering locations, and the lower row (e, f) the avalanche size. No data for wet-snow conditions for danger level 5-Very High.

at 3-Considerable (Fig. 6d). When frequency information was indicated, it was essentially always *a few* at 1-Low (98%) and always *many* at 4-High.

Avalanche size was often indicated (> 80% of the time), and increased from size 1 to 2 at 1-Low (46% and 53%, respectively) to size 2 to 3 at 2-Moderate (32% and 58%, respectively), to size 3 to 4 at 3-Considerable (57% and 39%, respectively), to size 4 at 4-High (92%, cf. Fig. 6f).

In summary, wet-snow avalanche or gliding avalanche conditions were typically described as (no data for 5-Very High):

- 1-Low: a few natural avalanches of size 2 are possible
- 2-Moderate: natural avalanches of size 3 are possible
- 3-Considerable: natural avalanches of size 3 are expected
- 4-High: many natural avalanches of size 4 are expected

5 Discussion

Our approach aimed to better understand how symbols, in our case words and phrases from a structured catalogue, are used to convey avalanche danger. In contrast to the relatively small number of other studies which have concerned themselves with the communication of avalanche danger through forecasts (e.g. Burkeljca, 2013; Engeset et al., 2018; St. Clair, 2019; Finn, 2020), our starting point was to explore exclusively how forecasters interpret (RQ1) and consistently use this text to convey avalanche hazard (RQ2). We took advantage of a unique dataset, in the form of forecasts written over eight winter seasons using this structured catalogue in Switzerland to perform our analysis. In the following, we discuss each research question from the perspective of the semiotic triangle introduced in the introduction, consider the implications of our results for users of avalanche forecasts, and list key limitations of our work.

5.1 Consistent use of terms to describe avalanche conditions

To answer the first research question, »How do forecasters use language to characterize the trigger required to release avalanches, the frequency of triggering locations or avalanches, and the expected avalanche size, and how consistent are they in doing so?», we asked forecasters to assign labels to values which we had extracted from forecasts (Sect. 3.2, Tab.s A3, A4). This annotation process was a necessary step in exploring our second research question, since we needed these labels to understand how avalanche danger was described by forecasters. However, equally importantly, it gives us insight into the degree to which a trained team of forecasters used language to describe different characteristics of avalanche danger. Since the task was performed in isolation - that is to say forecasters classed terms independently of a given avalanche situation or referent, we believe it relates to one side of the semiotic triangle - namely the relationship between thought (the abstraction of an avalanche situation by a forecaster) and symbol (the language used to convey this situation). Although the overall agreement in the assigned labels between forecasters was rather high (cf. Fig. 4, $\kappa > 0.67$), with 50% of the text symbols being assigned to the same class by all forecasters, it is important to note that these values are based on expert annotation by a team working together on a daily basis.

By zooming in to the individual classifications, it is possible to identify areas for discussion in the forecasting team with regard to three issues. Firstly, we identified a number of terms present in the structured catalogue which were never used by the forecasters. Secondly, the terms used most consistently were those taken directly from definitions. For example, there was 100% agreement about the use of terms used in the definition of avalanche size classes (e.g. small avalanche for a size 1 class avalanche or very large avalanche for a size 4 class avalanche). Thirdly, other terms were considered more ambiguous by the forecasters, with for example rather small avalanches being considered by 4 forecasters as representative of size class 1 and 4 forecasters of size class 1 – 2. This difference matters since size 1 avalanches are typically not associated with burials, while size 2 may «bury, injure or kill a person» (EAWS, 2019), and as size 2 avalanches are a typical class leading to burials of recreationalists in Switzerland.

In general, annotating and assigning words and phrases to particular situations gives very valuable insights into the ways in which avalanche forecasters provide information to the public.

5.2 Characterisation and consistency of danger descriptions

Our second research question asked »How does the use of language in danger descriptions relate to avalanche danger?»

Answering it provides us with knowledge as to how forecasters take a referent, in this case the expected evolution of the avalanche situation over the next 24 hours, and represent it through language. The annotations of words and phrases used in the avalanche forecast allow us to firstly characterize how avalanche danger is described, and secondly explore the consistency of descriptions of similar avalanche danger.

The description of the three elements characterizing the danger level - the trigger required to release an avalanche, the frequency of triggering locations, and the expected avalanche size, varied in their degree of completeness. Perhaps most importantly, danger level 2-Moderate avalanche danger in dry-snow conditions was characterized by all three factors only 21% of the time, and commonly (30%) of descriptions only mentioned 1 factor (most often the likely triggering spots of avalanches) (Tab. 3). Since in Switzerland many avalanche accidents happen at this level of forecast avalanche danger (e.g. Winkler et al., 2021), characterising the likely consequences and triggers of these avalanches more often may be useful in communicating the situation. For danger levels 3-Considerable and 4-High, the frequency of triggering locations was missing about half the time (Fig. 6c).

The distribution of missing information is clearly not random, and reflects systematic choices made by the forecasters in translating the avalanche danger (referent) to a danger description (symbol) through a thought process which is unknown to the user of a forecast. It appears that the cases where information is missing are those where values would likely describe the middle ground rather than the extremes. Since this middle ground is exactly where the interpretation of an avalanche forecast is likely to be more important and difficult for a recreationalist, and given that avalanche danger definitions include all three factors at all levels of avalanche danger, it is important to consider further the likely influence of missing information on users.

Irrespective of whether factors are described in a forecast, it is also important that the factors included are used consistently. In general, we found this to be the case and the description of the elements characterizing avalanche danger changed significantly from one danger level to the next (Fig. 6). As shown in Sect. 4.2, dry-snow and wet-snow avalanche conditions were described differently: natural avalanches are essentially always mentioned in danger descriptions describing wet-snow or gliding avalanches, regardless of danger level (Fig. 6c), while in dry-snow conditions primarily at 3-Considerable or higher danger levels (Fig. 6a, b). Differences also exist regarding the largest expected avalanche size: these tended to be larger for wet-snow than for dry-snow avalanche condition. For instance, for cases when avalanche size was described, size 3 avalanches were the most frequently expected avalanche size at 2-Moderate in wet-snow conditions (55%), and at 3-Considerable in dry-snow conditions (50%, Fig. 6e, f). These findings correspond well with a study exploring a large data set of avalanche occurrence data in the region of Davos (Eastern Swiss Alps), which showed that the largest observed avalanche was larger and that the number of natural avalanches was higher for wet-snow avalanches compared to dry-snow avalanches on days with the same forecast danger level (Schweizer et al., 2020). Although this means that the description of the forecast corresponds to observations, it also highlights an inconsistency in the application of the danger levels allowing more natural avalanches at larger size in wet-snow conditions than dry-snow conditions. This may also be one explanation for variations in the use of the danger levels in Switzerland, compared to - for instance - its neighbours in Italy (Techel et al., 2018). Furthermore, it highlights the considerable freedom left to interpret the qualitative descriptions of the five danger levels when assigning a danger level.

5.3 Implications for users of the avalanche forecast

The purpose of an avalanche forecast is, in the case of recreationalists, to provide useful information aiding decision making in planning and carrying out activities. The first requirement for a useful avalanche forecast is therefore that it is correct and consistent. Our results show that in general, the use of language to communicate and specify avalanche danger is (reasonably) consistent between forecasters and correlates with forecast avalanche danger.

However, our work explored the semiotic triangle from a single perspective – that of expert forecasters. It reveals that forecasters use of language to describe avalanches situations is more consistent using words and phrases which relate directly to definitions, and that the characterisation of avalanche danger is least complete where the situation is more ambiguous. Leaving out information, for example the likely triggers or size classes of avalanches expected for danger level 2-Moderate, may, for forecasters, actually convey information about the situation. However, it is unlikely that users of an avalanche forecast will interpret absence of information as information. One potential way of addressing this issue is by providing a yet more structured format, such as that used in Norway or in Canada, where important characteristics describing avalanche conditions, like the expected avalanche size or whether natural avalanches are expected, are provided in tabular format (Norway) or graphically (Canada). However, such approaches still assume that forecasters are able to classify information about all factors unambiguously. Our results suggest that, at least for non-extreme situations, this is rather difficult.

We suggest that future work on understanding how users interpret avalanche forecasts pays heed to important insights from our work. Firstly, our results suggest that communication of non-extreme situations is critical, and most subject to ambiguity and lack of information. Since these situations are also where most recreationalists are involved in accidents, exploring how avalanche danger is interpreted and used in decision making by users is most important here (e.g. St. Clair, 2019; Finn, 2020). Secondly, thinking about how the forecast is created (in our case using the semiotic triangle) helped us to interpret and understand our results.

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5.4 Limitations

We explored danger descriptions from avalanche forecasts published in Switzerland, using a structured sentence catalogue, where the operational language used by forecasters was German. Thus, care is required in generalising our results to forecasts published by other warning services in other languages, even where the same avalanche danger scale is in use. For instance, Techel et al. (2018) noted a different use of danger level 4-High in France and parts of Italy, which may indicate that these are interpreted in a slightly different way compared to forecasts issued in Switzerland or Austria.

Words and phrases were annotated by the forecasting team, who always work in pairs, and thus are very familiar with both the structured sentence catalogue and the avalanche situation in Switzerland. Our interannotator agreement may be therefore higher than for avalanche warning services where forecasters work alone, or where free text is used to write forecasts. Furthermore, situations with 4-High and 5-Very High avalanche danger were much rarer (N=158; N=4, respectively) than the large number of danger descriptions for danger levels 1-Low to 3-Considerable.

Finally, the structured sentence catalogue was not completely static in time (Hutter, 2020). Although we took account of changes to the available words and phrases, these changes (and changes to the various definitions used for, for example, avalanche size; EAWS, 2019) are likely to have influenced the interpretations made by the avalanche forecasting team in their annotation, and to the use of language in forecast.

6 Conclusions

We analysed the text describing the expected avalanche conditions in almost 6000 danger descriptions, written relying on a catalogue of phrases, published in the public avalanche forecast in Switzerland. We focused specifically on three factors described in the textual danger description: the trigger required to release an avalanche, the frequency of potential triggering locations, and the expected largest avalanche size, and their relation with the issued danger level. To conduct this analysis, the Swiss avalanche forecasters assigned categories to individual terms used in the danger description. Although the agreement in the labeling was rather high - 50% of the terms were assigned to the same class by all eight annotators, not all terms could be assigned to a specific class by some forecasters.

When we linked the factors used in danger descriptions to avalanche danger we found that, especially for 2-Moderate avalanche danger, only 21% of descriptions used all three factors and 30% of descriptions mentioned only a single factor. Furthermore, avalanche size classes are used differently to describe dry-snow and wet-snow or gliding avalanche conditions. The results highlight the demand to review and harmonize the use of terms to describe the trigger required to release an avalanche, the frequency of potential triggering locations, and the expected largest avalanche size, and their relation to the danger level. Since our approach is data driven, it provides very clear pointers as to terms which are used inconsistently or not at all by forecasters, and thus gives a valuable framework for forecasting services in reviewing the quality and consistency of written forecasts.

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However, we focused exclusively on the perspective of Swiss forecasters working in German. Our results cannot be directly transferred to other forecasting services and languages, and the analysis was greatly simplified by use of the sentence catalogue used to write Swiss avalanche danger descriptions.

Future work should also explore the perspective of the user of the avalanche forecast. Are danger descriptions the best-possible way to communicate important pieces of information including avalanche size or the occurrence of natural avalanches? Do users interpret this information in similar ways to forecaster?

Code and data availability. Code and data will be made available at the data repository of the Swiss Federal Institute for Forest Snow and Landscape Research WSL www.envidat.org.

Author contributions. This contribution is based on the MSc thesis by VH (Hutter, 2020). VH developed the study design, performed the annotation of the values and the initial analysis. FT and RP supervised the MSc thesis. For the purpose of this manuscript, FT re-analysed a subset of the data used in the MSc thesis, and conducted the survey of the avalanche forecasters. FT and RP wrote the manuscript, VH provided repeated feedback on the manuscript.

Competing interests. None.

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Appendix A: Data and Methods

Table A1. Shift in textual labels assigned to avalanche sizes according to the European avalanche Warning Services (EAWS) in 2018 (until 2018: SLF (2017), since winter 2018/19: (EAWS, 2019; SLF, 2019).

size class	label	
	until 2018	since winter 2018/19
1	sluff	sluff, small
2	small	medium
3	medium	large
4	large	very large
5	very large	extremely large

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Table A2. Annotation rules.

key factor	Assign expressions which indicate…
triggering level or release probability	… the occurrence of natural avalanches (e.g. *spontaneous*) or the probability of an avalanche release (e.g. *to be expected*) or the trigger required to release an avalanche (e.g. *human*). Consider also temporal aspects (e.g. *avalanches are possible any time*).
frequency and location of triggering spots	… the frequency or location of triggering spots. Distinguish between terms which indicate a frequency or number (e.g. *many* → frequency), and a location in the terrain (e.g. *close to ridge line* → location) describing triggering locations.
avalanche size	… an avalanche size. Consider terms officially defined by EAWS (Tab. A1, e.g. *large*, 2019), but also those which may be considered synonyms or placeholders for an avalanche size (e.g. *fairly large*).

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Table A3. Labels assigned to German text values, including the proportion of forecasters who assigned the respective label - sub-label combination to this value or group of values (in brackets), and their corresponding English translations. Bold - value was used during the eight years.

key factor	label	sub-label	german	english
trigger	natural		**spontan** (1); **(jederzeit) möglich** (1); **zu erwarten** (1)	**spontaneous / occur naturally**; **(any-time) possible**; **to be expected, proba-ble**
	additional load	low	**einzelner Wintersportler** (1); **Person** (0.88); **mit kleiner Belastung** (1); **störanfällig** (0.75); **können (sehr) le-icht ausgelöst werden**; **leicht auslös-bar**; Auslösebereitschaft ist (recht/sehr) gross; **Entlastungsabstände** (0.75)	**single winter-sport participants**; **per-son / human**; **even in case of small load**; **prone to triggering**; can be re-leased (very) easily; the release proba-bility is (rather/very) high; **maintaining distances between individuals**
		low or high	**auslösbar** (0.75); **können ausgelöst werden** (0.75); Bergsteiger (0.63); Fussgänger (0.63)	**capable of being triggered**; **can be re-leased**; climber; hiker
		high	**mit grosser Belastung** (1); Gruppe Per-sonen (1); Sprengung (1); gesprengt (1); kaum auslösbar (1)	**with large additional load**; group of people; explosives-triggered; unlikely to be released

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Table A4. Labels assigned to German text values, including the proportion of forecasters who assigned the respective label to this value or group of values (in brackets), and their corresponding English translations. The labels shown below were assigned afterwards according to Techel et al. (2020). Not shown are values which could not be assigned to a label (step 1, Sect. 3.1). Bold - value was used during the eight years.

key factor	label	german (proportion)	english
avalanche size	size 1	**kleine Lawine** (1); **Rutsch** (1); **Mitreiss- und Absturzgefahr** (1)	**small avalanche**; **sluff**; **danger of avalanches sweeping people along and giving rise to falls**
	size 1 or 2	**eher klein** (0.5); **nebst Verschüttungsgefahr vor allem Mitreiss- und Absturzgefahr beachten** (0.75)	**rather small**; **apart from the danger of being buried, restraint should be exercised in view of the danger of avalanches sweeping people along and giving rise to falls**
	size 2	**mittlere Lawine** (1)	**medium-sized avalanche**
	size 2 or size 3	**recht / ziemlich / gefährlich gross** (0.65)	**fairly / rather / dangerously large**
	size 3	**grosse Lawine** (1)	**large avalanche**
	size 4	**sehr grosse Lawine** (1); **Tallawine** (0.38); **bis in Tallagen**; grosse Tallawine (0.75)	**very large avalanche**; **avalanches capable of reaching the valley**; large avalanches capable of reaching the valley
	size 4 or size 5	**können ins Grüne vorstossen** (0.5)	**capable of reaching a long way into areas with no snow cover**
	size 5	**extrem grosse Lawine** (1); **können sehr/aussergewöhnlich weit vorstossen** (0.63); ausserordentlich gross (0.75); sehr grosse Tallawine (0.75); Lawinen, welche die üblichen Lawinenzüge in Länge oder Breite übertreffen (0.75)	**extremely large avalanche**; **avalanches capable of exceeding the length or width of the usual paths**; exceptionally large; very large avalanche capable of reaching the valley; capable of reaching a very / an exceptionally long way
frequency	low / a few	**(sehr) vereinzelt** (1); **lokal** (0.88); **(sehr / eher) selten** (0.63-1); **(nur) wenige** (1); **einzelne** (1)	**(very) isolated**; **in some localities**; **(very / rather) rare**; **(rather) few / a few**; **locally**
	medium / several	**teilweise** (1); **teils** (1); **stellenweise** (0.63); mehrere (0.88)	**in some cases**; **in some places**; several
	high / many	**(sehr) viele** (0.88-1); **zahlreiche** (1); **(weit) verbreitet** (0.63-1); **viele Stellen** (0.88); **vielerorts / an vielen Orten** (0.88); **allgemein** (0.63); **(sehr / recht) häufig** (0.63-1); **(sehr) oft** (0.5-1)	**(a great) many**; **numerous**; **(very) widespread / over a wide area**; **many locations**; **in many places**; **(very / rather) frequent**; **(very) often**

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Table A5. Text values providing location-specific information. Numerous combinations and variants exist. Not shown are values describing aspect and elevation, as these are normally shown in the aspect-elevation plot (cf. Fig. 1b), and values which were not used in the analysed forecasts. This list should therefore be seen as an example rather than an exhaustive list.

german	english
kammfern	at a distance from ridgelines
windgeschützte Lagen	protected from the wind
Geländekanten	behind abrupt changes in the terrain
Felswandfüsse	base of rock walls
Passlagen	pass areas
Kammlagen	adjacent to ridgelines
Gipfellagen	the vicinity of peaks
Böschungen	cut slopes
Grashänge	grassy slopes
felsdurchsetztes / absturzgefährdetes Gelände	rocky terrain / in terrain where there is a danger of falling
(steile / sehr steile / extrem steile) Hänge / Gelände	(steep / very steep / extremely steep) slopes / terrain
Übergänge von (wenig zu viel Schnee)	at transitions from a shallow to a deep snowpack
in Randbereichen	at their margins
bei Einfahrt in (Rinnen / Mulden)	when entering (gullies / bowls)
schneearme Stellen	where the snow cover is rather shallow
Triebschneehänge	wind-loaded slopes
(hoch gelegenen / (noch nicht entladenen) Einzugsgebieten	(high-altitude) starting zones (that have retained the snow thus far)
häufig befahrenes Variantengelände und Tourengelände	highly frequented off-piste terrain and on popular back-country touring routes
selten befahrenes Gelände	in little used terrain
Waldgrenze	at tree line