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On the correlation between the forecast avalanche danger and avalanche risk taken by backcountry skiers in Switzerland

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ABSTRACT

Rule-based decision frameworks are widely recommended to estimate the avalanche risk while planning a ski tour. However, these frameworks were developed relying primarily on accident data and usually did not consider backcountry travel data. Hence, they are not risk-based. Here, we address this gap and calculate the risk taken during backcountry touring in avalanche terrain and correlate it to the expected avalanche conditions as described in a public avalanche forecast. For this, we rely on 784 reported avalanche accidents and more than 2.1 million movement points in potential avalanche terrain, based on GPS tracks recorded in Switzerland for 14 winter seasons. Combining this data with the respective avalanche forecast, we show that risk increases fourfold from danger level 1-Low to 2-Moderate, and from 2-Moderate to 3-Considerable. Furthermore, at 2-Moderate and 3-Considerable, in the critical elevations and aspects specified in the avalanche forecast, the risk is nearly six times higher compared to locations outside this, so-called, core zone. For danger level 1-Low, where the Swiss avalanche forecast does not provide any information about the critical elevations and aspects, we derived a risk-based core zone. Within this core zone too, the risk is about six times higher than outside. These findings suggest an adaption of the rule-based decision frameworks to reflect the observed risk better. The proposed framework considers the strong influence of the elevation and reduces the effect of the aspect, compared to former decision frameworks. We emphasize that this new decision framework cannot replace on-site risk assessment. However, it allows backcountry users to come closer to the goal of achieving a minimum of avalanche risk while allowing a maximum of freedom of movement.

1. Introduction

Avalanches are a main hazard in snow-covered mountains. In Switzerland they cause on average 22 deaths per year (Zweifel et al., 2019) and are, as in some other countries, the deadliest natural hazard (Badoux et al., 2016). In the Alps, most avalanche accidents occur during leisure activities in unsecured terrain, like backcountry touring on skis or snow-shoes, or off-piste riding adjacent to ski areas (e.g. Techel and Zweifel, 2013; Jarry, 2011; Valt, 2009). Humans triggered 95% of these avalanches, generally the accident party themselves (Schweizer and Techel, 2017).

For many mountain ranges with a seasonal snow cover, a public avalanche forecast is provided. These forecasts inform and warn about avalanche danger in a specific area and time. In forecasts in Europe, North America and New Zealand, avalanche danger is described according to a five-level danger scale (in Europe: EAWS, 2020a). The danger levels are defined in terms of the release (or triggering) probability, the density (or number) of potential triggering spots and the potential avalanche size. All these factors are expected to increase with increasing danger level (Schweizer et al., 2020). However, the density of potential triggering spots increases more strongly with increasing danger level than avalanche size (Techel et al., 2020a). A similar finding was noted by Harvey (2002) and Schweizer et al. (2020), who observed that human-triggered avalanches were of similar size independent of the danger level. Most frequent were size 2 avalanches, which have the potential to seriously harm or kill a person (EAWS, 2020b).

Winter sports enthusiasts traveling in avalanche terrain are one of the main user groups of these forecasts. The information provided in the avalanche forecasts is particularly relevant during the planning phase of a tour (e.g. Munter, 1991).

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1.1. Rule-based decision frameworks for travel in avalanche terrain

Rule-based decision frameworks for traveling in avalanche terrain (e.g. Landrø et al., 2020), are tools, which can assist winter-sport enthusiasts in the planning of backcountry tours. These frameworks typically combine several cues, such as slope angle and avalanche danger level, yielding a numerical or ordinal indication of avalanche risk (McCammon and Haegeli, 2007).

The *Reduction Method*, later called *Professional Reduction Method PRM* (Munter, 1997), was based on accident data and stability distribution of many *rutschkeil* test results observed in different avalanche conditions (the rutschkeil is a wedge-shaped variation of the *rutschblock* test; Schweizer, 2002). Based on these data, Munter calculated the ratio of unstable locations in the "MISTA" model and called it the *risk potential (RP)*. He found an increase in RP by a factor of two from one danger level to the next. Within the *core zone* (the critical aspects and elevations specified in the avalanche forecast) Munter observed a RP four times higher than outside the core zone. This ratio in risk potential corresponds to a difference of two danger levels. However, in this method, the effective RP is often somewhat lower as additional factors (such as an increasing relevant slope area at higher danger levels) must be considered. The groundwork of Munter paved the way for many other rule-based decision frameworks. Most of them are presented in a graphical format like *Stop-or-Go* in Austria (Larcher, 1999), *SnowCard* in Germany (Engler, 2001) and the *Graphical Reduction Method (GRM)* in Switzerland (e.g. Harvey et al., 2016). They all use the slope angle and the danger level to assess the risk. In contrast to the PRM, the GRM assumes that the risk outside the core zone is one danger level lower instead of two. While this so-called 1-level rule is only a rule of thumb, it has proven to be applicable in many cases (SLF, 2019). Unlike the aforementioned frameworks, the Canadian *Avaluator* (Haegeli et al., 2006) does not use the slope angle, but the three-level *Avalanche Terrain Exposure Scale* (ATES; Statham et al., 2006).

The application of any of these rule-based decision frameworks allows determining particularly dangerous spots during the route planning process. While this restricts the freedom of movement, it reduces the number of avalanche accidents by about 60% to 90% (McCammon and Haegeli, 2007). All these rule-based decision frameworks were developed without reliable data regarding the backcountry travel frequency. However, using accident data without travel data implies that the terrain is equally frequented, independently of e.g. steepness, topography, elevation and the prevailing conditions. In this regard, already Haegeli et al. (2006, p. 257) noted: *"While risk-based decision tools can be used as predictive tools, decision tools based on prevention values do not have any predictive capacities. In other words, users cannot reliably use these tools to predict if a specific slope will likely avalanche or if an accident will occur. Instead, the decision tools provide the user with a measure of how often the current conditions have been observed in past accidents."* While Haegeli et al. (2006) referred to the Avaluator, this applies to all the before-mentioned rule-based decision frameworks.

1.2. Estimating avalanche risk for recreational activities in avalanche terrain

Risk considers three components: hazard, exposure, and vulnerability (e.g. Bründl et al., 2009). Thus, when estimating avalanche risk for recreational activities, where most avalanches are triggered by the person themselves, risk is primarily influenced by:

1. Hazard. The triggering probability of an avalanche mainly depends on the density of potential release points. A higher density of potential release points means a higher probability that a user will hit one of them and that an accident will occur. This parameter combines two of the three factors defining the avalanche danger levels (e.g. Statham et al., 2018; Techel et al., 2020a), namely snowpack stability (the locations where triggering by a human is possible) and the density of these triggering locations. The density of potential trigger points not only changes over time, but often also with terrain properties such as elevation or aspect and with the morphology of the slope (e.g. slope angle, curvature, or forestation, Harvey et al., 2018). Hazard is further influenced by avalanche size, the third factor in the definition of danger levels. However, for human-triggered avalanches it is less important, as they are of similar size regardless of danger level (1-Low to 4-High, Schweizer et al., 2020). Thus, the density of potential trigger points can be equated to the risk potential and, if the forecast is correct, has a correlation with the forecast danger level.
2. Exposure depends strongly on the terrain choices of a back-country user. A user is exposed to the hazard when entering potential avalanche terrain. Therefore, and given specific avalanche conditions, risk depends on the terrain used.
3. The vulnerability, i.e. the consequences for a back-country user when caught by a specific avalanche, depends, among other factors, on the location in relation to the avalanche (Jamieson and Jones, 2012), on the topography of the slope (e.g. Techel and Zweifel, 2013), and on the rescue devices used (e.g. balloon packs, Haegeli et al., 2014). We assume it to be rather constant over time in Switzerland.

Grímsdóttir and McClung (2006) defined avalanche risk as the probability of accidentally triggering an avalanche while traveling in avalanche terrain:

$$Risk = \frac{\text{events}}{\text{events} + \text{non-events}} = \frac{\text{accidents}}{\text{accidents} + (\text{accident-free backcountry use})}$$

While accident data (events) were one of the pillars that rule-based decision frameworks were built on, data about travel patterns (non-events) were initially missing. Approaches to estimate backcountry travel were manifold: the analysis of the key sections of planned tours from the German alpine club program (Munter, 1997); the exploration of heli-ski or national park registration logbooks (Grímsdóttir and McClung, 2006; Moss, 2009); counting users at the start- or endpoints of popular backcountry tours (Procter et al., 2013; Zweifel et al., 2006), or the analysis of entries on social media platforms (Techel et al., 2015). More recently, terrain preferences of backcountry skiers or off-piste riders have been explored using GPS-tracking devices (e.g. Hendrikx and Johnson, 2016; Hendrikx et al., 2016; Sharp et al., 2018; Thumlert and Haegeli, 2018; Sykes et al., 2020) or time-lapse photography (Saly et al., 2020). While all these studies were limited to either restricted user groups, small areas, or short periods, they showed that avalanche conditions influenced travel behavior to some extent. Furthermore, the dependence of risk on expected or encountered avalanche conditions (described by either avalanche danger level or snowpack stability) or slope angle was confirmed (Grímsdóttir and McClung, 2006; Zweifel et al., 2006; Techel et al., 2015). Finally, Winkler et al. (2016) calculated absolute avalanche risk per touring day in Switzerland relying on representative population surveys exploring the sport behavior of the Swiss resident population.

Relying on a large, multi-year data set of GPS tracks recorded during ski tours in Switzerland, Schmudlach et al. (2018a) derived the Quantitative Reduction Method (QRM). This is the only risk-based decision framework we are aware of, where risk was calculated by relating accident numbers to backcountry travel frequency. The QRM describes avalanche risk as a function of the danger level and the morphology of a slope (slope angle, curvature, slope size and land cover).

The objective of this study is two-fold: first, to explore the correlation between the forecast avalanche danger and the risk taken by backcountry skiers after they have adapted to the forecast and the encountered conditions. Second, based on these findings, to provide risk-based reduction factors related to the information provided in an avalanche forecast. For this, we combined and explored data sets of avalanche accidents and GPS tracks relating to backcountry touring activity in Switzerland. These data sets were already used by Schmudlach et al.

(2018a), and now updated with more recent data.

We focus on estimating relative risk as a function of information provided in the avalanche forecast and with respect to elevation and aspect of a point in the terrain, as this information is available during the planning phase of a tour. We address the following research questions:

1. How does the risk taken by backcountry skiers change with the forecast danger level, the indicated critical elevation and aspects? Does the risk also change with the forecast typical avalanche problem?
2. At danger level 1-Low, no core zone is specified in the Swiss avalanche forecast. Is the risk taken really the same everywhere, or are there differences that would justify a core zone here as well?
3. Are the reduction methods and the 1-level rule, the often-assumed reduction of one danger level outside the specified core zone, correct? Or should they be refined?

Beside these questions, we describe in detail the patterns observed in accident and travel usage data, as these are the basis for any risk calculation.

2. Data

We used two data sets relating to backcountry touring activity in Switzerland between November 2005 and May 2019: (1) avalanche accidents, and (2) a large data set of GPS tracks (Skitourenguru, 2020a). We combined the data sets with the avalanche forecast issued the evening before and valid at the respective time and location. Geographical information is calculated from the digital elevation model swissALTI3D (Swisstopo, 2020) with a resolution of 10 m. The tree line was taken from Paulsen and Körner (2009).

2.1. Avalanche forecast

We limited the study to the area of a single avalanche warning service to ensure that the danger levels were used as uniformly as possible (Techel et al., 2018). We relied on the avalanche forecast published daily in the evening (at 17.00 CET) by the Swiss national avalanche warning service SLF (WSL Institute for Snow and Avalanche Research SLF), valid until 17.00 CET the following day. Thereby, only regions with a warning for dry avalanches were considered. In addition to the danger level, we explored the elevation and aspects where the danger level was valid. We refer to this information as the *critical elevation* and *critical aspects*, or when combined as the *core zone* (explained in Section 3.3). We refer to the five danger levels by number and name (1-Low, 2-Moderate, 3-Considerable, 4-High, 5-Very High). We did not consider situations with the highest danger level 5-Very high. These conditions were only very rarely forecast (less than 0.1% of the days; SLF, 2019), and hence did not allow statistical evaluation.

Since the winter 2012/13, typical avalanche problems are given in the avalanche forecast (SLF, 2019; EAWS, 2020c). We extracted the problems describing dry conditions (*new-snow* problem, *snow-drift* problem, *old-snow* problem/persistent weak layers), regardless whether they described the main danger or a secondary danger. We did not explore the use of the problem *favourable situation* nor cases when no problem was indicated, because their use changed during the years. Furthermore, with the focus on dry conditions, the problems *wet-snow avalanches* and *gliding avalanches* were not considered.

2.2. Accidents

In Switzerland, the SLF maintains a database including all reported avalanche accidents. This data has been used in numerous studies to explore, for instance, accident patterns or temporal trends (e.g. Harvey, 2002; Schweizer and Lütschg, 2001; Techel et al., 2016). For most avalanche accidents, the trigger point is unknown. We therefore used the coordinate describing the release point of the avalanche, the only point available for all accidents. We extracted avalanche accidents for the 14 winters from 2005/06 to 2018/19 where at least one person was caught and filtered them according to the following criteria:

- The data entry was classified in the database as reliable and accurate.
- An avalanche forecast was available and included at least the danger level.
- The activity of the accident party was entered as a backcountry ski or snowboard tour, which is defined as an activity in which people ascend primarily by their own means. This contrasts to off-piste riding close to ski areas. Further, we excluded accidents on snowshoe tours. The selection ensures consistency with the GPS data set, which is important, as accident patterns differ between tours and off-piste riding (e.g. Techel and Zweifel, 2013), and possibly also between ski and snowshoe tours (e.g. Winkler et al., 2016).

Applying these filters, 808 of the 1884 reported accidents fulfilled all criteria. Of these, 111 caused at least one fatality, while in 247 accidents at least one person was injured or completely buried. For details on accident severity, see appendix A1.

2.3. Backcountry travel data

We relied on the GPS data set already processed by Schmudlach and Köhler (2016), Schmudlach et al. (2018a), including more recent data. The data set contains 279′000 km of GPS tracks, that were either submitted together with condition reports of backcountry activity to popular mountaineering websites (www.gipfelbuch.ch, www.camptocamp.org), or that were directly sent by individuals to G. Schmudlach. The website providers made the GPS tracks available in an anonymous way; hence, nothing is known about the people who submitted the tracks.

The vast majority of GPS tracks comes from ski and snowboard tours. They were filtered as follows, which is largely identical with the description in Schmudlach and Köhler (2016), Schmudlach et al. (2018a):

1. We discarded all GPS tracks that were outside Switzerland or were without valid time stamps.
2. We removed GPS tracks, for which no valid avalanche forecast containing at least the danger level was available.
3. Furthermore, GPS tracks had to be recorded during winter backcountry tours, either on skis or snowboard. We therefore only used tracks where users indicated that they were recorded during a corresponding backcountry tour. Nevertheless, some rare tracks of other activities may also be included.
4. We eliminated GPS tracks, which followed for more than 70% a road or a path (according to swissTLM3D-Streets), as we considered it questionable whether these tracks were effectively recorded during a backcountry tour.
5. Tracks received from different platforms, which were identical in time and place, were used only once.
6. An algorithm specifically designed to detect and remove erroneous GPS readings (commonly known as GPS spikes) was applied.

After this processing, 1′437′982 GPS points from 51′244 km of GPS tracks remained, recorded during 7355 backcountry tours during the 14 winters 2005/06 to 2018/19. For details on GPS data, see appendix A2.

3. Methods

3.1. Application of the danger level to individual points in the terrain

We applied the information of the avalanche forecast to individual points in the terrain, being aware that the purpose of the danger level is to provide a general overview of the severity of the current avalanche

conditions. The danger level describes the stability distribution of the snowpack over an entire region (at least 100 km^2, e.g. SLF, 2019). In addition, according to EAWS (2020a), the danger level cannot refer to a single slope. That may be true if we intend to assign a discrete property to one specific slope or point, but if we apply the danger level to a huge number of points, there has to be a correlation, despite all the spatial variability. Expressed differently: if there would be no correlation between the snowpack stability of a large number of points and the danger level, the danger level would be no better than random, and the concept of the "danger level" would be obsolete.

3.2. Preprocessing the data

3.2.1. Avalanche trajectories

The release point of an avalanche generally marks the highest point of the release area and does not necessarily represent the slope characteristics of the whole avalanche outline nor of the trigger point. To get a more representative picture of the slope, we introduced a trajectory, starting at the release point. We set the length of this trajectory to 60 m, as the release area of human-triggered avalanches typically has a length between 40 m and 80 m (e.g. Harvey et al., 2018; Schweizer and Lütschg, 2001). Along each trajectory, we equidistantly placed seven points with 10 m distance; the uppermost one being identical to the release point of the avalanche (Fig. 1).

For each point along the trajectory, we calculated a set of terrain properties (as *elevation*, *aspect* and *slope angle*) and avalanche forecast properties (as *danger level*, *critical elevation* and *critical aspects*). These properties characterize the situation at a specific point. The parameters *relevant slope area* (RSA), the *slope aspect interval* (SAI) and the *terrain indicator* (TI) additionally consider the surroundings of each point (Sections 3.2.3 and 3.3; Schmudlach and Köhler, 2016, Schmudlach et al., 2018a, 2018b). We relied on the mean (or median for ordinal properties) of the seven values along the trajectory as representative value for each accident slope.

3.2.2. Movement points

The GPS tracks were re-sampled at a fixed distance of 10 m (Fig. 1). The re-sampling distance was chosen arbitrarily to follow the tracks well in any case, but has no substantial influence as the range of the confidence intervals is dominated by the much smaller number of accidents, as explained in Section 3.5. We refer to these re-sampled points as *movement points*. This re-sampling approach ascertained that each of the movement points had the same weight in the data set. Thus, the influence of variations in the sampling frequency of the GPS device, of breaks during the tour, as well as differences in the speed between ascent and descent, were eliminated. After this processing, 5′124′661 movement points are available for further evaluation.

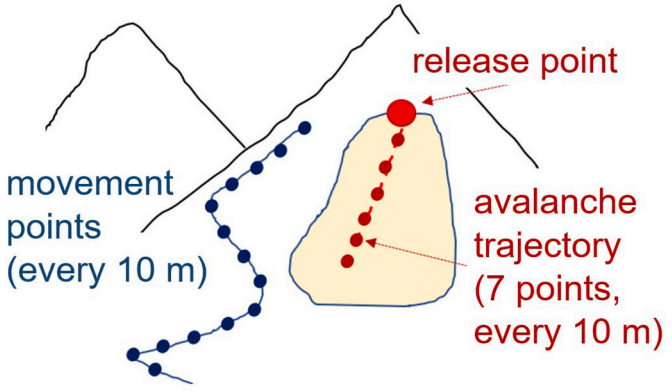

Fig. 1. Schematic representation of the movement points and the points along the avalanche trajectory.

For each movement point, we calculated an identical set of terrain properties as for the points along the avalanche trajectories. We additionally analyzed the steepest section per tour, as even demanding tours often contain sections of flatter terrain. We used the mean value of the ten most extreme points (in terms of slope angle) per tour to focus not too much on a short steep passage.

3.2.3. Relevant avalanche slopes

For some properties, like the slope angle, it is generally not sufficient to use the value directly at the movement point (Munter, 1997), and probably not even along the avalanche's starting point trajectory (Fig. 1). A correct comparison would have to consider the entire "relevant" avalanche slope. Unfortunately, there are still many questions unanswered about its best definition.

Harvey et al. (2018) developed an algorithm that analyzes the terrain from the perspective of the avalanche producing two maps. In one map, they classified the avalanche terrain thematically into: i) potential release areas, ii) areas with remote triggering potential, and iii) the runout zones of size 3 avalanches. In the second map continuous values illustrating how serious or dangerous the terrain is in terms of avalanche release and the consequences of being caught are provided.

Schmudlach and Köhler (2016) developed an algorithm that analyzes the terrain from the perspective of the skier: In a first step, a polygon describing the relevant slope area (RSA) was segmented for each point in the terrain. To calibrate the RSA algorithm, Schmudlach et al., 2018b relied on a data set of expert assessments. In a second step, the slope angles within the RSA were condensed to a terrain indicator (TI), representative for the terrain severity at the point linked to the RSA. The TI is a continuous, dimensionless parameter in the closed interval [0...1] and can be summarized in four classes: <0.25 *"no avalanche terrain"*; 0.25...0.5 *"atypical avalanche terrain"*; 0.5...0.75 *"typical avalanche terrain"*; >0.75 *"very typical avalanche terrain"*. Based on the TI, the Quantitative Reduction Method (QRM) was developed (Schmudlach et al., 2018a), showing the practical applicability of this approach.

From these two approaches providing an avalanche terrain indicator on a continuous scale, we decided to base our research on Schmudlach et al., mainly because it systematically considers a lateral extension (Fig. 2). Furthermore, the RSA allows to calculate a relevant slope aspect interval (SAI), well suited for determining all relevant aspects of a slope (Section 3.3). Values that consider the relevant slope area (e.g. SAI, TI) vary only slightly within an individual slope.

3.2.4. Restriction to points in avalanche terrain

With the intention to explore risk in avalanche terrain, we removed points in dense forests or flat terrain far away from any steep slope. We relied on the definition for *no avalanche terrain* introduced by Schmudlach et al. (2018a), and excluded all points with a TI < 0.25. In contrast to the slope angle, TI additionally considers the size of the relevant slope area and the morphology, particularly the steepest section, curvature and forestation. Introducing this threshold for data selection, 42% of the movement points (n = 2′137′837) and 97% of the accidents (n = 784) remained for analysis (Appendix A3).

3.3. Avalanche forecast properties and reference elevation

At level 2-Moderate or higher, the Swiss avalanche forecast specifies an elevation threshold and the aspects, where the danger level prevails. We explored whether an accident or a movement point was within the indicated critical values or not.

3.3.1. Slope aspect interval (SAI)

In a concave (or convex) slope, different aspects exist and should be considered (e.g. Munter, 1997; Harvey et al., 2016). As described in Section 3.2.3, Schmudlach and Köhler (2016), Schmudlach et al. (2018a) assigned a relevant slope area (RSA) to each point in the terrain

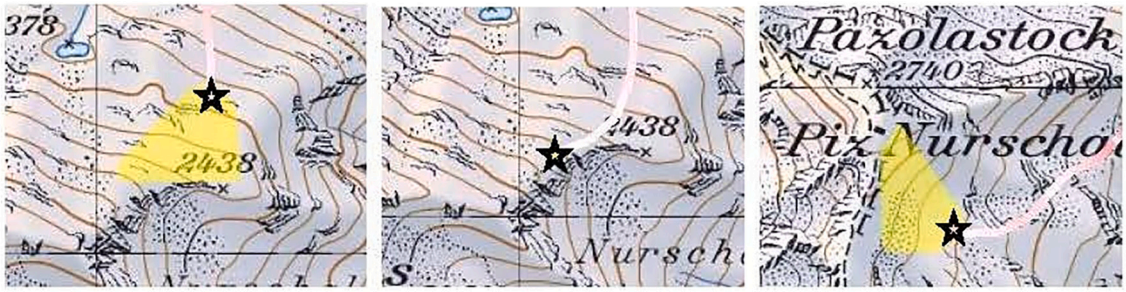

Fig. 2. Relevant slope area (RSA, yellow) used to calculate TI and SAI of the marked point. The lines show the planned route. The map extracts were taken from an explanatory video (Skitourenguru, 2020b). In the middle, the considered point is on a ridge, which reduces the RSA to a point. Background map source: Federal Office of Topography.

(Fig. 2). All aspects found within the RSA define the slope aspect interval (SAI) of a terrain point.

3.3.2. Aspect-overlapping factor (AOF)

The aspect-overlapping factor (AOF) of a point is the ratio of the SAI that overlaps with the critical aspects. We consider slopes with AOF $<$ 0.5 as *outside the critical aspects*. In Section 5.3 we further use AOF $= 0$, defining slopes *completely outside the critical aspects*.

3.3.3. Core zone (critical aspects and elevation)

Slopes that lie within both the critical elevation and aspects (e.g. $>$2200 m AND aspect W over N to NE) are considered as *within the core zone*, whereas all other slopes are considered *outside the core zone* (e.g. Engeset et al., 2018; SLF, 2019). At 1-Low, the Swiss avalanche forecast does not provide information about a core zone. We addressed this difference in Section 3.4.

3.3.4. Reference elevation

The Swiss avalanche forecast provides a critical elevation, depending on the conditions. Additionally, we explored the elevation relative to the local tree line – a reference widely used in avalanche forecasts in North America. As reference, we used the mean value of the tree line for each of the 149 warning regions, located between 1900 and 2350 m. In warning regions, which do not reach this elevation, we assume a tree line elevation of 1800 m.

3.4. Definition of a risk-based core zone at 1-Low

One of our objectives is answering the question: Does the absence of a core zone mean that there are no pronounced differences in risk as a function of aspect and elevation at 1-Low? (second research question).

To answer this question, we calculated the risk for different combinations of aspect (directly at the point, without using the AOF) and elevation. Comparing the values within and outside the different combinations of aspect and elevation show which one discriminates risk most effective. We treat these thresholds as a static core zone at 1-Low and name it "risk-based core zone". This post-hoc analysis approach of deriving a core zone is similar as in Schweizer et al. (2003) and Schweizer (2007), who defined a situation-specific core zone for several situations at 1-Low based on stability test results.

Compared to the core zones indicated in the forecast at higher danger levels, there are two differences. First, such a risk-based core zone is a core zone with fixed aspect- and elevation thresholds, and thus not adapted to the current situation nor transferable to other snow climates. Furthermore, it is calculated from the risk taken by backcountry skiers, while the core zone indicated in the avalanche forecast describes the danger potential.

3.5. Definition and calculation of risk, relative risks, and their confidence intervals

We define avalanche risk similar to other studies exploring the avalanche risk during recreational activities (e.g. Grímsdóttir and McClung, 2006; Techel et al., 2015), where the calculated risk corresponds to the risk taken by a backcountry-user after adapting their behavior to the conditions and managing their individual risk to the best of their knowledge and skills. As this adaption is reflected in the movement points, we analyzed terrain use. Looking at the movement points within potential avalanche terrain (TI $>$ 0.25, Section 3.2.4), we found that in different avalanche conditions comparably small variations in terrain use can be noted (Appendix A4).

Risk, as used in this study, depends on hazard, exposure, and vulnerability (Section 1.2), whereby vulnerability and exposure strongly depend on terrain use. With comparably small variations in terrain use in different avalanche conditions, risk becomes approximately proportional to the ratio of points, where triggering an accidental avalanche was possible under the given avalanche conditions, and thus to avalanche hazard.

To calculate the risk, each movement point was considered a non-event and each accident point an event. The available GPS tracks are only a small sample of the whole backcountry touring activity and we assume that the reporting rate remains the same under all conditions. Thus, all our risk calculations overestimate the absolute risk by the same factor. The absolute risk for given specific conditions (α) is:

$$Risk(\mathrm{A}=\alpha) = P(Acc=1|\mathrm{A}=\alpha) = \frac{N_{acc}(\mathrm{A}=\alpha)}{N_{acc}(\mathrm{A}=\alpha)+N_{non-acc}(\mathrm{A}=\alpha)} = \frac{N_{acc}(\mathrm{A}=\alpha)}{N_{acc}(\mathrm{A}=\alpha)+F_{rep}\times N_{mov}(\mathrm{A}=\alpha)} \approx \frac{N_{acc}(\mathrm{A}=\alpha)}{F_{rep}\times N_{mov}(\mathrm{A}=\alpha)},$$

where A is a stochastic variable describing the conditions like danger level, elevation or aspect and α as specific instance of A. The ratio between all tours and the reported ones is the reporting-factor, F_{rep}. Since the number of accidents (N_{acc}) is negligible compared to the number of movement points (N_{mov}), N_{acc} can be ignored in the denominator.

We cannot calculate absolute risk due to the unknown reporting factor. Thus, in the result section the relative risks (RR) between different conditions are calculated, e.g. between two danger levels, or between in- and outside the core zone. Here F_{rep} disappears and the risk between two conditions α_1 and α_2 becomes:

$$RR_{\alpha_1,\alpha_2} = \frac{Risk(A=\alpha_1)}{Risk(A=\alpha_2)} \approx \frac{N_{acc}(A=\alpha_1)}{N_{mov}(A=\alpha_1)} \Big/ \frac{N_{acc}(A=\alpha_2)}{N_{mov}(A=\alpha_2)} = \frac{f_{acc}(A=\alpha_1)}{f_{mov}(A=\alpha_1)} \Big/ \frac{f_{acc}(A=\alpha_2)}{f_{mov}(A=\alpha_2)},$$

where $f_{acc}(A=\alpha_1) = N_{acc}(A=\alpha_1)/N_{acc}$ is the fraction of accidents under condition $A=\alpha_1$.

Probability densities were calculated with the *geom_density* function in the R package *ggplot2* (R core team, 2020). Confidence intervals (CI) on these fractions are calculated with Wilson's formula in the R *binom* package (Dorai-Raj, 2015). In practice, the error is dominated by the error on the accident fractions. It is important to remark that Wilson's formula applies to a fraction of independent samples. The accidents can be considered independent; they occurred on different days or even seasons and on different locations. However, the dependence in the travel data is much bigger. However, even when only 1% of the travel data is considered (one point every kilometre), the error on the accident fractions is still the dominant one.

3.6. Reference risk factor (RRF)

Reduction factors, such as the factors used in PRM, assume an exponential increase in risk from one danger level to the next. To obtain such a factor for the danger levels, we define a *reference risk factor* (RRF) between two danger levels as the geometric mean of the two factors describing the increase in risk from 1-Low to 2-Moderate, and from 2-Moderate to 3-Considerable.

4. Results

4.1. Characteristics of data sets

We describe the key characteristics of the preprocessed accident and movement data, which allows a comparison with assumptions made in the existing rule-based decision frameworks. Further analyses, which explore additional attributes or subsets of the data, can be found in Appendices A4 and A5.

4.1.1. Accident points

Distinct patterns were noted for the 784 accidents.

- The median elevation of the accidents was 2′456 m (interquartile range IQR: 2′137–2′725 m) (Fig. 3a). Seventy-four percent of the accidents occurred above tree line. Accidents are rare at elevations below 1500 m and above 3300 m (1% and 3% of accidents respectively).
- Eighty-six percent of the accidents took place within the critical elevation indicated in the avalanche forecast (1-Low not considered because of missing critical elevation in the forecast). These proportions were 89% at 2-Moderate (median critical elevation 2′200 m) and 83% at 3-Considerable (2′000 m), respectively.
- Thirty-nine percent of the accidents happened on the northern quartile (NW-N-NE), 68% in the northern half aspects (W-N-E). About 2.8 times as many accidents occurred on slopes facing NW or N ($n = 303$) compared to S and SW aspects ($n = 108$) (Fig. 3b).
- Ninety-two percent of the accidents took place within the critical aspects indicated in the avalanche forecast (1-Low not considered because of missing aspects in the forecast). These values varied only slightly with danger level (91% at 2-Moderate, 93% at 3-Considerable).
- Half of the accidents (51%) occurred at 3-Considerable, 45% at 2-Moderate. Accidents were comparably rare at 1-Low (4%) and practically none happened at 4-High (0.1%; Table 1).
- The median slope angle of all avalanche points was 35° (Fig. 3c), and 39° if we only use the steepest point of each trajectory.

Table 1
Accidents, movement points and risk depending on the danger level. In brackets: 95% confidence interval.

Danger level	1-Low	2-Moderate	3-Considerable	4-High	all
Accidents	29	353	401	1	784
Movement points	532′022	1′183′560	421′033	1′056	2′137′671
Risk, relative to 1-Low	1	5.5 (3.7–8.0)	17.5 (12.0–25.4)	17.4 (2.4–127.3)	
Risk increase between danger levels		5.5 (3.7–8.0)	3.2 (2.8–3.7)	1.0 (0.1–7.1)	

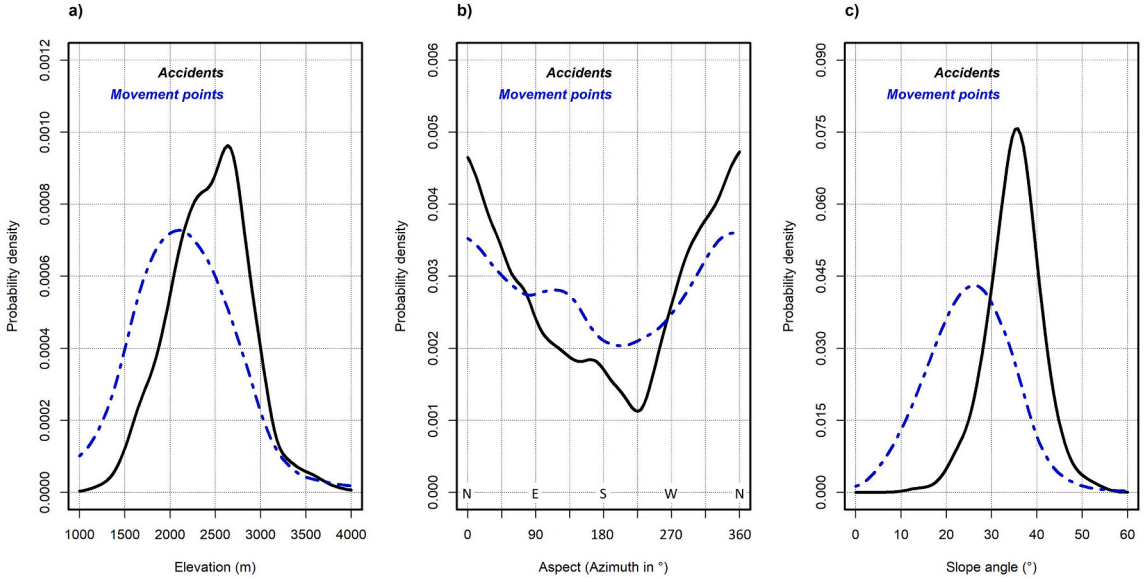

Fig. 3. Probability density for accidents (black) and movement points (blue), respectively. The diagrams show elevation (a), aspect (b) and slope angle (c).

4.1.2. Movement points

The 2′137′837 movement points in avalanche terrain showed that backcountry users did not access all types of slopes equally often (Fig. 3).

- The median elevation of the movement points was 2′140 m (IQR: 1′777–2′525 m) (Fig. 3a). In the Alps, this corresponds to the tree line plus minus a few hundred meters. Elevation above 3300 m was rarely used (2% of movement points).
- Forty-nine percent of the backcountry touring activity took place within the critical elevation specified in the avalanche forecast (1-Low not considered because of missing critical elevation in the forecast). This proportion decreased slightly with increasing danger level, even though the avalanche forecast defines generally higher critical elevation limits at 2-Moderate (mean: 2′132 m, median: 2′200 m) than at 3-Considerable (mean: 2′073 m, median: 2′200 m). Hence, at 3-Considerable less movement points were inside the critical elevation (44%) compared to 2-Moderate (51%).
- Northern slopes were used 1.7 times as often compared to southern or south-western slopes (Fig. 3b). At 2-Moderate, 71% of the touring activity took place inside the critical aspects indicated in the forecast, at 3-Considerable this proportion was higher (86%). These values correlate with the proportion of critical aspects given in the avalanche forecast, which are lower at 2-Moderate than at 3-Considerable (77% and 88%, respectively).
- About 55% of the movement points were registered at 2-Moderate; nearly all the others at 1-Low (25%) and 3-Considerable (20%). At 4-High, hardly any backcountry tours were undertaken (<0.1%). Compared to the frequency the danger levels were issued, 3-Considerable and 4-High are underrepresented in the movement points, indicating that the forecast danger level impacted travel behavior.
- The median slope angle for all movement points in avalanche terrain (TI > 0.25) was 25° (Fig. 3c). For the steepest section per tour, the slope angle was 39° and thus identical to the median slope angle of the steepest point of each avalanche trajectory.

4.2. Risk – By elevation and aspect

4.2.1. Elevation

The elevation distribution of avalanche accidents and movement points differed: accidents happened more often at higher elevation compared to movement points (median 2′456 m vs. 2′140 m, respectively; Fig. 3a). This leads to a distinct increase in risk with increasing elevation (black line in Fig. 4a) indicating that elevation is a main risk factor. The strongest increase in risk referring to an 800 m elevation band was found between 1900 m and 2700 m with a factor of 4.1. Above about 2700 m risk increased no further. Below about 1400 m risk was near zero. The tree line was a slightly better reference value as the sea level, with a factor of 4.6 from 300 m below to 500 m above.

4.2.2. Aspect

Avalanche accidents occurred 3.6 times more often on N-facing slopes compared to SW-facing slopes (Fig. 3b). Because N-facing slopes were also more frequently used, risk differed by a factor of 2.1 (CI = 1.5–2.9) between these aspects (Fig. 5, black line). Of note is the steep increase in risk between SW and NW aspects.

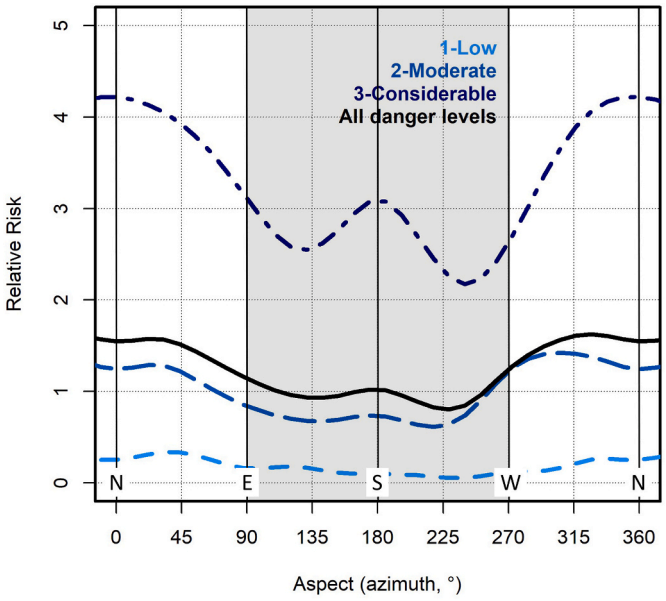

Fig. 5. Dependence of relative risk on the aspects, indicated by the azimuth and normalized with the mean value of 2-Moderate. The grey -shaded area shows the southern half.

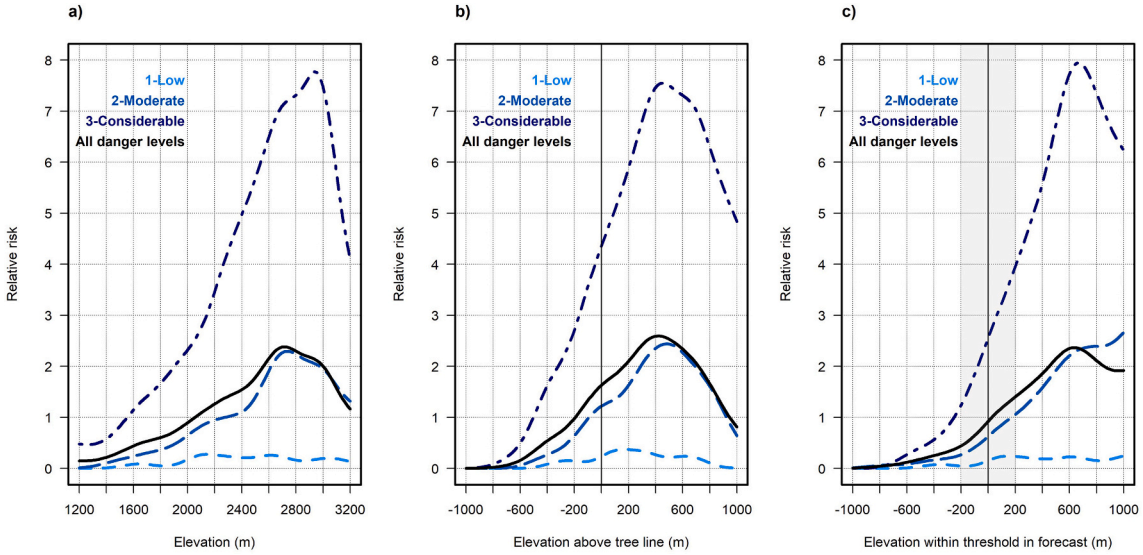

Fig. 4. Relative risk for different danger levels, normalized with the mean value of 2-Moderate. a) as function of elevation. b) as function of elevation above the tree line. c) as function of elevation above the critical elevation in the forecast, or above the risk-based core zone for 1-Low, respectively. The grey-shaded area (c) shows the ±200 m transition zone according to the SLF avalanche bulletin interpretation guide (SLF, 2019).

On the northern half aspects (W-N-E), risk was on average 1.7 (CI = 1.4–1.9) times as high as on the southern half aspects (*E*-S-W). In the northern quartile (NW-N-NE), risk was very similar (factor 1.04, CI = 0.9–1.2) as in the northern half aspects, independent of the danger level. Thus, risk inside the northern quartile was 1.4 (CI = 1.3–1.7) times as high as in the other aspects.

4.3. Risk – Including information provided in the avalanche forecast

4.3.1. Danger level

Avalanche risk increased strongly with forecast danger level: from 1-Low to 2-Moderate by a factor of 5.5, and from 2-Moderate to 3-Considerable by a factor of 3.2 (Table 1). The reference risk factor RRF (geometric mean) is 4.2. From 3-Considerable to 4-High, the risk did not increase further.

However, the small number of observations at 4-High results in a very broad confidence interval that prevents any meaningful conclusions about the true risk at this danger rating level. The magnitude of the risk strongly depends on the danger level, but the dependence of risk on altitude and aspects is very similar for the danger levels 1-Low to 3-Considerable (blue curves in Figs. 4 and 5).

4.3.2. Risk-based core zone at 1-Low

Comparing the values within and outside of different potential core zones showed that risk is not uniformly distributed across aspects and elevations at 1-Low (Fig. 6). We obtained the best discrimination in terms of risk when the core zone was defined as *>2000 m* on *W-N-SE - facing aspects*. Using this setting, 45% of the movement points and 83% of the accidents are within the risk-based core zone. This corresponds to a risk factor 5.9.

4.3.3. Critical elevation

From −200 m below to +600 m above the critical elevation, the risk increased within an 800 m elevation band by a factor 7.3. This is 1.8 times as high compared to the absolute elevation (factor 4.1 from 1900 to 2700 m; black line in Fig. 4c).

In the bulletin interpretation guide (SLF, 2019), a transition zone for the critical elevation is described as ±200 m. Within this range, avalanche risk increased by a factor of 3.4. Thus, the elevation range defining the transition zone was indeed in an elevation band with a strong increase in risk. However, it should be noted that the increase in risk continued approximately linearly the following 400 m of elevation.

Above the critical elevation indicated in the avalanche forecast, the risk was 7.8 (CI = 5.6–10.8) times higher than below at 2-Moderate, and 6.4 (CI = 4.9–8.3) times higher at 3-Considerable (Fig. 7a). Applying the risk-based critical elevation of 2000 m at 1-Low resulted in a lower factor of 4.6 (CI = 1.4–15.3). For all danger levels combined, the risk was about a factor 5.4 (CI = 4.4–6.6) higher for locations above the critical elevation compared to those below.

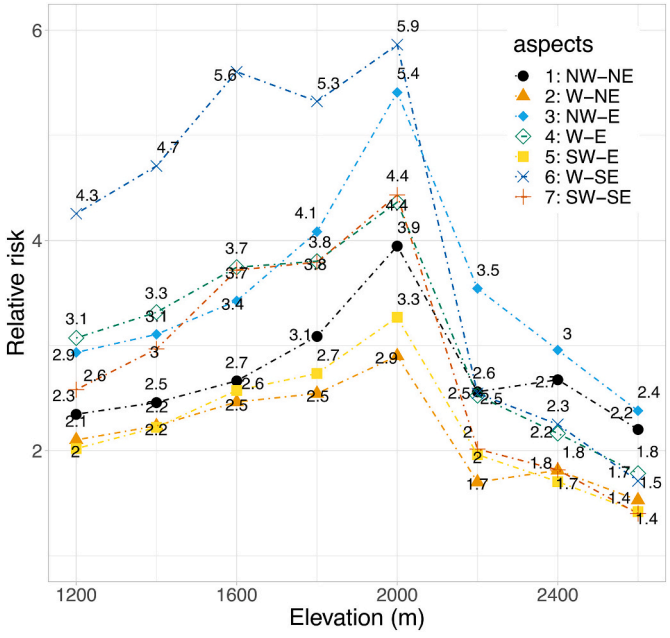

Fig. 6. Relative risk at 1-Low for different combinations of aspect and elevation considered as a static core zone, relative to outside this core zone. Aspects are described clockwise, always including the North sector (i.e. W-E corresponds to W-N-E).

4.3.4. Critical aspects

The risk was 4.1 (CI = 3.2–5.3) times higher for points within the critical aspects indicated in the forecast compared to those outside (Fig. 7b). However, this effect is in part caused by the increase in risk with the danger level, as at higher danger levels statistically more aspects are described as critical aspects. Considering each danger level individually leads therefore to lower factors of 4.0 (CI = 2.8–5.7) at 2-Moderate and 2.3 (CI = 1.6–3.4) at 3-Considerable, or a factor of 3.0 as geometric mean of these values. Nevertheless, the risk reduction achieved by avoiding the critical aspects indicated in the avalanche forecast is higher than by avoiding the northern-half aspects (factor 1.7, Section 4.2.2).

Even if we only consider points within the critical aspects, the risk is 1.3 (CI = 1.1–1.4; danger levels 2-Moderate to 4-High) times higher on days when all aspects are indicated as critical aspects in the forecast compared to days when only some of the aspects are indicated.

4.3.5. Core zone (critical aspects and elevations)

Within the core zone, the risk was 7.3 times higher than outside (CI = 5.6–9.4) at 2-Moderate and 5.4 times higher (CI = 4.3–6.8) at 3-Considerable (Fig. 7c). The corresponding factor derived for the static, risk-based core zone at 1-Low was slightly lower (factor 5.8, CI = 2.2–15.2). Overall, the risk within the core zone was 5.8 (CI = 4.9–6.9) times higher than outside. This is substantially higher than the risk reduction factor RRF (factor 4.2, Section 4.3.1).

Within the core zone (1-Low: risk-based core zone) the risk increased by a factor of 6.6 (CI = 4.4–10.1) from 1-Low to 2-Moderate and by 2.9 (CI = 2.5–3.4) from 2-Moderate to 3 Considerable (Fig. 7c). Outside the core zone, we obtained similar factors of 5.3 (CI = 2.1–13.2) and 3.9 (CI = 2.9–5.3), respectively.

4.4. Typical avalanche problem

Risk was about twice as high for the avalanche problem *new snow*, compared to the other problems. However, the use of the *new-snow* problem increased strongly with danger level and was used mostly at 3-Considerable and 4-High (69% of the times it was used). Accounting for this bias, we found no significant differences in risk between the forecast avalanche problems in our data set.

5. Discussion

5.1. Correlation between forecast avalanche danger and risk taken by backcountry users

5.1.1. Application of the danger level to individual points in the terrain

Applying the information provided in the forecast to many points in avalanche terrain, we have shown that both the danger level and the core zone strongly correlate with avalanche risk (Section 4.3), despite occasional forecast errors. The strong increase in risk with increasing avalanche danger level shows that the concept of the danger levels is applicable and that the information provided in the forecast is usually reliable.

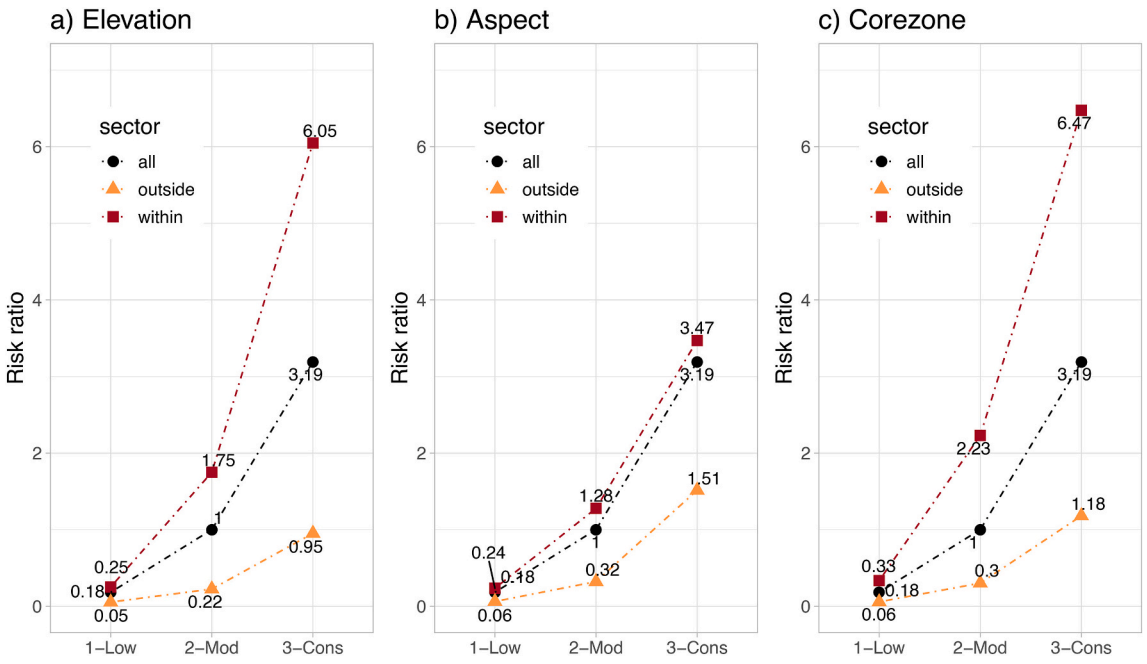

Fig. 7. Risk ratio for different danger levels. The plots show the dependency of the following information in the avalanche forecast: critical elevation (a), critical aspects (b) and core zone (c). At 1-Low, the thresholds for the risk-based core zone are used. The values are normalized with 2-Moderate, all data.

5.1.2. *Influence of danger level, critical elevation, and aspects on risk*

5.1.2.1. Danger level. Ignoring 4-High, the increase in risk between danger levels (reference risk factor RRF) was 4.2 and thus higher than the factor 2 suggested by the PRM (Munter, 1997). Other studies, in which the risk for backcountry tours in Switzerland was calculated, showed increases in risk by a factor between 2.5 and 3 (Harvey, 2002; Techel et al., 2015). Similarly, Grímsdóttir and McClung (2006), relying on heli-ski logs, showed an increase in risk with decreasing snow stability rating, as assessed by the heli-ski guides. Roth (2009), relying on some assumptions regarding the touring and off-piste riding activity at different danger levels, proposed a factor of 4. Lastly, Jamieson et al. (2009), relying on estimates from experts judging the probability to trigger a potentially fatal avalanche when making fresh tracks in a start zone at a specific danger level, suggested a ten-fold increase in the risk from one danger level to the next higher one.

4-High was comparably rarely forecast during the explored 14 years (less than 2% of cases), and touring activity was strongly reduced on those days (Table 1). Our finding that the risk does not increase further from 3-Considerable to 4-High is thus not well supported because of too few data.

5.1.2.2. Elevation. The critical elevation threshold indicated in the avalanche forecast provided the best reference elevation (factor 7.3, Fig. 4c). In comparison, simply considering the absolute elevation, risk only increased by a factor of 4.1 from 1900 to 2700 m, while considering the local tree line lead to a factor 4.6. Therefore, in Switzerland, where the critical elevation is provided in the forecast, the indicated elevation should be used rather than the absolute elevation or the tree line. Finally, at 1-Low, when risk is rather low in general, and when the Swiss avalanche forecast does not indicate a critical elevation threshold, we found a higher risk above 2000 m. A correlation between risk and elevation was also noted by Grímsdóttir and McClung (2006), who showed a higher risk for high elevations (above tree line).

In summary, the influence of elevation on risk has probably been underestimated so far. In contrast to the aspect, the elevation is neither explicitly included in the PRM, nor in other rule-based decision frameworks. In the Avaluator, however, it is considered indirectly via ATES.

5.1.2.3. Aspects. In our data, the risk in the northern-half aspects (W-N-E) was only about 1.7 times higher than in the southern-half aspects (Fig. 5). The difference was much lower than the RRF of 4.2 corresponding to the change in risk by one danger level, and substantially less than previously assumed. The reduction factor 3 for "avoiding the northern-half aspects" given in the PRM should therefore not be exploited entirely. The risk in the northern quartile (NW-N-NE) was only 1.4 times higher than in the other aspects. This criteria do thus not justify considering the northern quartile as a relevant reduction factor.

We assume that the overestimation of the importance of the aspect in existing decision frameworks, like the PRM, is because usage frequency was not accounted for. The large data set of movement points suggests that northern aspects are used more frequently by the backcountry-touring community in Switzerland. This reduces the risk in northern aspects, compared to deriving risk by assuming equal usage patterns in all aspects.

The critical aspects indicated in the avalanche forecast were a better discriminator than using a fixed aspect range. Within the critical aspects, risk was 3.0 times (geometric mean of the values at 2-Moderate and 3-Considerable) higher than outside. Munter (1997) already mentioned that not the average aspect of a slope, but rather the most unfavorable aspect present in the relevant slope area should be considered. We can confirm this: slopes completely outside the critical aspects (AOF = 0) showed a risk reduction of 6.1 (CI = 3.4–10.9) at 2-Moderate and 2.7 (CI = 1.5–4.8) at 3-Considerable. The geometric mean of these values (4.0) is very close to the reference risk factor RRF between successive danger levels.

5.1.2.4. Core zone. The currently used approach to specify no core zone at 1-Low in the Swiss avalanche forecast is in contradiction to the other danger levels. We suspect it is because of the PRM and the 1-level rule: Munter (1997), in his PRM, allowed a reduction by two danger levels outside the core zone. Meanwhile, it has become common practice to assume the danger level to be one level lower for slopes outside the core zone (e.g. SLF, 2019; Harvey et al., 2016). Thus, at 1-Low, the indication of a core zone and the application of this rule would lead to an undefined danger level 0 (or even less) for slopes outside the core zone, which could be misinterpreted as "no avalanche danger at all". According to

the bulletin interpretation guideline (SLF, 2019), no indication of a core zone in the forecast simply means that all aspects and all elevations must be considered as inside the core zone. However, this definition, applied to 1-Low, is not supported by our findings which showed that there are differences between the various aspects and elevations. In fact, the risk was by a factor of 5.8 higher in W-N-SE aspects above 2′000 m compared to other aspects and elevations (Section 4.3.2). As the Swiss avalanche forecast currently does not provide the core zone for 1-Low, we suggest using these thresholds as an approximation for a static, risk-based core zone when planning a backcountry tour in the Swiss Alps.

Considering all danger levels, the risk was 5.8 times lower outside the core zone than within (Section 4.3.5). This factor was higher than the ratio in the risk between successive danger levels (RRF = 4.2) and also exceeds the reduction factor 4 for "outside the core zone" given in the PRM. As the PRM assumes a doubling of the risk per danger level, a factor 4 corresponds to two danger levels. However, the effective reduction is often somewhat lower, because with increasing danger level the relevant slope area gets larger and certain additional restrictions are applicable in the PRM (e.g. <30° at 4-High). Because of the larger risk reference factor between the danger levels in our data, the risk outside the core zone is nevertheless reduced by less than two danger levels. The 1-level rule, as used in the GRM, is therefore closer to the pattern shown by the data than the doubling used in the PRM.

5.1.3. Typical avalanche problems

We found no significant differences in risk between the forecast avalanche problems. This contrasts to other studies which showed that (serious) accidents or triggering of avalanches by humans were more frequent when an old-snow problem was present (e.g. Schweizer and Lütschg, 2001; Logan and Greene, 2014; Techel et al., 2015). Apart from this, the results are not surprising, as the aim of the avalanche problems is not to rate the severity of the avalanche danger (for which the danger level is used) but to focus the backcountry user's attention on the main avalanche problem (SLF, 2019). However, as we are aware of some inconsistencies in the application of the avalanche problems by the avalanche forecasters, particularly during the first years after their introduction in the forecast, we recommend repeating the evaluation in a few years.

5.1.4. Transition zones and differences within a danger level

The calculated risks showed large transition zones in terms of both elevation and aspects, in which the risk gradually increased or decreased. With about 800 m, the transition zone was roughly twice as wide, at least in terms of elevation, as stated in the avalanche bulletin interpretation guide (SLF, 2019).

The risk was 1.3 times as high within the critical aspects on days when all aspects were indicated as critical in the forecast compared to days when only some of the aspects were indicated as critical (Section 4.3.4). There may be two explanations for this: first, the danger may have been in the upper range of the danger level in some aspects, and thus, these aspects with slightly more favourable conditions may still correctly have fallen within the same danger level. Second, some aspects should already have had a higher danger rating as indicated in the forecast. Regardless of the explanation, users should interpret such forecasts as an indication that the danger, within the forecast danger level, tends towards the next higher danger level.

The avalanche danger scale, with its five levels - of which only three are used during 98% of the time, and the discrete nature of both the danger scale and the core zone, inevitably lead to a loss of information as transitions cannot be communicated easily. For a manual application, however, the advantage of a simple number may outweigh a certain loss of information as whole danger levels can likely be understood by a user more easily than a probabilistic forecast (Murphy, 1993; Techel et al., 2020b). Therefore, if more detailed information regarding the avalanche conditions would be provided in the forecast, the comprehensibility and the usefulness of this information should be well studied. For computer calculations, on the other hand, it seems appropriate to use a data-driven algorithm that incorporates the best available information. For such an application, a refined danger rating if it were provided in the forecast could be beneficial (Techel, 2020). An alternative approach was followed by Schmudlach and Köhler (2016) and Schmudlach et al. (2018a), who derived a continuous *Danger Indicator* relying on information provided in the forecast.

5.2. Revising the 1-level rule

The 1-level rule can be applied if the risk outside the core zone is not higher than the risk within the core zone at the next lower danger level. We already showed in Section 4.3.5, that this criterion is fulfilled if all values are considered. Fig. 7c and Table 2 (inside the bold frame) show that this criterion is also satisfied for the individual danger levels:

- At 2-Moderate outside the core zone, the risk is marginally lower (factor 0.9) than at 1-Low within the risk-based core zone.
- At 3-Considerable outside the core zone, the risk is only half as large as at 2-Moderate within the core zone.

However, the simple distinction within/outside the core zone can be misleading because the risk is not evenly distributed outside the core zone (for instance, risk changes considerably above and below the critical elevation, Fig. 4c). Therefore, different combinations of elevations and aspects must be assessed individually.

Table 2 shows that the criterion of the 1-level rule is fulfilled everywhere, except on slopes that are outside the critical aspects but within the critical elevation. Outside both, the critical elevation and the critical aspects, there is only low avalanche risk. Is the 1-level rule also fulfilled for the risk-based core zone at 1-Low? As it is not possible to calculate the risks for a lower danger level than 1-Low, we used the risk at 1-Low inside the risk-based core zone (0.15) as reference, divided by the RRF (4.2). No colour is assigned to risks below this limit (0.04) in Table 2.

Table 2
Risk within and outside the critical aspects and elevations, normalized with the value of "within both" at 2-Moderate. The colours indicate the danger level to which the risk can be assigned: orange for 3-Considerable, yellow for 2-Moderate, light green for 1-Low and no colour for far below 1-Low (<0.04, the threshold is explained in the text). At 1-Low, the risk-based core zone is used. The values within the bold frame correspond to the 1-level rule.

critical elevations	critical aspects	1-Low	2-Moderate	3-Considerable
within both (core zone) here, the danger level is valid		0.15	1	2.90
not within both (outside core zone)		0.03	0.14	0.53
within	outside	0.03	0.25	1.49
outside	within	0.02	0.13	0.49
outside	outside	0.03	0.04	0.09

5.3. Risk-based reduction factors

Our findings allow to adapt existing rule-based decision frameworks (as the PRM), or terrain classification approaches, in terms of the weighting of elevation and aspects. Two options are possible:

- Fixed attenuation factors for elevations and aspects could be used to classify avalanche terrain. Using this approach, the applications of ATES (Statham et al., 2006; Larsen et al., 2020) would be extended to include the newly-determined elevation and exposure dependencies. However, we believe that the derived values are specific to the topographical and climatological situation in Switzerland.
- Elevations and aspects are assessed depending on the information given in the avalanche forecast. This approach is used by the QRM (Schmudlach et al., 2018a). We suspect that this approach allows a more general applicability.

We suggest using the second approach in regions where a regional avalanche forecast is available, as the thresholds in the avalanche forecasts showed a better correlation with avalanche risk than applying fixed values. However, the first approach may still have some merit to include a risk-component in large-scale terrain classification. However, to avoid double consideration, only one of the options should be used.

To obtain manually applicable reduction factors, the risk ratio between within and outside a criterion must be compared with the risk ratio between two successive danger levels. Using always the mean factor of 5.8 between within and outside the core zone would lead to a dangerous underestimation of the risk in slopes that are outside the critical aspects but within the critical elevation. A better approximation of the risk is obtained when aspects and elevations are considered separately (Table 3):

- In slopes that are outside the critical aspects (AOF < 0.5) but above the critical elevation, the risk reduction (factor 2.8) does not reach the RRF (4.2). For slopes completely outside the critical aspects (AOF $= 0$) a risk reduction of 4.0 is achieved, which is close to the RRF.
- Already 0 to 400 m below the critical elevation, the risk is at least one danger level lower, even within the critical aspects.
- Slopes that lie outside both, critical elevations and critical aspects, show a much lower risk.
- 400 m below the critical elevation, the risk is generally low. Only at 3-Considerable inside the critical aspects it is higher (factor 1.3) as at 1-Low. But even there, the risk is lower as for 1-Low within the core zone (factor 0.9).

Based on this findings, we propose to replace the 1-level rule with the values given in Table 4. If the reduced value becomes lower than 1-Low, the statistical risk is in fact lower than for 1-Low within the core zone. However, avalanches still remain possible, there is always a residual risk.

Table 3
Risk reduction as function of the critical elevation and aspects given in the avalanche forecast, for different danger levels. If the reduced danger level is below 1, the risk is lower than within the risk-based core zone of 1-Low. This does not mean that there is no avalanche danger at all. *) = geometric mean from levels 2-Moderate and 3-Considerable. Reference is the reference risk factor RRF = 4.2, for two levels the square of it (factor 17.5).

Elevation	Aspects	1-Low	2-Mod	3-Cons	Factor*)	Reduction
within both (core zone)		1	1	1	1	no reduction
above	outside (AOF < 0.5)	5.3	4.0	1.9	2.8	<1 danger level
above	completely outside (AOF $= 0$)	5.2	7.0	2.4	4.0	≈ 1 danger level
0 to 400 m below	within	4.2	6.0	3.8	4.8	≈1 danger level
0 to 400 m below	outside	3.3	15.3	17.7	16.5	≈2 danger levels
>400 m below	within	no accidents in database	13.0	21.4	16.7	≈2 danger levels
>400 m below	outside	no accidents in the database				>2 danger levels

5.4. Limitations and Outlook

It can probably be assumed that backcountry skiers try to find the optimal trade-off between good skiing, while simultaneously reducing the risk to be caught in an avalanche. Thus, their goal will be to avoid potential trigger points. If they are successful identifying these locations in the terrain, their risk is lower, compared to a random choice of terrain. If backcountry users can detect potentially unstable locations with the same probability, regardless of avalanche conditions, this does not influence relative risks as they were used in our study. However, we do not know whether the rate of avoiding these locations is independent of the danger level.

We described where backcountry users went as a function of forecast avalanche conditions (Section 4.1.2) and show that the behavioral adaption to conditions is small (Appendix A4). But we can't verify the assumption, that the reporting rate does not change with avalanche danger ratings.

We described where backcountry users went as a function of forecast avalanche conditions (Section 4.1.2) and ignored that users adapt their behavior depending on the conditions. In Appendix A4, we show that this adaption was only small. But still, we are aware that also small behavioral changes can influence the findings in one way or another. However, we are unable to quantify this effect.

We suggest that future investigations explore additional properties and propose to fit a multivariate model to address potential interdependencies appropriately. We believe that special attention should be given to the morphology of the slope, and particularly to the slope angle. The slope angle at a specific point is a noisy property, but highly relevant. To get a more reliable picture, it is widely recommended to consider terrain properties from an area around the respective point (e.g. Munter, 1997; Harvey et al., 2016). Terrain classifications, such as those proposed by Harvey et al. (2018) or Schmudlach and Köhler (2016) and Schmudlach et al. (2018a) are promising approaches in this direction. However, more research is needed to derive a property that describes the triggering potential, dependent on avalanche conditions, and the probability to be caught by an avalanche at a specific point in the terrain.

We determined the statistical avalanche risk more precisely than can be used in a simple, manually applicable rule-based decision framework

Table 4
Proposed risk reduction factors for manual application, using the critical elevation and aspects given in the avalanche forecast.

	within aspects	completely outside aspects
above elevation	**no reduction**	one danger level lower
just below elevation (0 to 400 m)	one danger level lower	two danger levels lower
far below elevation (>400 m)	two danger levels lower	two danger levels lower

(e.g. rules proposed in Table 4). Therefore, a logical step would be the integration of the statistical avalanche risk in computer-assisted models supporting backcountry users in their route planning.

6. Conclusions

Relying on two comprehensive multi-year data sets – GPS tracks recorded during backcountry tours and avalanche accidents – we quantified avalanche risk in Switzerland. Our data showed that there is a strong association between the danger level and the risk of backcountry skiers being involved in an accident. From low to considerable, the risk of a party being involved in an accident increases on average by a factor of four from one danger level to the next. This is more pronounced than indicated by Munter (1997). Furthermore, avalanche risk taken by backcountry skiers increased strongly with elevation, while the aspects had less influence on risk than previously assumed. For both, elevation and aspects critical values as indicated in the avalanche forecast correlated better with taken risks than constant values. Considering only points within the core zone, the risk was higher on days when all aspects were rated as critical, than on days when only some of aspects were indicated as critical in the forecast.

Even for danger level 1-Low, where the Swiss avalanche forecast does not provide any information about particularly affected slopes, we found a strong dependency of taken risk from elevation and aspects. In order to take this effect into account, a risk-based, static core zone was introduced.

Our data confirm the validity of the 1-level rule, “outside the critical aspects or elevations, one danger level lower”. However, we note that this rule of thumb overestimates risk on slopes, which are both outside the critical elevation and critical aspects indicated in the forecast. For manual applications, we therefore propose to consider the core zone information of the avalanche forecast with two separate reduction factors, one for aspects and one for elevation.

In summary, we conclude that information provided in the avalanche forecast is of high relevance when estimating avalanche risks taken on backcountry tours. Therefore, and despite the inherent mismatch in the spatial scale between a regional forecast (a few hundred square kilometres) vs. a single slope (a few thousand square meters), backcountry users should consider this information in their decision-making process. However, an optimal decision-making process must additionally include the information that becomes available when the user travels in the terrain. Hence, we emphasize that modern rule-based decision frameworks do not replace on-site risk assessment in any way, but they offer increasingly better opportunities to get the most out of the information available during the planning stage. In many countries, the avalanche forecast is available the night before a tour, and thus at a time when still many touring options are available. Refining risk-reduction methods will allow backcountry users to come closer to the goal of achieving a minimum of avalanche risk and a maximum of freedom of movement.

Data availability

The accident data set will become available at www.envidat.ch. According to the privacy agreement with the owners of the GPS tracks, it is not possible to publish the movement points. However, interested researchers can request a table containing all parameters for all movement points, except the geographical coordinates, for the exclusive usage of research verification. In order to enable the verification of the data table, eventual subscribers can request the geographical coordinates for 100 random lines out of the data table.

Author contributions

KW designed the study in close collaboration with GS. GS prepared the data. KW evaluated the data together with all other authors. KW and FT prepared the manuscript with substantial contributions from the other authors.

Declaration of Competing Interest

GS develops and operates www.skitourenguru.ch. The website provides a risk assessment of ski tour routes; risk is calculated using the current avalanche forecast and terrain information. For this purpose, the QRM (Schmudlach et al., 2018a) is applied. The QRM relies on the same data set as we used in our analysis.

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Appendix

First, we describe spatial distribution and influence of accident severity (A1, A2 and A4), then the impact of filtering the movement points (Section A3), and the correlation between the forecast avalanche conditions and terrain use (A5). While all this is not strictly necessary to understand the main part of the paper, it may highlight some of the uncertainties or bias related to the data.

A.1. Data – Accident severity and reporting rate

In Switzerland, the reporting of serious accidents, that is accidents which caused death, injury or full burial, or accidents that required organized rescue is reliable. This contrasts with less serious incidents, which are often reported by the public. This leads to an over-representation of serious accidents in the data set, also noted in other studies (e.g. in Canada: Jamieson and Jones, 2015). As the statistical significance of this paper is limited by the number of avalanche accidents, we nevertheless included less serious accidents to take advantage of the larger data set.

Accidents occurred all over the Swiss Alps. However, a distinct cluster in the Davos area, where SLF is located, can be noted (Fig. A1a). A considerably higher reporting rate of less serious accidents, compared to other parts of the Swiss Alps, is likely the main reason for this spatial bias (e.g. Schweizer and Lütschg, 2001; Techel and Zweifel, 2013). We therefore refrained from investigations concerning the spatial distribution.

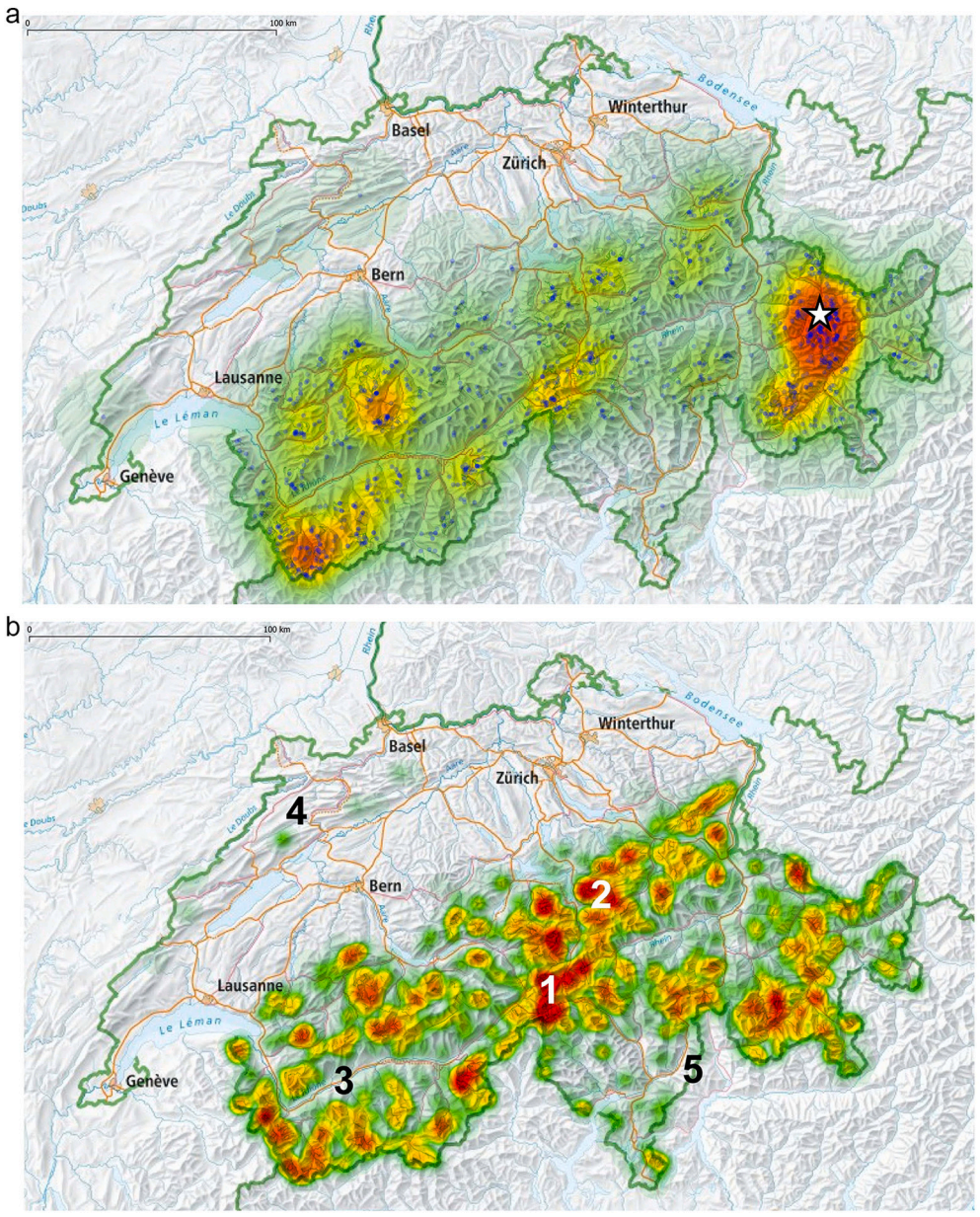

Fig. A1. Spatial distribution of a) avalanche accidents and b) movement points in Switzerland. Green indicates a low density, red a high density. The white star marks the Davos region. b) The numbers are explained in the text (Background map source: Federal Office of Topography). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A.2. Data - Spatial distribution of GPS data

The highest densities of movement points were found in the well-known backcountry-touring destinations (Fig. A1b), as for instance the Bedretto Valley / Urseren (1) or Lidernen / Muotatal (2). Lower-elevation regions, as the valley floor of the Valais (3) and the Jura mountains (4), and comparably remote areas, as the eastern Misox (5), showed hardly any backcountry travel. The spatial distribution of touring activity looks plausible. Furthermore, it is also similar to the spatial distribution of a large data set of planned backcountry tours in Switzerland (Schönenberger, 2018).

Schmudlach et al. (2018a) already compared the slope angle distribution of the GPS data set with route collections where a bias towards steeper and flatter terrain was expected. They noted that the slope angle distribution of the GPS data set was in between these route collections. Because there is no change in this regard with our extended data set we do not expose this again here.

A.3. Methods - Restriction to points in avalanche terrain

We focused on points in avalanche terrain and excluded all points with a TI < 0.25. As TI (Schmudlach and Köhler, 2016 and Schmudlach et al., 2018a) is still not well known, we show the influence of this filtering on slope angle and danger level.

At points outside avalanche terrain, the median slope angle, measured directly at the movement point, was 16°. In more than 96% of the cases, these points were in terrain with a slope angle less than 30°, and otherwise between 30 and 35° (Fig. A2a). In contrast, points located in potential avalanche terrain (TI > 0.25) were usually in much steeper terrain (median: 25°), despite the slope angle at this location still often measuring less than

30° (70% less than 30°). However, these points were located in slopes with steeper terrain above.

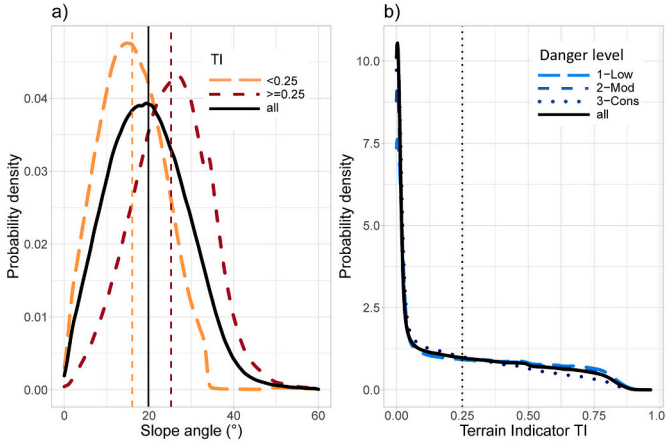

Fig. A2. Probability density of all data points. a) Slope angle for different TI, the vertical lines show the mean values. b) Terrain indicator (TI) for different danger levels. Points left of the dotted line (TI < 0.25) were considered no avalanche terrain and were eliminated.

A.4. Methods – Correlation between terrain use and avalanche forecast

Our data show that backcountry tourer adapted their behavior to the conditions by traveling less often in avalanche terrain at higher danger levels. This does not affect our results, because in the risk calculation accidents are divided by movements. The question is therefore only whether qualitatively different avalanche terrain is entered depending on the conditions.

At higher danger levels, lower-elevation terrain was used more frequently; the median elevation decreased from 2229 m at 1-Low to 2002 m at 3-Considerable (Fig. A3a). These findings agree with Schönenberger (2018), who analyzed a large data set of planned ski touring routes. Elevation of accidents showed no clear trend with danger level (2426 m at 1-Low, 2572 m at 2-Moderate and 2376 m at 3-Considerable, Fig. A3a).

The median slope angle for points in avalanche terrain (25°) decreased by 0.7° from one danger level to the next higher one. Further, we observed that backcountry users were somewhat more frequently in less typical avalanche terrain with increasing danger levels (Fig. A2b), with a median TI of 0.51 at 1-Low decreasing to 0.46 at 3-Considerable (Fig. A3b).

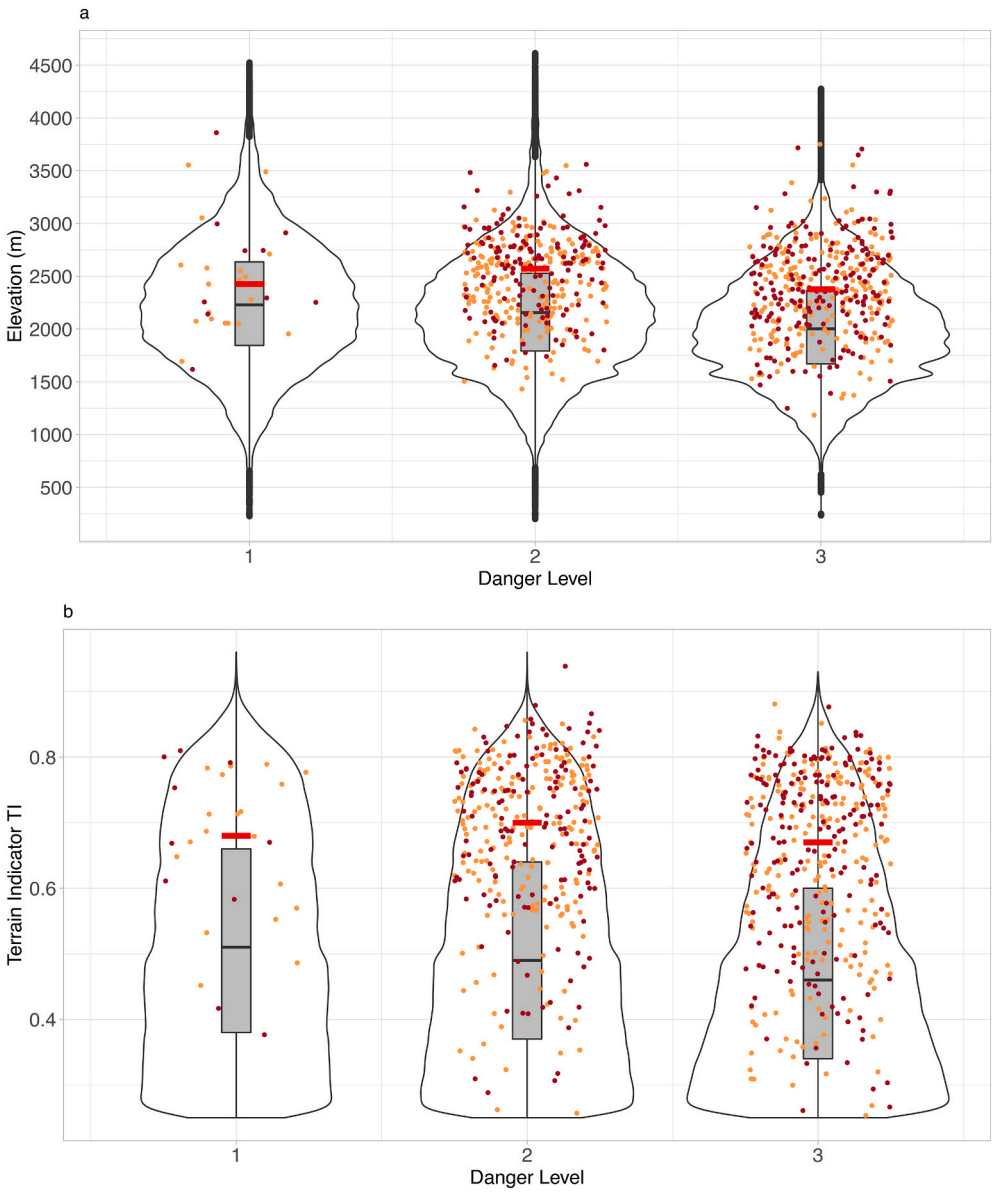

Fig. A3. Elevation (a) and terrain indicator TI (b) as function of the danger level. The movement points are visualized with a violin- and a boxplot (black and grey). The accidents points are visualized with a dot (dark red for serious accidents and light red for less serious accidents, respectively) and the median in red. Only points in avalanche terrain were considered (TI $\geq$ 0.25). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The median of the steepest section per tour (ten steepest points) decreased from 1-Low (41°) to 2-Moderate (39°) and to 3-Considerable (37°). The ten points with the highest terrain indicator (TI) of each tour were in very similar avalanche terrain at 1-Low and 2-Moderate (median TI of 0.77 and 0.76, respectively), representing *very typical* avalanche terrain (TI > 0.75). Only at 3-Considerable, with a median TI of 0.69, most backcountry tours did not access *very typical* avalanche terrain.

These results suggest that backcountry skiers used slightly less often steep terrain with increasing danger level, but mainly avoided larger slopes outside the forest, when the danger level was 3-Considerable. The TI of accidents, on the other hand, showed no clear dependence on danger level (median: 0.68 at 1-Low, 0.70 at 2-Moderate and 0.67 at 3-Considerable; Fig. A3b). Without this behavioral adjustment, the risk taken would increase somewhat more from 2-Moderate to 3-Considerable.

Depending on the avalanche forecast, the avalanche terrain entered differs in various parameters. However, all these differences are quite small. The risk taken is therefore far from constant. Rather, it is strongly influenced by the risk potential and can be equated with it as a rough approximation.

A.5. Results – Accident severity

Serious accidents occurred on the same aspects (Fig. A4b), but at slightly higher elevation (median 2′507 m, IQR = 2178–2779 m) compared to less serious accidents (median 2′426 m, IQR = 2099–2679 m) (Fig. A4a), and somewhat more often at 3-Considerable (55% of serious accidents, 48% of less serious accidents) (Fig. A5). Looking at the mean slope angle along the trajectory, serious accidents happened on slightly steeper slopes (36.3° vs 34.7°, respectively; Fig. A4c). In terms of TI, the difference is even smaller (0.69 vs 0.70, respectively).

Relying on serious accidents only for risk calculation leads to an increase in risk by a factor of 6.5 (CI = 3.4–12.4) from 1-Low to 2-Moderate, and by

3.7 (CI = 3.0–4.6) from 2-Moderate to 3-Considerable. The reference risk factor RRF is therefore about 1.17 times higher as when all accidents are considered, but the confidence interval also becomes larger.

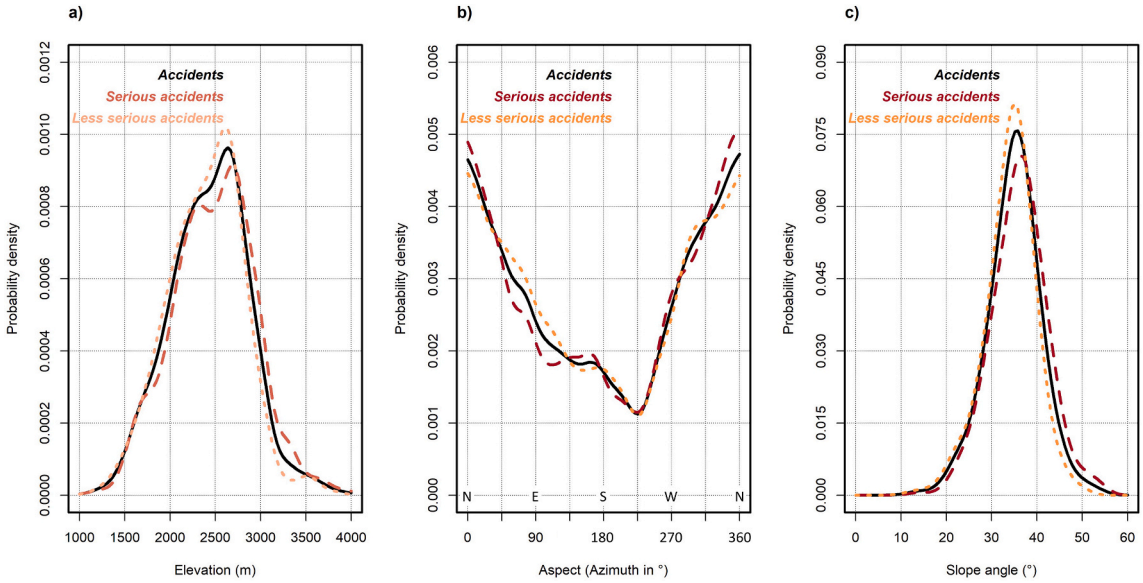

Fig. A4. Probability density for all (black), serious (red) and less serious (orange) accidents, respectively. The diagrams show elevation (a), aspect (b) and slope angle (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

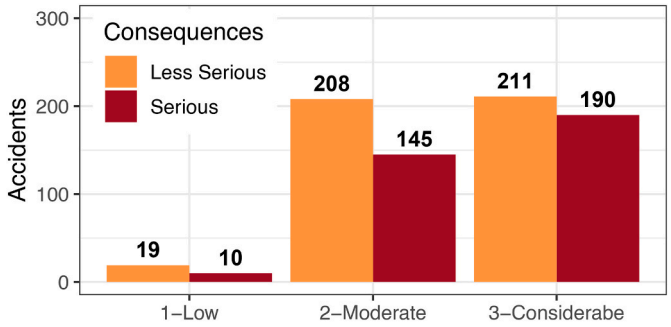

Fig. A5. Accidents as function of the danger level for serious (dead, injured or completely buried) and less serious accidents respectively.

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