CHARACTERISTICS OF AVALANCHE ACCIDENTS IN DIFFERENT SNOW CLIMATE REGIONS IN THE ALPS

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ABSTRACT: Avalanche accidents evidence periods of increased avalanche danger that avalanche forecasters want to pinpoint. Accidents records reveal periods with dangerous situations that may be difficult to grasp in forecasts or manage in the terrain. Hence, analyzing accidents has merit for enhancing avalanche forecasting, danger communication and avalanche education, alike. We analyzed avalanche records from forecasting regions in the French Alps, the Swiss Alps and Tyrol in the Austrian Alps. Including fatal accidents only, we obtained a multinational record that is almost complete with respect to location, date, trigger and simple terrain characteristics, such as slope aspect. A recently developed snow avalanche climatology describes the climatological variations in French Alpine regions. The local conditions were completed with snow cover modelling based on reanalyzed meteorological data. Our results confirm that fatalities with natural release have become rare today. Fatal backcountry avalanches are more frequent on north-facing aspects and occur with dry-snow conditions. Comparisons with the snow climates demonstrate that accidents are more common in regions which are prone to form persistent weak layers. Differences between the three Alpine countries were, for instance, related to the forecast danger level. Blending snow cover modeling with avalanche accident reports, facilitates analyses across borders in an objective manner and can provide a more complete set of information concerning the regional conditions, including regional climate.

KEYWORDS: avalanche accidents, snow climates, snow cover model.

1. INTRODUCTION

Avalanche accident data represent a very small but specific share of avalanche situations. Even though, all factors leading up to the accident can hardly ever be identified or analyzed, such data represent a wealth of information for improving forecasting and avalanche risk management. Forecasters search to pinpoint critical situations to issue accurate warnings. So, studying accident records, i.e., situations with dangerous situations, has merit for identifying situations that are hard to grasp or when communication is not optimal in forecasts. For risk management operations, the danger in combination with the consequences, are the two important elements for decision making. Knowing patterns from accidents can help avoid typical scenarios in the future, notably combinations of increased danger and severe potential consequences.

Efforts have been made to compile avalanche accident data across borders in Europe or the United States. The number of avalanche accidents is about stable today in the Alps (Techel et al., 2016) and the vast majority occurs in the backcountry (Techel and Zweifel, 2013).

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Apart from simple facts, accident information is not readily shared due to different recording standards. Hence, analyses of accident reports are rather communicated in the countries. In France, the association ANENA compiles accident data and publishes in "Neige et Avalanches", in Switzerland information is found online and in more detail in the annual reports "Winterbericht" (SLF, 2023) and accidents in Tyrol are compiled in the "Analyse Berg" reports. Nevertheless, some studies, such as for the Swiss Alps, have brought a number of important results for avalanche forecasting and risk management.

Fatal avalanches are dry-snow slab avalanches that are typically released by the travelling party. The typical terrain is on shady aspects and steeper than 30° (Schweizer and Lütschg, 2001). Avalanche accidents cluster in specific areas in the Alps, which are popular, but also seem climatologically prone for persistent weak layer situations which are the most critical for backcountry travel (Techel et al., 2015).

We are extending the analysis of fatal avalanche characteristics into the Austrian and the French Alps to cover a wider range of snow climates and finally to better represent the European Alps – beyond political borders.

In 2017, European avalanche forecasting services, began communicating avalanche problems. Even still not in consistent use today, the concept has much value to describe avalanche situations at daily but also at climatological scales (Reuter et al., 2023). We employ snow cover simulations to derive the avalanche problems from measured or reanalysis weather data. On one hand, this allows us to reconstruct regional conditions before individual accidents in a consistent manner across borders. On the other hand, this novel analysis brings insight into the climatology of the accidents.

Our goal is to describe the circumstances and the snow conditions of fatal avalanche accidents as well as provide the climatological context in the European Alps. We point out future research paths that come into perspective when blending accidents records and snow cover modelling.

2. DATA

We compiled data from fatal avalanche accidents reported to Météo-France, the WSL Institute for Snow and Avalanche Research SLF in Switzerland and to the Tyrolean avalanche warning service in the country of Austria, covering the alpine regions of France and Switzerland and the state of Tyrol in Austria.

2.1 Accident data

In the French Alps 379 fatal avalanche accidents are recorded between 2002 and 2020.

In Switzerland 342 fatal avalanche accidents are recorded between 2002 and 2022.

In the region of Tyrol in Austria 93 fatal avalanche accidents are recorded between 2011 and 2023.

2.2 Snow cover simulations

Snow cover simulations were driven from the Safran–Surfex–Mepra reanalysis data set (Vernay et al., 2022) that describes the past meteorological conditions in 23 regions of the French Alps, which are diverse at a climatological scale (Durand et al., 2009). The snow cover was simulated for a flat field site with the average regional conditions at 300 m elevation intervals. The simulations were used to derive avalanche problems and seasonal snow climate indicators, i.e., the flat field simulation at similar elevation (±200m) was chosen to represent the accident.

3. METHODS

3.1 Accident data

We provide an overview of the reported fatal avalanche accidents from the three Alpine countries. Our analysis is not exhaustive, but includes most properties that were measured in similar manner in the three countries. The data are summarized using standard statistical techniques, such as sums, averages and percentage ratios.

Rates in percent refer to a base value (N) that varies, because particular data can be unavailable in some cases.

We merged the data from the three countries for a joint analysis of certain properties, e.g., slope angle, if the distributions of the property were similar between countries according to a U-test (Mann-Whitney). If this was not the case, we show the individual distributions to discuss the differences. To compare proportions, we used the Chi-square test. A level of significance $p=0.05$ was chosen to decide whether the observed differences were statistically significant.

3.2 Avalanche problems

The snow cover simulations were post-processed with a snow instability algorithm to derive the prevailing avalanche problems for the accident day in the region (Reuter et al., 2022). The choice of avalanche problem is mainly guided by the type of the weak layer. Non-persistent weak layers in snow cover simulations lead to wind slab or new snow problems, which cause short-lived instabilities on the scale of a few days. Persistent weak layer problems originate from weak layers with persistent snow grains and typically last several days up to weeks. In case of weak layer wetting a wet-snow problem can be assigned based on the evolution of the liquid water content index.

3.3 Climatology

We use two snow climate classifications, the standard snow climate classification (Mock and Birkeland, 2000) and a climatology based on avalanche problems (Reuter et al., 2023). The first one allows us to classify the average conditions in the region during the season the accident happened. Hence, every accident can be attributed a snow climate. Finally, the number of accidents can be grouped by “coastal”, “continental” or “intermountain” climate.

The second classification, is based on avalanche problems and requires a long time series of snow cover simulations to determine the average occurrence of avalanche problems in a region. Hence, every region is attributed a probability belonging to one out of four clusters, which has unique characteristics of avalanche problem occurrence. In the French Alps the four clusters correspond to “northern”, “inner-Alpine”, “front-range”, and “southern” regions.

For regions with sufficient data, the number of avalanche accidents that happened in the region was multiplied by the probability of the region to belong to one cluster. So, for each cluster a measure is obtained of how likely avalanche accidents occur. In other words, the most likely climatological pattern for avalanche accidents is the one of the most accident-prone clusters – provided travel frequencies are not too different between the regions.

4. RESULTS

Overview of the circumstances/facts of the accidents are provided, such as elevation or slope aspect of the avalanche release area.

In a second step a comparison sheds light on potential differences between the countries in view of the issued danger level, for instance.

In a third step we investigate climatological patterns in the French Alpine regions.

4.1 General analysis across the three countries

The recorded avalanches (*N*=752) were mostly

- Slab avalanches (97%, *N*=586)
- releasing in dry-snow (93%, *N*=515)
- in an elevation range between 1800 and 2800 m (71%, *N*=736)
- on north- (20%), northeast- (18%) or northwest-facing (19%) slopes (57%, *N*=734)
- always inclined by 30° or more (*N*=478).

The other aspects had lower rates between 8 and 9%; on south-facing slopes 4% of the accidents occurred. In 430 out of 470 cases (92%) the slope angle in the release area ranged between 30° and 45°. There were no significant differences between countries (*U*-Test, p<0.05).

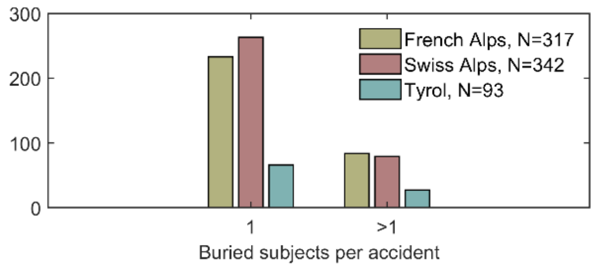

Figure 1: Number of buried subjects per accident for the 3 countries.

Cases with more than one buried subject, so called multi-victim scenarios, were reported considerably less frequently than one-victim scenarios: 74% of the cases in France (*N*=317), 77% in Switzerland (*N*=342) and 71% in Tyrol (*N*=93). So, in about one quarter of the cases, still more than one victim was buried. Our data set contains information about the number of buried subjects in many cases (*N*=574); if the number of buried subjects was not reported, we assumed the number equals the number of fatalities (*N*=178). The differences between France and Switzerland or Tyrol, as well as between Switzerland and Tyrol were non-significant (*p*=0.31; *p*=0.63; *p*=0.24).

Accidents with more than 1 fatality had longer avalanches (U-Test, *p*=0.05), wider slabs (U-Test, *p*<0.01) and a more important fracture depth (U-Test, *p*=0.07, *N*=87). The number of fatalities increased with the avalanche length and the width of the initial slab (stepwise regression, p=0.04 and p<0.01, respectively, N=266.

4.2 Differences between the three countries

Figure 2 shows that in the three countries the largest part of the accidents happened in the backcountry, though sometimes close to a ski resort, but not in resorts or on roads. The most common danger level forecast for accident day was “3-considerable”. The following differences appear between the countries:

More avalanche accidents happened during backcountry activities including hiking, alpine or ice climbing (i.e., other than skiing or snowboarding) in Switzerland in proportion (11%) compared to France (6%, *p*=0.01) or Tyrol (3%, *p*=0.02). The ratios between backcountry touring and off-piste skiing are fairly close to 4:3 in France (1.33) with slightly more accidents in the backcountry. In Switzerland (1.53) and Tyrol (1.73) the ratios are higher, but the differences between the countries regarding backcountry or off-piste accidents are not significant (all *p*>0.5).

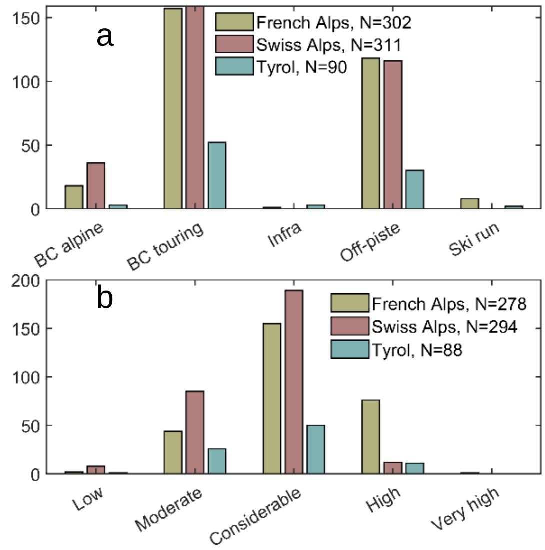

Figure 2: (a) Activity during avalanche accidents and (b) issued danger levels in the French Alps, in the Swiss Alps and the Tyrolean Alps.

Yet, small differences, should not be overstated as European resorts have no boundaries and the classification is occasionally ambiguous.

In all countries most accidents occurred when the danger level “3-considerable” was forecast. In France, the danger level with the second most important share of accidents was “4-high”, whereas in

Switzerland and Tyrol this level was “2-moderate”. Level “4-high” was significantly more frequently forecast in accidents in France than in Switzerland and Tyrol (both *p*<0.01). On the other hand, accidents with level “2-moderate” were significantly more frequent in Switzerland and Tyrol than in France (both *p*<0.01).

4.3 Avalanche problems and accidents

Blending snow cover simulations with avalanche accident data we can obtain an objective guess of the avalanche problem in the accident situation i.e., at daily resolution.

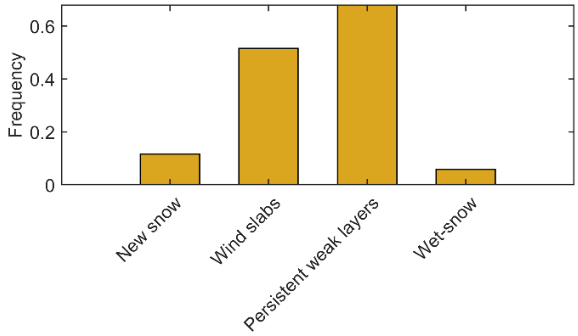

Figure 3: Frequency of avalanche problems in fatal avalanche accidents in the French (N=208).

In the French Alps the most common avalanche problem in avalanche accidents was the persistent weak layer problem (68%), followed by the wind slab problem (51%) (Figure 3).

4.4 Character of the winter and accidents

In accident records, we typically observe strong fluctuations between seasons.

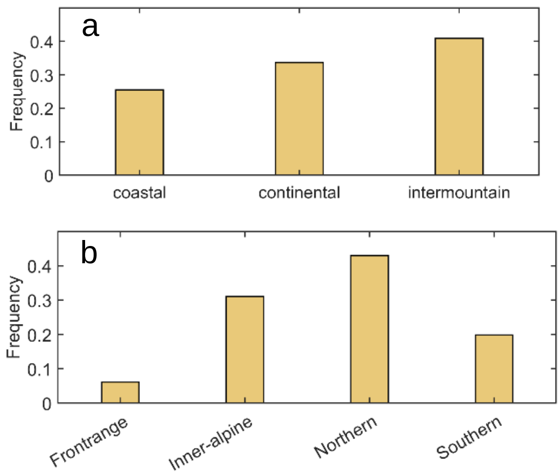

Figure 4: Avalanche accident frequency (a) by snow climate (Mock and Birkeland, 2000) for accidents in the French Alps (N=342). Avalanche accident frequency (b) by snow avalanche climates for accidents in the French Alps (N=277).

The snow cover simulations can tell us more about the characteristics of the winter seasons when the accidents occurred. We applied the snow climate classification of Mock and Birkeland (2000) to our data set. Figure 4 a shows the frequency of accidents by seasonal climate character for the French Alps. The seasons when accidents occurred had more often intermountain, than continental or coastal climate characteristics. Coastal seasons are characterized by substantial rain (> 80mm), elevated mean air temperatures (> 3.5°C) or important snow mass accumulation (snow water equivalent > 1000 mm) during the months of December to March, whereas intermountain seasons on the other end, show moderate mean air temperatures and abundant snow accumulation (new snow sums > 5.6 m) but with lower density (snow water equivalent < 100m mm).

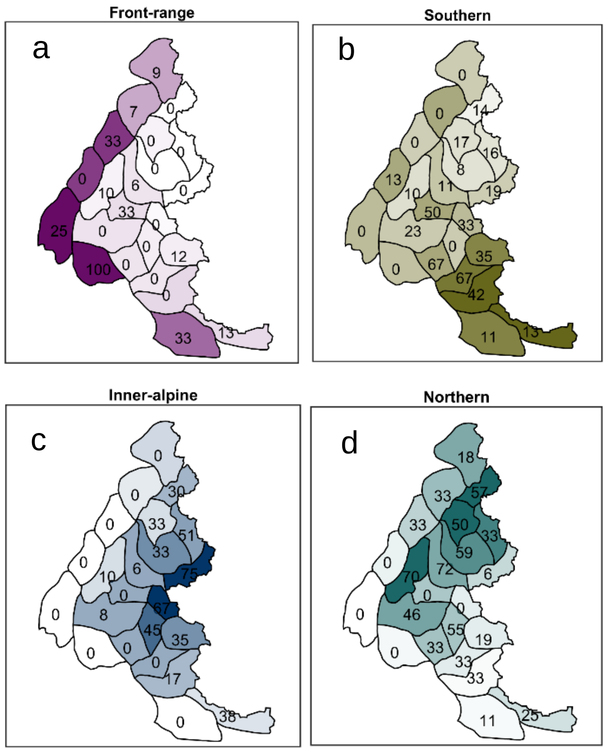

Figure 5: Snow avalanche climatology for the French Alps with distinct groups: (a) “front-range”, (b) “southern”, (c) ”inner-Alpine” and (d) “northern” cluster. The number in each region is the percentage of accidents in that region during a typical season, i.e. with a climate typical of the cluster (N=277).

In the snow avalanche climatology for the French Alps (Reuter et al., 2023) an intermountain climate comes close to the “northern” cluster. Along with the “inner-Alpine cluster, both clusters gather almost 3 quarters of the accidents (Figure 4 b). Out of 277 accidents 119 accidents occurred in seasons which had the climate characteristics of the “northern” cluster (43%). Inner-Alpine characteristics were simulated in 86 of the cases (27%). Seasons with typical characteristics of the “southern” (17%) or the “front-range” cluster (5%) were less common.

Hence, in the French Alps the majority of the accidents occurred in seasons with either, relatively many persistent weak layers ("inner-Alpine" cluster) or, in seasons with relatively many new snow situations and persistent weak layers ("northern" cluster).

4.5 Snow climates and accidents

The maps in Figure 5 help locating the clusters in the French Alps. The color coding corresponds to the probability that region belongs to a cluster based on data from 62 years (Reuter et al., 2023). The percentage of accidents that fell into a season with the characteristics of the cluster is provided for every region. In many cases the highest values coincide with the dark shading. That means that a large part of the accidents in the region occurred in seasons that were typical of the region. From this analysis, it seems that the accidents do rather not occur in seasons with unusual characteristics.

5. DISCUSSION AND CONCLUSIONS

Our analysis of 752 avalanche accidents from three Alpine countries confirms the well-known characteristics of fatal avalanches: Dry-snow slab avalanches on rather shaded aspects on slopes inclined by 30 degrees or more. The results are coherent with previous observations in Switzerland (Schweizer and Lütschg, 2001).

In avalanche accidents multi-victim scenarios are reported in about one quarter of the cases. The ratio is in line with previously reported values in France (Jarry, 2022) and Switzerland (Schweizer and Techel, 2017). In France, the number of accidents with multi-victim scenarios is stable (Jarry, 2022). We found that avalanche length, slab width and fracture depth are important indicators if more than 1 victim was killed.

The unique data compilation also provides insight into differences between the Alpine countries:

The proportion of backcountry accidents during hiking, alpine or ice climbing was higher in Switzerland compared to France and Tyrol. This difference may, however, be related classification issues.

The ratios of backcountry to off-piste accidents for the period we considered, were on the same order in France as previously reported based on 35 years of data before 2016 (1.28) (Pfeifer et al., 2018). After the season of 2009-10 the long-term average ratio seems to turn, due to a decline in off-piste accidents (Jarry, 2022). In Switzerland, Pfeifer et al. (2016) reported a ratio of 1.78 for the 35-years period, which is slightly lower than the one we found for 20 years. In this context, an analysis of the seasonal climate characteristics would be interesting.

The most frequently forecast danger level for an accident day was "3-considerable" in all three countries. However, the second most frequent danger level was "4-high" in France, but "2-moderate" in Switzerland and Tyrol. This difference between Swiss and French forecasts is known (Greene et al., 2006) and may partly be related to the more extensive use of the danger level "4-high" in France for situations of skier-triggering only.

In the French Alps fatal accidents were most frequent during winter seasons characterized as "intermountain". In two thirds of the cases the snow cover models suggested a persistent weak layer problem. In about half of the situations a wind slab problem was present. Hence, not seldom problems overlap. This result from fatal avalanches, which are almost exclusively human-triggered dry-snow slab avalanches, suggests that neither new snow situations nor wet snow situations, but persistent weak layer and wind slab situations are more critical for recreationists.

Our results for the French Alps indicate that climate regions favoring the formation of persistent weak layers are more accident-prone. Accidents during seasons with the characteristics of the "northern" or the "inner-Alpine" clusters gathered about 70% of the accidents. In comparison with the snow climate classification "intermountain" seasons had relatively more accidents than continental or coastal seasons. As "intermountain" characteristics correspond to the "northern" cluster, the results seem in line. Hence, in fatal avalanches persistent weak layers dominate avalanche problems in simulations. Moreover, persistent grain types also dominated in the observed weak layers.

Finally, we graphed regional accident occurrences to compare with the regional climate. It seems that accidents occur in winter seasons that are typical and not unusual for the climate of the region.

Blending snow cover modeling with avalanche accident reports, allows analysis across borders in an objective manner, that will provide deeper insight into the characteristics of accidents. The further analysis of this data set can provide a better understanding of the snow conditions before the accidents at the regional scale.

Given that the interannual variability of the number of avalanche accidents is large, for instance in France ranging between 12 (2019-20) and 57 (2005-06) accidents in the studied period (Jarry, 2022), studying the temporal evolution of accident characteristics seems worthwhile. Moreover, the characteristics of accidents for different scenarios, such as avalanche problems is another avenue for further research.

ACKNOWLEDGEMENTS

We are grateful for discussions with Frederic Jarry of ANENA (Association Nationale pour l'Étude de la Neige et des Avalanches) on trend of accidents in France.

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