ON SNOW AND AVALANCHE CLIMATES IN THE SWISS ALPS

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ABSTRACT: The snow and avalanche climate types maritime, transitional (or intermountain), and continental are well-established in North America, but rarely used in Europe and particularly not known for the Swiss Alps. While the Swiss climatology is well-established for snow precipitation, there is no classification of snow and avalanche climate types. Recent efforts have addressed the lack of consistent avalanche climatology for the European Alps by considering the occurrence of avalanche problem types, expanding beyond the standard snow climate classification based solely on weather variables. Simulated snow stratigraphy obtained with a numerical snow cover model allows taking into account not only meteorological data but also snowpack properties for classification. Following the approach established in North America, we analyzed the data from 128 automated weather stations, in total 2230 winter seasons, to derive the snow climate types maritime, transitional and continental. The snow climate in the Swiss Alps is primarily transitional (45%), with large parts having a strong maritime influence (34%), and a few regions with a continental influence (21%). There are distinct regional differences. On the northern slopes of the Alps, the snow climate is predominantly maritime, less so on the southern slopes. In between, the climate class is mainly transitional, and in some regions of the Engadine and the Valais, the snow climate is to a good part continental. To expand the classification of the snow climates, the snow stratigraphy was analyzed with regard to the avalanche problem types and the frequency of four classes of grain types, notably persistent grain types and melt forms. While in the maritime snow climate we found many melt form layers and few persistent grains, the snowpack classified as continental included primarily persistent grains and rarely showed melt forms. Considering the simulated avalanche problem types suggested that the snowpack in regions with a transitional snow climate is more avalanche-prone than in the maritime and continental snow climates. These findings manifest the large variations seen in snow and avalanche climates across the Swiss Alps. Establishing a closer link between snow climates in the Swiss Alps and avalanche characteristics holds promise for avalanche forecasting, avalanche training and accident analysis.

KEYWORDS: snow climate, avalanche climate, avalanche formation, snow stratigraphy, avalanche problem type

1. INTRODUCTION

In North America, the snow and avalanche climates are well established. The classification is considered useful to describe avalanche formation in a broad sense since the character of snow avalanching in a mountain range can be roughly assigned to one of two basic types: *maritime* or *continental* (McClung and Schaerer, 2022, p. 26). Snow climates in between continental and maritime are termed *intermountain* or *transitional*.

Different climatic zones were first described by Roch (1949). Armstrong and Armstrong (1987) characterized the three types for the western United States in terms of air temperature, precipitation, snow depth, new snow density, and temperature gradient. Based on these snow and weather data Mock and Birkeland (2000) suggested a binary classification system for snow avalanche climates based on thresholds for five weather and snow variables: air temperature, rain, snowfall, snow water equivalent (SWE), and snowpack temperature gradient. This classification is still in use and has also been applied by Hägeli and McClung (2003) to characterize the avalanche activity in the Columbia Mountains of western Canada. They pointed out that in the analysis by Mock and Birkeland (2000) there was an increase in mean elevation from maritime to continental stations. This increase has a prominent impact on the classification, as air temperature is one of the main discriminating variables. Furthermore, they concluded that it is not sufficient to consider only weather and snow data for the classification of avalanche climates, but that avalanche characteristics should also be taken into account. Although the snow climates were related to the avalanche climates, they suggested that the terms should be used distinctly.

In Europe, snow and avalanche climate classification was not a significant focus for a long time.

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In Switzerland, for instance, the prominent differences in snowfall amounts in the Alps were known, repeatedly analyzed (e.g., Blanchet et al., 2009; Laternser and Schneebeli, 2003; Zingg, 1954), and applied to determine the design snow load. Similar studies were conducted for France (e.g., Durand et al., 2009) and Austria (e.g., Spreitzhofer, 1999). Only recently, Reuter et al. (2023b) determined the snow and avalanche climates of the French Alps, employing a new approach using simulated avalanche problem types based on snow cover simulations. They then compared their results to the classification by Mock and Birkeland (2000). The snow and avalanche climate also influences the frequency of avalanche accidents. In France, the avalanche problem type *persistent weak layers* was the most frequently identified in avalanche accidents (Reuter et al., 2023a). Similarly, Techel et al. (2015) reported that the relative frequency of avalanche accidents in Switzerland was largest in regions that are considered as inner-alpine where the avalanche problem type persistent weak layers is often dominant. For the purpose of avalanche forecasting, the Swiss Alps were divided in seven geographical regions that also may experience different snow climates (e.g., Laternser and Schneebeli, 2003).

In this study, we aim to determine the snow and avalanche climatology for the Swiss Alps with the methods of Mock and Birkeland (2000), and Reuter et al. (2023b) using snow cover simulations driven with the data of the Swiss network of automated mountain snow and weather stations (IMIS). In addition, we compare the frequency of grain types in simulated snow stratigraphy throughout the Swiss Alps (Mayer et al., 2024).

2. METHODS

We applied the methods of Mock and Birkeland (2000), and Reuter et al. (2023b) using the data of the Swiss network of automated mountain snow and weather stations (IMIS) where the snow stratigraphy is simulated with the numerical snow cover model SNOWPACK (Lehning et al., 1999).

2.1 Data

The IMIS network of automated weather stations includes about 130 so-called snow stations where not only meteorological but also snow parameters are measured. The stations are located at elevations of typical avalanche starting zones. For our study, we analyzed data from 128 stations. Their median elevation was 2300 m a.s.l. The first stations were built in 1996, and by 2010 most of the present stations were operational (Liechti and Schweizer, 2024). Hence, for most stations, data for 20 or more years were available. For the Swiss Alps, there are of course also longer time series of snow data but from stations located mostly below 1800 m a.s.l. making those less suitable for our purpose.

2.2 SNOWPACK simulations

For each of the snow stations, the numerical snow cover model SNOWPACK (Lehning et al., 2002) was driven with the data measured at the station. The simulated snow stratigraphy has been available for most stations since they were built. The historical data were frequently re-processed when an updated version of SNOWPACK was available. We used the flat-field simulations generated for the operational avalanche warning service based on the operational version of SNOWPACK for the winters 1996/97 to 2021/22. As the time series were incomplete for some winters, and a few stations were only recently built, the number of years analyzed per station varied between 25 years and 1 year; the median number of years was 20, and for 110 out of 128 stations (86%) the number of years analyzed was 10 or more.

2.3 Classification

For the snow climate classification by Mock and Birkeland (2000), we used the data from the snow cover simulations (either from the input file (smet) or the output file (pro)): liquid precipitation (rain), new snow height, and snow water equivalent (SWE) cumulated for the winter season from 1 December to 31 March, as well as average air temperature for the same period, and average snowpack temperature gradient for December. The temperature gradient was averaged from daily values calculated from daily average air temperature (if < 0 °C) and average snow depth, and assuming a snow temperature of 0 °C at the bottom of the snowpack. The binary classification procedure (including seven decisions) is reproduced in Figure 1. For each IMIS station and winter season, the climate type according to the flowchart in Figure 1 was classified and the decision (1-7) was recorded. Finally, the frequency of each of the three climate types was obtained for each station. In total, we analyzed 2230 winter seasons.

The approach by Reuter et al. (2023b) is based on simulated avalanche problem types which are determined by following critical weak layers in simulated snow stratigraphy and rating their severity based on stability metrics (Reuter et al., 2022). For each IMIS station and each day of the winter season (1 October to 31 May), the frequency of four avalanche problem types was obtained: new snow, wind slab, persistent weak layers, and wet snow.

For each station and each day of the winter season (1 December to 31 March) we also analyzed the frequency of grain type classes in simulated stratigraphy following Mayer et al. (2024). They grouped the simulated primary snow grain types into four classes to combine grain types with similar microstructural characteristics and similar significance for avalanche formation: new snow (PP, DF), rounded grains (RG), persistent grains (FC, DH, SH, FCxr) and melt forms (MF, MFxr, IF) (grain type code according to Fierz et al., 2009). Only days when the snow height was >40 cm, were considered for analysis.

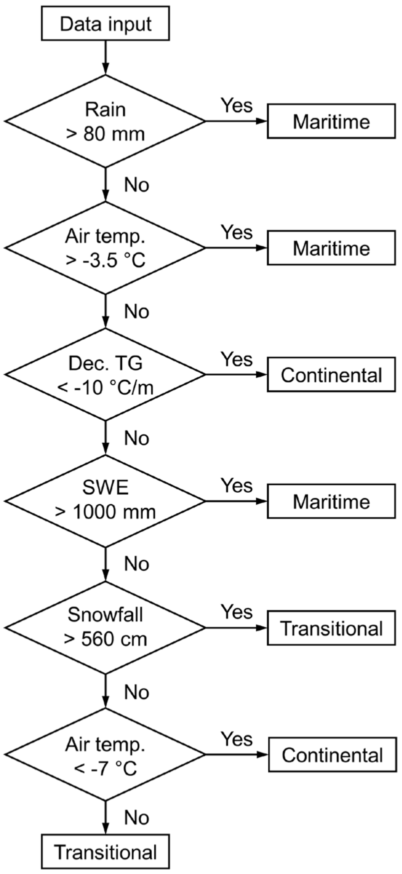

Figure 1: Snow climate classification after Mock and Birkeland (2000)

3. RESULTS AND DISCUSSION

Applying the classification of Mock and Birkeland (2000) suggests that the snow climate in the Swiss Alps is predominantly transitional (45%), to a good part maritime (34%) and continental (21%). Only three stations with more than 10 years of data were classified consistently with one climate type. At all other stations, there was a dominant class, with lower frequencies for at least one of the other two classes. At six stations there were ties. There, we selected one of the two as the dominant class considering the surrounding stations.

The frequency of the three climate classes across the Swiss Alps, for the locations of the IMIS stations, showed distinct patterns (Figure 2). The maritime climate class was mainly found on the northern slopes of the Alps and the southern slopes, albeit somewhat less prominently. In between, the transitional (intermountain) climate class was predominant. In some parts of the southern Valais and the Engadine, the frequency of the continental class was highest.

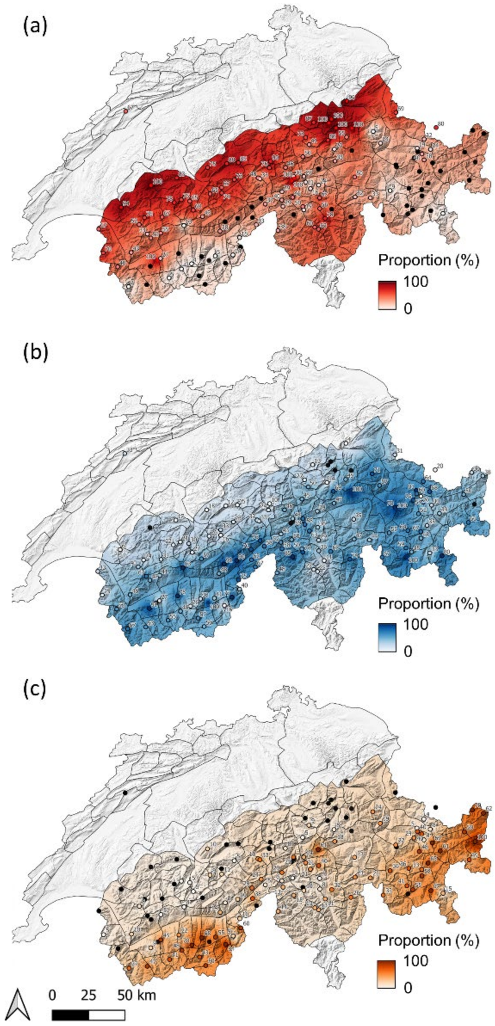

Figure 2: Snow climate prevalence for the Swiss Alps: (a) maritime, (b) transitional, and (c) continental snow climates according to Mock and Birkeland (2000). Numbers indicate frequency at IMIS stations; inverse distance weighted interpolation between stations, not considering topography.

These patterns agree well with long-term patterns of extreme snowfall or snow depth (e.g., Blanchet and Lehning, 2010). In the southern Valais and parts of Grisons, there are some inner-alpine, rather dry valleys surrounded by high mountains, which shade them from precipitation.

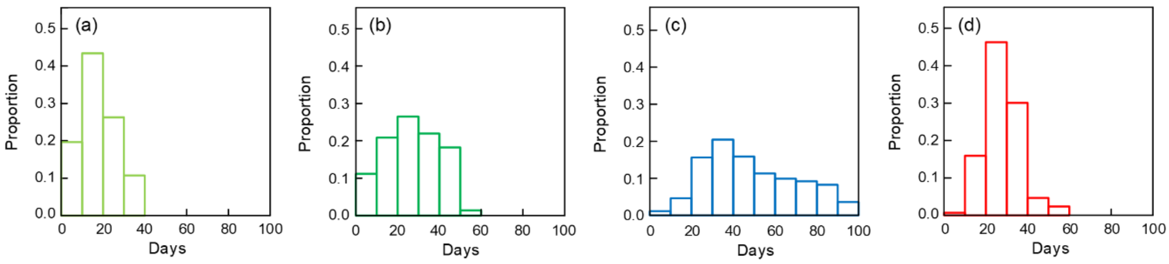

Figure 3: Frequency of simulated avalanche problem types for the Swiss Alps: (a) new snow, (b) wind slabs, (c) persistent weak layers (incl. deep persistent weak layers), and (d): wet snow. The relative frequency indicates on how many days per season an avalanche problem type (natural release) was considered critical (*N* = 2157).

As pointed out by Hägeli and McClung (2003) the elevation has a strong influence on the classification via air temperature. In fact, our analysis showed that stations below the median elevation (2299 m a.s.l.) were mostly classified as maritime (57%), and stations above as transitional (55%).

Avalanche mapping after an extensive avalanche cycle revealed that the typical mean elevation of avalanche starting zones in the Swiss Alps was about 2400 m a.s.l. (Bründl et al., 2019). This suggests that the IMIS stations (~2300 m a.s.l.) may be suited to assess the snow and avalanche climate. Still, we deal with point measurements and some of the stations may not be representative of the conditions in the surrounding terrain.

Figure 3 shows the frequency of the avalanche problem types for all stations in the Swiss Alps. The number of avalanche problem types rated as critical was on average 121 per season and station. Most frequently (41%), the avalanche problem type persistent weak layers (including deep persistent weak layers) was critical (considering natural release). Some less frequent were non-persistent problem types (new snow: 14%, wind slab: 22%) and the wet snow problem type (23%). In some seasons for some stations, the problem type persistent weak layers prevailed for up to 100 days. Its frequency distribution (Fig. 3c) was much wider than for the non-persistent weak layers, which were more short-lived (Fig. 3a,b).

Relating the problem types to the snow climate classes showed that the number of days when at least one avalanche problem type was rated as critical was 40, 48 and 38 for the stations classified as maritime, transitional and continental, respectively. The total number of avalanche problem types rated as critical, was on average 100 per season and station in the maritime climate class, 143 in the transitional, and 104 in the continental climate class. These findings suggest that in general the transitional climate class is more avalanche-prone than the maritime and continental climate classes.

On the other hand, the relative frequency of the avalanche problem types did not vary particularly between the snow climate classes (Figure 4). The persistent weak layers problem type was most frequently simulated and the proportion was largest (43%) for the transitional snow climate class. The wet snow problem type was the least frequent, whereas the non-persistent problem types (new snow, wind slab) were similarly frequent, between 34 and 37%.

Finally, we analyzed differences in snow stratigraphy by simply counting the presence of the primary grain types. Considering the weighted average (per year of data) of the four grain type classes for all stations revealed that layers with persistent grains were most frequently found (35%), followed by the class melt forms (29%), rounded

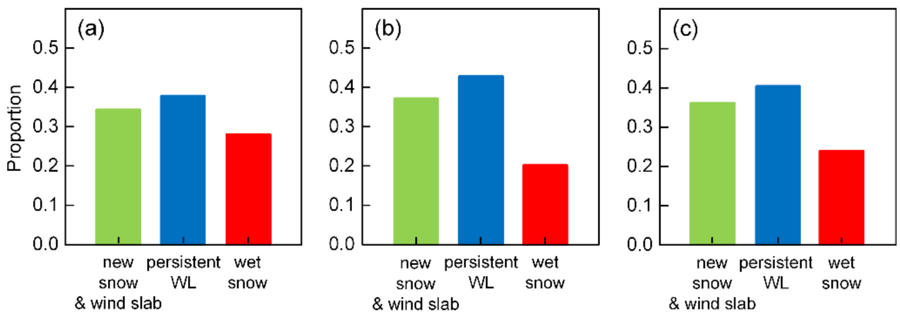

Figure 4: Frequency of the four avalanche problem types per snow climate class: (a) maritime, (b) transitional, and (c) continental: average proportion weighted by number of seasons analyzed (*N* = 128).

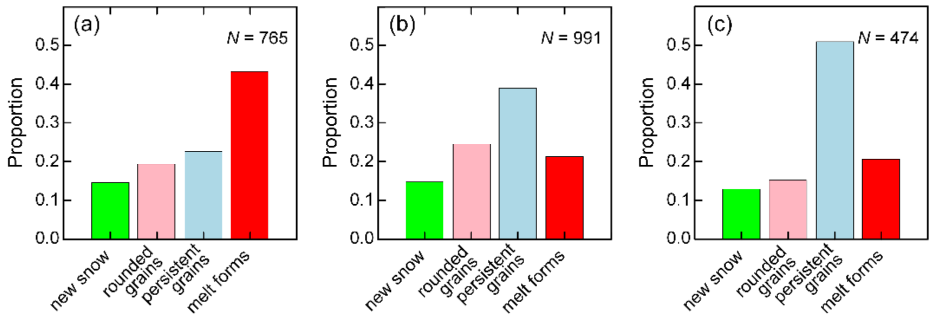

Figure 5: Frequency of the four classes of grain types per snow climate class: (a) maritime, (b) transitional, and (c) continental.

grains (21%) and new snow (15%). Prominent differences between the snow climate classes were evident (Fig. 5). The proportion of persistent grain types was higher in the continental and transitional climate classes, while melt form layers were more frequently found in the maritime class. The other two grain type classes (new snow and rounded grains) showed little variation between the snow climate classes.

Relating the snow climates to the two classifications based on avalanche problem types and grain type classes suggests that the three snow climates in the Swiss Alps may have distinct avalanche characteristics, as manifested, for instance, by the predominance of persistent grain types and avalanche problem types in the regions with little or no maritime influence. This pattern has also been found for the French Alps (Reuter et al., 2023b).

4. CONCLUSIONS

We have classified the snow and avalanche climate in the Swiss Alps based on snow cover simulations at the locations of 128 automated weather stations. Within the relatively small area of the Swiss Alps (north-south extension of about 100 km), surprisingly large differences in snow climate exist. From predominantly maritime to predominantly continental snow climates, the variety is large. Moreover, there can be significant variation between seasons. Most stations were classified as predominantly transitional with an often substantial minority class of either maritime or continental.

The snow climates also have different snow stratigraphy, for instance, predominantly layers with persistent grain types in the continental and transitional climate classes, suggesting that the avalanche characteristics differ among the snow climate classes. In particular, considering simulated avalanche problem types, the number of days per season when at least one avalanche problem was rated as critical was 40, 48 and 38 for the maritime, transitional and continental climate classes, respectively. This finding suggests that the snowpack in regions with a transitional snow climate is more avalanche-prone than in the maritime and continental snow climates. Hence, this first preliminary analysis showed that the snow climates derived from snow data may well have different avalanche characteristics. Establishing a closer link between snow climates in the Swiss Alps and avalanche characteristics holds promise for avalanche forecasting, avalanche training and accident analysis.

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