Journal of Glaciology

Article

Cite this article: Reuter B, Hagenmuller P, Eckert N (2023). Snow and avalanche climates in the French Alps using avalanche problem frequencies. *Journal of Glaciology* **69**(277), 1292–1304. https://doi.org/10.1017/jog.2023.23

Received: 25 July 2022
Revised: 21 February 2023
Accepted: 19 March 2023
First published online: 18 May 2023

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Snow and avalanche climates in the French Alps using avalanche problem frequencies

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Abstract

Avalanches result from an interaction of weather and terrain, where past weather and internal snow cover processes play important roles. So far, climatology was mainly based on weather data, as regional snow instability information, such as avalanche activity, is scarce on climatological time scales. We present a new approach to create a snow avalanche climatology from simulations of avalanche problem types based on snow cover simulations of reanalysis data and a cluster analysis. Analyzing the winters between 1958 and 2020 in the French Alps, wet-snow situations dominated natural release. Dry-snow situations with non-persistent and persistent weak layers occurred each on at least one third of the days. Four typical patterns of avalanche problem types were identified. They follow the main orography with more new snow situations in the northern regions and more cases of persistent weak layers in inner-Alpine regions. In the front-ranges and in southern regions wet-snow situations occurred early in winter – typical for coastal snow climates. Agreement with the standard snow climate classification and the geography of the French Alps suggests that mountain regions with similar conditions can now be outlined. This method for snow avalanche climatology will inform avalanche forecasting and facilitate climate change impact studies.

1. Introduction

Avalanche activity generally depends on a sequence of meteorological events (Atwater, 1954). The snowpack archives the meteorological history during winter and thus, it reflects the local snow climate. In his pioneering work, Roch (1949) summarized the layering and its average stability in regions of the western United States. The four distinct snow climate zones he described were then refined from an avalanche forecasting perspective (LaChapelle, 1966) and eventually characterized with meteorological observations (Armstrong and Armstrong, 1987). Based on time series of up to 52 years including climate and avalanche observation Mock and Birkeland (2000) studied the variability between the earlier suggested snow climate zones and introduced a seasonal classification based on meteorological variables. Peculiarities in the atmospheric conditions may promote temporal deviations from the general snow climate (Mock and Kay, 1992), and thus, one season, for instance, can fall into the coastal regime although usually the regime is transitional. Apart from such limitations, which are common in classification approaches, the nature of the data and the spatio-temporal availability challenge snow climate classifications as weather, snow and avalanche observations are limited across mountain ranges, in particular during winter. Nevertheless, existing classifications were applied and tested using various types of data including reanalyses and avalanche forecasts in different areas – yet, mainly in North American mountain ranges. In the transitional snow climate of the Columbia Mountains, Hägeli and McClung (2003) analyzed jointly the snowpack and avalanche characteristics in sub-regions. Their analysis demonstrates how large-scale atmospheric conditions translate into regional avalanche climates and what role snowpack properties, such as weak layer type, play in driving local avalanche activity. Studying the relationship between climate and avalanches, i.e., avalanche climates rather than snow climates, requires additional information on the snowpack that forms avalanches. Inspired by this finding, Shandro and Hägeli (2018) analyzed avalanche forecasts to characterize patterns of snow instability in different climate regions of Western Canada. Apart from regional differences, the temporal variations of avalanche problem types in western Canada seem to be at least partially related to large-scale atmosphere-ocean oscillations (Hägeli and others, 2020).

The snow climates in the European Alps have been studied early on (e.g. Zingg, 1954) and spatial differences across the Alpine ridge described with several climate regions, such as seven alone for the Swiss Alps (Laternser and Schneebeli, 2003). However, to date, there is no climatological analysis addressing the different regional snowpack properties regarding avalanche release in the European Alps. Yet, Sielenou and others (2021) analyzed a dataset of meteorological and simple snowpack properties to group the regions in the French Alps according to the natural avalanche activity. The clusters they obtained partly relate to typical winter weather patterns that manifest as different avalanche situations in the regions. For new snow situations intense enough to produce natural release, an optimal combination of moisture advection and blocking by the mountain barrier (e.g. Whiteman, 2000) is generally required. In the northern

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French or the western Swiss Alps this translates into a strong north-westerly flow from around 295° (Hächler, 1987) that drives weather fronts to the north-western end of the Alps. For the southern Swiss Alps, that optimal angle would be 185° and was observed in avalanche activity reports (Calonder, 1986; Schneebeli and others, 1998). More protected regions closer to the Alpine ridge on average receive smaller amounts of new snow (Durand and others, 2009), and even intense winter storms remain preferential of the front-ranges (Gaume and others, 2013; Le Roux and others, 2021). With lower new snow amounts and temperatures, regions closer to the Alpine ridge are prone to develop persistent weak layers, as accident reports from south-western parts of Valais, for instance, suggest (Techel and others, 2015). Regional snowpack characteristics can apparently account for such differences in avalanche activity – but it is presently not clear, where similar patterns of avalanche problems are found in the European Alps. Given the interest in climate change impact on natural hazards such as avalanches (Hock and others, 2019; Giacona and others, 2021), an avalanche climatology is needed to form a baseline for studying future change and impacts.

Since climate describes patterns of typical weather conditions over many winters, it is secondary for avalanche forecasting, which relies on recent snowpack observations and a short-term weather outlook (LaChapelle, 1970). Nevertheless, different snow climates require forecasting tools that are sensitive to the local conditions. In climates where snow storms are common, forecasting routines should include tools to monitor short-term snow instability trends, such as the time derivative of the stability index (Conway and Wilbour, 1999). On the other hand, simulations of the liquid water index can be key in regions with recurring melt cycles to predict wet-snow instability (Mitterer and others, 2011). Apart from understanding winter climate and the meteorological processes driving avalanche activity, outlining regions with similar snow conditions for avalanche release also has merit to inform avalanche forecasting practices.

Although primarily introduced as a communication vehicle for avalanche danger in North America (Statham and others, 2018) and in Europe (EAWS, 2019) avalanche problem types have become an indispensable classification beyond the forecasting context as they reflect the characteristics of avalanche danger. A snow cover simulation-based approach has been developed recently to assess avalanche problem types (Reuter and others, 2022). Interpreting the simulated stratigraphy in view of the common avalanche release processes, different avalanche situations can be described with avalanche problem types, i.e. the new snow, the wind slab, the persistent weak layer or the wet snow problem. To characterize avalanche climates, meteorological data are ideally combined with snowpack properties (Hägeli and McClung, 2007); thus, the avalanche problem types provide a classification that is well suited to study snow avalanche climates. The described approach to assess avalanche problem types has already been tested with different snow cover models and in different climate regions (Reuter and others, 2022), and hence seems fit for building a snow climatology.

Despite evidence for climatological differences, the European Alps lack an avalanche climatology. Methods and data are available to create a characterization that can complement the standard snow climate classification, which is based on weather rather than snow cover data. We develop a simulation approach to obtain information on regional snow instability, as direct evidence such as avalanche data, is scarce on climatological time scales. Our method separates different climate regions based on a cluster analysis of the occurrence of simulated avalanche problem types. We use a reanalysis dataset that provides the meteorological input for the French Alps (Vernay and others, 2021) to simulate the snow cover with the model Crocus (Vionnet and others, 2012). From the simulations we derive avalanche problem types for the winter seasons between 1958 and 2020 at daily resolution. The seasonal occurrences of avalanche problem types summarize the snow climate during one winter. The regional patterns of the seasonal occurrences can then be separated with a cluster analysis. In addition to our approach based on the avalanche problem types, we also apply the reference snow climate classification (Mock and Birkeland, 2000) in order to relate to previous work and compare our results. Then, we demonstrate the consistency of our results with the orography of the French Alps (Fig. 1), an area where no snow avalanche climate zones have been defined so far.

2. Data and methods

Based on a meteorological dataset the historic snow cover is simulated. From the snow cover data every winter season can be classified into a snow climate (Mock and Birkeland, 2000) and described in terms of avalanche problem occurrence. Both ways of describing climate are compared. We suggest an avalanche climatology based on patterns of avalanche problem occurrence that we determine with a cluster analysis.

2.1 Meteorological data

The S2M (Safran–Surfex–Mepra) dataset (Vernay and others, 2021) describes the past meteorological conditions in the French mountain ranges. The French Alps are divided into 23 regions (Fig. 1), often referred as to massifs, under the assumption that in a region the main drivers of spatial variability are elevation, slope and aspect (Durand and others, 1999). The S2M dataset was created from the SAFRAN reanalysis of numerical weather prediction model output and observations that were used to drive the SURFEX/ISBA-Crocus snow cover model. Thus, the S2M dataset contains the relevant meteorological forcing for snow cover simulations, including, for instance, the snow surface temperature (Vernay and others, 2021). Hence, for each mountain region, the snow cover can be simulated from the S2M dataset at 300 m elevation intervals, at 8 different aspects and at varying slope angles (0°, 20°, 40°).

2.2 Release area elevation

In the 23 French Alpine regions, we performed snow cover simulations at 1800, 2100, 2400, 2700 and 3000 m, and not exceeding the summit elevation of each region. For the analysis of avalanche problem types, we used the simulation at the elevation which is closest to the median elevation of the release areas in each region (Duvillier and others, 2023). In all regions the selected elevation lay in the interquartile range of the release area elevations, which represents half of the release areas, except for the Chartreuse region, where half of the release areas actually lie between 1544 and 1748 m (1st and 3rd quartile) and we had to use the simulations at 1800 m. Hence, when comparing different regions, our simulations may be less representative of the conditions in the Chartreuse region, as actual release areas are slightly lower.

We also compare with simulations at constant elevation. To do so, we chose an elevation of 2400 m, which is a typical elevation for most regions – except for some front ranges of the French Alps where the highest summits do not reach 2400 m and we chose 2100 m as S2M data are not available at 2400 m (regions of Vercors, Chartreuse and Bauges, Fig. 1). Isolating the effect of the latitude allow us to assess the correlation between avalanche problem occurrence and terrain. This comparison is relevant as mountain regions in the north are considerably higher on average.

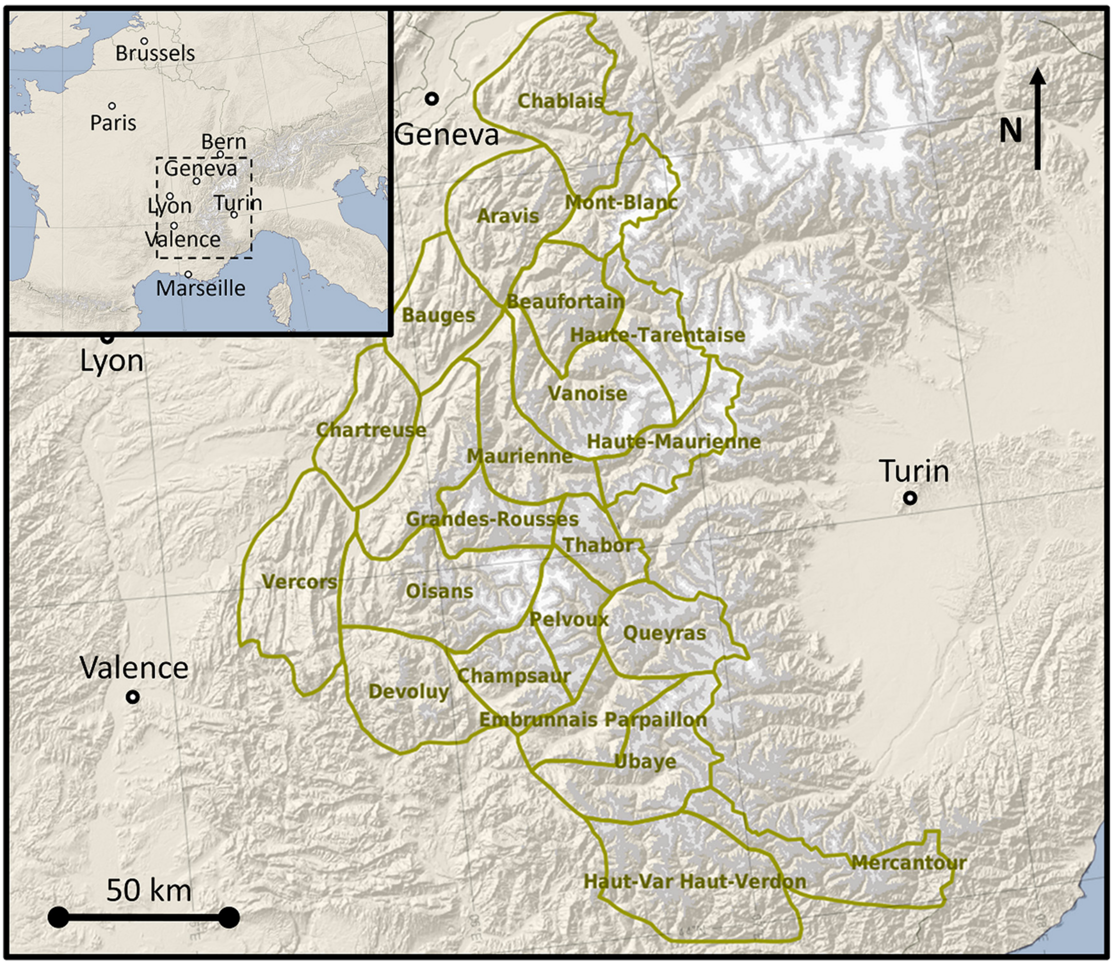

Figure 1. The French Alps stretch about 280 km from north to south, and about 130 km from west to east. For climatology and avalanche forecasting this area is classically divided into 23 regions, so-called massifs.

If not specified otherwise in the text, we always refer to the simulations at the relevant release area elevation.

2.3 Snow cover simulations

For our goal to analyze the seasonal occurrence of avalanche problem types in mountain regions, we assume that flat field simulations can describe the relevant average conditions on a climatological scale. For the winter seasons from 1958/59 to 2019/20, Crocus simulations (Vionnet and others, 2012) were initialized on 1 August using the settings described in Lafaysse and others (2017). Mass and heat exchange with atmosphere and soil was simulated with ISBA (Decharme and others, 2011) using Neumann boundary conditions. We neglected the feedback of snow transport on the snow cover and only estimated snow transport based on a threshold wind speed of 7.5 m s^{-1} (Li and Pomeroy, 1997). Utilizing snow transport modules would require slope simulations that we avoided given the study's climatological interest. The snow cover simulation ran until 31 May outputting snow profiles at 6:00 and 15:00 UTC.

The analyzed dataset consists of two daily snow cover simulations at different elevations, i.e. at 2400/2100 m and closest to the median release areas elevation. The following snow cover properties were extracted from this dataset: layer thickness, snow density, snow grain shape, shear strength and liquid water content for all snow layers simulated with Crocus. In addition, meteorological variables including new snow amount within the past 24 h, snow depth and wind speed, were output for further analysis with the algorithm to simulate avalanche problem types.

2.4 Avalanche problem types from snow cover simulations

Avalanche problem types were derived from an automated analysis of snow cover simulations. The analysis includes an approach to detect and track weak layers to eventually assess their stability. The employed methodology relies on a process-based approach and so, it is suited for analyzing nonstationary data series. Thresholds for weak layer stability assessment have been calibrated once at Weissfluhjoch with a seismic avalanche catalog (Reuter and others, 2022), as they can depend on the snow cover model and the parametrizations therein. The comparisons with avalanche data and with an alternative snow cover model, as well as the tests in different climate zones, provide confidence that the results of the model chain are robust (Reuter and others, 2022).

For natural dry-snow slab avalanche release weak layers are detected by comparing subsequent snow profile simulations at 6:00 UTC, and then tracked over time according to their properties through the snow cover simulations. Snow instability indicators determine how critical a weak layer is at a certain time step. We described the natural failure initiation process with the expected time to failure t_f (Conway and Wilbour, 1999) and the subsequent stage of crack propagation with the critical crack length a_c (Reuter and Schweizer, 2018). The expected time to failure t_f,

$$t_f(t) = \frac{S_n(t) - 1}{\frac{dS_n}{dt}} \tag{1}$$

includes the time derivative of the stability index $S_n = \tau_p/\tau$ which relates shear strength in the weak layer (τ_p) to additional shear stress due to the weight of the slab (τ) on an inclined slope of 38°. If values decrease towards zero, the expected time indicates a propensity for failure initiation. Accordingly, decreasing values of the critical crack length indicate a propensity for crack propagation. If the thresholds for both criteria are met (Reuter and others, 2022), the weak layer is considered unstable.

Avalanche problem types of expected natural avalanches can be derived based on snow instability indicators and meteorological properties. Threshold values for snow instability indicators depend on the snow cover model and were determined by Reuter and others (2022). Figure 2 summarizes the decisions for the choice of avalanche problem types. We only assessed avalanche problem types for natural release and did not consider artificial triggering.

We identified a new snow problem or a wind slab problem when:

- a non-persistent weak layer and a relevant slab
- are loaded by new snow or drifting snow, and
- snow instability indicators become critical in this weak layer.

In the case of new snow, a new snow problem is chosen, in the case of snow transport, a wind slab problem is chosen. Both avalanche problem types may co-exist.

We identified a persistent weak layer problem when:

- a persistent weak layer and a relevant slab
- are loaded by new snow or drifting snow and
- snow instability indicators become critical in this weak layer.

In natural release, persistent weak layers often co-exist with new snow or wind slab situations. However, loading can activate a persistent weak layer without forming a non-persistent weakness. In this case, neither a new snow nor a wind slab problem is called. In addition, we also call a persistent weak layer problem if a new snow or wind slab problem is identified and an aging persistent weak layer is still present. Whereas an aging persistent weak layer by itself is no longer sensitive to new snow or wind loading, the release of this weak layer may occur as a secondary process – after a primary release due to a new snow problem, for instance.

For natural wet-snow avalanche release, the snow profiles simulated at 15:00 were analyzed. We considered the days after the onset of a wet-snow avalanche cycle (liquid water content index > 1), as days with a wet-snow situation provided that:

- the liquid water content in the snowpack has increased from the previous day, but
- for no longer than 4 subsequent days since the last time the snowpack became isothermal.

2.5 Snow climate classification

The snow climate classification (Mock and Birkeland, 2000) is based on weather data that are available from the snow cover simulations. The classification is based on 24-h rain, snow water equivalent and snowfall amounts cumulated from 1 December to 31 March, as well as average air temperature and average temperature gradient over the same period. The frequency of seasons with a coastal, transitional or continental snow climate type then describes the regional climate.

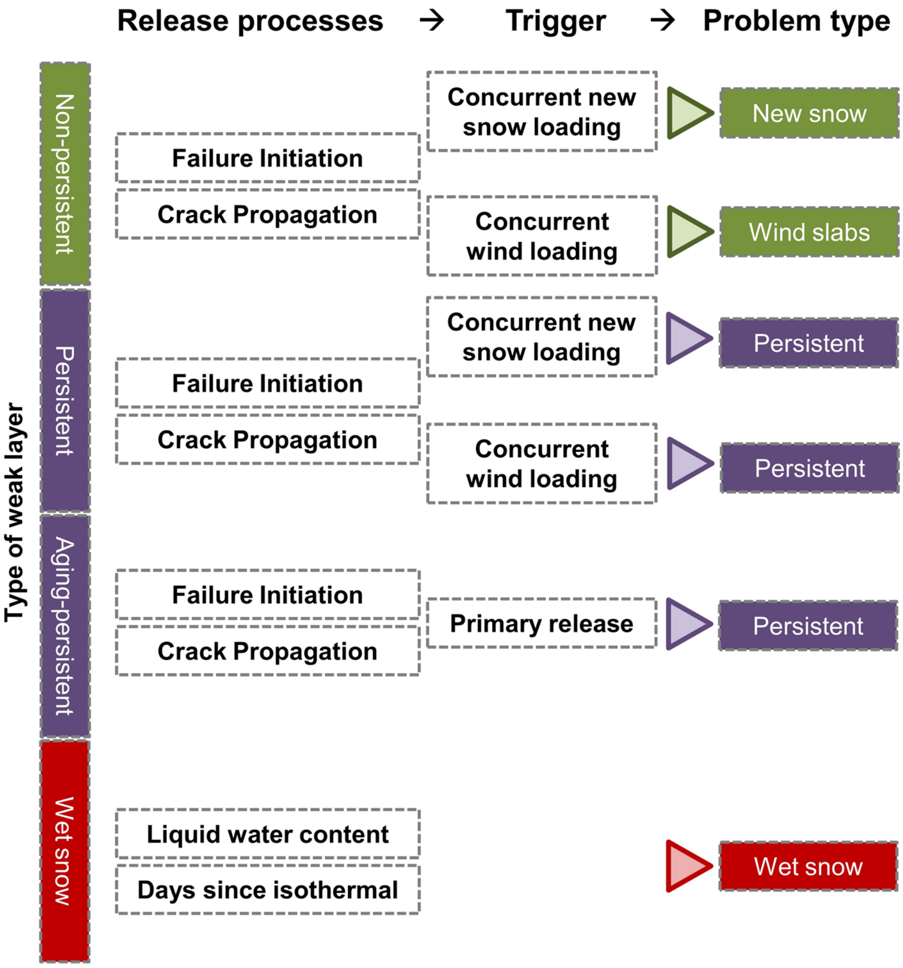

Figure. 2. Assessing avalanche problem types for natural release: the type of weak layer and the snow instability indicators for two avalanche release processes are subsequently combined with weather information (trigger) to derive the problem type. In some cases, two avalanche problem types are used to describe the situation, e.g. a non-persistent weak layer within the recent snow and a persistent weak layer.

2.6 Statistical post-processing and clustering

We use correlation analysis to explore geographical trends at the scale of the French Alps and analyze regional climatological characteristics with a clustering method. The differences between the novel approach for a climatology of avalanche problem types and the existing snow climate classification are also investigated.

2.6.1 Geographical trends

Avalanche problem types were simulated at daily resolution. We calculated seasonal counts for each problem type by adding up all avalanche problem type occurrences during a winter season and average seasonal counts by calculating the mean of the seasonal counts across the 62 winter seasons. We summarize the seasonal counts of the avalanche problem types in histograms and provide the mean and standard deviation. The values of relative frequency in the histogram explain how often an avalanche problem type occurred in the French Alps. To explore the variability of avalanche problem type occurrence within the mountain regions, avalanche problem type occurrence and simple geographic characteristics were contrasted using the geographical coordinates and the elevation in each region. We calculated gradients of elevation, latitude and longitude and assessed correlation. This simple approach was chosen to briefly introduce the dataset, and in particular the geographical characteristics, before the more detailed analysis. We provide the Pearson correlation coefficient r and the value of significance p to describe the strength of a linear relationship between two quantities.

2.6.2 Patterns of avalanche problem occurrence

We employed the k-means (e.g. Seber, 1984) clustering method to group mountain regions with similar climatological conditions. This method partitions data according to its geometric position in the coordinate space and hence, the analysis steps can be followed without difficulty. We clustered the data of the seasonal avalanche problem type information. The data include the number of days in a season with a specific avalanche problem type, the total number of days when at least one avalanche problem type occurred and the onset date of wet-snow avalanches in spring.

Our k-means clustering technique (Seber, 1984) starts at different randomly chosen locations in the dataset, and then, replicates the cluster, to avoid local minima in the optimization process. We used the function kmeans in Matlab (2018) and chose 99 replications. The final solution for the cluster centers after bootstrapping was chosen based on the lowest value of the total sum of distances between the data and the cluster centers (Σ_{CC}) the data points were assigned to. We altered the number of clusters (N_{C}) and determined an optimum number of clusters according to the Calinski Harabasz criterion (Calinski and Harabasz, 1974), which compares the variance between the clusters and within the clusters. The criterion searches for the optimum tradeoff between number of clusters while minimizing the ratio between the within-cluster variance and the variance between the clusters. Apart from the technical perspective, the cluster separation is also simply visible. The silhouette values that we present also help to decide how many clusters are needed. They are a measure of the distance of data points to the neighboring clusters and illustrate how the data were partitioned into the clusters. Values close to 1 indicate that a data point lies far from neighboring clusters. Silhouette values around 0 indicate that a data point is not a distinct member of the cluster and negative values mean that a data point was likely assigned to the wrong cluster. So, besides, the silhouette graphs provide a measure of confidence.

To describe a region's climate, each season of a region was assigned to one of the clusters. The largest proportion of seasons belonging to a certain cluster finally translates to a pattern of avalanche problem types that dominates in that region. The patterns can be described in terms of the frequency of new snow situations or the onset date of wet-snow avalanches, for instance. The pattern of a cluster becomes apparent when the most frequent observations of the variables are compiled. We provide a table based on thresholds for each observation, for instance, the number of days with new snow situation.

2.6.3 Comparison of classifications

To discuss the differences between the patterns that are typical of each one of the clusters, we selected one region per cluster where the cluster's particular pattern was prominent.

3. Results

3.1 Frequency of avalanche problem types

Figure 3 presents the occurrences of avalanche problem types and gives a first insight into the characteristic snow instability patterns across the 23 French Alpine regions. The avalanche problem types were determined for natural release from the simulations of the 62 winter seasons from 1958/59 to 2019/20. Figure 3a shows that in about three quarters of the 1426 regions-seasons, non-persistent weak layers were analyzed as critical due to new snow on less than 10 days. In more than 80% of the seasons, snow transport contributed to natural release on less than 15 days per season (Fig. 3b). The prevalence of persistent weak layers was more variable as the histogram shows a wider distribution. The corresponding avalanche problem type appeared to be important in one third of the seasons when the problem appeared on more than 15 days per season (Fig. 3c). According to our simulations, natural wet-snow avalanches were expected on more than 5 days per season in almost all cases (94%) (Fig. 3d).

The number of days when the model anticipated natural avalanches, i.e. at least one critical weak layer was identified with an avalanche problem type, varied between 15 and 56 days per season (mean: 31, standard deviation: 11). Considering all seasons and regions ($N = 1426$), wet snow was the most common avalanche problem type occurring on 47% of the days when natural release was expected. Persistent weak layers contributed to the avalanche situation on 38% of the days. On 39% of the days the simulated avalanche problem was related to new snow and wind slab situations. At the scale of the French Alps, none of the avalanche problem types occurred substantially less frequently than the others – all play a role in natural avalanche release.

Figure 4 contrasts the frequency of avalanche problem types with simple geographical properties. Figure 4a relates the average number of days per season that an avalanche problem type occurred in the 23 Alpine regions to relevant release area elevation. Wind slabs and persistent weak layers were significantly more prevalent in higher release areas. Wet snow situations were more common at lower elevation. Considering a horizontal cross-section across the mountain range, our simulations at 2400 m (Fig. 4d and e) showed a significant influence of latitude on the number of days with new snow and wind slab avalanche problems, which were more common in northern regions of the French Alps. This effect was less pronounced if relevant release area elevation was considered (Fig. 4b and c), as the northern regions are higher on average than the southern regions. We did not observe significant trends in avalanche problem frequency with longitude.

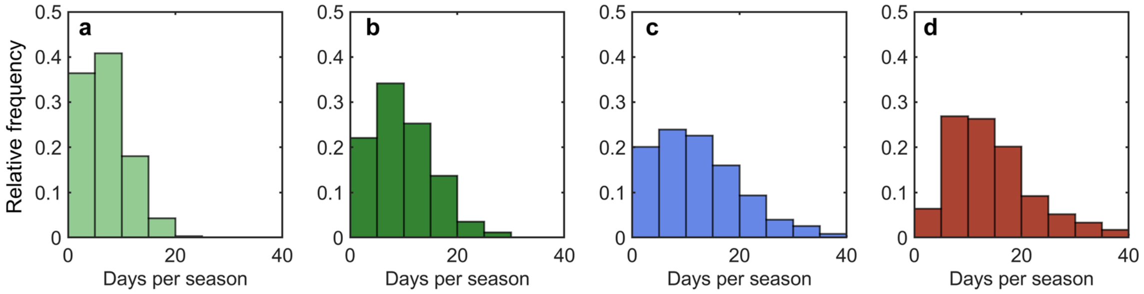

Figure. 3. Simulated avalanche problem types for the winter seasons from 1958 to 2020 for the French Alps: (a) new snow, (b) wind slabs, (c) persistent weak layer and (d) wet snow situations. Histograms showing the relative frequency of four avalanche problem types, i.e., on how many days per season an avalanche problem type was simulated during the 62 winters in the 23 Alpine regions ($N = 1426$) at the relevant release area elevation.

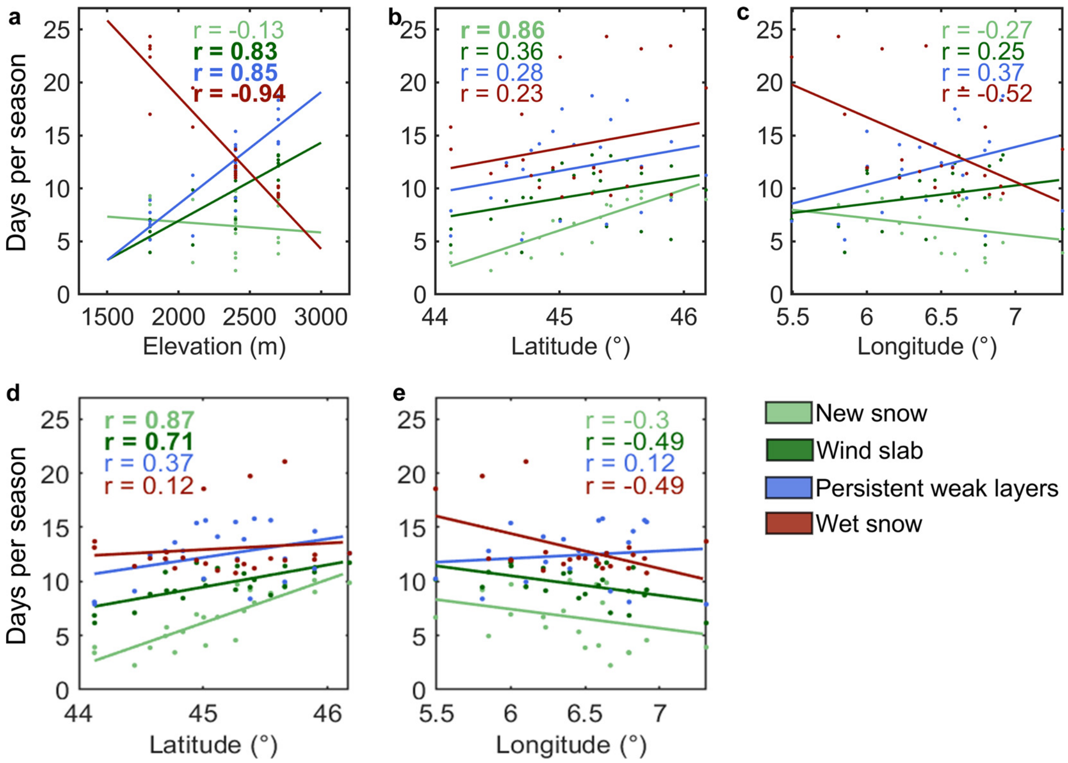

Figure. 4. Average seasonal occurrence of the 4 avalanche problem types in the 23 regions from simulations at the relevant release area elevation ($N = 92$), in relation to (a) elevation, (b) latitude and (c) longitude. Average seasonal occurrence of avalanche problem types from simulations at a constant elevation of 2400 m (2100 m in Chartreuse, Bauges and Vercors, $N = 92$), in relation to latitude (d) and longitude (e). Trend lines from linear regression. Inserts provide correlation coefficients with bold figures denoting significant relationships ($p < 0.05$).

3.2 Cluster analysis of avalanche problem types

The 3 variables 'number of days with new snow', 'number of days with persistent weak layer problem types per season' and 'onset date of wet-snow avalanches' represent a subset of uncorrelated variables ($r < 0.4$; $p > 0.05$) and contain most of the information of the dataset. In Fig. 5 we present the cluster analysis of this subset, because the information loss is small, but the interpretation is easier. In fact, including all 6 variables in a cluster analysis, we obtained an average silhouette value of 0.30, 3% negative silhouette values indicating possible misclassifications and 67% of the silhouette values representing distinct members of the clusters. A cluster analysis of the 3 most important variables separated the clusters similarly well (Fig. 5d).

According to the Calinski Harabasz criterion the optimal number of clusters was $N_C = 4$. Hence, the data can be arranged into 4 groups with each group belonging to a cluster center that is defined by the 3 variables. The silhouette values in Fig. 5d represent a distance measure between a data point (located with the 3 variables) and neighboring clusters. The graph explains how the clusters group the data, in other words, if a data point clearly belongs to the cluster (positive values) or, if it is not a distinct member of that cluster (values close to 0) or, if it actually lies closer to other clusters (negative values). About 6% of our data had negative silhouette values, meaning these data were possibly misclassified and about 65% of the data had values larger than 0.05 indicating that they are distinct members of one cluster. The average silhouette value was 0.27.

3.3 Interpreting the clusters: patterns of avalanche problem types

To visualize how the clustering partitioned the data, pairs of the 3 variables are graphed in Figs 5a–c with colors highlighting the data separation. Behind the 4 clusters lie patterns of avalanche problem type occurrence that describe the avalanche conditions between 1958 and 2020 in the French Alpine regions.

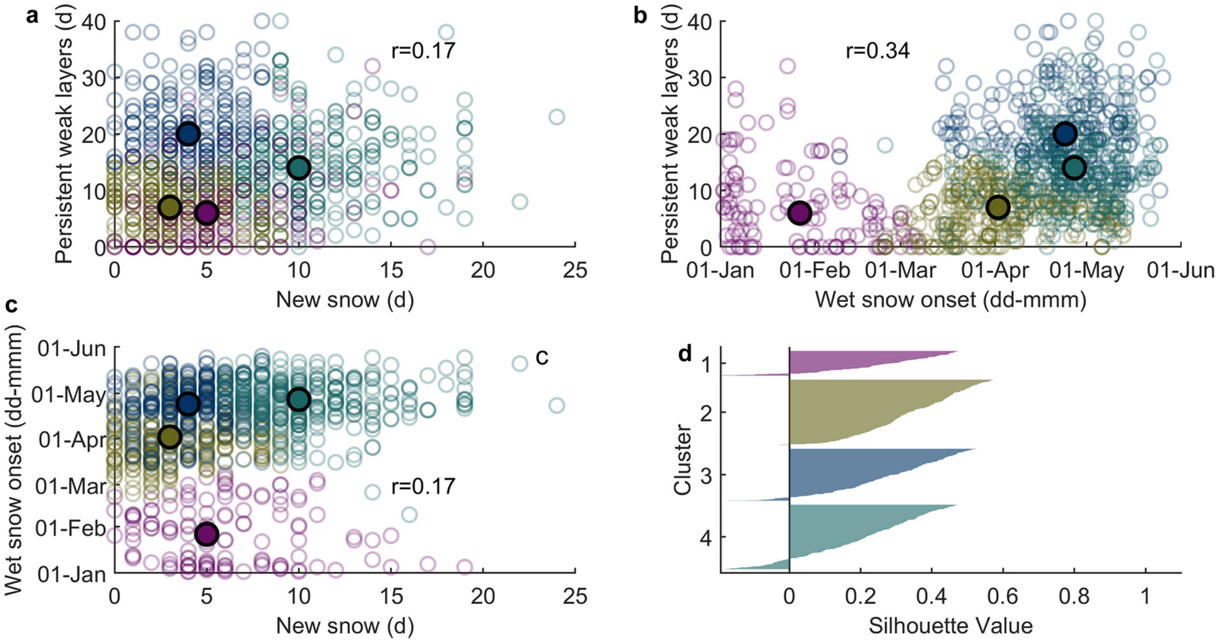

Figure. 5. Clustering of avalanche problem types for the French Alpine regions simulated for the period between 1958 and 2020. Simulations refer to relevant release area elevation. (a–c) Number of days with new snow, number of days with persistent weak layer problem types and onset date of wet-snow avalanches in spring are intercompared in panels. Colors indicate which cluster a data point was assigned to. Circles with black edges denote cluster centers, $N = 1426$. (d) Separation of the data into 4 clusters. Negative silhouette values (about 6% of the data) indicate cases of misclassification.

These patterns can be described in relative terms by comparing the occurrences of avalanche problem types between the clusters. Table 1 is a schematic presentation of the characteristics of the 4 clusters that simplifies the complexity of Fig. 5. The blue cluster is characterized by many persistent weak layer problems – compared to the other 3 clusters. The seasons within this cluster had rather few days with new snow problems and a rather late onset date of the wet-snow avalanches in spring, typically during April or later. The pattern was prominent in the Haute-Maurienne (HMA) region (Fig. 6).

In the 'new snow' cluster (green cluster), the number of days with persistent weak layers was rather low and the onset date of wet-snow avalanches was seldom before 1 April. This characteristic was found in many seasons in the Mont Blanc (MTB) or Beaufortain (BEA) regions (Fig. 6). In our dataset, the clustering did not isolate other combinations when new snow problems were frequent.

In the case that neither new snow, nor persistent weak layers were relatively common, the onset date of wet-snow avalanches separates two clusters. The violet cluster describes cases with an early onset of wet-snow avalanches, typically before 1 March, the khaki cluster a later onset of wet-snow avalanches, rather after 1 March. The khaki cluster stands for the characteristics common in the winter seasons in the southern French Alps, such as in the Ubaye (UBA) or the Mercantour (MER) region. In the front range mountains of Vercors (VER) or Chartreuse (CHT), many seasons have characteristics corresponding to the violet cluster (Fig. 6).

Table 1. Conceptual description of snow avalanche climates in the French Alps presenting the patterns found in a cluster analysis including the number of days with new snow and the number of days with persistent weak layer problem types as well as the onset date of wet-snow avalanches.

	Few days with new snow		Many days with new snow	
Many cases with persistent weak layers	Wet-snow onset mostly after beginning of April		Few data	Few data
Few cases with persistent weak layers	Wet-snow onset before end of February	Wet-snow onset in March or later	Few data	Wet-snow onset in April or later

3.4 Avalanche problem types in 4 French Alpine regions

Each panel of Fig. 7 shows a region that is representative of one of the presented clusters. In Vercors (VER), wet snow situations were the most common, consistent with the violet cluster. Wet snow remains the most important avalanche problem type in the Ubaye (UBA) region, but with a later onset date – which is typical of the khaki cluster. The Mont Blanc (MTB) region is an example of the green cluster, where non-persistent weak layers, i.e. new snow and wind slab situations, represent the primary instability – ahead of avalanche problems related to persistent weak layers and wet snow. Persistent weak layers have the highest prominence in the Haute-Maurienne (HMA) region, consistent with the blue cluster.

3.5 Snow climates in French Alpine regions

The snow climate classification introduced by Mock and Birkeland (2000) was applied to the French Alpine regions. The four panels in Fig. 8 show the snow climate classification for four regions which are representative of the four clusters.

Considering the elevation of avalanche release areas, Vercors (VER) is representative of a coastal climate, while Haute-Maurienne (HMA) is the region with the most continental influence in the French Alps. Regarding all 23 Alpine regions, several regions identified with the same class as the neighboring region (Figs 11 and 13). The regions Vercors (VER) and Bauges (BAU), along with neighboring Chartreuse (CHT), all fall into the same group which has almost exclusively coastal seasons. Similarly, the characteristics in the regions Vanoise (VAN), Haute Tarentaise (HTA) and Haute-Maurienne (HMA), which lie close to another, look alike; the 3 regions all share transitional and continental influence.

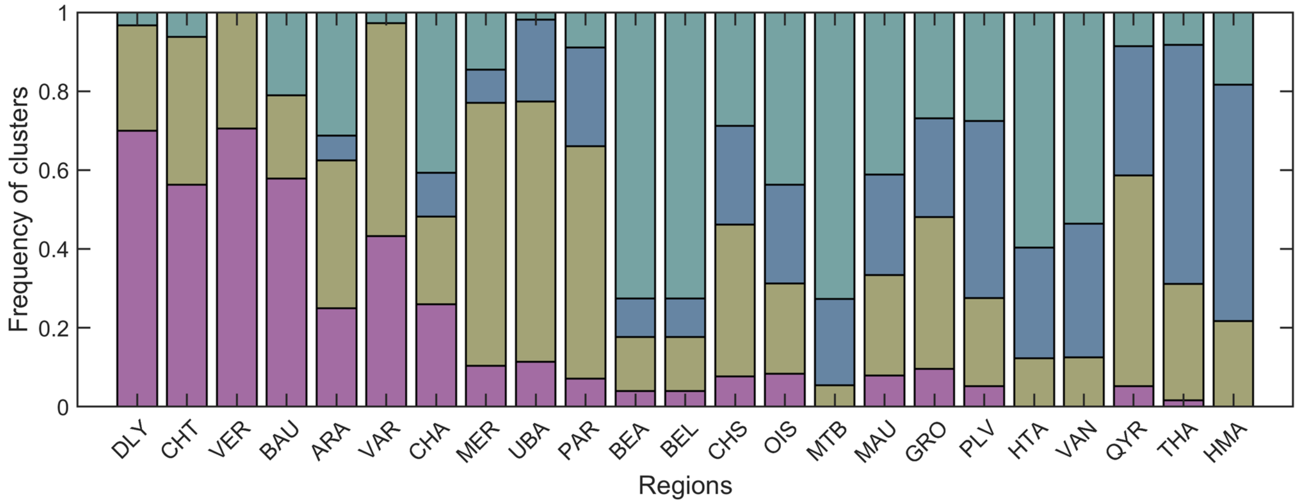

Figure. 6. Frequency of climatological patterns of avalanche problem types for the 23 regions in the French Alpine regions according to a k-means cluster analysis for the period 1958–2020. Simulations refer to relevant release area elevation. Colors refer to 4 clusters featuring relatively many persistent weak layer problems (blue), relatively many new snow problems (green) or – with few new snow and persistent weak layer problems – featuring an early onset of wet-snow avalanches (violet) or a late onset of wet-snow avalanches (khaki). For acronyms see Table 2, Appendix A.

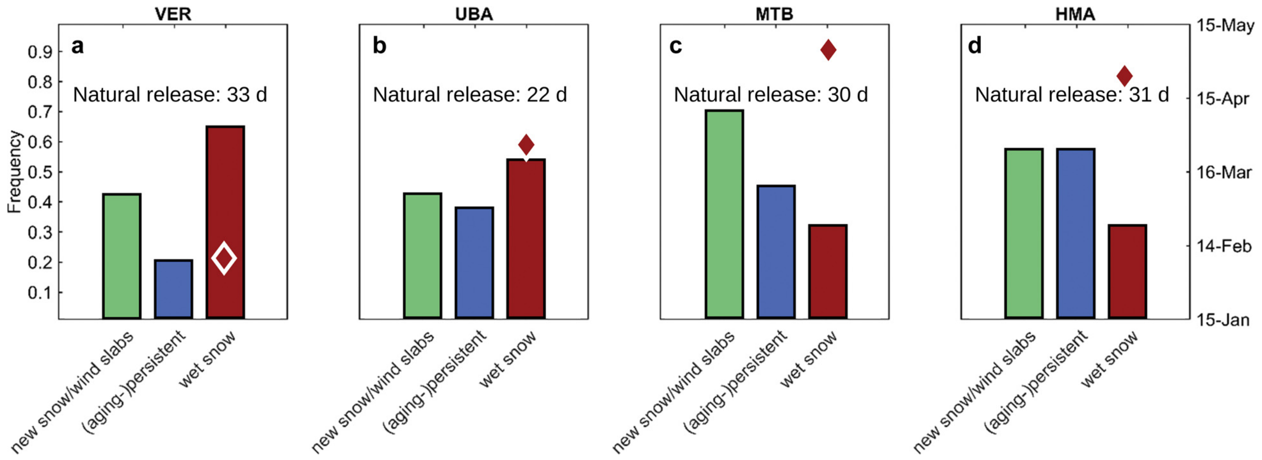

Figure. 7. Avalanche problem types simulated for days with expected natural release for four regions representing each one cluster. Simulations refer to relevant release area elevation. Bars represent frequency of new snow and wind slab (green), persistent weak layer (blue) and wet snow (red) problems for the period 1958–2020. Red diamonds show the average onset date for wet snow avalanches. Inserts show the average number of days with expected natural release.

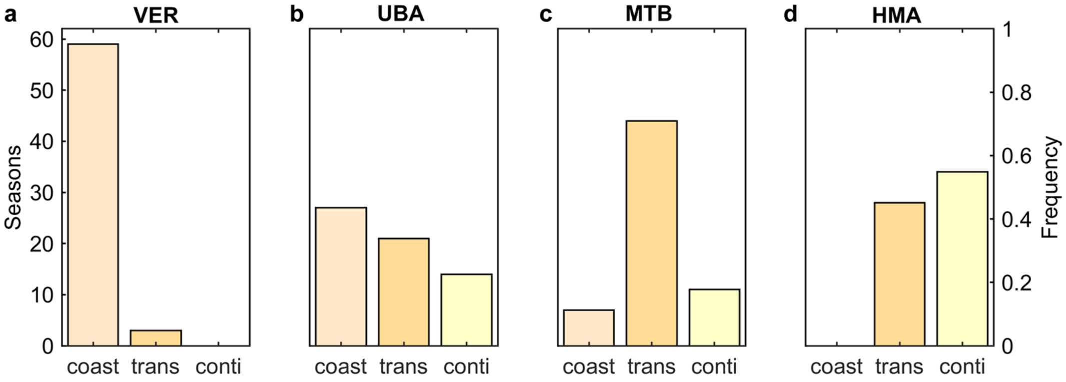

Figure. 8. Number of seasons with coastal (apricot), transitional (orange) or continental (lemon) snow climate characteristics after Mock and Birkeland (2000) for the entire period 1958–2020. Simulations refer to relevant release area elevation. Four typical regions are shown (a) Vercors (VER), (b) Ubaye (UBA), (c) Mont Blanc (MTB) and (d) Haute-Maurienne (HMA) to illustrate snow climate variability. From left to right, the number of coastal seasons decreases while the continental influence grows.

The simulations at constant elevation can be interpreted as a cross-section across the French Alps, where the location but not the elevation of the regions is accounted for. At an elevation of 2400/2100 m the regional snow climate characteristics also range from a majority of seasons classified as coastal on one end to important continental influence on the other end. In between are many regions with a majority of transitional seasons that can be organized from strong coastal (weak continental) to weak coastal (strong continental) influence: The region with the most coastal influence was Chartreuse (CHT). On the other end lies Haute-Maurienne (MAU), where the continental influence was most important (Fig. 10, in Appendix A). In this analysis neighboring regions, however, are less likely to be close on the diagram, in other words they were less likely assigned the same class.

3.6 Avalanche problem types and snow climates

Comparing Fig. 7 with Fig. 8 we can relate the snow climate classification to avalanche problem type occurrence: Vercors (VER) and Haute-Maurienne (HMA) had strong coastal or continental influence, respectively. Mont Blanc (MTB) and Ubaye (UBA) represent transitional cases, featuring a majority of transitional seasons or mingling transitional seasons with coastal and continental influences, respectively. In the Vercors (VER) region, where wet snow was the predominant avalanche problem type and the onset date is early compared to the other regions, winter seasons almost exclusively classified as coastal snow climate.

With growing continental influence, the examples in Figs 7 and 8 demonstrate from left to right that wet snow avalanche problems appeared later in the season. At the same time, persistent weak layers became more important that matches an increasing continental influence. For instance, persistent weak layer problems were not frequent in the Vercors (VER) region, but they dominated the mostly continental snow climate in the Haute-Maurienne (HMA) region. Situations with non-persistent weak layers seem most frequent in transitional climates such as in the Mont Blanc (MTB) region. In this region non-persistent outnumbered persistent weak layers.

Despite their different approach, the frequency distributions of avalanche problem types parallel the snow climate classification.

3.7 Interpreting spatial differences between French Alpine regions

Mapping the results of the cluster analysis allows us to locate patterns of the occurrence and timing of the simulated avalanche problem type geographically. The color shading in Fig. 9 can be interpreted as the likelihood that a particular region follows the climatological patterns of a cluster.

The regions that had many members in the khaki cluster are found in the southern part of the French Alps. Seasons in these regions had few situations with persistent weak layers, few new snow situations and a late onset date of the wet-snow avalanches in spring. New snow avalanche problems were more common in the northern regions, where the green cluster dominates.

Persistent weak layers were more common in the inner-Alpine regions, where seasons often showed the characteristic pattern of the blue cluster. The front-range mountains that lie in the western part of the French Alps, on the other hand, often had seasons with comparatively few cases of persistent weak layers and new snow. Front-range regions have an early onset of wet-snow avalanches compared to the regions in the south that belong to the khaki cluster.

The maps of the avalanche problem clusters are in qualitative agreement with the map of the standard snow climates for the same period (Fig. 14, in Appendix A). Adjacent regions identify with the same cluster or climate. Moreover, the distribution of the snow climates corresponds to three of four the clusters, for example, coastal climate to the front range cluster. This instills confidence in the presented avalanche climatology.

4 Discussion

4.1 Patterns of avalanche problem types in the French Alps

4.1.1 Snow climates in France

Given the lack of an avalanche climatology in the Alps, we applied the standard classification for snow climates to the French Alps. The smaller topographical size of the French Alps does not mean that differences are too small for the snow climate classification to be identified. Analyzing the S2M reanalysis dataset at an elevation of 2400/2100 m revealed pronounced differences between regions. These differences became more pronounced when the average elevation of relevant release areas in the regions was considered. Snow climates ranged from strong coastal to strong transitional influence, with even an important continental contribution in some inner-Alpine regions. Continental snow climate characteristics were not dominant in any French Alpine region. We selected 4 examples that represent typical characteristics of the French Alps. In the selected examples the known effects of precipitation shielding of inner-Alpine areas and enhancement in front-ranges (e.g. Frei and Schär, 1998) became apparent in the frequency of coastal and continental seasons. Moreover, it turned out that the examples are also typical representatives of patterns of avalanche problem types that summarize meteorological effects on snow instability.

4.1.2 Avalanche problem types

Using available methods and data, a novel way to characterize avalanche climates was applied to the French Alps. The Alpine

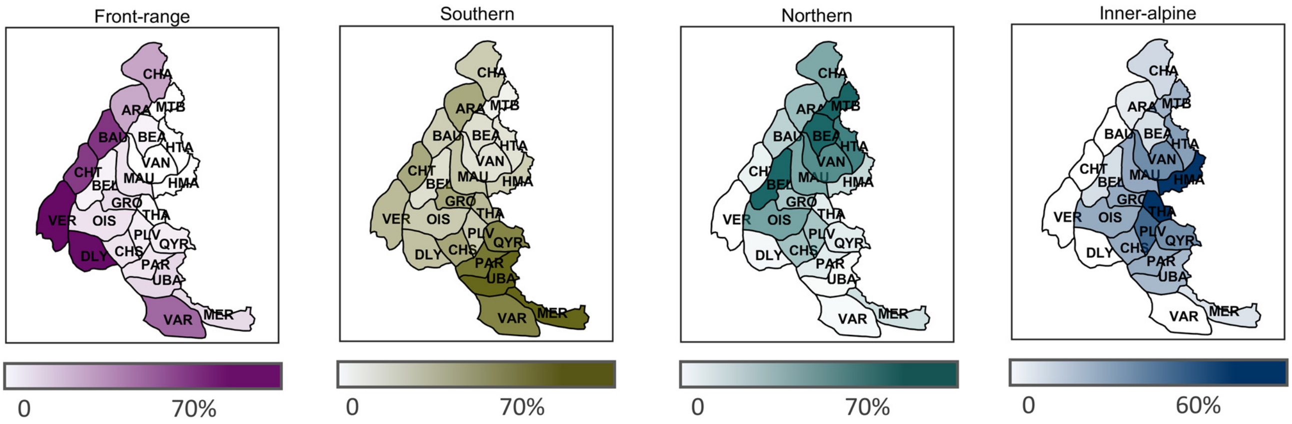

Figure. 9. Maps of the French Alpine regions highlighting the frequency of winter seasons assigned to one of the 4 typical patterns: front-range, southern, northern or inner-Alpine regions. Simulations refer to relevant release area elevation in the regions and include data from 1958 to 2020. For acronyms see Table 2, Appendix A.

regions showed an expected diversity beyond the three-level snow climate classification, which can be observed, for instance, in the regions Vercors (VER) and Haut-Var-Haut-Verdon (VAR) (c.f. Figs 11 and 13, in Appendix A). When analyzing regional avalanche problem frequencies, the Calinski Harabasz criterion suggested 4 clusters instead. Moreover, the importance of persistent weak layer and wet snow avalanche problem types varied gradually across the range from strong coastal to continental influence (Fig. 12, in Appendix A). Similarly, in the transitional climate of Canada's Columbia Mountains the persistent weak layer problem can in some regions be the primary driver for avalanche activity (in up to 40% of the days), while in other regions it is clearly less relevant (Hägeli and McClung, 2003).

Wet snow situations in a Canadian analysis (Shandro and Hägeli, 2018) occurred on about 8% of the days. In our analysis, wet snow problems were assessed on 47% of the days with natural release. As wet-snow avalanches do typically make an important contribution to natural avalanche activity (Schweizer and others, 2020), the reason for this difference is probably not related to snow climates, but different evaluation periods. In Canada avalanche forecasts are not issued consistently after 15 April. Wet-snow situations had a higher prevalence in seasons that classified as coastal in the Canadian dataset. We also observed that wet snow situations played a more important role in regions with a primarily coastal snow climate – and a less important role in regions with transitional or even continental influence.

Situations with persistent weak layers were similarly important. In our analysis, which is focused on natural release, they contributed to the hazard on 37% of the days. In the Canadian dataset persistent weak layers added to the hazard of natural or artificial release on 48% of the days.

Shandro and Hägeli (2018) highlighted that new snow and wind slab situations had a high prevalence in regions with costal characteristics – compared to continental snow climates. In the French Alps, predominantly coastal climates were not marked by a high frequency of new snow or wind slab avalanche problems, as the example of Vercors shows. However, where transitional characteristics dominated, for instance in the Mont Blanc region, non-persistent weak layers made an important contribution to avalanche situations.

4.1.3 Interpretation of the clustering results

To synthesize the results and to visualize the climatology we presented Table 1 which shows how the dominant three avalanche problem types combine: the frequency of non-persistent weak layers, the frequency of persistent weak layers, and the timing of wet-snow avalanches. To simplify the results, we may consider each variable has either high or low values or an early/late date, respectively. This allows us to summarize the combinations of avalanche problem types that describe typical winter regimes. Many days with new snow coincided with infrequent persistent weak layers. If days with persistent weak layers are relatively common, then days with new snow are rather infrequent in the season. In both cases, the wet-snow onset is comparatively late. If days with both new snow and persistent weak layers are limited during a season, then earlier or later onset of wet-snow splits the latter group into another two clusters – making four clusters in total.

One decisive criterion apparently relates to the timing of wet-snow avalanches that also LaChapelle (1966) described when he grouped regions in the U.S. and gave guidelines for forecasting. The inverse relationship i.e., frequent new snow and rare persistent weak layer problems or rare new snow but frequent persistent weak layer problems, also appears in early descriptions of snow climates (Roch, 1949) and in a more recent analysis of avalanche problems for Western Canada (Shandro and Hägeli, 2018). To summarize, the snow climates along the Pacific coast of Southwestern Canada and the Northwestern U.S. favor heavy snowfall or rain that promote short-term instabilities – while persistent weak layers are rare. The shallow Rocky Mountain snowpack on the other hand, maintains persistent instabilities that occasionally overlap with new snow situations. In the French Alps, the closest match for these extreme cases would be Chartreuse on one end and Haute-Maurienne on the other.

Whereas we used k-means clustering, Shandro and Hägeli (2018) utilized self-organizing maps. They found 12 avalanche hazard situations that are combinations of the 8 avalanche problem types used in Canada. Reducing to the 7 most important situations, they reported that persistent weak layers (48% of the days), new snow (31% of the days), wind slab (18% of the days) and wet-snow situations (8% of the days) were the most important problem types – in European terminology. The order in this list is similar to the French dataset – except for the last two situations, which could be related to underreporting of wet-snow events in the Canadian dataset after the forecasting period and the uncertainty in the frequency of wind slabs in our approach. Analyses of long time series, such as the mentioned Canadian dataset (Shandro and Hägeli, 2018) or the presented French dataset, show that avalanche problems can shed light onto the inner-seasonal variability. The avalanche problem types provide details on the variability beyond the snow climate classification.

Projecting the four typical patterns on a map of the French Alpine regions shows that the 4 groups correspond to geographical areas: southern, northern, front-range and inner-Alpine regions. When Sielenou and others (2021) mapped clustering results of primary indicator variables for natural avalanche activity, the French Alps split into front range and inner-Alpine regions – a trend that is apparent in mean winter precipitation (Durand and others, 2009). The overlapping north-south trend we identified in our analysis parallels the known north-south variation of winter temperatures in the French Alps (Durand and others, 2009) that also manifests in the avalanche activity observed in northern and southern regions in the French Alps (Lavigne and others, 2015). Besides, the dominance of the blue cluster in inner-Alpine regions, where persistent weak layers are frequent, agrees with accident reports from the Swiss Alps that incidents with human triggering on persistent weak layers are more common in these regions (Techel and others, 2015).

4.2 Uncertainties and limitations

4.2.1 Snow instability assessment

During natural dry-snow avalanche release, pre-existing persistent weak layers are just as important as temporary, i.e. non-persistent weaknesses, as the frequency distributions of the avalanche problem types in Fig. 4 explain. Nevertheless, new snow is the most important ingredient for natural release and hence, results are sensitive to the new snow amounts the simulations consider. The meteorological data we used include field observations as well as weather model data and represent the best available historic dataset for the area. The agreement of average precipitation amounts in the reanalysis data with observed averages (Vernay and others, 2021) makes us confident that the frequencies of avalanche problems during natural release are realistic. Still, the time series may include biases due to changing frequency or quality of observations that can affect the conclusions. In fact, between 1990 and 1991 the number of observations that were available to compile the reanalysis changed (Vernay and others, 2021). In our analysis natural release became slightly less frequent in the second part of the study period, decreasing by about 8% in the French Alps. Even if slight differences were observed from the first to the second period of the dataset, the relative frequencies of avalanche problem types seemed stable.

Regarding snow transport, we only flagged wind slab situations and avoided simulations of preferential disposition or snow redistribution, as currently it is not clear to what extent a climatological study would benefit from adding this layer of complexity. Simulating these processes would considerably increase the computational costs for snow cover and snow instability simulations (Mott and Lehning, 2010; Vionnet and others, 2014).

Moreover, we only evaluated the average conditions at one elevation per region. Regarding the wet-snow onset, we concluded that – at relevant release elevations – wet-snow avalanches release before 1 March in the front-ranges and typically not before 1 April in inner-Alpine regions. The pattern of an earlier onset in the front-range also appeared in the simulations at constant elevation i.e., at 2400 m, but the onset dates were closer (before 1 April in the violet cluster and after 1 April in the blue cluster). The long delay in the simulations at relevant release area elevation may be due to our simple analysis that neglects lower elevations in high mountain ranges.

4.2.2 Snow climates and avalanche problem types

Coastal, transitional and continental snow climate are general descriptions of the average winter weather (Mock and Birkeland, 2000) and do not say much about avalanche release or weak layer types. The snow climate classification combines meteorological variables (e.g. snowfall amounts) including some indicators for the snowpack layering, whereas the avalanche problem types are based on snow stratigraphy and snow instability indicators. To describe regional climates in view of snow instability patterns, the successions of atmospheric conditions need to be considered, which is information that is stored in the snowpack layering.

To this end, Hägeli and McClung (2003) included avalanche data that allowed them to explain different regional patterns of avalanche activity in an overall transitional snow climate and hence explain the subtleties behind general patterns (e.g. LaChapelle, 1966; Fig. 1). Persistent weak layers are less common in regions with coastal influence than in regions with transitional or continental influence – results confirmed in the more recent work of Shandro and Hägeli (2018) who analyzed forecast avalanche hazard situations in Western Canada. Their results agree with ours from simulated avalanche problem types, to the extent that the frequency of persistent weak layers increases with continental influence.

5. Conclusions and outlook

We presented a novel approach to introduce avalanche release processes into snow climatology and showed how the occurrence of simulated avalanche problem types can be used to create a snow avalanche climatology. This approach is universally applicable – provided appropriate time series of snow stratigraphy are available.

Compared to the existing snow climate classification, we demonstrated that using avalanche problem types can provide deeper insight into the characteristics of avalanche activity and the details of climate variability. This makes the novel approach a valuable complement when studying snow and avalanche climatology. Moreover, our simulations of avalanche problem type frequency can explain variability of avalanche situations across a mountain range and explain the ties with regional snow climates which is informative for avalanche forecasting services.

On the scale of the French Alps, the wet snow avalanche problem type occurred in almost half of the days during the 62-year period that the model anticipated natural release. In 38% of the cases, persistent weak layers and in 39% of the cases new snow or wind slab situations were involved.

A cluster analysis revealed patterns of avalanche problem types in the French Alpine regions. In simple words, many days with new snow meant persistent weak layers were relatively infrequent, which was typical in the northern regions. In turn, the pattern of comparatively many persistent weak layer situations and few new snow problems is found in inner-Alpine regions. In both cases, the first wet-snow avalanche cycles of the season were expected at the beginning of April at the earliest. When new snow and persistent weak layer situations were both infrequent, the timing of the onset of wet-snow avalanches creates another separation. At relevant release elevations the onset of wet-snow avalanches occurred later in the southern regions than in the front-ranges.

When comparing snow climates and avalanche problem type frequency in the French Alps, we observed that coastal characteristics go along with many wet-snow situations. With growing transitional and continental influence wet snow avalanche problems became less frequent and situations with persistent weak layers more prevalent. New snow and wind slab situations were more frequent in predominantly transitional climates. Applying the snow climate classification to the reanalysis dataset we found regions with exclusively coastal seasons, regions primarily under coastal and some transitional influence, regions with a majority of transitional seasons and regions that share continental and transitional influence about equally. Distinct examples of continental snow climates were rare in the winter seasons of the French Alps.

Comparisons with the North American snow climates show qualitative agreement. In fact, the occurrence of new snow, persistent weak layer and wet snow avalanche problems were long deemed characteristic for different American snow climate regions. Our modeling approach can independently confirm with data from a different mountain range that occurrences of avalanche problem types are linked to the snow climates.

Studying temporal change and the driving agents are challenges that require an appropriate methodology to reveal how daily variations of snow conditions account for seasonal trends. Our novel methodology brings this goal into reach. Analyzing temporal change in the presented dataset is a natural next step. The modeling approach allows us to close observation gaps, which are typical with avalanche data. Provided that reanalysis data or long time series of weather observations are available, snow avalanche climates can now be consistently described in any mountain region. Drawing a coherent picture of snow avalanche climates in the Alps – following in the footsteps of Shandro and Hägeli (2018) and their study for Western Canada – is another logical progression, if appropriate meteorological data from the Alpine countries can be compiled. Apart from understanding winter climate and the meteorological processes driving avalanche activity, the presented methodology is well-suited for studying climate change impacts on avalanche danger. The method utilizes the current knowledge on avalanche formation, is universally applicable to snow cover models and is appropriate for nonstationary data.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2023.23

Author contributions. NE acquired the funding for the project. PH ran the snow cover simulations. BR analyzed the data. BR wrote the manuscript with contributions from the co-authors.

Acknowledgements. We thank Pascal Hägeli and Karl Birkeland for their constructive reviews. We are grateful to everybody who contributed to the development of the reanalysis dataset and the snow cover model.

Financial support. Statistical modeling for the assessment and mitigation of mountain risks in a changing environment – SMARTEN program (ANR-20-Tremplin-ERC8-0001). INRAE/ETNA and CNRM/CEN are members of Labex OSUG.

Conflict of interest. The authors declare that they have no conflict of interest.

Data availability. The simulation results and the analysis code for the occurrence of avalanche problem types are available upon request.

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