62 YEARS OF AVALANCHE PROBLEMS IN THE FRENCH ALPS – CLIMATE AND TRENDS

Benjamin Reuter[1,2], Pascal Hagenmuller[2], Nicolas Eckert[3]

[1] *Météo-France, Direction des opérations pour la prévision, Toulouse, France*
[2] *Univ. Grenoble Alpes, Univ. de Toulouse, Météo-France, CNRS, CNRM, Centre d'Etudes de la Neige, Grenoble, France*
[3]*Univ. Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France*

ABSTRACT:
Avalanches became less frequent in typical large avalanche paths in France. Today, avalanches run shorter and deposits are more often wet, observers report from low elevation sites. Observations from higher elevation, however, where most release areas are located, are sparse. We employ a simulation approach to model conditions in the release areas to understand the occurrence of avalanche problems and the origin of natural release. Our 62-year data set reveals four typical patterns of avalanche problems across the French Alps. The climate patterns follow the main orography, such as proximity to the main ridge, 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 provides confidence in the modelling approach. Over the past 62 years avalanche problem occurrences underwent marked changes, in particular after a transition period around 1989, when strong changes appeared in French Alpine regions. The changes we observe after 1989, refer to an increase in new snow situations in northern regions at high elevation, a general shift of the wet-snow cycles to earlier dates and an overall slight increase of days when natural avalanches. At lower elevation the known retreat of the snow cover can be confirmed to limit the days with natural release. Our results portray the ongoing change and allow to inform avalanche forecasters and local decision makers of the individual regional response to climate change in coming years.

KEYWORDS: snow climates, avalanche problems, climate change, snow cover model.

1. INTRODUCTION

The European Alps are one of the best monitored mountain ranges regarding weather conditions. Snow fall is more often giving way to rain (Nicolet et al., 2018) and air temperatures increases lead to shorter winter seasons (Marty, 2008), for instance. Although, precipitation or temperatures are important for avalanche danger assessment (LaChapelle, 1980), direct conclusions on snow instability can hardly be made – too important is the role of the snow cover properties. On the other hand, some observations describe the changing characteristics of avalanche danger in the past. Large natural avalanches reached the valley floor less often and on their way powder clouds developed rarer (Eckert et al., 2013). More frequently wet-snow was observed in avalanche deposits (Naaim et al., 2016;Pielmeier et al., 2013). Despite some clues, our knowledge on the temporal change of avalanche danger characteristics is limited (Hock et al., 2019) – more specifically, when and how often did specific avalanche conditions, such as wet-snow situations, occur?

Some archives of avalanche observations span long time periods, and allow to estimate the past activity of large avalanches (Eckert et al., 2010). Information on the nature of avalanche danger, such as the conditions leading to the event, are, however, typically limited. Snow cover simulations, on the other hand, provide that information. In combination with homogenized meteorological data (Vernay et al., 2021) we can reconstruct the snow cover of the past. In a next step, avalanche problems can be derived to describe the typical avalanche situations during a winter season. This concept, that is used in avalanche danger communication (EAWS, 2019;Statham et al., 2018), also already proved useful to classify avalanche situations in Western Canada or Europe (Shandro and Haegeli, 2018;Reuter et al., 2022).

We use the simulation approach as models are fit now and can help us draw a complete picture of regional differences and temporal changes regrading avalanche danger. The meteorological data cover 62 winter seasons between 1958 and 2020 and were used to drive the snow cover model Crocus. We employ two methods to assess regional differences and temporal change: clustering of avalanche problem occurrences and regression analysis of time series of avalanche problem occurrences.

2. DATA AND METHODS

Snow cover simulations from the SAFRAN–SURFEX/ISBA-Crocus–MEPRA (S2M) data set were analyzed. The data can be regarded a reanalysis that describes mountain weather and snow conditions. The version of the data set we used covers the 62 winter seasons between 1958 and 2020 for the 23 avalanche forecasting regions in the French Alps.

2.1 Snow cover simulations

Crocus simulations (Vionnet et al., 2012) were initialized on 1 August using the standard settings (Lafaysse et al., 2017). The simulations were used previously to validate the approach (Reuter et al., 2022). Simulations ran until 31 May outputting snow profiles at 6:00 and 15:00 UTC.

2.2 Avalanche problem

We assessed avalanche problems with the approach presented by Reuter et al. (2022). Weak layers are detected and tracked over time in the snow cover simulations. Depending on the type of the weak layer (Figure 1) different snow instability indicators determine how critical the weak layer is at a certain time step. Avalanche problems are derived based on meteorological parameters which describe the potential trigger. In some cases, e.g. with non-persistent weak layer within the recent snow and a persistent weak layer, two avalanche problems are used to describe the situation.

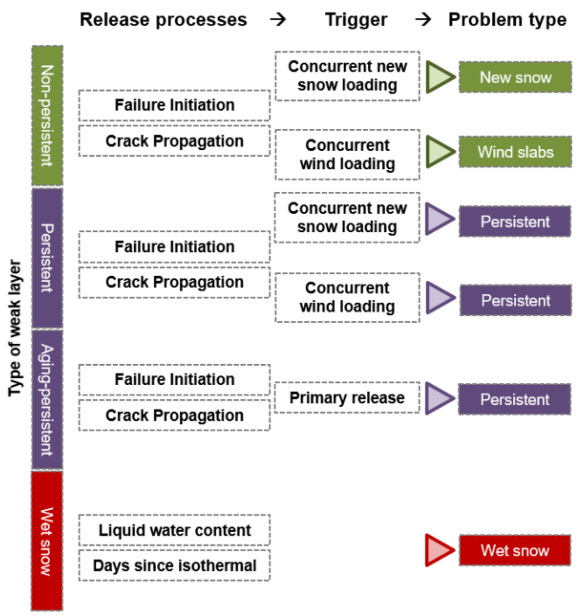

Figure 1: Assessing avalanche problems for natural release: the type of weak layer type and the snow instability indicators for two avalanche release processes are subsequently combined with weather information (trigger) to derive the problems.

The avalanche problem data we process to assess snow climates, contain the

- number of days with new snow per season,
- number of days with persistent weak layers per season, and the
- onset date of the first wet-snow avalanche cycle in spring.

In addition, we also use the number of days that at least one of the 4 avalanche problems occurred as a measure of the number of days with natural avalanches. We analyze these variables in the 23 regions of the French Alps at 1800, 2100, 2400, 2700 and 3000 m.

2.3 Spatial analysis: clustering

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. We clustered the data of the seasonal avalanche problems. The clustering routine starts at different randomly chosen locations in the data set, and then, replicates the cluster, to avoid local minima in the optimization process. 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.

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 problems that dominates in that region.

2.4 Temporal analysis: linear regression

The seasonal counts of avalanche problems are compiled at the models' elevation which is closest to the typical release area elevation in the region (Duvillier et al., 2022). For visualization, we normalized occurrences of avalanche problems, such as seasonal counts of new snow situations, by subtracting the mean and dividing by the standard deviation of the time series. The time series of avalanche problem occurrence were smoothed using moving averages with constant a window size of 9 years.

We use Pearson's correlation coefficient r, the R^2 value in the sense of variance explained by linear regression, and the p-value to describe significance of linear trends in time series.

3. RESULTS

We first show a spatial analysis highlighting the different climate regions based on the avalanche problems, before we discuss changes related to the occurrence of avalanche problems.

3.1 Spatial analysis: climate clusters

Erreur ! Source du renvoi introuvable. 3 variables "number of days with new snow", "number of days with persistent weak layer problems per season" and "onset date of wet snow avalanches" represent a subset of uncorrelated variables (all $r < 0.4$; all $p > 0.05$) and contain most of the information of the data set. Hence, the three properties can be used to describe the climatological differences between the French Alpine regions. Two of the three variables are graphed in Figure 2. The colors indicate how the data separates into the 4 groups, the so-called clusters. Apparently, the two graphed variables do not separate well the blue and the dark green group of data points, i.e. the "inner-Alpine" from the "northern" cluster. In this case, the third variable is decisive: the number of days with new snow problems (not shown).

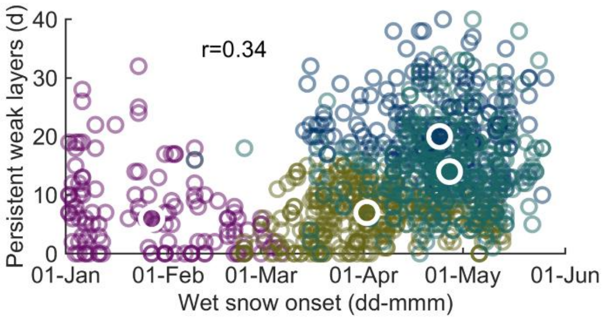

Figure 2: Clustering of the two variables: number of days with persistent weak layer problems and onset date of wet-snow avalanches. Open circles denote the cluster a day way assigned to. Full circles denote the centers of the four clusters: "northern" (dark green), "southern" (khaki), "inner-Alpine" (blue), and "front-range" (violet) (N=1426).

The four clusters have the characteristics described in Table 1. The "inner-Alpine" cluster is characterized by many persistent weak layer problems – compared to the other 3 clusters. The pattern was prominent in the Haute-Maurienne region close to the Alpine ridge. In the "northern" 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. The Mont Blanc region is a typical example.

Table 1: Description of snow avalanche climates in the French Alps by occurrence of three avalanche problems: new snow, persistent weak layers and onset date of wet-snow avalanches.

	Few days with "new snow"		"New snow" frequent	
"Persistent weak layers" frequent	Wet-snow onset > 1April		Few data	Few data
Few "persistent weak layers"	Wet-snow onset < 1 March	Wet-snow onset > 1 March	Few data	Wet-snow onset > 1 April

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 data points describe cases with an early onset of wet snow avalanches (Figure 2), typically before 1 March, the khaki data points have a later onset of wet snow avalanches, rather after 1 March. Chartreuse and Ubaye are regions representative of the "front-range" and the "southern" cluster, respectively.

Patterns of the occurrence and timing of the simulated avalanche problems can be located on a map (**Erreur ! Source du renvoi introuvable.**). The color shading can be interpreted as the likelihood that a particular region has the climatological patterns of a cluster.

The snow climate classification introduced by Mock (Mock and Birkeland, 2000) was applied to the French Alpine regions. The three panels in Figure 4 show the snow climate classification for the French Alps. Despite their different approach the avalanche problem-based classification parallels much the snow climate classification. Front-range regions are found in the coastal regions, inner-Alpine regions match quite well the "continental" regions. The "northern" and the "southern" clusters make up for the majority of the "intermountain" regions.

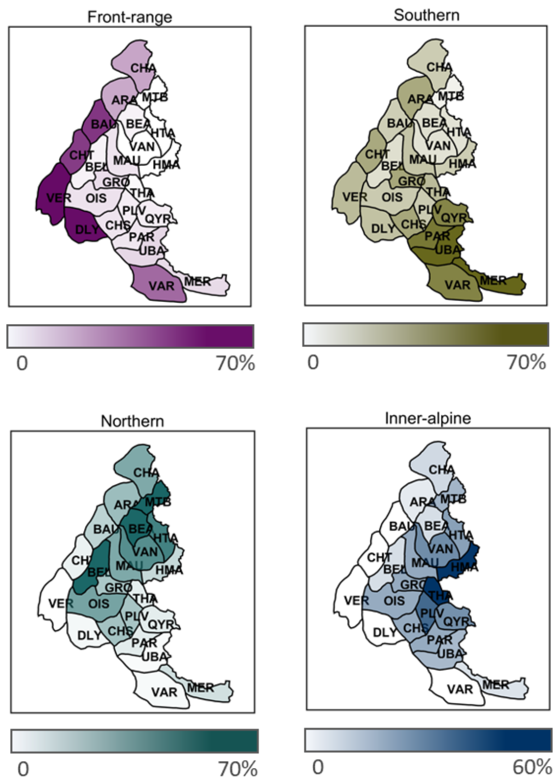

Figure 3: Maps of the French Alpine regions highlighting the frequency of winter seasons assigned to one of the 4 typical patterns: front-range, southern, northern or inner-Alpine regions.

3.2 *Temporal analysis*

Figure 5 compiles the seasonal occurrences of avalanche problems and days with natural release in typical release areas. A marked decrease in avalanche problem frequency separates two distinct periods on the graphs of Figure 5 a, b and d. The average seasonal occurrence of situations with new snow, persistent weak layers or natural release was rather stable or increased gradually, until around 1989 a decline of numbers of situations set in. In the second part of the data set, occurrences drew near the previous level again. The onset date of wet-snow avalanches shifted more rapidly towards earlier dates after 1989.

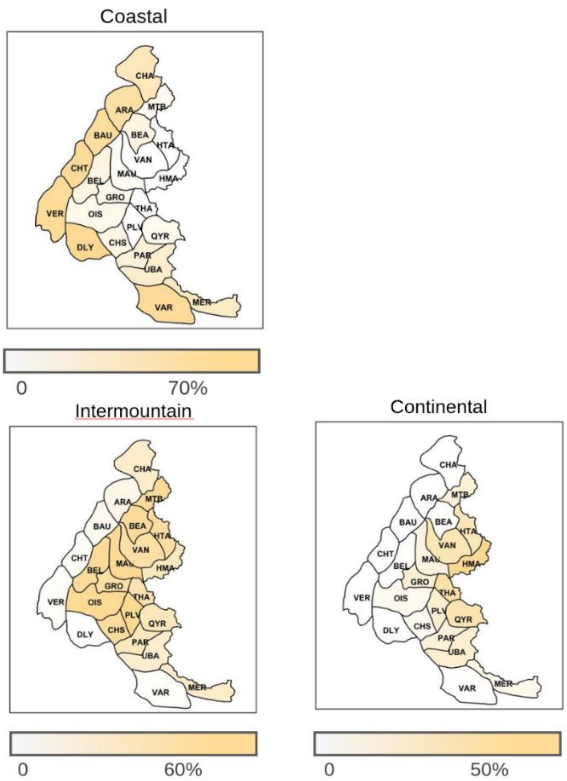

Figure 4: Maps of the French Alpine regions highlighting the frequency of costal, intermountain and continental snow climates during the period between 1958 and 2020.

Considering all regions between 1958 and 2020, new snow situations decreased by about half a day, persistent weak layer situations decreased by about 4 days, the wet-snow onset date advanced by about 1 month and natural release increased by about 1 day.

Looking at change in the second period (1989 – 2020) provides a more diverse picture. The change the regions underwent can be summarized for every avalanche problem as follows:

- New snow situations became more frequent in most of the regions (63%) and at most of the elevations (80%) during the second period. The second period follows a short transitional period with strong decrease. In the second period and at higher elevation positive trends were significant in several inner-Alpine regions.
- Regarding persistent weak layer problems, after an abrupt decrease in the transition to the second period, trends of increase and decrease were balanced.
- The onset date of wet-snow avalanches shifted to earlier dates in the majority of the cases during the second period (60%). In particular in northern regions, were trends significant at one elevation per region at least. The shift of the wet-snow onset was less distinct in the southern regions.

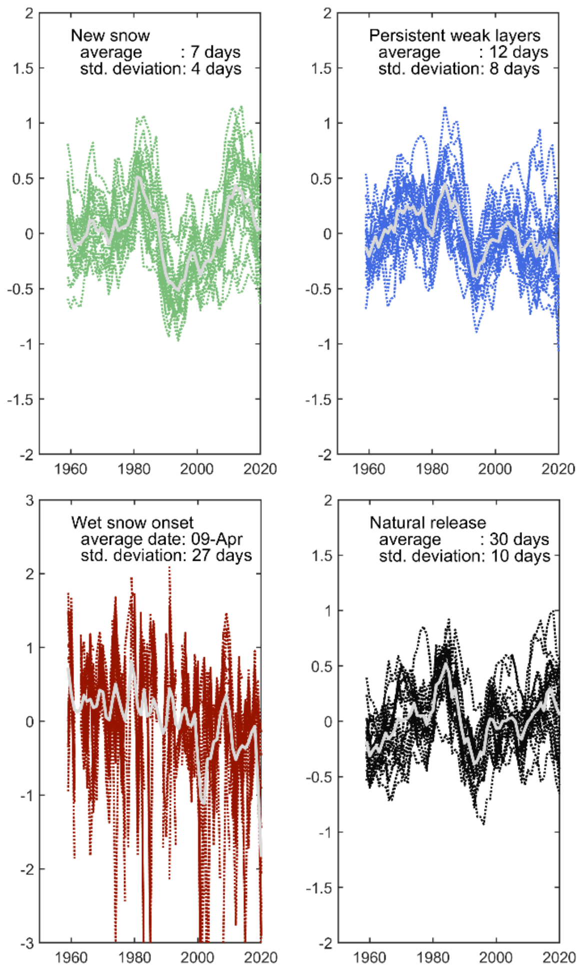

Figure 5: Normalized seasonal occurrence of (a) new snow situations, (b) persistent weak layers, (c) onset date of wet-snow avalanches and (d) natural release between 1958 and 2020. Dotted, colored lines represent average conditions in every region of the French Alps. Data were smoothed with a 9-year moving average. Average conditions in the entire French Alps by full, grey lines.

- Natural release became more frequent with slightly more increasing trends in the second period after a sharp decrease around 1989. During the second period the increase was significant in some of the northern regions at around 2400 m.

4. DISCUSSION

4.1 Comparison with North-American climates

The smaller topographical size of the French Alps, compared to North-American mountain ranges, where snow climatology was developed firstly, does not mean that differences are too small to be identified. In fact, the Alpine regions show a diversity beyond the three-level snow climate classification that becomes apparent in a novel, finer classification based on avalanche problems. This classification is applicable to any mountain region with sufficient meteorological data so snow cover modeling is possible.

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 recent analysis of avalanche problems for Western Canada (Shandro and Haegeli, 2018). To summarize, the snow climates along the Pacific coast of Southwestern Canada and the Northwestern U.S. favor heavy snow fall 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 in the front-ranges on one end and Haute-Maurienne as an inner-Alpine valley on the other.

4.2 Temporal change

A regression analysis for the entire 62-year time series revealed the strongest trend for the onset date of wet-snow avalanches, which shifted by about one month over the period. New snow and persistent weak layer situations did not change significantly at that scale.

The simulated avalanche problem frequencies showed a marked decrease at the beginning of the 90s. This abrupt change parallels documented fluctuations of air temperature, snow accumulation or heavy precipitation (Ceppi et al., 2012;Schöner et al., 2019;Scherrer et al., 2016). Two periods become obvious, the first one including the seasons until 1989 and the second one thereafter. Zooming in on the second period, we observe a regional response of avalanche danger to climatic changes that are documented in the Alpine regions (Beniston, 2012). Rates and amplitudes of change depend on season and elevation, and so are our results diverse at the scale of the avalanche forecasting regions.

4.3 Wet-snow

Past research has put forward the idea of an increase in wet-snow situations. However, more frequent observations of so-called wet-snow avalanches (Naaim et al., 2016;Pielmeier et al., 2013) refer to the snow wetness in the runout zone, where observations are typically made, and not the release area. Wet-snow avalanches occur when a weak layer loses strength due to wetting. A rain event, for instance, alone does not make for a wet-snow avalanche cycle as long as the weak layer stays dry, which is hard to observe. The presented simulations consider this detail and allow for an objective assessment. Our data do not indicate an overall increase of wet-snow avalanche situations, that would give rise to an activity increase. Considering all regions at the typical release area elevation wet-snow situations increased, because many regions hadn't seen an important contribution of wet-snow at this elevation, yet. The changes at the regional level, however, indicate that the occurrence of wet-snow situations shifts upwards, with the observed upwards shift of the snow line and the snow-rain limit (Serquet et al., 2013). This does not mean that the overall number of avalanches increases, but that the typical release area of wet-snow avalanches changes.

4.4 Limitations

Limitations of the presented classification ae related to the meteorological data we used. The reanalysis includes field observations as well as weather model data and represents the best available historic data set for the area. Nevertheless, as new snow is the most important ingredient for natural release, results are sensitive to the new snow amounts in the data set. 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.

5. CONCLUSIONS

We utilized an approach to derive a snow avalanche climatology based on avalanche problems. Application to the French Alps identified four typical patterns of avalanche problems. 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.

The most pronounced trends we observed from 1989 on were (1) an unbroken frequency of natural release, (2) an increase of new snow situations, in particular in inner-Alpine regions and (3) an earlier onset of wet-snow avalanches, in particular in northern regions. Change occurs at the regional scale and is rather individual to a region. The trends fit into the general picture of Alpine climate trends, where a warmer average atmosphere forces shorter snow seasons, while high elevations still favor snow fall over rain.

The presented snow avalanche climatology shows that climate zones can be outlined based on avalanche problems which is informative for avalanche forecasting and climate change impact studies.

This research explains the response of avalanche hazard to climatic change in typical release areas. Given that our results are based on simulations form one meteorological reanalysis data set, the research should be confirmed in a next step, ideally when future trends from climate projections are analyzed which facilitates model comparisons.

ACKNOWLEDGEMENT

We are grateful to everybody who contributed to the development of the reanalysis data set and the snow cover model.

REFERENCES

Beniston, M.: Is snow in the Alps receding or disappearing?, Wiley Interdisciplinary Reviews: Climate Change, 3, 349-358, 10.1002/wcc.179, 2012.

Ceppi, P., Scherrer, S. C., Fischer, A. M., and Appenzeller, C.: Revisiting Swiss temperature trends 1959–2008, International Journal of Climatology, 32, 203-213, https://doi.org/10.1002/joc.2260, 2012.

Duvillier, C., Eckert, N., Evin, G., and Deschâtres, M.: Development and validation using ground truth of a new method to identify potential release areas of snow avalanches based on watershed delineation, Natural Hazards and Earth System Sciences Discussions, 2022.

Avalanche Problems: https://www.avalanches.org/standards/avalanche-problems/, access: 1 November 2019, 2019.

Eckert, N., Baya, H., and Deschatres, M.: Assessing the response of snow avalanche runout altitudes to climate fluctuations using hierarchical modeling: Application to 61 winters of data in France, Journal of Climate, 23, 3157-3180, https://doi.org/10.1175/2010JCLI3312.1, 2010.

Eckert, N., Keylock, C. J., Castebrunet, H., Lavigne, A., and Naaim, M.: Temporal trends in avalanche activity in the French Alps and subregions: From occurrences and runout altitudes to unsteady return periods, Journal of Glaciology, 59, 93-114, 10.3189/2013JoG12J091, 2013.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., A. Milner, Molau, U., Morin, S., Orlove, B., and Steltzer, H.: High Mountain Areas, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., E. Poloczanska, Mintenbeck, K., Alegría, A., M. Nicolai, Okem, A., Petzold, J., Rama, B., and Weyer, N. M., 131-202, 2019.

LaChapelle, E. R.: Avalanche forecasting - a modern synthesis, IAHS Publication, 69, 350-356, 1966.

LaChapelle, E. R.: The fundamental process in conventional avalanche forecasting, Journal of Glaciology, 26, 75-84, 1980.

Lafaysse, M., Cluzet, B., Dumont, M., Lejeune, Y., Vionnet, V., and Morin, S.: A multiphysical ensemble system of numerical snow modelling, The Cryosphere, 11, 1173-1198, 10.5194/tc-11-1173-2017, 2017.

Marty, C.: Regime shift of snow days in Switzerland, Geophysical Research Letters, 35, L12501
10.1029/2008gl033998, 2008.

Mock, C. J., and Birkeland, K. W.: Snow avalanche climatology of the western United States mountain ranges, Bulletin of the American Meteorological Society, 81, 2367-2392, 10.1175/1520-0477(2000)081<2367:SACOTW>2.3.CO;2, 2000.

Naaim, M., Eckert, N., Giraud, G., Faug, T., Chambon, G., Naaim-Bouvet, F., and Richard, D.: Impact du réchauffement climatique sur l'activité avalancheuse et multiplication des avalanches humides dans les Alpes françaises, Houille Blanche-Revue Internationale de l'Eau, 12-20, 10.1051/lhb/2016055, 2016.

Nicolet, G., Eckert, N., Morin, S., and Blanchet, J.: Assessing climate change impact on the spatial dependence of extreme snow depth maxima in the French Alps, Water Resources Research, 54, 7820-7840, 10.1029/2018wr022763, 2018.

Pielmeier, C., Techel, F., Marty, C., and Stucki, T.: Wet snow avalanche activity in the Swiss Alps - trend analysis for mid-winter season, Proceedings ISSW 2013. International Snow Science Workshop, Grenoble, France, 7-11 October 2013, 2013.

Reuter, B., Viallon-Galinier, L., Horton, S., van Herwijnen, A., Mayer, S., Hagenmuller, P., and Morin, S.: Characterizing snow instability with avalanche problem types derived from snow cover simulations, Cold Regions Science and Technology, 194, 103462, 10.1016/j.coldregions.2021.103462, 2022.

Roch, A.: Report on snow and avalanche conditions in the U.S.A. Western ski resorts, Swiss Federal Institute for Snow and Avalanche Research, Davos, SwitzerlandInternal report, 98, 43, 1949.

Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., and Knutti, R.: Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, Journal of Geophysical Research-Atmospheres, 121, 2626-2637, 10.1002/2015JD024634, 2016.

Schöner, W., Koch, R., Matulla, C., Marty, C., and Tilg, A.-M.: Spatiotemporal patterns of snow depth within the Swiss-Austrian Alps for the past half century (1961 to 2012) and linkages to climate change, International Journal of Climatology, 39, 1589-1603, https://doi.org/10.1002/joc.5902, 2019.

Serquet, G., Marty, C., and Rebetez, M.: Monthly trends and the corresponding altitudinal shift in the snowfall/precipitation day ratio, Theoretical and Applied Climatology, 114, 437-444, 10.1007/s00704-013-0847-7, 2013.

Shandro, B., and Haegeli, P.: Characterizing the nature and variability of avalanche hazard in western Canada, Natural Hazards and Earth System Sciences, 18, 1141-1158, 10.5194/nhess-18-1141-2018, 2018.

Statham, G., Haegeli, P., Greene, E., Birkeland, K., Israelson, C., Tremper, B., Stethem, C., McMahon, B., White, B., and Kelly, J.: A conceptual model of avalanche hazard, Natural Hazards, 90, 663-691, 10.1007/s11069-017-3070-5, 2018.

Vernay, M., Lafaysse, M., Monteiro, D., Hagenmuller, P., Nheili, R., Samacoïts, R., Verfaillie, D., and Morin, S.: The S2M meteorological and snow cover reanalysis over the French mountainous areas, description and evaluation (1958 - 2020), Earth System Science Data Discussions, 2021, 1-36, 10.5194/essd-2021-249, 2021.

Vionnet, V., Brun, E., Morin, S., Boone, A., Faroux, S., Le Moigne, P., Martin, E., and Willemet, J. M.: The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geoscientific Model Development, 5, 773-791, 10.5194/gmd-5-773-2012, 2012.