EFFECTS OF CLIMATE CHANGE ON SNOW AVALANCHE ACTIVITY IN THE ALPS: INSIGHTS FROM A 456-YEAR TREE-RING DERIVED CHRONOLOGY IN THE QUEYRAS MASSIF (FRANCE)

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ABSTRACT: Alpine regions have experienced a significant warming with temperature increases during the 20th century. Such warming strongly alters the components of the cryosphere, including shift from solid to liquid precipitation and more frequent and intense snowmelt. Such changes are expected to lead to changes in spontaneous avalanche activity. However, the IPCC notes that "avalanches are one of the least understood processes of the cryosphere in terms of response to warming". This research gap is mainly due to the insufficient documentation of past events, based on (1) historical chronicles, often discontinuous and focused on catastrophic events, or (2) on systematic inventories limited to the second half of the 20th century which do not allow a comparison of climatically different periods. The dendrogeomorphic approach has been shown to be a reliable complement to historical archives and systematic observational series. However, most dendrogeomorphic studies have failed to identify clear relationships between avalanche activity and climate variability due to (i) the limited number of avalanche tracks included in the reconstructions; (ii) potential non-stationarities related to increasing sample depth over time. Using a hierarchical Bayesian network, we (1) developed a multicentennial (1560–2016) regional reconstruction for the Queyras Massif (French Alps) and (2) compared avalanche activity with climatic fluctuations on different time scales. Over 1801–2016, our study shows a global increase in avalanche frequency during cooler and wetter periods, and reduced activity during warmer and drier periods. At the centennial scale, avalanche activity shows a decrease at the end of the 20th century with a release probability significantly lower than in the pre-industrial period. These preliminary results suggest a climatic control of avalanche activity and a direct impact of global warming on the frequency of snow avalanches in the southern French Alps.

KEYWORDS: Tree-ring, regional activity, Climate control, Hierarchical Bayesian modelling, French Alps.

1. INTRODUCTION

Alpine regions, such as the Alps, is experiencing a temperature increase twice as much as the global average during the 20th century (Auer et al., 2007). Such warming strongly alters the components of the cryosphere: the snow-meteorological regime (Beniston et al., 2018; Hock et al., 2019), the genesis, structure and persistence of the snow cover (Uhlmann et al., 2009), with a shift from solid to liquid precipitation and more frequent and more intense snowmelt phases, at the location of the snow-rain interface. It has been shown theoretically and empirically that such changes are expected to induce changes in spontaneous avalanche activity (Mock and Birkeland, 2000).

On the same time, the growing population, tourism, and socioeconomic development increased the exposure of people and infrastructure to natural hazards, including snow avalanches (Hock et al., 2019). In this context, the IPCC Special Report on Oceans and Cryosphere (SROCC) (Hock et al., 2019) mentions that "avalanches are one of the least understood processes of the cryosphere in terms of response to warming".

This research gap is mainly due to the insufficient documentation of past events, based on (1) historical chronicles, often discontinuous and focused on catastrophic events, or (2) on systematic inventories limited to the second half of the 20th century which do not allow a comparison of climatically different periods.

On forested slopes, dendrogeomorphology allows the continuous reconstruction of avalanche activity on a multi-secular scale with annual resolution (Favillier et al., 2018; Stoffel et al., 2010; Stoffel and Corona, 2014). Based on these reconstructions, several studies have attempted to highlight the snow-meteorological covariates that explain the interannual variations in avalanche activity. However, the impact of climate variability on avalanche activity has rarely been investigated due to (i) the limited number

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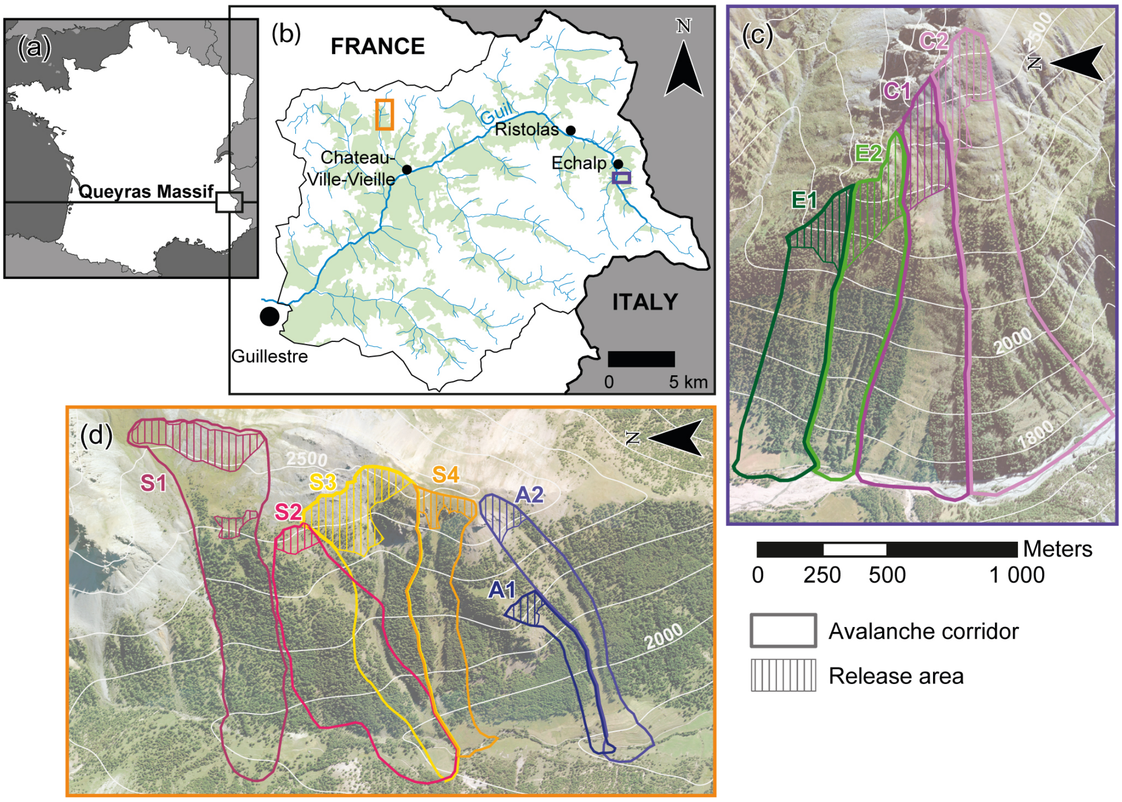

Figure 1: Location of the slopes of (a) the Queyras massif, Hautes-Alpes, France, (b) the upper Guil valley, and (c) the Souliers valley.

of avalanche tracks included in the sutides, which makes it impossible to free oneself from local characteristics; (ii) the lack of consideration of non-stationarities related to the dendrogeomorphological approach or the potential interference between avalanche dynamics, land use changes and climate variability (Giacona et al., 2017; Zgheib et al., 2020; Favillier et al., 2023); (iii) the period covered by the reconstructions, which rarely exceeds a century, does not allow the documentation of avalanche activity in recent decades with very different periods from a climatic point of view, such as the pre-industrial period or the cold phases of the Little Ice Age.

In this context, to determine the impact of recent global warming on avalanche activity, (i) the dendrogeomorphological reconstructions obtained on the 11 avalanche corridors on three slopes of the Queyras massif (French Alps) (Figure 1) were aggregated into a regional reconstruction; (ii) this reconstruction was homogenized using a hierarchical Bayesian approach (Favillier et al., 2023) in order to correct for the trends induced by the past decline in dendrogeomorphological potential; finally, (iii) the decadal to centennial variations detected in the homogenized reconstruction were compared with variations in mean temperature and winter precipitation totals.

2. STUDY AREA

To reconstruct avalanche activity, three study sites were selected in the Queyras massif: the slopes of the Ravin de la Salce (de Bouchard d'Aubeterre et al., 2019) and the Echalp (Corona et al., 2013) in the upper Guil valley (Figure 1c) and the upper Souliers valley (Mainieri et al., 2020; Figure 1d).

The slope of Ravin de la Salce is located upstream of the hamlet of Echalp, on the right bank of the Guil (44°44'47''N, 6°59'42''E; 1740-m asl; Figure 1c) and consists of four avalanche corridors (1740–2700-m asl). Corridors E1 and E2 are forested, with an understorey dominated by herbaceous species and shrubs from their starting areas (2110–2340-m asl) to their deposition zone located near of the Guil river (1740–1750-m asl). Corridors C1 and C2 are mostly forest-free. Their release areas (2290–2620-m asl) are devoid of forest cover. Snow avalanches released in these corridors are deposited at the level of the thalweg of the Guil valley (1760–1790-m asl).

The Souliers slope (Mainieri et al., 2020) is located upstream of the Souliers valley (Figure 1d). The slope is 1500-m long and ranges from 1900-2050 m at the level of the talweg of the Souliers stream to 2400-2580-m at the level of the Crête de Crépaud. A total of six forested avalanche paths have been identified and their release zones (2300–2580-m asl) by geomorphological and diachronic analyses.

The transversal zoning of the vegetation typical of snow avalanches (Malanson and Butler, 1984) characterizes most of the investigated snow avalanche corridors. The central zone, where the return periods are the shortest, is generally colonised by herbaceous species and pioneer low woody, heliophilic species, such as the European mountain ash (*Sorbus aucuparia* L.) or Alpine juniper (*Juniperus comunis* subsp. *alpina*). In the more outlying areas, where avalanches are less frequent, the forest vegetation is composed exclusively of European larch (*Larix decidua* Mill.), between 2050 and 2400-m asl. The undergrowth vegetation is dominated by herbaceous species and shrubs, especially *Rhododendron ferrugineum* L. and European blueberry (*Vaccinium myrtillus* L.).

According to the data of the nearest meteorological station, located in Saint-Véran (44°41'54"N, 6°52'06"E, 2039 m, 1928-2019), the annual temperature is 5.3°C and the total annual rainfall is 710 mm, for the period 1980–2010. From December to April, the average temperature is -0.2°C. The cumulative precipitation reaches 237 mm and falls mainly in the form of snow.

3. METHODOLOGY

The tree-ring dataset used in this study combines the reconstructions developed in the Souliers valley (Mainieri et al., 2020), the Ravin de la Salce (de Bouchard d'Aubeterre et al., 2019), and the Echalp slopes (Corona et al., 2013) in the upper Gul valley. It includes 1,595 increment cores from 1293 European larch (*Larix decidua* Mill.) trees. The sampling strategy was implemented according to the recommendations of Stoffel and Corona (2014). Samples were prepared according to the standard procedure described in Stoffel and Bollschweiler (2008). Growth disturbances (GD) were visually identified in the tree-ring series and cross-dated with the local reference chronologies calculated from undisturbed trees (Corona et al., 2013; Saulnier et al., 2017). Identified growth disturbances were then classified according to signal strength into weak, moderate, and strong responses (Stoffel and Corona, 2014). Clear evidence of snow avalanche-induced injury was considered intensity class 4.

We adopted the four-step procedure (Favillier et al., 2017) to reconstruct past avalanche events in the Souliers valley and in the Ravin de la Salce slope. This procedure disentangles potential avalanche effects on tree growth from disturbance pulses caused by climatic or exogenous factors, such as cold/dry years or larch budmoth (LBM) outbreaks. The three years following an LBM outbreak (Saulnier et al., 2017) and region-specific information on extremely cold and/or dry summers (Battipaglia et al., 2010; Auer et al., 2007) were used to filter out non-avalanche signals in the reconstructions and to assign a confidence level to each reconstructed event (see Favillier et al., 2017, for further details).

4. RESULTS & DISCUSSION

4.1 Snow avalanche chronology

The dendrogeomorphological approach applied to 11 avalanche tracks in the Queyras massif has allowed the reconstruction of avalanche activity during the period 1560–2016. The dating of 4604 growth disturbances in the ring width series of 1293 European larch trees (*Larix decidua* Mill.) tree allowed the identification of 156 snow avalanches years since 1560. The 26 avalanches reconstructed by Corona et al. (2013) on the Echalp slope were added to the regional chronology (11 corridors) for a total of 182 events. Echalp events were arbitrarily considered with a low level of confidence due to the less restrictive discriminative criteria used for detection.

The rigour of the detection method used guarantees a limited inclusion of noise—linked to potential interference between avalanche activity and exogenous signals (climatic, tornado epidemics)—in the reconstruction. It also allows a qualitative estimate of the level of confidence associated with each reconstructed event. Thus, with 89 events (48.9% of the total) classified with a very high or a high confidence level, the Queyras chronology appears to be more robust than that of the Goms valley (Favillier et al., 2023), where only 29% of the events had equivalent confidence levels. This robustness is linked to the high frequency of high and very high intensity growth disturbances (noted 3 or 4) dated in the ring width series.

4.2 Robustness of the reconstruction

Despite the quality of the chronology, the latter is still characterised by a very marked trend, since 59% of avalanches were reconstructed during the 20th century and 43% after 1950. This non-stationarity can be explained by (i) the increase in the number of living trees in recent decades, (ii) the difficulty in recovering impacts after healing (Favillier et al., 2018, 2017), but also by (iii) an often too large sampling of visible injuries (de Bouchard d'Aubeterre et al., 2019; Favillier et al., 2018). Furthermore, the correlation matrix shows synchronous functioning on the scale of a few corridors (Figure 3; S1-S2-S3, S4-A1-A2, E1-E2) but also the absence of significant correlations between neighbouring corridors (Fig 3.; S3-S4) and between the corridors on the slopes of the Souliers and those of the Ravin de la Salce. This limited synchronism can be attributed to the morphological characteristics of each corridor, as we have shown on the Ravin de la Salce slope (de Bouchard d'Aubeterre et al., 2019) but also, at Souliers, to non-stationarity induced by logging and then sylvo-pastoral shift (Mainieri et al., 2020).

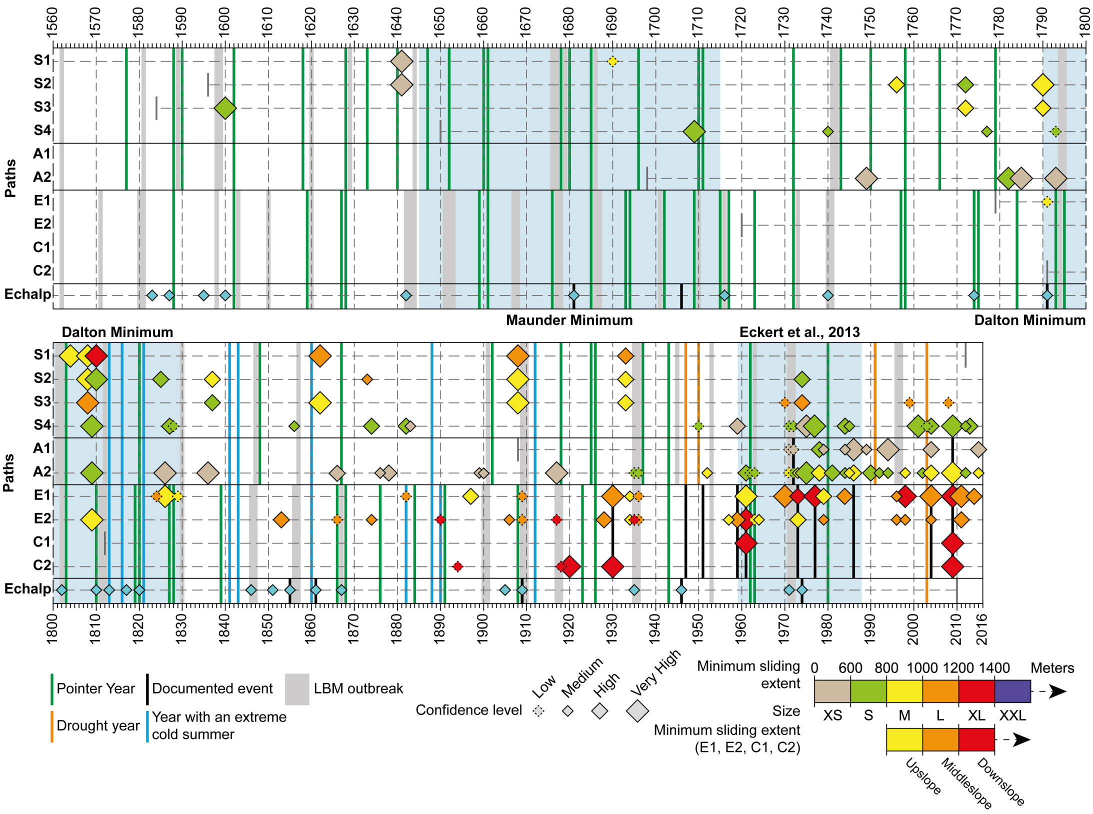

Figure 2: Reconstructed avalanches for 1560–2017 in the ten studied avalanche paths. The symbol size is proportional to the confidence level, and the colors indicate the minimum extent of each event estimated from the spatial arrangement of the damaged trees in the corridors. The gray bands represent the years of budmoth outbreaks. Vertical lines indicate snow avalanches documented in historical records (black), extremely dry (orange) and cold (blue) summers, and the narrow rings observed in reference chronologies developed from unaffected trees (green). Light blue areas correspond to peaks of snow avalanche activity observed in the literature (Jomelli et al., 2009; Eckert et al., 2013; Fouinat et al., 2018), characterized by cooler and wetter periods.

4.3 Regional snow avalanche activity

Despite these limitations, the snow avalanche chronology appears to be synchronous with the main peaks of snow avalanche activity and cool and wet climatic conditions observed in the French Alps. The aggregated snow avalanche chronology shows that an avalanche maximum was observed in the Queyras between the 1770's and 1830's, with 27 (17.3%) reconstructed snow avalanches, during the Dalton solar minimum, characterized by rather cold temperatures and significant glacial advance in the Alps (Brönnimann et al., 2019). These results are consistent with the lichenometric analyses carried out on boulders deposited in avalanche stopping zones in the Ecrins Massif (Jomelli and Pech, 2004), in particular for the periods 1780–1830 and 1830–1950, characterized by strong, and then more moderate avalanche activity respectively. Similarly, the minimum identified in the lichenometric data between 1830 and 1850 is clearly observed in the dendrogeomorphological reconstruction. They also converge with the sedimentological analyses carried out in Lake Lauvitel (Massif des Ecrins, Fouinat et al., 2018), which show a marked increase in avalanche frequency at

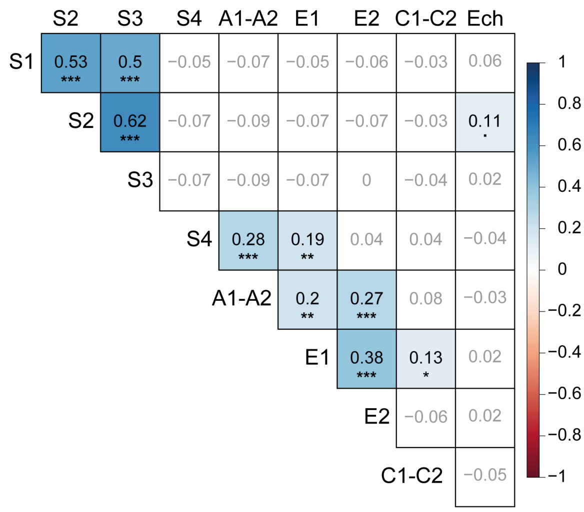

Figure 3: Avalanche activity comparison by couloir for 1790-2016. To allow comparison with other couloirs for the same period, couloirs A1 and C1 have been paired with A2 and C2, respectively. Non-significant regression coefficients are shaded. Significance levels of p-values are indicated by a . (α=0.1), * (α=0.05), ** (α=0.01), *** (α=0.001).

the end of the 18th century and then a maximum in the decades 1800–1820. The maximum snow avalanche activity was observed between 1959 and 1987, with 39 (25%) snow avalanches, corresponding to the increase in avalanche activity in the southern French Alps observed by Eckert et al. (2013) in the systematic snow avalanche records of the *Enquête Permanente sur les Avalanches*.

Despite the rigorous detection methods, Mainieri et al. (2020) demonstrated the potential influences of land cover and socioenvironmental factors on the decreasing avalanche activity during the 20th century. The rural depopulation and the abatement of pastoral activities during the 20th century led to an encroachment of both avalanche corridors and release areas in the Alps (Mainieri et al., 2020; Zgheib et al., 2020). The presence of trees is a critical factor in stabilizing the snowpack and limiting avalanche release to the steepest slopes (Schneebeli and Bebi, 2004).

5. CONCLUSION

In this study, the regional chronology developed for the Queyras massif is unique on the alpine scale. The tree-ring analysis allowed the reconstruction of 156 avalanche events on 11 avalanche tracks over a period of 456-years. The tree-ring derived snow avalanche chronology highlights that the high activity periods correspond to cool and warm periods identified within the literature. These preliminary results suggest the existence of climatic control over avalanche activity, despite the limited synchrony of tree-ring derived snow avalanche events at the path scale. Further analyses are ongoing to homogenize and standardize the chronology at the regional scale using the Bayesian logistic regression with a double spatial and temporal component developed in Favillier et al. (2023). This statistical framework will allow the comparisons with long climatic series and reanalyses and will provide insight into the climatic control of avalanche activity over the Queyras Massif in the southern French Alps.

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