Upslope migration of snow avalanches in a warming climate

Florie Giacona, Nicolas Eckert, Christophe Corona, Robin Mainieri, Samuel Morin, Markus Stoffel, Brice Martin, Mohamed Naaim

Upslope migration of snow avalanches in a warming climate

Florie Giacona[a], Nicolas Eckert[a,1], Christophe Corona[b], Robin Mainieri[a], Samuel Morin[c], Markus Stoffel[d,e,f], Brice Martin[g], and Mohamed Naaim[h]

[a]Unité de Recherche Erosion Torrentielle Neige et Avalanches (ETNA), Université Grenoble Alpes, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environement (INRAE), Grenoble 38402, France; [b]Laboratoire de Geographie Physique et Environementale (GEOLAB), Unité Mixte de Recherche 6042, Centre National de la Recherche Scientifique/Université Clermont-Auvergne, Clermont-Ferrand, 63057, France; [c]Centre National de la Recherche Scientifique (CNRS), Centre National de Recherche Météorologique (CNRM), Centre d'Etude de la Neige (CEN), Université Grenoble Alpes, Université de Toulouse, Météo-France, Grenoble 38400, France; [d]Institute for Environmental Sciences, University of Geneva, Geneva 1205, Switzerland; [e]Department F.-A. Forel for Environmental and Aquatic Sciences, University of Geneva, Geneva 1205, Switzerland; [f]Department for Earth Sciences, University of Geneva, Geneva 1205, Switzerland; [g]Centre de Recherches sur les Economies, les Sociétés, les Arts et les Techniques (CRESAT), Université de Haute Alsace, Mulhouse 68100, France; and [h]Département Eaux (AQUA), INRAE, Paris 75007, France

Edited by Juerg Schweizer, Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) Institute for Snow and Avalanche Research (SLF), Davos Dorf, Switzerland, and accepted by Editorial Board Member Jean Jouzel September 13, 2021 (received for review April 18, 2021)

Snow is highly sensitive to atmospheric warming. However, because of the lack of sufficiently long snow avalanche time series and statistical techniques capable of accounting for the numerous biases inherent to sparse and incomplete avalanche records, the evolution of process activity in a warming climate remains little known. Filling this gap requires innovative approaches that put avalanche activity into a long-term context. Here, we combine extensive historical records and Bayesian techniques to construct a 240-y chronicle of snow avalanching in the Vosges Mountains (France). We show evidence that the transition from the late Little Ice Age to the early twentieth century (i.e., 1850 to 1920 CE) was not only characterized by local winter warming in the order of +1.35 °C but that this warming also resulted in a more than sevenfold reduction in yearly avalanche numbers, a severe shrinkage of avalanche size, and shorter avalanche seasons as well as in a reduction of the extent of avalanche-prone terrain. Using a substantial corpus of snow and climate proxy sources, we explain this abrupt shift with increasingly scarcer snow conditions with the low-to-medium elevations of the Vosges Mountains (600 to 1,200 m above sea level [a.s.l.]). As a result, avalanches migrated upslope, with only a relict activity persisting at the highest elevations (release areas >1,200 m a.s.l.). This abrupt, unambiguous response of snow avalanche activity to warming provides valuable information to anticipate likely changes in avalanche behavior in higher mountain environments under ongoing and future warming.

natural hazards | cryosphere | climate change | historical data | hierarchical Bayesian modeling

Over the last decades, global warming has led to widespread shrinking of the cryosphere (1–4). The reduction of snowfall and amounts of snow on the ground (2) are increasingly well documented, notably in Europe (4–6). Likewise, climate models project further drastic reductions in snow cover extent and duration (1, 4, 7, 8), especially in low-elevation mountain environments (2). Changes in snowfall and snow cover characteristics already have direct consequences on the occurrence and magnitude of natural hazards (1, 2, 4, 9). Among these, snow avalanches not only are a major threat to mountain populations and their assets (10, 11) but also represent the mass-movement process for which climate is considered to exert the largest control through changes in rain–snow partitioning of precipitation and snow cover characteristics (2, 8, 12).

Although systematic avalanche records typically extend back to ca. the 1950s, it has so far remained difficult to observe unequivocal trends on climatically driven changes in avalanche numbers, runout distances, or flow types (13–15). Likewise, literature is also critically lacking regarding future avalanche activity in a warmer climate—the only study currently available (16) points to a 20 to 30% reduction in avalanche numbers in the French Alps by the end of the twenty-first century as compared to the reference period 1960 to 1990. Several factors explain this lack of direct evidence: first, homogeneous time series of snow avalanches have remained too short for trend analyses over time scales relevant for the detection of climate change impacts (12, 17). Second, interpretations may have suffered from confounding influences of climatic and socioeconomical drivers or biases in the proxy data (14, 17–20). Eventually, with warming, a temporary increase in extreme snowfall or wet-snow amounts could emerge at higher elevations (2, 21, 22), which in turn could enhance avalanche activity (23). For instance, during the exceptional avalanche episode of January 2018 in the European Alps, and despite extremely high air temperatures, numerous avalanches were triggered across the Alps (24) [in a subregion of Switzerland alone, nearly 19,000 avalanches were observed on satellite images (25)]. Similarly, a drastic increase in avalanche activity has been evidenced lately on high-elevation slopes in the Himalayas and attributed to the increase in increasing air temperatures (2, 25).

SUSTAINABILITY SCIENCE

ENVIRONMENTAL SCIENCES

Significance

Snow avalanches represent a major threat in mountain environments, where they cause damage to critical infrastructure and claim hundreds of lives every year. Here, we document an unambiguous upslope migration of snow avalanches with climate change, a physical mechanism whose existence could previously not be demonstrated. In the Vosges Mountains, we show evidence that winter warming of +1.35 °C induced a sevenfold reduction in the number of avalanches, as well as a reduction of their magnitude and shortening of the avalanche season. These results show that low-to-medium elevation mountain ranges may serve as sentinels to anticipate future changes in snow processes and related risks in higher mountain environments and could thus help in the design of efficient adaptation strategies.

Author contributions: F.G. and N.E. designed research; F.G. and N.E. performed research; F.G. and N.E. contributed new reagents/analytic tools; F.G., N.E., C.C., R.M., S.M., M.S., B.M., and M.N. analyzed data; and F.G., N.E., C.C., R.M., S.M., M.S., B.M., and M.N. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. J.S. is a guest editor invited by the Editorial Board.

[1]To whom correspondence may be addressed. Email: nicolas.eckert@inrae.fr.

This article contains supporting information online at http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2107306118/-/DCSupplemental.

Published October 25, 2021.

Yet, the role of climate in controlling snow avalanching at decadal to centennial time scales remains poorly understood and therefore precludes robust anticipation of future changes (1, 2, 8, 12). Closing this gap needs an assessment of avalanche activity in a longer-term context and a focus on areas and/or climate transitions that may have caused significant shifts in avalanche regimes in the past. To this end, we analyzed an extensive compilation of 734 historical records of avalanche events (20) that occurred in the low-to-medium elevation Vosges Mountains (northeast France) over the period 1774 to 2013 (Fig. 1). We developed a statistical framework that 1) accounts for the possible pitfalls affecting historical sources (e.g., biases in observations toward large, destructive snow avalanches; completeness of the record; accuracy of the information) and, 2) quantifies the respective roles of climate and changes in the sources reporting observed snow avalanches. Our analysis reveals a substantial decrease in avalanche frequency between the end of the Little Ice Age (LIA) (26, 27) and the Early Twentieth Century Warming (ETCW) (28, 29), known as one of the most prominent phases of accelerated warming prior to the current anthropogenic warming. Hence, we shed light on an unambiguous relation between climatic changes and snow avalanche activity to demonstrate that the warming-induced shrinkage of snow amounts and snow cover duration led to an upslope migration of snow avalanches. We also evidence that warming resulted in a rapid shift from a widespread to a residual activity—which in addition is restricted to the highest release areas—with a concomitant decrease in avalanche size and a shortening of the avalanche season. Eventually, we discuss how these results allow anticipating likely changes in avalanche behavior in a variety of higher-elevation mountain ranges under future warming.

Results

Evolution of Snow Avalanche Activity since 1774 CE. The Vosges Mountains are a midlatitude (48°N, 7°E), low-to-medium elevation (≤1,424 m above sea level [a.s.l.]) and rather small (7,300 km^2) mountain range. Due to its topographic and climatic conditions (*SI Appendix, Supplementary Material S1-1*), snow avalanche activity is significant, notably due to cornice collapses triggering avalanches in the eastern cirques of the Vosges Mountains shaped by Pleistocene glaciers (*SI Appendix*, Fig. S1). Most of the avalanche-prone areas are currently found at the highest elevations of the mountain range (ca. 50% of which have mean elevations >1,000 m a.s.l.). The long-standing

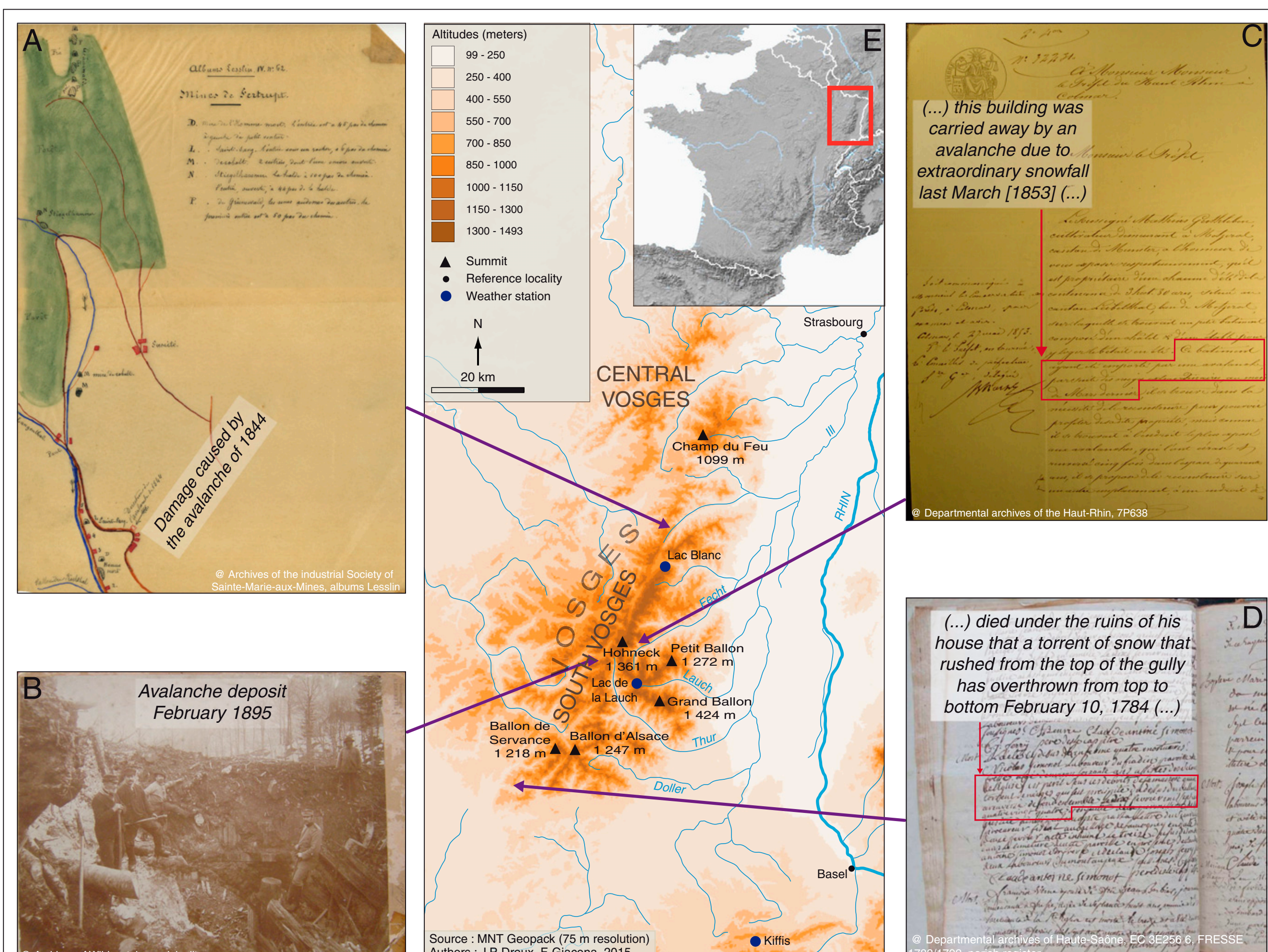

Fig. 1. Study area and historical archives relating to past snow avalanches. (*A*) Map from the mid-nineteenth century localizing a house damaged by an avalanche (flow direction is indicated); (*B*) old photograph of an avalanche that reached a valley in year 1894; (*C* and *D*) written sources relating to building destruction and casualties by snow avalanches in 1852 and 1783, respectively; (*E*) the four avalanches are mapped on the topography of the Vosges Mountains. The three weather stations indicated have long snow series (*SI Appendix, Supplementary Material S1-7*).

human occupation of the mountain range, from the valley floors to the mountain ridges, allowed detailed geohistorical investigations of all avalanche-prone areas since 1774 CE (*Materials and Methods*). Spatiotemporal variations in reconstructed avalanche activity relate to 1) differences in avalanche activity across the Vosges Mountains, and 2) an ever-rising number of increasingly reliable sources over the study period. We decomposed space–time variability in avalanche series by combining data mining tools and a hierarchical Bayesian model (*Materials and Methods*). The latter expresses past process activity as a homogenized mean annual number of avalanches for each individual path of the Vosges Mountains. Spatial and temporal patterns explain 39 and 61%, respectively, of total avalanche variability. In addition, the smoothed trend of avalanche activity dominates over the year-to-year variability and explains 59% of the temporal signal (*SI Appendix*, *Supplementary Material S2*). This variance decomposition points to 1) a strong spatial consistency of avalanche activity across the Vosges Mountains, much more pronounced than, for example, in the Northern French Alps where only ca. 5% of total variability is shared between avalanche paths (30). In addition, findings also highlight 2) substantial multidecadal changes in avalanche activity within the Vosges Mountains. Indeed, the dramatic decrease in avalanche frequency over the 1865 to 1910 period is clear and unambiguous (Fig. 2), even if the smaller number of data leads to higher uncertainties in avalanche activity estimates until the mid-nineteenth century.

This means that between 1774 and 1864, our analysis indicates a mean of 0.74 avalanches per path and year over the entire mountain range. During the same period, we find that the avalanche activity of every single year is clearly above the mean observed over the full period under investigation as well (i.e., 1774 to 2013; mean: 0.25 events per path and year). Eventually, 23 out of the 24 most active avalanche years since 1774 (>90th percentile) are found before 1865, with a peak in activity between 1825 and 1855 and—to a lesser degree—in the 1780s and 1790s. Two clear maxima are visible in the smoothed trend, with 0.53 and 1.18 avalanches per year and path, respectively, around 1789 and 1845. This high frequency of snow avalanches before 1865 fairly well corroborates findings of proxy-based reconstructions of smaller, spatially limited, avalanche time series in other mountain ranges (relying mostly on lichens) with lower dating resolutions (31–33). By contrast, after the strong 1865 to 1910 decrease in snow avalanching, activity stabilized at a mean of 0.09 avalanches per path and year over the period 1910 to 2013 (−92% with regards to [wrt] 1774 to 1864). Notably, the weakest activity over the entire period was recorded between 1910 and 1935, with only 0.04 avalanches per path and year. The Student's *t* test confirms that the differences found in avalanche activity between the subperiods 1794 to 1909 and 1910 to 2013 are statistically significant (Table 1). This major avalanche activity regime shift inferred from our data corresponds fairly well to the transition from the late LIA to the ETCW that occurred, according to the literature, between the mid-nineteenth century and the first decades of the twentieth century (28, 29, 34). From this perspective, the year 1951 stands out as the only "LIA-like" (>90th percentile) avalanche winter that occurred since the shift, as a singular relic of

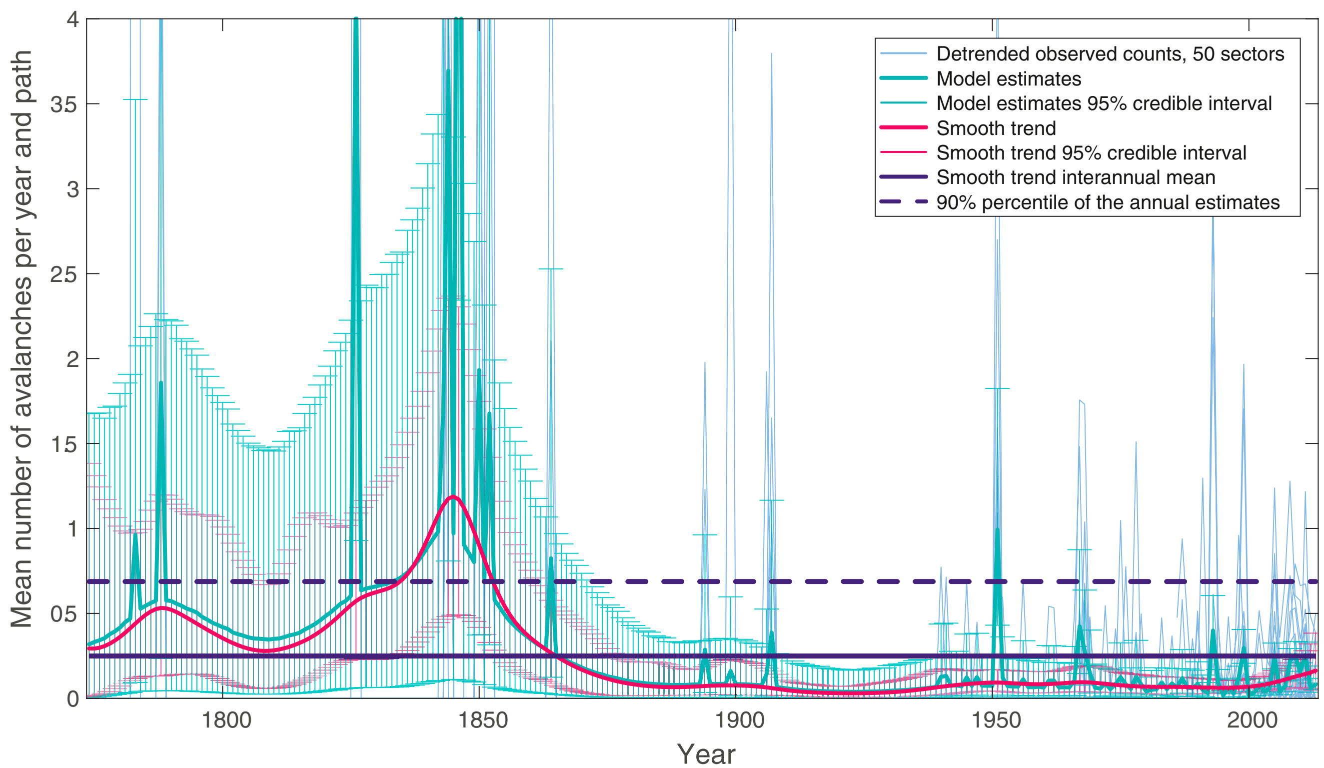

Fig. 2. Homogenized avalanche activity in the Vosges Mountains over the period 1774 to 2013. Each year represents a winter, starting from mid-November of a given year and ending around end of April the following year. Smoothed and annual estimates quantify the average number of snow avalanches per year and avalanche path (*SI Appendix*, Eq. **S2.19**). The 95% credible intervals indicate related uncertainties. Exceedances of the 90th percentile of annual estimates (dotted line) correspond to the harsh years during which avalanche activity was highest. The interannual mean of the smoothed trend is 0.25 avalanches per year and path. Smoothed trends are systematically above 0.25 avalanches per year and path up to 1865 and below 0.25 avalanches per year and path since 1866. The 50 local detrended series show the similarity in activity between all avalanche-prone areas of the Vosges Mountains. This common behavior is exploited by our hierarchical Bayesian approach (*SI Appendix*, *Supplementary Material S2*).

Table 1. Differences in means between the 1909 and 1910 to 2013 subperiods for avalanche activity and climate variables

	Variable	1794 to 1909 mean	1910 to 2013 mean	Student's *t* test *P* value
Avalanche activity	$\hat{f}_t$ (number of avalanches per year and path)	**0.53**	**0.09**	**<0.0001**
	$\hat{f}_{t_{smooth}}$ (number of avalanches per year and path)	**0.39**	**0.07**	**<0.0001**
	Size index	**3.3**	**2.1**	**<0.0001**
	Calendar day	**124**	**101**	**0.019**
DJF climatology	Mean temperature [°C, Casty et al. (35)]	**0.14**	**1.03**	**<0.0001**
	Total precipitation [mm w.e.q., Casty et al. (35)]	**190**	**215**	**0.001**
	Snow precipitation [mm w.e.q., Chimani et al. (36), z = 509 m]	111	101	0.13
	Snow precipitation [mm w.e.q., Chimani et al. (36), z = 1,201 m]	193	210	0.07
	Fraction of precipitation in solid form [%, Chimani et al. (36), z = 509 m]	**49**	**38**	**<0.0001**
	Fraction of precipitation in solid form [%, Chimani et al. (36), z = 1,201 m]	**78**	**71**	**<0.0001**
NDJFMA climatology	Mean temperature [°C, Casty et al. (35)]	**2.68**	**3.37**	**<0.0001**
	Total precipitation [mm w.e.q., Casty et al. (35)]	**388**	**434**	**<0.0001**
	Snow precipitation [mm w.e.q., Chimani et al. (36), z = 509 m]	**197**	**176**	**0.014**
	Snow precipitation [mm w.e.q., Chimani et al. (36), z = 1,201 m]	393	412	0.19
	Fraction of precipitation in solid form [%, Chimani et al. (36), z = 509 m]	**41**	**32**	**<0.0001**
	Fraction of precipitation in solid form [%, Chimani et al. (36), z = 1,201 m]	**70**	**64**	**<0.0001**

Each year represents a winter, starting from mid-November of a given year and ending around the end of April the following year. DJF stands for the December to February and NDJFMA for the November to April winter periods, respectively. w.e.q. stands for meter water equivalent. Values given in bold point to a significant difference between the two subperiods (0.05 level). $\hat{f}_t$ (*SI Appendix*, Eq. **2.19**) and $\hat{f}_{t_{smooth}}$ refer to the homogenized avalanche activity and size index (20) and calendar day to the avalanches from the sources (*Materials and Methods*). For the Chimani reconstruction (36), two grid points corresponding to elevations of 509 and 1,201 m a.s.l., respectively, within the Vosges Mountains are considered. For the Casty (35) reconstruction, only the mean over the four grid cells covering the Vosges Mountains is considered. Year 1910 represents the end of the LIA–ETCW transition. Evaluation of the mean by subperiod and determination of the significance of their difference is performed, in each case, over the period for which the considered snow/climate variable is available (*SI Appendix*, Supplement S1-7), for example, 1800 to 2013 for the Chimani (36) reconstruction of snow precipitation and fraction of precipitation in solid form. Analysis with the 1794 to 1865 and 1866 to 2013 subperiods as discriminant factor leads to very similar results (*SI Appendix*, Table S10).

what harsh winters used to be in the Vosges Mountains before 1865 CE.

Long-Term Changes in Snow-Climate Conditions Control Reduction in Avalanche Activity. Monthly resolved, multicentennial climate proxies (35, 36) (*Materials and Methods*) confirm that the drastic reduction in snow avalanche activity in the Vosges Mountains occurred during a period of major winter warming. Warmer air temperatures were accompanied by drastic changes in snow cover depths and snow cover duration; the latter were favored by reduced snowfall and enhanced snowmelt (2, 4). The Student's *t* test (Table 1) demonstrates that differences in local snow-climate conditions before and after the 1865 to 1909 transition period are significant. In detail, between 1910 and 1935—a period that roughly corresponds to the ETCW and for which we document minimal avalanche activity—winter season air temperatures were +1.35 °C above those observed during 1774 to 1864 (i.e., the last decades of the LIA). Hence, during the transition from the LIA to the ETCW (defined here as 1865 to 1909), winter air temperatures in the Vosges Mountains increased by ca. 0.3 °C per decade. This warming corresponds to a >2.5-fold increase compared to global trends at that time (34). At the same period, December to February (DJF) precipitation totals increased by ca. 13%. Whereas a large proportion of DJF precipitation was still in the form of snow during the late nineteenth century, winter warming reduced snowfall significantly at elevations <900 m a.s.l. ever since (Fig. 3). Only above 1,200 m a.s.l., the impact of increasing temperatures has been offset to some extent by rising precipitation totals. Furthermore, at Lac de la Lauch (Fig. 1, 940 m a.s.l.), DJF 1893 to 1910 mean snow depths were 24.5 cm, with ca. 60 d during which more than 5 cm of snow were recorded. During the 1910 to 1935 period, these values dropped to 11.2 cm (−54%) and ~40 d (−33%), respectively. Proxy sources confirm that half of the winters were particularly cold and/or snowy during the last phase of the LIA (1774 to 1864) (37, 38) and that snow cover persisted much longer in the higher parts of the mountain range at that time. A local report (39) even stated that, in 1860, small snow patches still "survived" up to the next winter, something that has not been observed ever since. While the annual fraction of solid precipitation was estimated to two-thirds during the late LIA at the highest ridges of the Vosges Mountains (39) (1,200 m a.s.l.), precipitation nowadays does not even occur systematically in the form of snow during winter.

A causal linkage between substantial changes in local snow-climate conditions and the sharp drop in avalanche activity during the LIA–ETCW transition (1865 to 1909) is supported by physical evidence. The peaks found in avalanche activity in 1780 to 1790 and 1835 to 1855 coincide with periods characterized by the harshest DJF conditions. For example, in 1788, the cooccurrence of extremely cold temperatures (−2.5 °C compared to 1951, the only LIA-like winter of the twentieth century) and high precipitation (+32% compared to 1951) led to an avalanche activity that was 88% higher than in 1951. In continuous records, significant correlations exist between avalanche activity and multicentennial climate proxies, notably November to April air temperatures (−0.59), solid precipitation (+0.43), and mean snow cover depth (+0.88, Table 2). Notably, air temperatures and snowfall at elevations <600 m a.s.l. and/or over an extended cold-season period (i.e., November to April) are better predictors for the long-term evolution of snow avalanching than are DJF conditions at 1,200 m a.s.l. alone. This indicates that the drop in avalanche activity at the transition from the LIA to the ETCW was mostly driven by scarcer snow conditions at low elevations of the Vosges Mountains and/or at the beginning/end of the winter season.

We analyzed the characteristics of avalanche events in our historical record (*Material and Methods*) to further understand

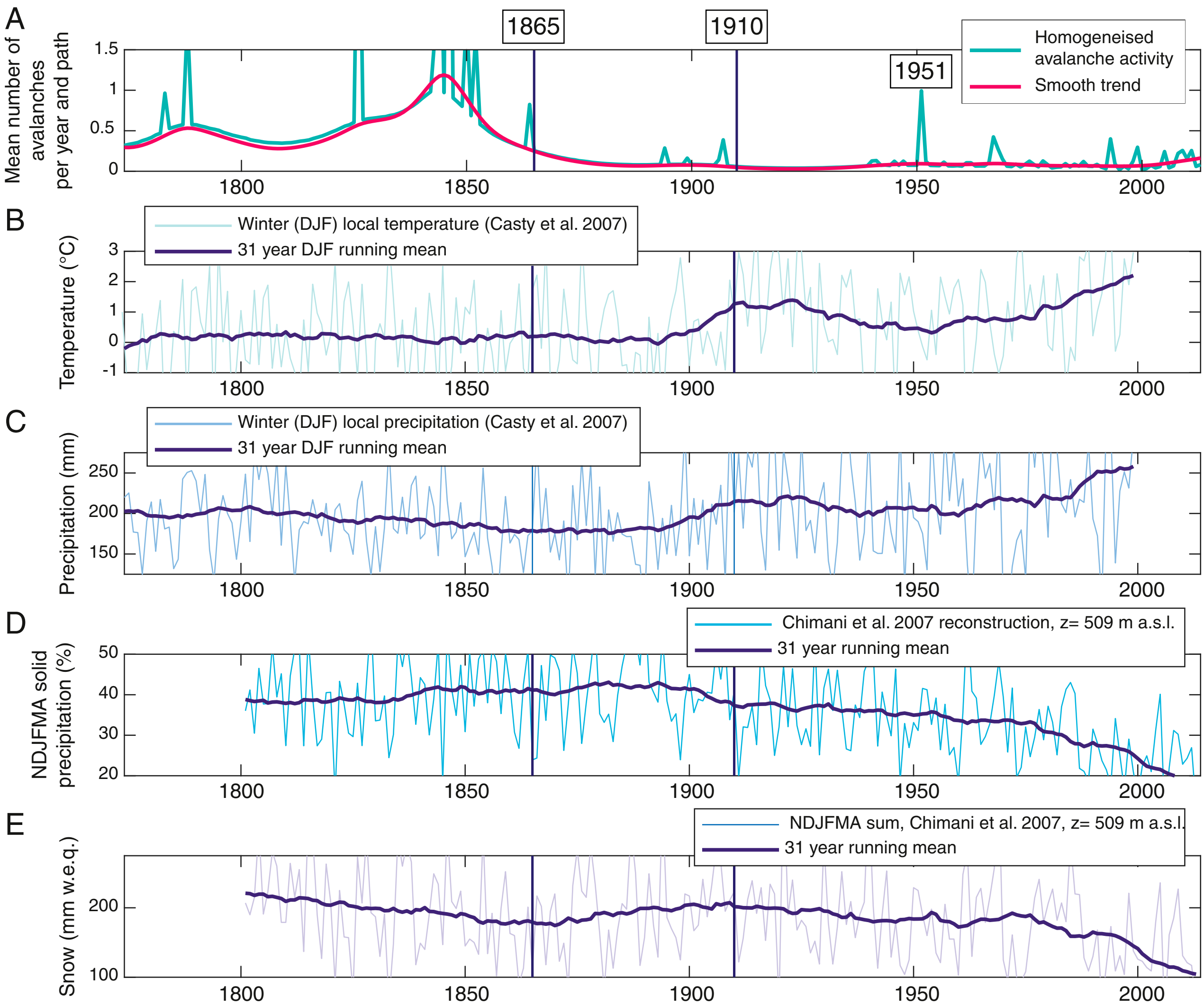

Fig. 3. Homogenized avalanche activity versus snow-climate conditions in the Vosges Mountains over the period 1774 to 2013. (*A*) Average number of snow avalanches per year and path (*SI Appendix*, Eq. **S2.19**) and the underlying smoothed trend; (*B*) winter temperature and (*C*) winter precipitation from the Casty reconstruction (36), mean over the four grid cells covering the Vosges Mountains; (*D*) fraction of solid precipitation and (*E*) snow precipitation from the Chimani reconstruction (37), 509 m a.s.l. within the Vosges Mountains. Each year represents a winter, starting from mid-November of a given year and ending around end of April the following year. DJF stands for the December to February and NDJFMA for the November to April winter periods, respectively. The period 1865 to 1909 forms the LIA–ETCW transition from a high avalanche activity regime during the last decades of the LIA to the current residual avalanche activity regime. Note the very low avalanche activity during the ETCW. Year 1951 is the only "LIA-like," high avalanche activity year since 1866 (>90th percentile of interannual distribution).

how the LIA–ECTW climate transition changed avalanche activity in the Vosges Mountains. Prior to 1910, most avalanches exceeded size 3, and about one-third were rated size 4 or 5. By contrast, since 1910, most avalanches are now rated size 1 to 3, and the proportion of size 4 to 5 avalanches has dropped to 3% (Fig. 4*B* and Table 1). Despite the known bias toward the preferential recording of large events in historical sources (40), this quasi absence of size 4 to 5 events over the recent period clearly indicates that the decline in avalanche numbers at the transition from the LIA to the ETCW was accompanied by a sharp reduction in avalanche size. This finding is supported by the detailed comparison of the LIA-like year 1951 and the strongest avalanche cycle of the recent past, 2009, in the Rothenbachkopf sector, one of the most prominent avalanche-prone areas of the Vosges Mountains (41). Whereas the 1951 avalanches reached runout elevations of 600 m a.s.l., those of 2009 all stopped above 810 m a.s.l. (Fig. 5). Despite comparable air temperatures (+0.3 °C in 2009 wrt to 1951) and proportions of solid versus liquid precipitation (3% lower in 2009 compared to 1951), mean snow depths and days during which snow cover was >50 cm at *Lac de la Lauch* station have been reduced by 35 cm (−62%) and 24 d (−61%), respectively (*SI Appendix*, Table S4). From a mechanistic perspective, the lack of cold and erodible snow along the flow path very likely explains the much shorter runout distances reached in 2009 compared to 1951, as basal friction must have been higher within the avalanche flow (42, 43).

We also considered calendar dates to investigate the exact timing of past avalanches. We find a shortening of the avalanche season by 23 d after 1910, thus eliminating almost completely avalanche activity that existed in April (Fig. 4*A* and Table 1). This finding also explains the slightly better correlation between long-term changes in avalanche activity and November to April snow conditions (rather than only DJF conditions, Table 2). Eventually, most sectors of the Vosges Mountains with release area elevation below 820 m a.s.l. have seen

SUSTAINABILITY SCIENCE

ENVIRONMENTAL SCIENCES

Table 2. Correlation between trends in homogenized avalanche activity and past snow-climate conditions over the 1774 to 2013 period

		$\hat{f}_{t_{smooth}}$	
	Variable	DJF	NDJFMA
Casty et al. (35)	Temperature	**−0.53**	**−0.59**
	Precipitation	**−0.38**	**−0.24**
Snow precipitation, Chimani et al. (36)	Min	**−0.18**	−0.12
	Max	**0.30**	**0.41**
	Mean	**0.16**	**0.27**
Fraction of precipitation in solid form, Chimani et al. (36)	Min	**0.23**	**0.22**
	Max	**0.38**	**0.38**
	Mean	**0.34**	**0.34**
Mean snow depth	Lac Blanc station	**0.88**	**0.88**
	Lac de la Lauch station	**0.50**	**0.47**
	Kiffis station	**0.85**	**0.75**
Number of days with hs > 5 cm	Lac Blanc station	**0.88**	**0.88**
	Lac de la Lauch station	**0.32**	**0.33**
	Kiffis station	**0.85**	**0.74**

DJF stands for the December to February and NDJFMA for the November to April winter periods, respectively. For the Chimani (36) reconstruction, Min, Max, and Mean correlations are the minimal, maximal, and mean correlations obtained over the 925 series corresponding to all grid points within the Vosges Mountains. For the Casty (35) reconstruction, only the mean over the four grid cells covering the Vosges Mountains is considered. $\hat{f}_{t_{smooth}}$ is the estimate of the smooth trend in the homogenized number of avalanches per year and path (Fig. 2). hs stand for snow depth. For consistency with estimates of avalanche activity, 31-y running mean of all snow-climate variables are considered. Correlations are evaluated, in each case, over the period for which the considered snow/climate variable is available (*SI Appendix*, Supplement S1-7). Values given in bold are nonzero at the 0.05 significance level .

their last avalanche before 1865. By contrast, all avalanche sectors with release area elevations exceeding 1,200 m a.s.l. remain active under current climatic conditions (Fig. 4*C* and *SI Appendix, Supplementary Material S1-5*). In other words, whereas avalanche activity has vanished almost completely at low-elevation sites, it can currently only persist at the highest elevations of the Vosges Mountains.

Discussion

In this paper, we document a sharp, more than sevenfold, decrease in avalanche activity in the Vosges Mountains at a time corresponding to the LIA–ETCW transition. The drastic reduction in the number of events was accompanied by a severe shrinkage of snow avalanche size, a shortening of the avalanche season, and a reduction of the extent of avalanche-prone terrain. Hence, a clear shift in activity occurred, from a stage of intense and widespread avalanching across all elevations of the Vosges Mountains during late LIA to a still existing relict stage in which avalanches are restricted to the highest cirques. The latter include the sole potential release areas that still receive sufficient snow to generate size 1 to 3 (very occasionally size 4, as in 2009) avalanches under current climate conditions. We explain this upslope migration of snow avalanches by the observed abrupt and marked +1.35 °C local warming of winter climate. This warming resulted in a rapid upward displacement of the zero-degree isotherm, resulting in increasingly scarcer snow conditions at low-to-medium elevations (600 to 1,200 m a.s.l.) of the Vosges Mountains. Arguably, the decrease in avalanche activity has been enhanced by two nonlinear system responses to warming. First, any minor rise in temperature around 0 °C has strong effects on snow–rain partitioning. Second, the resulting changes in snow cover characteristics affect the conditions that lead to the release of snow avalanches. The findings presented here, thus, are a clear example of how the exacerbated sensitivity of mountains to climate warming leads to abrupt changes in process activity. However, due to the high year-to-year variability of winter climate, and notably snowfall amounts, one can neither exclude high avalanche activity winters in the Vosges Mountains under current conditions nor the punctual occurrence of large avalanches, as in 2009, completely. Yet, winters with conditions favorable for the release of avalanches are clearly becoming less frequent as a result of ongoing, anthropogenic climate warming.

The assumption that increasingly scarce snow conditions will result in a significant reduction of snow avalanche activity is intuitive but has not been supported by field evidence so far. On the contrary, several past studies realized in the Alps and the Himalayas reported an ongoing evolution toward higher avalanche activity and notably an increasing number of wintertime wet-snow avalanches, with the latter being driven by more heavy snowfall and/or the prevalence of wet snow at higher elevations (2, 16, 24, 44). Our study now overcomes this paradox by showing an unambiguous reduction of avalanche activity from lower to increasingly higher elevations as a response to climate warming. Our findings are thus in line with observations pointing to a threefold decrease in snow avalanche activity in the French Alps for events occurring below 2,000 m a.s.l. over the period 1980 to 2010 (23) and likewise point to anthropogenic warming as a possible driver of these changes. In the Vosges Mountains, where we address changes in process activity over a much longer time period extending up to the last phase of the LIA, we are able to put these findings covering the recent past into perspective. In addition, our study also allows highlighting a stronger reduction of avalanche numbers, size, season, and terrain prone to avalanching, as well as analyzing the underlying climatic causes from an extensive set of covariates. The physical mechanism explaining a temporary increase of avalanche activity—if any—is likely of limited duration and should be considered transient: we posit that this temporary increase observed in the Alps and Himalayas will eventually vanish as warming will become more pronounced to reduce snow cover at increasingly higher elevations. As a consequence, this transient regime may correspond to the very high activity we documented in the Vosges Mountains during the last decades of the LIA (1825 to 1855) and could have been very short due to the limited altitudinal extent of the mountain range (see next paragraph) and the absence of an increasing trend in precipitation totals at that time (Fig. 3).

We find that avalanche activity is most affected by warming when snow conditions are altered at elevations from which snow avalanches are released, thus implying a strong elevation dependence of changes in snow avalanche activity. We therefore posit that the limited altitudinal range of the Vosges Mountains may have enhanced the response of avalanche activity to climate warming more clearly than in other mountain ranges where the larger altitudinal range may better preserve a (sometimes large) fraction of release areas from warming effects. However, we argue that the pivotal role that the transition between the widespread and marked cooling of the LIA to the warm ETCW has had on avalanche activity in the Vosges Mountains provides valuable information to anticipate likely changes in avalanche behavior in higher-elevation environments under ongoing and/or future, anthropogenically driven warming (1, 34, 45). Indeed, climate warming is projected to increase by ca. +0.3 °C per decade in high mountain areas over the decades to come, with accelerating rates of further warming toward the end of century depending on greenhouse gas emissions (2, 33). Hence, the anticipated amplitude of warming will not only be much larger than the one

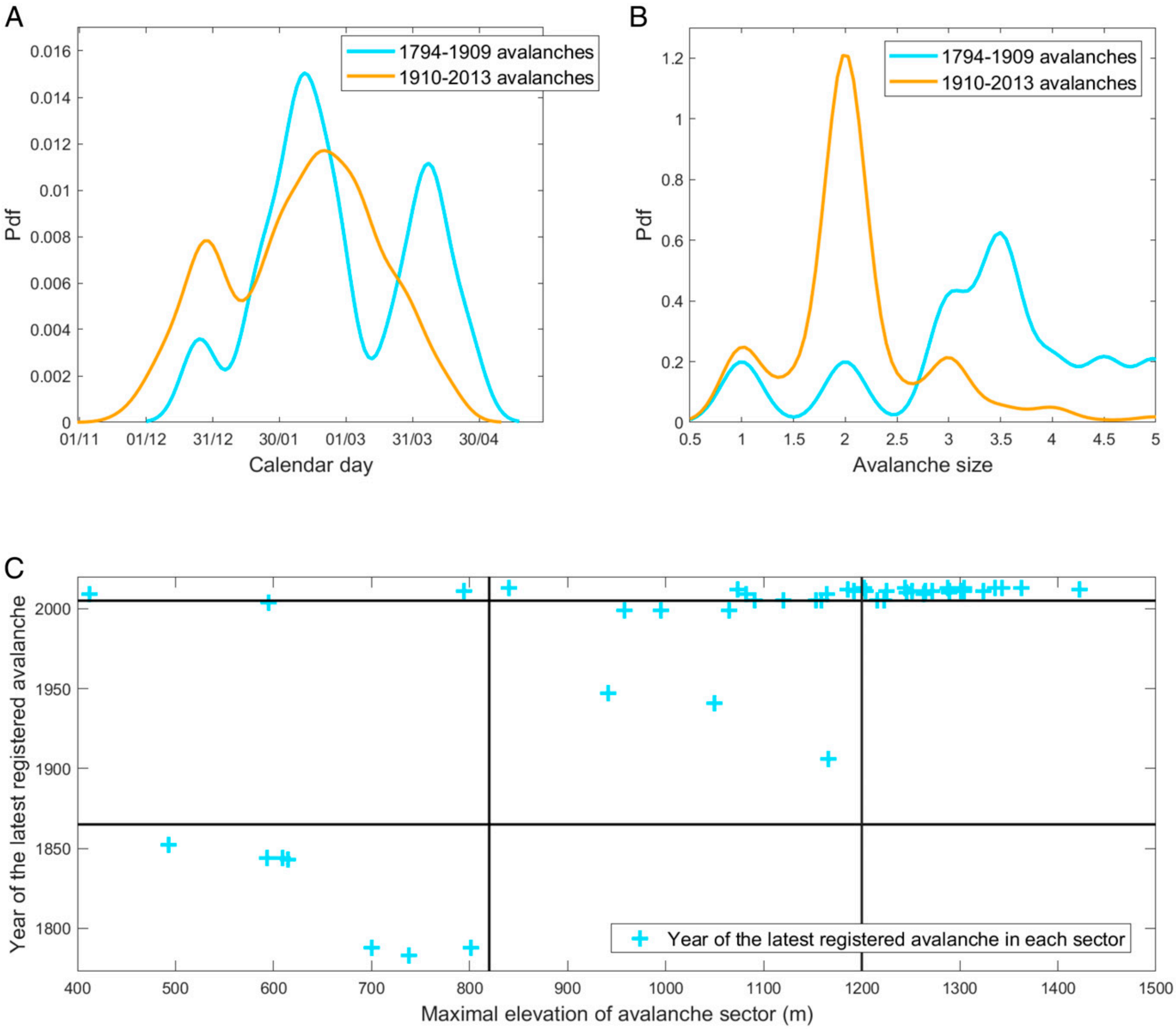

Fig. 4. Characteristics of snow avalanches from historical sources as a function of time. (*A*) Seasonal distribution of calendar dates, kernel smoothing; (*B*) size on 1 to 5 scale [*Materials and Methods* (20)], kernel smoothing; (*C*) year of the latest avalanche registered in each sector as function of the maximal elevation of each sector. In *A* and *B*, year 1910 represents the end of the LIA–ETCW transition. In *C*, horizontal thick lines highlight different time periods: late LIA (up to 1864), 1865 to 2004 and recent years (from 2005), and thick vertical lines distinguish three groups of avalanche sectors as function of their maximal elevation: below 820 m a.s.l., between 820 and 1,200 m a.s.l., and above 1,200 m a.s.l.

we studied but will also very likely affect the rain–snow partitioning and freeze/thaw cycles at increasingly higher elevations and over increasingly larger regions (i.e., entire mountain ranges or increasingly larger fractions of mountain ranges with large elevation gradients). One can thus expect a generalized upslope migration of snow avalanches across mountain regions worldwide, with a stark reduction in avalanche sizes, avalanche season, and avalanche terrain at low elevations. Hence, avalanche activity will progressively be restricted to increasingly higher elevations of mountain ranges as warming continues, as already observed in the Vosges Mountains where process activity vanished from low elevations after the LIA–ETCW transition (Fig. 4*C*). The decrease in mean avalanche activity of ca. 30% that has been projected by the end of the twenty-first century at the scale of the entire French Alps (16), where elevations yet reach as much as 4,800 m a.s.l., corroborates this assumption. As a result, avalanche hazards will arguably be reduced in the future in many medium to high mountain ranges, decreasing the threat of avalanches to currently exposed settlements and livelihoods. Obviously, this does not imply that harsh winters/large snow avalanche events will disappear completely anytime soon—even less so in mountains where conditions favorable for the release of avalanches may resist the effects of global warming over the next few decades, at least in the highest release. Also, the overall patterns and changes may be more nuanced locally, depending on topography (altitudinal range, but also terrain that controls avalanche trigger and propagation). This means that a reduction of avalanche hazards 1) may potentially be enhanced in contexts where snow conditions become affected strongly and homogeneously by global warming, like in the Vosges Mountains, or 2) tempered where large elevation ranges may induce additional complexity [transient regime enhanced by the currently documented trend toward more intense snowfall at high elevations (22) or by possible specific responses of different avalanche types to climate change (2, 17)].

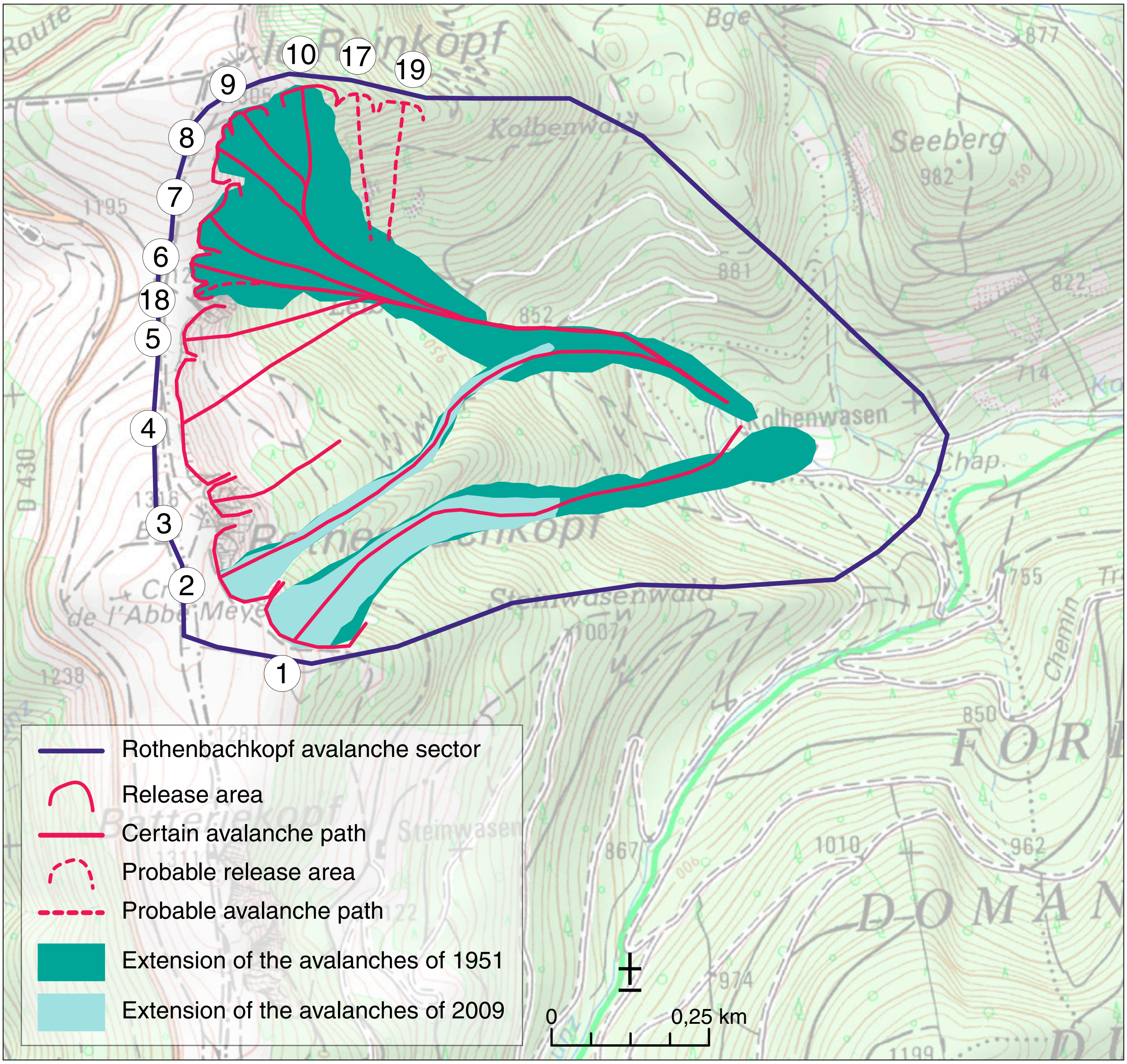

Fig. 5. "LIA-like" avalanche activity (1951) versus last major observed avalanches (2009) in the Vosges Mountains. Minimal extensions of the avalanches of years 1951 and 2009 were retrieved from aerial photographs in the Rotenbachkopf sector, an archetypal avalanche-prone area of the Vosges Mountains (42) (*SI Appendix, Supplementary Material S1-6*). Numerals 1–19 are the labels of avalanche paths in the sector: 10 certain paths and 3 probable paths. At least one event could be retrieved in historical sources for each of the 10 certain paths. For the 3 probable paths, only visible marks of avalanche activity were identified in the field but no mention of past events was found in historical sources. Topographic map from French Geographical Institute.

Ascertaining these assumptions will require 1) avalanche records that are even longer than the ones we analyzed in this study, that is, historical records extending from the core of the LIA or even earlier, 2) refined forecasts up to the end of the twenty-first century, and 3) reproducing similar analyses in different mountain environments.

Furthermore, our approach associates geohistorical analyses and a statistical framework designed to remove biases intrinsic to the use of historical sources. The efficiency of our innovative and interdisciplinary combination of methods is highlighted by the climatic relevance of the temporal pattern inferred from homogenized avalanche activity, obtained independently from past climate observations, yet fully consistent with the local evolution of snow-climate conditions. In that sense, our methodological framework could be used 1) in other mountain areas, and 2) for other gravitational or hydrological mountain hazards whose evolution under ongoing climate change remains lacunar (2, 8).

Materials and Methods

Geohistorical Documentation of Avalanche Activity in the Vosges Mountains. In France, low-to-medium elevation mountain ranges are not covered by systematic avalanche surveys. The chronology of avalanches presented here results from an extensive survey of historical sources combined with field visits. It covers the entire Vosges Mountains (20). Avalanche records were retrieved from institutional archives, oral testimonies, media, scientific literature, local novels, travel guides, publications of historical societies and hiking clubs, photographs, postcards, forums and websites supplied by practitioners of winter sports, toponyms, memorial crosses, impacts on vegetation and buildings, and a few other sources. We analyzed the 734 avalanches from this chronology. They occurred between 1783 and 2013. In total, 60% of these avalanches were corroborated by several sources (up to 60) written at the time of the avalanche events or a posteriori. Each source may refer to one or several avalanches (e.g., a diary with observations covering a long period referring to many distinct avalanches).

The 734 avalanches occurred in 50 sectors corresponding to all significant avalanche-prone areas of the Vosges Mountains. We derived topographic characteristics of these sectors from a 1-m-resolution Digital Elevation Model.

Each sector is a few square kilometers wide and includes 1 to 25 avalanche paths (most sectors have less than 5 avalanche paths). We assigned all avalanches to the sector in which they occurred. In this work, each year corresponds to a winter, starting around mid-November of a given year and ending usually at the end of April of the following year. We assigned a year for each of the 734 avalanches compiled in the dataset (*SI Appendix, Supplementary Material S1-2*).

Three specific avalanche characteristics were analyzed further: size, date of occurrence within the winter season, and year of occurrence. The size of each avalanche was rated on a specific avalanche size classification with five levels (from one, small size, to five, exceptional size). This scale was designed for the Vosges Mountains (20). It is a function of the avalanche runout distance and avalanche volume. Avalanche size classes could be attributed to 347 avalanches of the dataset. For a few avalanches, it was impossible to firmly discriminate between two size classes because of values at the limit between two classes and/or high uncertainty. Intermediate sizes were attributed in these cases, for example, 2.5, 3.5, etc. Also, we documented the precise date of occurrence for 193 of the 734 avalanches of our dataset. By precise date, we mean the exact day or a time window not exceeding 1 wk. In that latter case, the center of the time window was considered as the exact date. Eventually, we precisely mapped the extensions of the avalanches that occurred during the 1951 and 2009 winters in the Rothenbachkopf sector using a diachronic analysis of aerial photographs (*SI Appendix, Supplementary Material S1-6*).

Accounting for the Increasing Availability of Sources with a Bayesian Approach. The spatial inhomogeneity of the avalanche dataset (*SI Appendix*, Fig. S3) is predominantly linked to the natural variability between sectors (as a function of their different number of paths, elevation, etc.). By contrast, the temporal increase in the records common to all sectors directly results from historical sources. Accounting for this effect is crucial to extract the signal in natural avalanche activity potentially related to changes in climate conditions. We achieved this using data mining and Bayesian techniques (46–48). Our approach potentially smoothed some genuine low marked temporal patterns: that is, real changes in natural avalanche activity that are not related to changes in information sources. However, few studies already showed that removing trends related to population and source increase in chronologies of flood events contributed to make historical records much more insightful in terms of past changes in hazard and risk (49).

In detail, we first analyzed the quantitative and qualitative increase of the written and oral documentary sources related to avalanches over the period studied. This allowed modeling of the source availability as a function of time in the form of a continuous source potential function (*SI Appendix, Supplementary Material S1-3*). Second, we identified missing observations (in terms of number of avalanches per year and sector) using statistical tests (*SI Appendix, Supplementary Material S1-4*). Third, we developed a specific hierarchical Bayesian model to produce a homogenized avalanche activity record (*SI Appendix, Supplementary Material S2*). By "homogenized" we mean the records "that would have been retrieved if archival sources were as comprehensive and abundant as over recent years during the whole study period." Our approach uses the concept of model-based inference (46, 50) to perform model inference and detrending with the source potential altogether. Hence, it takes full advantage of having at hand 50 correlated time series of avalanche occurrences (one in each sector) instead of only one, thereby allowing inference of the temporal signal at the scale of the mountain range with more power. The model also removes local effects and "random" errors and accounts for detected missing occurrences in a fully rigorous way. All in all, it achieves a complete decomposition of space–time effects with rigorous quantification of the different uncertainty levels combined, including the one related to the low number of events/sources at the beginning of the study period.

Linkages between Avalanche Activity and Climate Conditions. We analyzed a large corpus of data related to past snow and climate conditions in the Vosges Mountains: long-term multiproxy reconstructions, point measurements, and historical sources related to winter climate during the ninteenth century (*SI Appendix, Supplementary Materials S1-7 and S1-8*). In addition to graphical comparisons (Fig. 3), we evaluated differences in the mean values of the avalanche and snow and climate variables before/after the LIA–ETCW transition (Table 1) and performed correlation analyses (Table 2). Annual estimates of homogenized avalanche activity do not capture the year-to-year variability over the first part of the study period (*SI Appendix, Supplementary Material S2*). Consequently, we computed correlations between the underlying smooth trend and the smooth trend within the different considered climate variables. For highly correlated variables, we selected one or two representative examples. For example, we employed the Casty (35) temperature reconstruction averaged all over the Vosges Mountains as an archetype of all temperature series. Yet, for the elevation-dependent snow precipitation and fraction of precipitation in solid form (36), we computed correlations with our homogenized avalanche activity for the 925 series corresponding to all grid points within the Vosges Mountains. This shows how the linkage between avalanche activity and snow conditions evolves with elevation (*SI Appendix*, Fig. S12).

Data and Code Availability. The spatiotemporal avalanche dataset (number of avalanches per year and sector and covariates) on which this study grounds is available on Zenodo, https://doi.org/10.5281/zenodo.4639769. The repository includes the new open-source statistical code that can be used to reproduce our results and to analyze other datasets for similar, wider problems.

ACKNOWLEDGMENTS. This work was supported by Université Grenoble Alpes with the Grant "RARETES" and within the Cross Disciplinary Program—Trajectories by the French National Research Agency in the framework of the *investissements d'avenir* program (ANR-15-IDEX-02). We thank B. Chimani for useful insights regarding her gridded snow precipitation reconstructions, all the numerous people that contributed by their observations to build the avalanche dataset on which the study grounds, and the two referees, the editor, and chief editor whose constructive comments and suggestions allowed substantial improvement of the paper. INRAE and CNRM/CEN are members of Labex Observatoire des Sciences de l'Univers de Grenoble.

1. IPCC, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner *et al.*, Eds. (IPCC, 2019).
2. R. Hock *et al.*, "High mountain areas" in *IPCC Special Report on Ocean and Cryosphere in a Changing Climate*, H.-O. Pörtner *et al.*, Eds. (IPCC, 2019).
3. M. Zemp *et al.*, Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568**, 382–386 (2019).
4. M. Beniston *et al.*, The European mountain cryosphere: A review on past, current and future issues. *Cryosphere* **12**, 759–794 (2018).
5. M. Matiu, *et al.*, Observed snow depth trends in the European Alps 1971 to 2019. *Cryosphere* **15**, 1343–1382 (2021).
6. C. Marty, Regime shift of snow days in Switzerland. *Geophys. Res. Lett.* **35** (L12501), 1–5 (2008).
7. S. B. Kapnick, T. L. Delworth, Controls of global snow under a changed climate. *J. Clim.* **26**, 5537–5562 (2013).
8. P. A. O'Gorman, Contrasting responses of mean and extreme snowfall to climate change. *Nature* **512**, 416–418 (2014).
9. M. Stoffel, C. Huggel, Effects of climate change on mass movements in mountain environments. *Prog. Phys. Geogr.* **36**, 421–439 (2012).
10. Eidgenössisches Institut für Schnee- und Lawinenforschung, *Der Lawinenwinter 1999: Ereignisanalyse* (Eidgenössisches Institut für Schnee- und Lawinenforschung, 2000).
11. B. Frigo, P. Bartelt, B. Chiaia, I. Chiambretti, M. Maggioni, A reverse dynamical investigation of the catastrophic wood-snow avalanche of 18 January 2017 at Rigopiano, Gran Sasso National Park, Italy. *Int. J. Disaster Risk Sci.* **12**, 40–55 (2021).
12. C. J. Mock, K. C. Carter, K. W. Birkeland, Some perspectives on avalanche climatology. *Ann. Assoc. Am. Geogr.* **107**, 299–308 (2017).
13. N. Eckert, H. Baya, M. Deschatres, Assessing the response of snow avalanche runout altitudes to climate fluctuations using hierarchical modeling: Application to 61 winters of data in France. *J. Clim.* **23**, 3157–3180 (2010).
14. M. Laternser, M. Schneebeli, Temporal trend and spatial distribution of avalanche activity during the last 50 years in Switzerland. *Nat. Hazards* **27**, 201–230 (2002).
15. N. Eckert, C. J. Keylock, H. Castebrunet, A. Lavigne, M. Naaim, Temporal trends in avalanche activity in the French Alps and subregions. *J. Glaciol.* **59**, 93–114 (2013).
16. H. Castebrunet, N. Eckert, G. Giraud, Y. Durand, S. Morin, Projected changes of snow conditions and avalanche activity in a warming climate. *Cryosphere* **8**, 1673–1697 (2014).
17. P. Haegeli, B. Shandro, P. Mair, Using avalanche problems to examine the effect of large-scale atmosphere-ocean oscillations on avalanche hazard in western Canada. *Cryosphere* **15**, 1567–1586 (2021).
18. C. García-Hernández *et al.*, Reforestation and land use change as drivers for a decrease of avalanche damage in mid-latitude mountains (NW Spain). *Global Planet. Change* **153**, 35–50 (2017).
19. R. Mainieri *et al.*, Impacts of land-cover changes on snow avalanche activity in the French Alps. *Anthropocene* **30**, 1–13 (2020).
20. F. Giacona, N. Eckert, B. Martin, A 240-year history of avalanche risk in the Vosges Mountains based on non-conventional (re)sources. *Nat. Hazards Earth Syst. Sci.* **17**, 887–904 (2017).
21. J. I. López-Moreno, S. Goyette, M. Beniston, Impact of climate change on snowpack in the Pyrenees: Horizontal spatial variability and vertical gradients. *J. Hydrol. (Amst.)* **374**, 384–396 (2009).
22. E. Le Roux, G. Evin, N. Eckert, J. Blanchet, S. Morin, Elevation-dependent trends in extreme snowfall in the French Alps from 1959 to 2019. *Cryosphere Discuss.* **15**, 4335–4356 (2021).

23. A. Lavigne, N. Eckert, L. Bel, E. Parent, Adding expert contribution to the spatio-temporal modeling of avalanche activity under different climatic influences. *J. R. Stat. Soc. C*, **64**, 651–671 (2015).
24. M. Stoffel, C. Corona, Future winters glimpsed in the Alps. *Nat. Geosci.* **11**, 458 (2018).
25. Y. Bühler, E. D. Hafner, B. Zweifel, M. Zesiger, H. Heisig, Where are the avalanches? Rapid SPOT6 satellite data acquisition to map an extreme avalanche period over the Swiss Alps. *Cryosphere* **13**, 3225–3238 (2019).
26. J. M. Grove, *The Little Ice Age* (Taylor & Francis, London/New York, 1988).
27. O. N. Solomina *et al.*, Glacier fluctuations during the past 2000 years. *Quat. Sci. Rev.* **149**, 61–90 (2016).
28. A. N. Grant, S. Brönnimann, T. Ewen, T. Griesser, A. Stickler, The early twentieth century warm period in the European Arctic. *Meteorol. Z. (Berl.)* **18**, 425–432 (2009).
29. G. C. Hegerl, S. Brönnimann, A. Schurer, T. Cowan, The early 20th century warming: Anomalies, causes, and consequences. *Wiley Interdiscip. Rev. Clim. Change* **9**, e522 (2018).
30. N. Eckert, E. Parent, R. Kies, H. Baya, A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change. *Clim. Change* **101**, 515–553 (2010).
31. D. McCarroll, J. A. Matthews, R. A. Shakesby, Late-holocene snow-avalanche activity in southern norway: Interpreting lichen size-frequency distributions using an alternative to simulation modelling. *Earth Surf. Process. Landf.* **20**, 465–471 (1995).
32. V. Jomelli, P. Pech, Effects of the little ice age on avalanche boulder tongues in the French Alps (Massif des Ecrins). *Earth Surf. Process. Landf.* **29**, 553–564 (2004).
33. C. Corona *et al.*, Seven centuries of avalanche activity at Echalp (Queyras massif, southern French Alps) as inferred from tree rings. *Holocene* **23**, 292–304 (2013).
34. IPCC, "Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" T. F. Stocker *et al.*, Eds. (Cambridge University Press, Cambridge, UK, 2013).
35. C. Casty, C. C. Raible, T. F. Stocker, J. Luterbacher, H. Wanner, A European pattern climatology 1766-2000. *Clim. Dyn.* **29**, 791–805 (2007).
36. B. Chimani, R. Böhm, C. Matulla, M. Ganekind, Development of a long term dataset of solid/liquid precipitation. *Adv. Sci. Res.* **6**, 39–43 (2011).
37. J. C. Flageolet, *Ou sont les Neiges d'Antan? Deux Siècles de Neige dans le Massif Vosgien* (Presses Universitaires de Nancy, Nancy, 2005).
38. J. S. Beck, *2000 Ans de Climat en Alsace* (Coprur edition, Strasbourg, 2011)
39. C. Grad, "Observations sur les petits glaciers temporaires des vosges" in *Bulletin de la Société d'Histoire Naturelle de Colmar* (Société d'Histoire Naturelle de Colmar, 1871).
40. C. Pfister, *Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995)* (Haupt Verlag, Bern, 1999).
41. F. Giacona *et al.*, Avalanche activity leave strong footprints in forested landscapes. *Ann. Glaciol.* **59**, 111–133 (2018).
42. G. Casassa, H. Narita, N. Maeno, Measurements of friction coefficients of snow blocks. *Ann. Glaciol.* **13**, 40–44 (1989).
43. M. Naaim, Y. Durand, N. Eckert, G. Chambon, Dense avalanche friction coefficients: Influence of physical properties of snow. *J. Glaciol.* **59**, 771–782 (2013).
44. J. A. Ballesteros-Cánovas, D. Trappmann, J. Madrigal-González, N. Eckert, M. Stoffel, Climate warming enhances snow avalanche risk in the Western Himalayas. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 3410–3415 (2018).
45. A. Gobiet *et al.*, 21st century climate change in the European Alps—A review. *Sci. Total Environ.* **493**, 1138–1151 (2014).
46. E. Parent, J. Bernier, *Le Raisonnement Bayésien: Modélisation et Inférence* (Springer, Paris, 2007).
47. W. R. Gilks, S. Richardson, D. J. Spiegelhalter, *Markov Chain Monte Carlo in Practice* (Chapman & Hall/CRC, Boca Raton/London/New York, 2001).
48. N. Cressie, C. K. Wickle, *Statistics for Spatio-Temporal Data* (John Wiley & Sons, Hoboken, 2011).
49. H. Sangster, C. Jones, N. Macdonald, The co-evolution of historical source materials in the geophysical, hydrological and meteorological sciences: Learning from the past and moving forward. *Progress Phys. Geog. Earth Environ.* **42**, 61–82 (2018).
50. P. J. Diggle, P. J. Ribeiro, *Model-Based Geostatistics* (Springer, New York, 2007).