Recent changes in avalanche activity in the French Alps and their links with climatic drivers: an overview

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ABSTRACT: This paper synthetizes our ongoing work on relations between natural avalanche activity and climate change in the French Alps and subregions. Firm results mainly concern occurrences, runout altitudes and high return period avalanches on long time scales (averages over "full" winters and winter-spring sub-seasons) since ~1950. Work in progress concerns extrapolation under future climate, shorter time scales (avalanche cycles), and more generally risk assessment under unstationarity. The strength and interest of the approach rely on the exceptional quality/quantity of avalanche records and snow and weather covariates available/used and on the development of specific statistical treatment methods.

KEYWORDS: Avalanche activity, Climate Change, Time trends, French Alps.

1 INTRODUCTION

Mountainous areas are very sensitive to climate change. Variations during the 20th century are now fairly well documented, for instance in the European Alps (e.g., Beniston et al., 1997). Natural avalanches are directly controlled by snow and weather parameters. Hence, they are intuitive high altitude proxies whose changes result from a mixed temperature and precipitation signal. Furthermore, studying their past temporal fluctuations is help to understand their physics and anticipate the future evolution of the related risk.

Past work has more tried to correlate avalanche activity to climatic factors, rather than analyse avalanche time series directly (Keylock, 2003), primarily because most available avalanche data series are short and inhomogeneous. In addition, while possible changes in avalanche activity are likely to be related to climate fluctuations, historical records are also affected by countermeasures. This makes standard methodologies for trend detection such as stationarity tests hard to implement, precluding firm conclusions. For example, Laternser and Scheneebeli (2002) found no changes in avalanche activity over the 1950–2000 period in Switzerland, and Schneebeli et al. (1997) no modifications in the number of catastrophic avalanches around Davos during the 20th century.

In the French Alps, Jomelli and Pech (2004) used indirect avalanche data from dendrochronology in the Ecrins massif to show that major avalanches of the type that occurred during the Little Ice Age have not been encountered in recent decades. Martin et al. (2001) used models of weather and snowpack evolution following climate change scenarios to suggest that changes in triggering mechanisms are already in progress (less dry snow but more wet snow releases). Following these precursor approaches and grounding on an exceptional set of avalanche records and snow and weather covariates, we are currently developing specific statistical treatment to infer recent changes in avalanche activity in the French Alps and their links with climatic drivers. This paper aims at summarizing our main findings to date and at listing research axis still under development.

2 DATA

Our analysis is based on the very detailed French avalanche chronicle EPA (Mougin, 1922). Its major advantage for the detection of time trends is to contain long data series from a sample of paths for which all avalanches are theoretically recorded, instead of trying to collect all major events everywhere such as in an atlas. Furthermore, in order to record mainly natural and unperturbed avalanche activity, the proportion of artificial or accidental triggers is very low on EPA paths, and they are little affected by the construction of recent countermeasures.

In this work, we mainly used from EPA occurrences, runout altitudes and flow regime data recorded since ~1950. They were confronted to series of snow and weather measurements and other high altitude proxies (e.g., glacier mass balance). Refined gridded snow and weather

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data (Durand et al., 2009) and instability indexes resulting from the Meteo France SAFRAN-CROCUS-MEPRA (SCM) model chain were also used to represent the mean behaviour at large spatial scales better than point measurements. The SCM chain assimilates all available snow and weather information, simulates meteorological parameters, snow stratigraphy at various altitudes, aspects, and slopes according to physical rules and performs an expert assessment of snow stability.

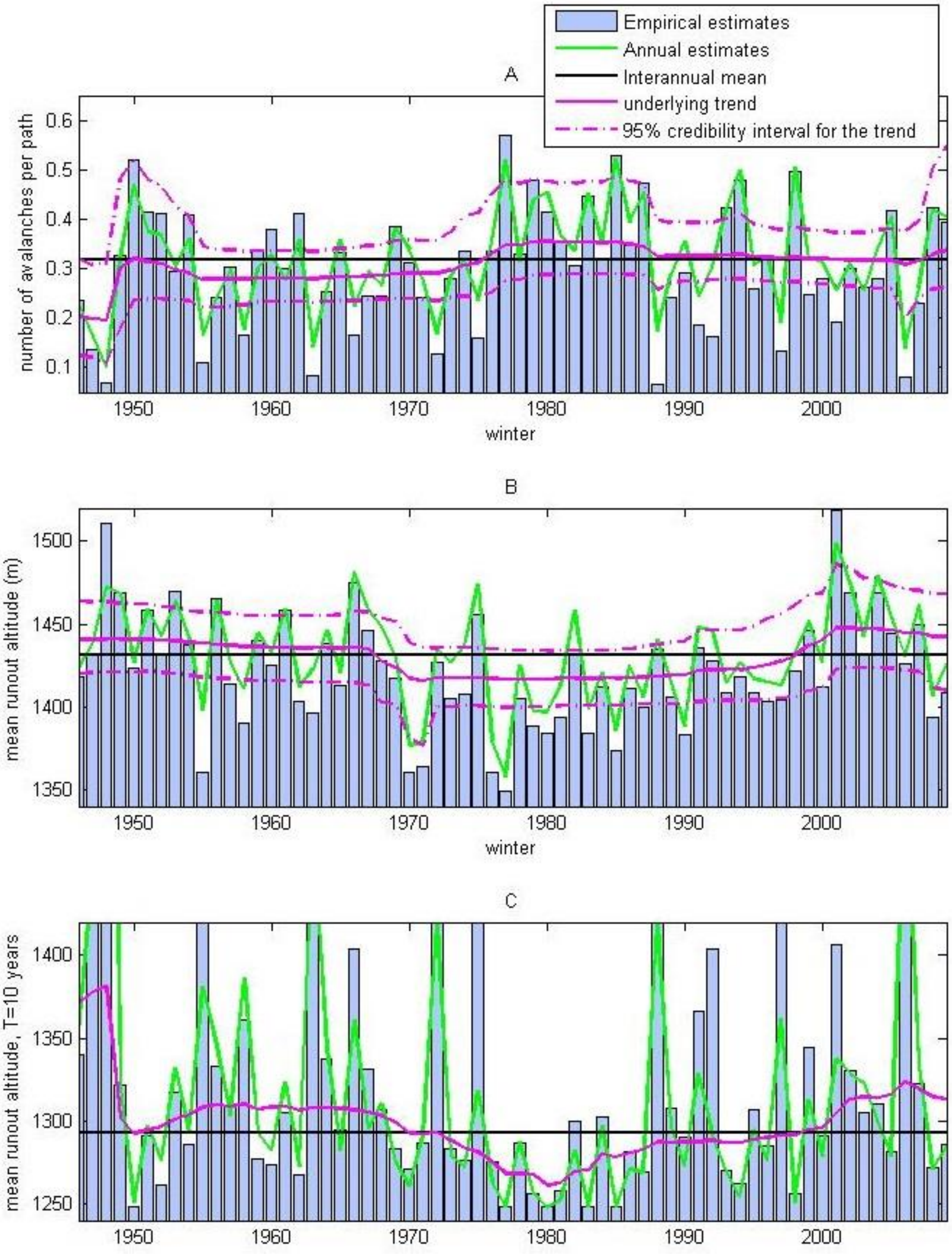

Figure 1, derived from Eckert et al., 2013. A) Mean number of avalanches per winter and path at the entire French Alps scale: annual signal and underlying trend. B) Mean runout altitude. C) Runout altitude corresponding to a return period of 10 years (mean 10 year return level).

3 METHODS

To date, we mostly considered “large” spatio-temporal scales: the entire French Alps and north/south subregions on the one hand, and “full” winters and winter-spring sub-seasons on the other hand. The idea was that averaging the record should discard local artefacts, making it easier to link avalanche activity with regional forcing such as climate change.

To infer the predominant temporal patterns in the analysed avalanche time series at these scales, we used a hierarchical Bayesian model-based framework, which allows easy distinction of the common behavior from site specific effects. In addition, with regards to more empirical approaches, Bayesian hierarchical modelling permits refined underlying trends and significant patterns such as change points to be extracted and studied, with the different sources of uncertainty treated rigorously, *e.g.* taking into account missing values and the uncertainty regarding annual estimates when inferring the structured temporal patterns of interest.

Application to avalanche occurrences in the Northern French Alps with different autoregressive and shifting level models over the 1946-2005 period was conducted in Eckert et al. (2010a). Similarly, in Eckert et al. (2010b), a single change point model was applied to all available runout altitudes. The approach has been generalised and expanded to high return period avalanches in Eckert et al. (2013). Finally, Lavigne et al. (2012, 2013) have studied how, for occurrences, the spatial classification problem and extra data knowledge regarding the north-south climate transition could be included into the modelling, so as to better show distinct temporal patterns in subregions and highlight their altitudinal control. In all these papers, consistency of the highlighted temporal patterns has been searched by performing simple correlation studies with the available climate and climate-related (proxies) covariates.

In parallel, a time-implicit approach has been developed by Castebrunet et al. (2012) to directly model different avalanche activity indexes as combinations of SCM snow and weather covariates, allowing to better characterize their respective weights, discriminating high/low peaks and trends of climatic relevance from observation artifacts, and opening the door to future extrapolation under ongoing climate change.

4 RESULTS

At the entire French Alps scale, the time series for the mean annual avalanche occurrence number on a mean path (Figure 1A) is less structured than for the annual mean runout altitude on a mean path (Figure 1B), making it harder to distinguish structured patterns from the interannual variability. However, for both variables, there is a major change point ~1978, with a difference of ~0.1 avalanches per winter and path in occurrences and ~55 m in runout altitude between this change point and the beginning/end of the 1946-2010 period.

There is a significant correlation between annual occurrences numbers and mean annual runout altitudes which enhances temporal patterns in high return period avalanches. This correlation is also enhanced while looking at trends. Hence, concomitant high avalanche occurrences and low runout altitudes lead to minimum high return period runout altitudes around 1978. Furthermore, a marked upslope retreat of high return period avalanches occurred over the 1980/85-2000/05 period, for instance ~80 m for the 10 year return period runout altitude (annual mean on a mean path), which makes an horizontal runout distance difference as high as ~450 m on a typical 10° runout slope (Figure 1C). However, higher avalanche counts since around 2005, and lower runout altitudes since around 2000, have led to high return period avalanches again slightly lower in the most recent winters.

There has been a general decrease of around 12% in the proportion of powder snow avalanches since 1973, mostly consistent with the evolution of occurrences and mean and high magnitude runouts.

All these patterns are highly correlated with temperature and snow depth covariates and other proxies, especially in terms of change points dates, and of trends. However, the climate control seems stronger in terms of interannual variability for avalanche occurrences, and at longer time scales for runout altitudes and flow regime. This leads to a mixed climatic control on high return period avalanches, but with a clear impact from warming on large avalanche retreat over the 1980/85 to 2000/05 period.

Considering fixed subregions shows that the ~1978 change detected at the entire Alps scale was more a dramatic shift between two distinct levels in 1977 in the northern Alps and a more gradual 1979-84 transition in the southern Alps. Furthermore, while for occurrences a partial coupling exists between the north/south regions (similar high/low values each winter in the two regions), runout altitudes between the north/south regions are nearly decoupled. Finally, there is greater influence of snow depth on avalanche activity variables in the northern Alps, and of temperature in the southern Alps.

The recent results of the spatio-temporal classification approach of Lavigne et al. (2012,

13) suggest that the north/south differences in avalanche occurrence regimes result from complex interactions between predominant atmospheric flows, their regional changes and topography. For instance, the predominant pattern at the entire Alps scale includes a decreasing component at low altitude in agreement with snow cover reduction under climate warming and a higher altitude increase potentially related to more intense heavy snowfall.

Finally, for all avalanche index series considered in Castebrunet et al. (2012), accurate regression models with a small number of physically meaningful SCM covariates could be developed, strengthening our confidence in the climate control of avalanche activity fluctuations in the French Alps. For instance, winter (December to March) activity was logically found to be driven by a smaller number of variables than spring (March to May) activity, so as to represent the greater variety of triggering contexts in late season.

5 WORK IN PROGRESS

On this basis, current work now concerns extrapolation under future climate, shorter time scales (avalanche cycles), and, more generally, risk assessment under unstationarity.

The first axis grounds on the regression approach of Castebrunet et al. (2012) that we are currently coupling with detailed snow and weather simulations for the middle and end of the XXIth century (Rousselot et al., 2012). Hence, despite many uncertainty sources, we may anticipate future changes in avalanche activity in a consistent way, i.e. from the changes in its predominant control variables.

The second axis involves the development of extreme value statistical models able to detect similar patterns at the shorter time scale of the most severe avalanche cycles. To do so, we are currently trying to bridge the spatial analysis of extreme snowfall of Gaume et al. (2013) with the analysis we made of the dramatic 2008 cycle (Eckert et al., 2010), but taking into account temporal changes explicitly such as in Marty and Blanchet (2012).

The third axis is the inclusion of our results in hazard and risk assessment rules. It may be necessary since we show that the assumption of stationarity always made in long term forecasting (risk zoning and the design of defence structures) is presumably not valid under ongoing climate change. To do so, we are working on (i) the evaluation of temporal fluctuations of high return period avalanche at the local scale by expanding the approach of Lavigne et al. (2012, 2013) to runout altitudes, and on (ii) the development of statistical-dynamical simulations for long term forecasting (Eckert et al. 2010d) taking into account a temporal change component.

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