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Climate of the Past Discussions

Snow and weather climatic control on snow avalanche occurrence fluctuations over 50 yr in the French Alps

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Abstract

Snow avalanche activity is controlled to a large extent by snow and weather patterns. However, its response to climate fluctuations remains poorly documented. Previous studies have focused on direct extraction of trends in avalanche and winter climate data, and this study employs a time-implicit method to model annual avalanche activity in the French Alps during the 1958–2009 period from its most representative climatic drivers. Modeled snow and weather data for different elevations and aspects are considered as covariates that explain actual observed avalanche counts, modeled instability indexes, and a combination of both avalanche activity indicators. These three series present relatively similar fluctuations over the period and good consistency with historically harsh winters. A stepwise procedure is used to obtain regression models that accurately represent trends as well as high and low peaks with a small number of physically meaningful covariates, showing their climatic relevance. The activity indicators and their regression models seen as time series show, within a high interannual variability, a predominant bell-shaped pattern presumably related to a short period of colder and snowier winters around 1980, as well as a very slight but continuous increase between 1975 and 2000 concomitant with warming. Furthermore, the regression models quantify the respective weight of the different covariates, mostly temperature anomalies and south-facing snowpack characteristics to explain the trends and most of the exceptional winters. Regional differences are discussed as well as seasonal variations between winter and spring activity and confirm rather different snow and weather regimes influencing avalanche activity over the Northern and Southern Alps, depending on the season.

1 Introduction

Mountainous areas, as high latitudes, are very sensitive to climate change. Variations in mountain climate during the 20th century are now fairly well documented in the

European Alps and in other mountainous regions of the globe (e.g., Beniston et al., 1997). A net warming since the end of the Little Ice Age (∼1850) is now well established. However, this warming has not been constant, with periods of less marked temperature increase or even cooling and accelerated warming over the 1985–2000 period (e.g., Beniston, 2005a). One of the most direct impacts is a snow cover decrease at low and mid elevations, both in terms of local cumulated snow depth and snow cover duration (e.g., Falarz, 2002; Laternser and Schneebeli, 2003). Increased variability has also been observed, especially for winter temperatures, inducing an increasing number of warm winter spells (Beniston, 2005b).

Natural avalanche activity is directly controlled by topography as well as snow and weather parameters, for instance the quantity and quality of available snow (recent snowfalls, cumulated snow depth, snow stratigraphy, moisture, grain size, etc.), and temperature fluctuations. Evaluating avalanche sensibility as a function of the most pertinent covariates at short time steps is therefore a meteorology problem, with a long history of analysis that is important for the safety of mountain communities and ski resorts. Local variables are usually used (e.g., Smith and McClung, 1997), but good correlations between periods of high avalanche activity and synoptic variables have also been identified (e.g., Birkeland et al., 2001). Although still a field of ongoing research, avalanche statistical forecasting models able to work in an operational context have been developed (e.g., McClung and Tweedy, 1994; Gassner and Brabec, 2002; Schirmer et al., 2009). These approaches have also been used to define homogenous zones in terms of avalanche activity (Mock and Birkeland, 2000) and/or snowpack characteristics (Haegeli and McClung, 2007).

Over longer time steps, climatic influence on fluctuations of natural avalanche activity is intuitive, but has been much less investigated and documented. Indirect avalanche data from dendrochronology (Jomelli and Pech, 2004) and lichenometry (McCaroll et al., 1995) indicate that major avalanches such as those that occurred during the Little Ice Age have not been recorded during recent decades. Models of snowpack evolution following climate change scenarios suggest that trigger type changes are already in progress (Martin et al., 2001), with fewer dry snow avalanches compared to wet snow avalanches, and that this trend may persist during the 21st century (Lazar and Williams, 2008), especially at low and mid elevations because of climate warming (López-Moreno et al., 2009). Finally, previous works focusing on the direct extraction of trends in avalanche data suffer from the lack of long and homogenous series. Collecting avalanche data involves field work in mountain terrain during wintertime, often difficult and dangerous. Available series are therefore often imperfect, precluding firm conclusions on possible trends (Laternser and Schneebeli, 2002). Therefore, the consequences of the recent changes in mountain climate on natural avalanche activity and its future evolution in terms of possible modifications of the frequency and intensity of both ordinary and extreme events remain poorly understood, making the current context of climate change hard to take into account for risk management purposes.

A major obstacle to progress is the lack of statistical methodologies adapted to the complex problem of extracting a climate signal from avalanche data. Recently, Eckert et al. (2010a,b) have proposed refined time trend analyses performed in a hierarchical Bayesian context to extract the common predominant temporal patterns from a set of local avalanche series. Application to runout elevations and avalanche counts from the exceptional French avalanche chronicle called the Enquête Permanente sur les Avalanches (EPA, see next section) has given promising preliminary results. However, this purely data-oriented approach is limited in that the climatic relevance of the extracted temporal signals is not guaranteed. This must be proven a posteriori, with, for example, correlation studies with the evolution of known constraining parameters, so as to discard changes in avalanche series that result from changes in data collection protocol, construction of countermeasures, etc.

This article presents an alternative time-implicit approach to infer the temporal signal in avalanche occurrences at the annual/seasonal time scales based on modeling the relation between avalanche activity and snow and weather covariates. The objective is to detect exceptional winters and trends with climatic relevance. This is applied to the whole French Alps over 51 yr, based on avalanche counts from the EPA report and

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refined snow and weather data as well as instability indexes issued by the SAFRAN-CROCUS-MEPRA model chain (see below). Section 2 focuses on data description and explains how statistical models are built to relate different avalanche activity indicators to snow and weather covariates at the annual/seasonal time scale. Section 3 details the results for the French Alps and two subregions, highlighting climatic trends in avalanche activity and the respective contribution of the different covariates to these trends and to exceptional winters. Section 4 discusses the main outcomes of the study and presents the study's conclusions.

2 Data and methods

The primary data set used in this study consists of daily observed avalanche data and modeled snow and weather data. All data are considered at the massif scale, which is used for snow and weather simulations. The 23 massifs of the French Alps used for avalanche forecasting in an operational context are shown in Fig. 1. The surface area of each massif is about 500 km^2, and the key assumption is their spatial homogeneity, especially for precipitation.

2.1 Avalanche data from the EPA database

The "Enquête Permanente sur les Avalanches" (EPA) is a report describing the avalanche events on approximately 3900 designated paths in the French Alps and Pyrenees since the beginning of the 20th century (Mougin, 1922). The most common use for EPA data is hazard (e.g., Ancey et al., 2004; Eckert et al., 2007a) and risk (e.g., Eckert et al., 2009) assessment at the path scale. However, the EPA is also well suited for large-scale studies on relations with snow and weather covariates (Jomelli et al., 2007), major avalanche cycles (Eckert et al., 2010c), and spatial variations in avalanche activity (Eckert et al., 2007b).

For climate studies, the EPA's major advantages are:

- the long time span of the available data series. The data collection protocol and observation network have undergone several changes since the beginning of the report, including a major update in 2002 (Bélanger and Cassayre, 2004). However, its philosophy has remained similar enough to ensure a certain homogeneity and continuity is the data series, at least at scales sufficiently large to smooth local errors and discrepancies (see below).
- a well-structured observation network: the field observations are collected by predominantly motivated forest rangers and centralized and stored by the Cemagref research institute.
- the recording of mainly natural and undisturbed avalanche activity: the proportion of artificial or accidental triggers is very low on EPA paths, and they are relatively unaffected by active and passive countermeasures.
- the focus on a sample of sites for which all avalanches are theoretically recorded instead of trying to collect all major events everywhere such as in an avalanche atlas, giving a relatively accurate view of the spatiotemporal fluctuations of natural avalanche activity in France over the last century.

Different quantitative (runout elevations, deposit volumes, etc.) and qualitative (flow regime, snow quality, etc.) data (Jamard et al., 2002) are recorded. Sources of uncertainties and systematic errors in the estimation of certain variables are numerous. In this study, among all the available information, only avalanche counts, the most natural variable to describe the frequency of the phenomenon, are considered. For this quantity, the predominant source of error to be considered is missing events. Locally, the quality of the records depends to a large extent on rangers' careful data recording, making certain series poor, at least during the years corresponding to a ranger's career. However, once the avalanche counts are aggregated at the massif scale, these local heterogeneities are smoothed, making the automatic detection of abnormally low

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records very difficult, because, of all the local series, no error-free modeled series is available. Homogenization methods (e.g., Caussinus and Mestre, 2004) were therefore not used in this study, which must be kept in mind when interpreting results. The total number of avalanche events over the period of study is 46 610, with 220–1844 avalanches per year throughout the Alps and 369–4554 avalanches per massif during the entire period.

In terms of climatic interpretation, the EPA chronicle underestimates avalanche activity at high elevations, because human observations concern mainly paths selected because they are visible from valley floors, another potential source of bias. To limit this bias, a composite index taking into account high-elevation activity is proposed (see Sect. 2.5).

2.2 Modeled snow and weather data and natural avalanche activity

Since winter 1970–1971, Météo-France has been in charge of avalanche hazard forecasting in France, based on regular monitoring of snowpack conditions. The Météo-France observation network provides snow and weather data. However, its spatial coverage is insufficient to characterize snow and weather conditions at a massif scale. Since the early 1990s, Météo-France has used an automatic system based on three numerical models to assimilate the available information and simulate meteorological parameters, snow cover stratigraphy, and avalanche risk (i.e., susceptibility of release) at various elevations, aspects, and slopes for the 23 French massifs (Durand et al., 1999):

- SAFRAN (Durand et al., 1993) is a meteorological application that performs an objective analysis of weather data available from human and automatic meteorological networks over the elevations and aspects considered for the different massifs. SAFRAN combines the data observed with a preliminary estimation generally provided by large-scale weather forecasting models.

- CROCUS (Brun et al., 1989, 1992) is a numerical snow model used to calculate changes in energy, mass, and stratigraphy of the different layers in the snow cover. It uses only the meteorological data provided by SAFRAN as inputs and simulates temperature, density, liquid water content profiles, and snowpack layering at different elevations, slopes, and aspects, including the internal metamorphism processes.

- MEPRA (Giraud, 1993) is an expert system of mechanical stability analysis of the snowpack that deduces from the CROCUS simulations additional characteristics (shear strength, ram resistance, and grain types) and modeled natural snowpack instability. A modeled daily natural avalanche activity index can be obtained by aggregating the MEPRA analysis by elevation, aspect, and slope on a daily basis. It corresponds to the "daily maximum of the mean by aspect" (Martin et al., 2001). This avalanche activity index, called here MEPRA index, varies between 0 and 8, and is somewhat dependent on massif characteristics. For example, the highest values are obtained in the highest massifs, where snowfalls are the most intense, leading to higher instability.

The SAFRAN-CROCUS-MEPRA (SCM) model chain has been used for retrospective snow and weather climate analyses. Using 44 yr of newly analyzed atmospheric model data from the 40-yr European Centre for Medium-Range Weather Forecast (ECMWF) reanalysis (ERA-40) project (ECMWF, 2004) and completed by datasets extracted from the operational databases of Météo-France, the SCM model chain has been run on an hourly basis for a period starting in winter 1958/59. The simulation setup, validation, and results concerning air temperature and precipitation trends are detailed by Durand et al. (2009a). The results regarding average conditions (spatial variability) and long-term trends (temporal variability) for various snow cover parameters are discussed by Durand et al. (2009b).

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In the present study, various daily outputs of these simulations are used for each of the 23 alpine massifs over the period 1958/59 to 2008/09 for three elevations: 1800, 2400, and 3000 m (57 variables total):

- precipitation (rain and snow), temperature (minimum, maximum, and mean), maximum wind speed, and the associated direction (SAFRAN outputs);
- for the four main aspects (northern, eastern, southern, and western) and a 40° slope, the total snow depth, the thickness of surface wet snow and the thickness of surface recent dry snow. These variables are derived from the standard CROCUS outputs: the total snow depth is the sum of all snow depth layers, the thickness of surface wet snow is taken as the sum of the contiguous wet snow layers characterized by a liquid water content greater than 0.01 %, from the surface, and the thickness of the surface recent dry snow as the depth of the deeper recent snow layer characterized by a dendricity greater than 0.25;
- natural snowpack instability through the MEPRA index (MEPRA output) which gives an information of the avalanche hazard without being certain that a triggering occurred.

2.3 Standardized large-scale data

For this study, annual and seasonal (winter and spring) series of anomalies were built from the daily EPA and SAFRAN-CROCUS-MEPRA model output data at the massif scale. Winter and spring seasons are defined as the 15 December to 14 March and 15 March to 15 June subperiods, respectively. Furthermore, we focus here on spatial scales larger than the massifs: the whole Alps (all 23 French massifs), the Northern Alps, and the Southern Alps (Fig. 1). Among the 46 610 avalanche events over the entire period throughout the Alps, 72 (28 %) occurred in the northern (southern) regions, whereas 66 (34 %) are considered as winter (spring) events.

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Once averaged over these three areas to represent a mean massif of each zone considered, the different variables X_{jt} where j denotes the variable and t the year/season of the year were standardized to produce annual/seasonal anomaly series:

$$X_{jt}^{\text{norm}}(t) = \frac{X_{jt} - \mu_j}{\sigma_j} \quad (1)$$

where μ_j and σ_j are the interannual mean and standard deviation of X_{jt}, respectively. All dimensionless series X_{jt}^{norm} roughly fall in the [−2,2] interval (95 % confidence interval of a Gaussian distribution). The goal is to facilitate intervariable comparison, for instance to interpret the respective contribution of the covariates to the interannual fluctuations of avalanche activity.

The standardized variables were divided into two groups:

- the 57 explanatory SAFRAN-CROCUS snow and weather covariates that are assumed to explain the fluctuations of avalanche activity;
- the two explained response variables: standardized EPA avalanche counts and the MEPRA instability index.

In full rigor, the standardized MEPRA index, taken here as one of the explained variables, is a hybrid. As an instability indicator, it is an indicator of potential avalanche activity, but as a product of the SCM chain it is also an acute physically based synthetic combination of all snow and weather parameters.

2.4 Composite index

A third explained variable was considered: a composite index (CI) based on the two other indices:

$$\text{CI}_t = \frac{1}{3}\left(0.5 \times \text{EPA}_t^{\text{norm}} + 0.5 \times \text{MEPRA}_t^{\text{norm}} + \rho_t\right) \quad (2)$$

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with MEPRA^{norm} and EPA^{norm} the annual anomalies of the instability index and avalanche counts, and ρ_t the correlation coefficient between their daily values during the year/season t. As EPA counts are mainly controlled by observations from valley floors, and the MEPRA index is strongly influenced by avalanche activity at high elevations, this composite index was designed to combine both information to better represent the overall natural activity. It gives similar weight to EPA counts and the MEPRA index, as well as to the advantages and disadvantages, and years or seasons where they are coherent or incoherent through the coefficient correlation ρ_t. Finally, standardization is used to spread the values over a [−2,2] range similar to that corresponding to the other two explained variables.

2.5 Stepwise regression

To choose the best explanatory snow and weather covariates of the three natural avalanche activity indicators considered, a stepwise regression was undertaken (e.g., Saporta, 2006) that is to say a variable selection procedure for linear models in which the set of predictive variables retained is selected by an automatic sequence of Fisher F-tests. Starting from an initial model with no covariates (or a small number of covariates) and then comparing the explanatory power of incrementally larger and smaller models, it combines:

- forward selection, which tests the variables one by one and includes them if they are statistically significant based on the p-value of the F-statistics;
- backward elimination, which starts with all candidate variables and tests them one by one for statistical significance, deleting any that are not significant on the basis of the p-value of the F-statistics.

This systematic method has the advantage of generally leading to a multiple regression model that is a good compromise between a nearly maximal explanatory power and a restricted number of retained covariates, so that the statistical model obtained is interpretable in terms of physics. However, this is not always easy, because correlation between explanatory variables can lead to masked effects. For example, snow depth data necessarily contain information already given by snowfall, etc.

Formally, the regression model obtained relates the series y_t of annual and seasonal anomalies in the avalanche activity indicator to P selected standardized explanatory variables such as:

$$y_t = \sum_{j=1}^{p} X_{jt}^{\text{norm}} \beta_j + \varepsilon_t \tag{3}$$

with β_j the weighting coefficient representing the contribution of each predictive variable retained to the fluctuations of avalanche activity, and ε_t the residual activity not predicted by the model. The values of ε_t are modeled as independent and identically distributed realizations of a centered Gaussian random number. Such regression models have been established for the three response variables (EPA, MEPRA, and CI), for the whole French Alps, the Northern Alps, and the Southern Alps, at the annual scale and for winter and spring periods.

2.6 Stationarity test, climatic trends, and abnormal winter detection

In this study, no direct time series analysis was undertaken. However, a time series of climatic relevance $\sum_{j=1}^{P} X_{jt}^{\text{norm}} \beta_j$, i.e., the retained regression model, was extracted from each avalanche activity series studied. Its explanatory power was quantified by the classical determination coefficient R^2 comparing the respective weight of explained variance and random fluctuations (variance of the residuals).

The stationarity of the avalanche activity time series was roughly evaluated using the nonparametric Spearman rank correlation test (e.g., Dodge, 1993). The test was also applied to regression models to investigate potential non-stationarity in avalanche activity related to non-stationarity in covariates (Table 1).

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Finally, two thresholds were considered to detect the years or the seasons with the highest avalanche activity. They correspond to the 80th and 90th percentiles of the interannual distribution of the avalanche activity indicator and regression model considered, meaning that 20 % and 10 %, respectively of the annual and seasonal values exceed these thresholds. For instance, a CI value higher than the 90 % threshold indicates a year with very high avalanche activity, with excellent agreement between EPA counts and the MEPRA index (Table 2). This was used to validate the composite index CI and more generally check the consistency of the indicator series with historical information by comparing the detected winters with field reports of abnormal activity (Goetz et al., 2008) and annual summaries of EPA counts (e.g., Cemagref ETNA, 2006).

3 Results

3.1 Changes in avalanche activity indicators over the last 51 yr

Figure 2 presents temporal variations of the three explained annual anomaly series: EPA counts, the MEPRA instability index, and the composite index for all of the French Alps, the Northern Alps, and the Southern Alps between 1958/59 and 2008/09. In each region, we observe relatively similar fluctuations for the three indicators in terms of trend and high and low peaks. For example, for the whole French Alps, the correlation coefficients between the three indicator series are 0.71 (MEPRA/EPA), 0.91 (MEPRA/CI), and 0.92 (EPA/CI). This indicates that they capture roughly the same interannual variability even if the intensity of the peaks can be somewhat different from one indicator to another. The interannual variability is very high, with for all indicator series years of high activity directly followed by years of low activity (and vice-versa), with no real clustering of years of high or low activity at any time during the study period.

Moving averages were calculated over 5 and 20 yr (dashed and solid lines, respectively). For the whole French Alps and the Northern French Alps and the three indicators, the 5-yr moving average presents a bell-shaped pattern between roughly 1975

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and 1990, separating two periods of a rather flat trend. For the Southern Alps, the data are less clear, but two less pronounced bulges centered around 1978 and 1986 can be seen, mainly for EPA counts and the composite index.

The 20-yr moving average increases for the three indicator series in the whole Alps and the Northern Alps between roughly 1975 and 2000, whereas no obvious low frequency trend appeared for the Southern Alps. The similarity between the features of the whole Alps and the Northern Alps stems from the greater weight of this subregion in the entire Alps. In addition, the Northern alpine region contains more homogeneous massifs than the Southern Alps region.

Statistically speaking, slight non-stationarity can be detected for the MEPRA index and the composite index in the whole Alps and the Northern Alps, with Spearman p-values approximately 0.04, just below the 0.05 (95 %-significance) limit. On the other hand, no non-stationarity is detected in the other indicators and areas, even though several series show p-values just above the 0.05 significance limit (Table 1). This result, in addition to the high interannual variability of the response variables, which makes the low-frequency structured signal very noisy, shows how difficult it is to analyze potential trends in the avalanche activity indicators studied using simple statistical tests. The study of regression models will make it possible reconsider this point by directly linking avalanche activity with snow and weather parameters, so as to highlight potential non-stationarity due to climate change.

3.2 Regression models

Selected regression models for the different avalanche indicator series are summarized in Tables 3–5. All determination coefficients are very good (higher than 0.8), which illustrates the relevance of explaining avalanche activity with a few (from four to eight) snow and weather covariates. This is especially true at the annual scale for the whole French Alps, with determination coefficients between 0.85 and 0.88, showing excellent agreement between the three indicator series and their regression models (Fig. 3).

For the MEPRA index (Table 3), only four variables are necessary to obtain a determination coefficient of 0.88. This is presumably related to the fact that the MEPRA index is evaluated from the SAFRAN-CROCUS daily outputs, so that few of them can provide a reasonable approximation for annually averaged instability indexes. The regression model mainly consists in snowpack variables at high elevations (three out of four) and for northern slopes (all four). The possible reason is that the MEPRA index was built for operational avalanche forecasting, making it highly sensitive to full winter conditions around ski resorts.

Among the four selected variables, three have a rather intuitive positive contribution ($\beta_j > 0$), indicating that positive anomalies at the annual scale increase instability. Positive marginal correlations between the MEPRA index and the selected weighted covariates are particularly strong for the thickness of surface recent dry snow at 3000 m and the thickness of wet snow at 1800 m ($\rho = 0.86$ and 0.75, respectively), presumably roughly representing dry and wet snow triggers. The positive correlation is lower for the thickness of wet snow at 3000 m, indicating that the variable contributes less. This variable possibly represents the destabilizing contribution of high temperature anomalies at high elevations, since there is no other temperature variable in the model.

On the contrary, the total snow depth has a negative contribution ($\beta = -0.30$) to the MEPRA model, indicating that, on average, positive total snow depth anomalies reduce instability. In general, a negative contribution is harder to interpret, since ideally one would prefer only positive contributions, explaining the activity observed each year by a sum of explicative factors whose weights vary from one year to another, depending of the annual values of the different covariates. In this case, the negative contribution may be attributed to the stabilizing effect of large accumulations. Another possible (and presumably combined) explanation is a partial artifact of the stepwise procedure used that searches for the best fit among a large set of correlated variables without considering physical realism as a selection criterion. Note, however, that the correlation coefficient between the weighted snow depth and the model is negative ($\rho = -0.45$). This highlights the fact that, even if the variable has a stabilizing effect in the model,

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years with high instability correspond well to years with an excess in snow depth, which sounds logical.

Contrary to the MEPRA index, the EPA counts, corresponding to actual avalanche observations, are represented by a more complex model, with four CROCUS snowpack variables for southern slopes and four SAFRAN temperature variables. This highlights that the EPA records avalanche activity throughout the season (e.g., fresh dry snow avalanches in winter and wet snow avalanches in late spring), making more covariates necessary to represent the different trigger contexts, but in all cases mostly at mid and low elevations whose changing conditions (temperature fluctuations around the freezing level, presence or absence of snow, etc.) are presumably better (roughly) represented by a south-facing slope and temperature anomalies.

In detail, among the eight selected covariates, snow depth and the thickness of recent dry snow at 2400 m negatively contribute to the recorded activity ($\beta_j > 0$) but with negative correlation coefficients between the weighted covariates and the model. Hence, they should presumably be interpreted like the thickness of wet snow at 3000 m for the MEPRA index, i.e., as actual stabilizing factors and/or as artifacts due to the stepwise selection procedure, but whose excesses are concomitant with avalanche counts above the average. Similarly, the thickness of surface recent dry snow at 3000 m and of wet snow at 1800 m contributes positively, with relatively high positive marginal correlations, representing dry and wet snow triggers as discussed for the MEPRA index (only the aspects differ).

The temperature variables reflect a more complicated situation, and the two variable pairs at 1800 and 3000 m must be distinguished. At high elevation (3000 m), maximal temperatures higher than the average result in more avalanches ($\beta > 0$ for T_{max}), whereas minimal temperatures lower than the average favor high avalanche numbers ($\beta < 0$ for T_{min}). These results are understandable: warm winter spells destabilize the snowpack, leading to the positive contribution of T_{max} excesses. However, the majority of winters with high avalanche activity are cold winters (T_{min} and T_{max} below the average), which is consistent with the marginal negative correlation of modeled avalanche counts with maximal temperature anomalies ($\rho = -0.15$) and the positive correlation ($\rho = 0.64$) with weighted minimal temperature anomalies. At the lower elevation (1800 m), the variables' effect is the opposite: $\beta > 0$ for T_{min} and $\beta < 0$ for T_{max}. Hence, high-temperature excesses reduce avalanche activity, probably because they reduce the snowpack, whereas minimal temperatures above the average increase avalanche activity, possibly by favoring wet snow triggers (less severe freezing during the night). The correlation coefficients remain consistent with the fact that high-activity winters are predominantly winters colder than average ($\rho = -0.34$ and 0.09 with weighted minimal and maximal temperatures, respectively).

Finally, the CI model is a hybrid. Its complexity is similar to the MEPRA index's complexity (five variables), but it mainly consists in the same covariates as the EPA model, with similar contributions in terms of signs and correlations. With regards to the EPA model, the two temperature variables at 1800 m and the thickness of recent dry snow at 2400 m are no longer necessary to obtain the best fit, because the MEPRA information were incorporated into the analysis. The CI model retained is analyzed in greater detail in Sects. 3.4 and 3.5.

Figure 4 presents temporal variations of the CI (colored solid line) and its associated regression model (colored dashed lines) for the whole Alps, the two subregions considered, and for the winter and spring subperiods. For all series, the CI and its associated model display very good agreement, showing that the model reproduces the ordinary interannual variability fairly well. In particular, residuals are zero on average, with no apparent temporal structure and a quasi-Gaussian interannual distribution (not shown) compatible with the underlying statistical modeling assumptions. Furthermore, the composite index model also detects the major years when high avalanche activity was observed on the field. For example, both the CI and its model detect 5 yr of high avalanche activity with the 90th percentile threshold at the entire Alps scale (1977/1978, 1985/1986, 1994/1995, 1998/1999, and 2005/1906, Table 2), also detected by the MEPRA index, EPA counts and their associated models.

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All in all, the CI can be considered a good compromise between the MEPRA index and the EPA, and its regression model seems efficient in terms of trend and high peak reproduction. Since in addition the three different avalanche activity indicators capture relatively similar fluctuations, the results will be discussed hereafter mainly for the CI, first throughout the Alps at the annual temporal scale, then for smaller spatiotemporal scales separately in Sects. 3.6 and 3.7.

3.3 Years of high avalanche activity

In detail, Table 2 presents the years for which the three different indicators exceed the 80th and 90th percentile thresholds. At the whole Alps and Northern Alps scales, the composite index exceeds the 90th percentile threshold for 1977/1978, 1985/1986, 1994/1995, 1998/1999, and 2005/2006, as stated above. At the Southern Alps scale, the CI exceeds the same threshold for 1970/1971, 1977/1978, 1985/1986, 2000/2001, and 2008/2009. Major avalanche cycles possibly including high-magnitude events were recorded during most of these years over part or all of Alpine massifs. For instance, the famous avalanche cycle of February 1999 was due to heavy snowfalls and cold temperatures over the northern massifs. It included a major avalanche that killed 12 persons in Montroc, Chamonix valley (Ancey et al., 2000; Rousselot et al., 2010) and also caused widespread damage in Europe, including the Austrian and Swiss Alps (SLF Davos, 2000). Similarly, the December 2008 avalanche cycle in the eastern part of the Southern French Alps, generated by easterly fluxes early in the season, caused considerable traffic disturbances and damaged or destroyed equipment and buildings (Eckert et al., 2010c). It also affected the Western Piedmont Alps (Maggioni et al., 2009).

However, several important avalanche cycles observed in the field (Goetz et al., 2008) were not detected by the CI (neither were they detected by the MEPRA index nor the EPA counts) considering this 90th percentile threshold. Using an 80th percentile threshold (Table 2) allows one to detect additional years: 1962/1963, 1983/1984, and 2008/2009. Among them, 2008/2009 affected the Southeastern French Alps only, as

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mentioned above. Furthermore, an avalanche cycle was recorded in the Grandes-Rousses, Oisans, Thabor, and Dévoluy massifs between 6 and 9 February 1984. This illustrates the bias stemming from annual averages when thinking in terms of avalanche cycles instead of abnormally high years. Our approach provides a smooth signal that can make a locally spatially and/or temporally strong signal look rather ordinary at a larger spatiotemporal scale or, on the contrary, mark as abnormal a year with an accumulation of several ordinary cycles.

Among the 8 yr for which both the CI and its associated regression model exceed the 80th percentile threshold at the whole Alps scale, 1962/1963 is the only winter for which the threshold is exceeded by the CI, the MEPRA index, and their regression models, but not by the EPA avalanche counts, indicating that this year was characterized by unstable snow and weather parameters rather than by actual intense activity, or possibly by only high-altitude activity missed by the EPA report.

Contrary to the rough CI, the CI regression model detects 1965/1966 and 1969/1970, which is consistent with observations. Two avalanche cycles occurred in 1965/1966, one in mid-December and another at the end of February, in the Haute-Tarentaise and Haut-Var-Haut-Verdon massifs, respectively. Intense activity was recorded in 1969/1970 during February–March in the northern massifs including the avalanche occurring on 10 February 1970, which struck a cottage in Val d'Isère (Haute-Tarentaise massif, in the Northern Alps) and killed nine persons (Villecrose et al., 1999). Winter 1965/1966 is also detected by the MEPRA index and its associated model, whereas 1969/1970 is only detected by the regression models of the three indicators. These two years suggest that the present approach can detect high-avalanche winters even if a few observations are missing, by providing, through the regression models, combinations of covariates that should led to high avalanche activity.

On the other hand, 1987/1988 and 1993/1994 are detected by the CI, but not by its regression model, whereas for both years intense avalanche records were reported in the field. Two intense cycles occurred at the end of January and beginning of February 1988 in the Northern Alps and a third lower one at the end of February and beginning

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of March 1988. A high-avalanche activity period occurred at the beginning of January 1994 in the Pelvoux, Champsaur, and Haut-Var-Haut-Verdon massifs. Both years are detected in the EPA counts and their associated regression model, whereas the MEPRA index and its model failed to reproduce them, at least at these time and space scales. The composite index is not perfect and this highlights the relevance of a watchful analysis on the original series (EPA counts and the MEPRA index) to detect years of major activity.

3.4 Climatic trends in avalanche activity

Moving averages were calculated over 5 and 20 yr for the composite index regression model (Fig. 4, black dashed and solid lines, respectively). The same features as in Fig. 2 appear. First, the 5-yr moving average presents a bell-shaped pattern between 1970 and 1990 for the Alps and the Northern Alps, both at the annual scale and for the winter and spring subperiods, and a less marked structured signal for the Southern Alps including two small bulges around the middle of the study period.

Second, as for the CI, an increasing trend is illustrated by the 20-yr moving average for the whole Alps and the Northern Alps. Indeed, using the Spearman test, clear non-stationarity is detected at the annual scale with p-values of 0.014 and 0.021 for the Alps and the Northern Alps, respectively. This test was also applied to model's covariates, and net non-stationarity characterizes the maximal temperatures at 3000 m (p-value = 4×10^{-6} and 2×10^{-5} in the entire and Northern French Alps, respectively), attributable to a clear increase during the period studied of all mean temperature series in the French Alps (Durand et al., 2009a). Conversely, the assumption of stationarity is not rejected for the CI model in the Southern Alps, although non-stationarity (p-value = 0.0013) is detected for one of its covariates, the thickness of wet snow at 3000 m (north aspect).

Figure 5 presents the temporal evolution of the five selected covariates for the composite index regression model at the Alps scale, and scatter plots between the composite index and each weighted covariate $X_{jt}^{\text{norm}} \cdot \beta_j$. The positive correlation is strong

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with three weighted variables: the thickness of surface recent dry snow at 3000 m ($\rho = 0.75$), the thickness of wet snow at 1800 m ($\rho = 0.65$), and the minimal temperature at 3000 m ($\rho = 0.60$). In the latter case, this comes from the negative value of β, indicating that high-avalanche activity preferentially occurs during years with minimal temperatures below the average at high altitudes. These three weighted variables contribute positively to avalanche activity similarly to their effect on the EPA counts, which is physically logical. Similarly, the snow depth anomaly at 2400 m contributes negatively ($\beta = -0.85$), stabilizing the snowpack (at least statistically), even if the fact that the correlation coefficient is also negative ($\rho = -0.55$) indicates substantial concomitance between years of high activity and snow depths deeper than average. More interestingly, these four weighted variables clearly show a period of 10 years of generally high (for the three positively correlated weighted covariates) and low (for the weighted snow depth at 2400 m) anomalies centered around 1980. Hence, these years correspond to a period of snowy and cold winters that explain the bell-shaped pattern in both the CI and the CI model. This avalanche activity pattern in the French Alps therefore seems driven by temperature and snow cover changes that occurred around 1980, with a time scale of around 10 yr.

Despite a low correlation coefficient ($\rho = -0.01$), the weighted maximal temperature at 3000 m also plays a significant role in explaining the temporal trend in the CI. If this variable is omitted, the determination coefficient of the regression model drops to 0.79. Moreover, according to the Spearman test results, this variable introduces a non-stationary information into the model, which is clearly visible in Fig. 5. Hence, it may be responsible for the slight but continuous increasing low-frequency trend visible in Fig. 4 between 1975 and 2000, leading to slightly higher instability at high elevations with climate warming.

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3.5 Contribution of the regression models' variables to high avalanche activity years

Figure 5 shows that high peaks in the CI model generally correspond well to high peaks in the three selected weighted covariates, which are highly positively correlated with the CI model, and to sharp "anti-peaks" in the negatively correlated weighted snow depth at 2400 m. In detail, the relative contribution of each of the five selected variables to the 5 yr of highest activity (90th percentile threshold) is showed in Fig. 6.

The years 1977/1978, 1985/1986, and 1994/1995 show the contribution of the model's four additional significant covariates, which is compatible in terms of sign with the interannual mean effect captured by the regression model: positive destabilizing contributions of the thicknesses of wet and surface recent dry snow and of the weighted minimal temperature (i.e., a negative contribution of minimal temperature anomalies) and a negative stabilizing contribution of the snow depth at 2400 m. Among these three years, 1985/86 presents the highest annual anomaly of the CI model (black squares) due to substantial positive anomalies in the thickness of wet and recent dry snow at 1800 and 3000 m, respectively, coupled with a negative anomaly in the weighted snow depth at 2400 m lower than in 1977/1978.

The years 1998/1999 and 2005/2006 behave rather differently: they are characterized by more limited snowpack anomalies, the absence of negative contribution, a greater contribution of negative anomalies at minimal temperatures at 3000 m compared to snowpack covariates, and a positive contribution of snow depth at 2400 m. This is, for instance, in agreement with the analysis of the 1998/1999 winter in France. The beginning of the winter was not very snowy. The high snowfalls that occurred in February 1999 therefore fell on a rather thin snowpack. Furthermore, they were accompanied by very cold temperatures, leading to high instability and long runouts of the avalanches released, even if, at the end of the season, the cumulated snow depth was not exceptional. According to the model, winter 2005/2006 can be explained similarly, although there was much less damage, and, again, caution should be exercised

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when thinking in terms of avalanche cycles when analyzing the results at the annual scale. Nevertheless, this analysis highlights an important point: although on the average a variable has a certain effect (positive or negative) on instability in the model, the opposite effect can be obtained for certain years, showing exceptional activity because of an unfavorable combination of factors.

Finally, among the five years detected, 1977/1978 is the only one with a negative and relatively substantial contribution of the maximum temperature anomaly at 3000 m. Later, the contribution becomes positive, in agreement with climatologic trend analyses, indicating that warming may indeed have increased instability at high elevations during exceptional winters, similar to its mean effect in the model. However, its contribution is very modest, again, similar to its mean effect in the model.

3.6 Regional differences

The covariates retained from the regression models at the Northern and Southern Alps scales illustrate a very different influence of the snow and weather parameters on avalanche activity in the two subregions (Table 4). The model at the Northern Alps scale is nearly the same as at the entire Alps scale, which is not surprising with regard to the predominance of the Northern massifs in the French Alps. The CI is positively correlated with snow precipitations at 1800 m, weighted minimal temperatures at 3000 m, and snowpack characteristics for the southern aspect (thickness of wet snow at 1800 m and thickness of surface recent dry snow at 3000 m), whereas it is negatively correlated with the weighted snow depth at 2400 m and the maximal temperature at 3000 m. Nevertheless, avalanche activity is greater during years of high snow depths, and positive maximal temperature anomalies at high altitude contribute positively to instability. All these correlations and contributions have already been discussed for the CI and the EPA models at the entire Alps scale.

At the Southern Alps scale, the model provided rather different results. Whereas the Northern massifs are linked with south-facing snowpack conditions, the Southern massifs are mostly influenced by snowpack characteristics for the northern aspect (Table

4). A possible explanation is the generally higher elevation of southern massifs that make them less sensitive to fluctuations of the freezing level, which are better captured by the southern aspect. The CI is highly positively correlated with the thickness of wet snow at 1800 m (northern aspect) and the thickness of surface recent dry snow at 3000 m and 1800 m (northern and eastern aspect, respectively). To a lesser extent, the thickness of wet snow at 3000 m also contributes positively, whereas snow precipitation at 3000 m and the thickness of wet snow at 1800 m (southern aspect) contribute negatively and are therefore stabilizing factors in the model. For these two weighted variables, the correlation with the model is negative, however, with logically greater avalanche activity when there is more snow.

Considering the temporal evolution of each of the covariates retained (Fig. 7), the bell-shaped pattern discussed at the Northern Alps scale for the CI (Fig. 4) is clearly visible for most of its covariates: the snow precipitation at 1800 m and the three snowpack variables, with an inversed bell-shaped pattern for the weighted snow depth at 2400 m due to a negative weighting coefficient, as for the entire Alps. A clear increasing trend throughout the period is notable for the maximal temperature at 3000 m, inducing statistical non-stationarity in the variable series, also detected for the model (Table 1), as for the entire Alps. Finally, concerning the minimal temperature at 3000 m, no non-stationarity is detected over the full study period because the main temporal pattern is first an increase from the beginning of the period since 1983, then a strong decrease between 1983 and 1990, before a slight but rather continuous increase. The strong decrease between 1983 and 1990 marks the end of the bell-shaped pattern, i.e., of the short period of winters that are snowier and colder than the average.

Except for the thickness of wet snow at 1800 m (northern aspect), the weighted covariates of the Southern Alps scale regression model show a relatively weak interannual variability. No marked trend is clearly visible for the thickness of wet snow at 3000 m despite detection of non-stationarity. On the other hand, the structured signal observed for both the CI and its model, including two small bulges around 1977 and 1985, is clearly identifiable for the thickness of wet snow at 1800 m (northern aspect)

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and to a lesser extent for the thickness of recent dry snow at 3000 m (northern aspect), two variables that very strongly influence the interannual fluctuations of the model.

When the ability of the regression models at the scales of the Northern Alps and Southern Alps to reproduce the CI's behavior at the Southern Alps and Northern Alps scales is tested, weak determination coefficients are found (respectively, 0.17 and 0.16), which confirms the existence of rather different snow and weather regimes influencing avalanche activity over these two regions.

Finally, as stated in Sect. 3.3, some years with abnormally high avalanche activity are detected only for subregions, indicating that they were not sufficiently strong to be detected at the averaged scale of the entire Alps (Table 2). This may be the case for cycles of medium intensity with an intermediate spatial extent or for very strong cycles, but which affected only a few (one to three) massifs. This is what occurred in the years 1959/1960, 1970/1971, and 1976/1977, only detected at the Southern Alps scale, in agreement with historical observations. On the other hand, all the years detected by the CI and its model at the whole Alps scale are also detected at the Northern Alps scale, illustrating once again the heavier weight of the northern massifs at the entire Alps scale, except for 2008/2009, which was indeed a truly exceptional winter in the Southern Alps, but quite ordinary more northward.

3.7 Seasonal differences

Despite good determination coefficients (0.80 and 0.85; Table 5), seasonal averages show slightly less good agreement between the CI and its associated regression model (Fig. 4). Indeed, various years with high avalanche activity are only detected by the model or the variable (numerous yellow and grey bands in Fig. 8). However, interannual fluctuations of both models and variables remain similar enough to consider the models as reasonable approximations, even if the threshold is not exceeded for one year or another.

During winter (15 December to 14 March), the composite index is mainly described by the SAFRAN variables (snow precipitations and temperatures at mid and low

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elevations) and is only slightly influenced by aspects (Table 5). The only CROCUS variable is the thickness of surface recent dry snow at 3000 m (southern aspect), with a high positive correlation coefficient common to all the CI models presented Tables 3–5, except for the Southern Alps at the annual scale where the northern aspect is more frequent.

During spring (15 March to 15 June), the model is only described by the snowpack characteristics (thicknesses of wet and surface recent dry snow) at various aspects and elevations (Table 5). The presence of fresh dry snow and wet snow variables for different aspects and elevations presumably indicates that, in spring, a higher variability of triggering contexts can be encountered than in winter, with, for example, wet snow avalanches at the end of the season after a progressive warming of the snowpack, but still dry snow avalanches after a cold late season storm. Being relatively complex (eight covariates), the model is hard to interpret in greater detail. For instance, the spring model is highly positively correlated with the thickness of surface recent dry snow at 3000 m for northern and eastern aspects, but negatively for the southern aspect. This result could be related to the fact that during spring, the daily snow transformation stabilizes the snowpack for southern aspects due to higher temperatures, but possible compensations between the different correlated covariates retained is another possible explanation.

Slight non-stationarity is detected for the winter CI model (p-value = 0.049) linked with clear non-stationarity of maximal temperatures at low elevation (p-value = 10^{-4}), explained by a visible increase over the study period (Fig. 8, third panel from the left). The bell-shaped pattern is also clearly visible in the temporal evolution of three covariates: snow precipitation and minimal temperature at 1800 m and the thickness of surface recent dry snow at 3000 m (southern aspect). This last covariate is especially well correlated with the model, for instance during the period of harsh winters between 1980 and 1985, with almost the same anomalies.

Even if no trend is detected for the CI spring model, non-stationarity exists in the three thicknesses of wet snow retained in the model, probably due to their high dependence on temperature variations. However, the increasing trend is barely visible in the weighted covariates over the period of study (Fig. 8, right panel), and these weighted covariates are even characterized by a very small interannual variability with regard to the model's interannual variability because of small weighting coefficients. Hence, the model's interannual variability seems to be mainly controlled by the thicknesses of surface recent dry snow, in a positive way for the northern and eastern aspects and in a negative way for the southern aspect depending on the sign of their respective contributions.

These seasonal averages also detect some years with high avalanche activity, not detected for larger temporal scales (Table 2). This is the case of the years 1970/71 and 1982/83, detected with spring averages but not at the annual scale, indicating an abnormally strong activity late in the season.

4 Discussion, outlooks, and conclusion

This paper has proposed a time-implicit approach for the detection of abnormal years and low-frequency trends for various indicators of natural avalanche occurrence. Contrary to a more traditional time series analysis, the temporal patterns were not extracted from the avalanche data only, but also from selected snow and weather covariates. This may detect only temporal fluctuations that are clearly related to the temporal fluctuations of the covariates, thus lowering the intrinsic limit in terms of the quality of the record of all avalanche databases. This study has also provided a better understanding of the response of avalanche occurrences to changes in the most important constraining factors. Furthermore, their respective weight can be easily accessed in the regression model retained when using standardized variables.

Based on the availability of an exceptional record of mostly natural and unperturbed avalanches and refined snow and weather data over 51 yr, this modeling study has been applied to the whole French Alps and for two northern and southern subregions

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as well as two winter and spring subperiods for three avalanche activity indicators including a composite index between real observations and a modeled instability index. For all the indicators, regions, and time periods, simple (i.e., with a small number of covariates) linear regression models able to represent both high and low peaks and trends were obtained, indicating a clear statistical relation between the fluctuations of avalanche activity and those of the selected covariates in each case. The use of these regression models to discuss the contribution of the selected covariates to trends and exceptional winters has been illustrated mostly with the composite index.

A possible explanation of the somewhat surprisingly good results obtained is the relatively large spatiotemporal scales considered. Actually, the avalanche release process is a strongly discontinuous response to weather patterns and changes in snowpack characteristics. Averaging over large areas and relatively long periods smoothes this process, switching from weather and snow control to climatic control, and making it possible to capture the predominant factors for the long-term interannual evolution with simple statistical regression models.

The regression models obtained are, however, only statistical models that highlight a coherent interannual evolution of avalanche activity indicators and selected covariates, but correlation is not causality in general. On the other hand, the selected variables and their modeled effect on avalanche occurrences are generally meaningful from a physical point of view, which gives some confidence that their explanatory power can actually be attributed to the physical processes involved in the climatic control of snow avalanche releases. This has been particularly highlighted by the results obtained for the different indicators, the different spatial and temporal subscales, and the brief analysis of the years of highest avalanche activity. For instance, the contribution of most of the selected predictive variables was found to be relevant in terms of a mean interannual effect and consistent with weather and snow conditions of well-known avalanche storms having occurred during the years of highest activity. Nevertheless, the regression models selected by the automatic stepwise procedure are not always fully interpretable because of the correlations between the large set of

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possible covariates considered, as exemplified with the eight snowpack variables of the CI spring model. Further work could therefore be done, starting from the selected models, to search for combinations of variables with a similar explanatory power but that are easier to interpret.

Another limit of the approach is that modeled snow and weather data were used instead of actual observations. However, these data result from assimilation of all available information and reliable physical rules regarding the rain–snow limit, snow metamorphism, snowmelt, etc. They have been largely validated with comparison to point measurements (Durand et al., 2009a) and have the great advantage of having spatial significance, making a sound comparison with aggregated avalanche counts possible.

Similarly, the MEPRA index is a synthetic combination of SAFRAN/CROCUS snow and weather data relevant to estimating avalanche susceptibility rather than a true measure of avalanche activity. Nevertheless, the annual large-scale MEPRA index used in this study is already far from the direct daily values by massif and aspect used in avalanche forecasting. When used as a single response variable, results have shown its high sensitivity to high-elevation fresh snowfalls. This was found to be useful in introducing the CI, to lower the bias due to the preferred data collection at low elevations in the EPA report. The proposed CI, when compared to historically harsh winters, gave relatively probative results, and has therefore been used for most of the analyses proposed. Alternatively, the study could have been conducted with the EPA counts only, with no major changes in terms of results, since the EPA and the CI were shown to present similar fluctuations over the study period.

Regarding trend analyses and stationarity of avalanche indexes and regression models, it is important to note that no strong generalized change was found in the avalanche occurrence process induced by changes in the climatic control parameters over the whole period of study in the French Alps (and in subregions and subseasons), or only small changes were found with regards to the interannual variability, making it hard to detect. This is especially true for limitations in terms of data quality. Indeed, even if the French case is useful in the general context of avalanche studies, the analyzed signal is certainly not free of errors, possibly precluding firm conclusions. A similar result was obtained for Switzerland over the second half of the 20th century by Laternser and Schneebeli (2002) and by Eckert et al. (2010a) in their time-explicit analysis of avalanche counts over a slightly longer period in a subregion of the French Alps, the Savoie and Haute Savoie departments, i.e., approximately two-thirds of what is called the Northern French Alps is this study.

Nevertheless, the highly refined data available and the time-implicit approach employed highlighted two interesting temporal patterns. First, at very low frequencies, a short increase was found over the main part of the recorded period (i.e., roughly from 1970 up to 2000) for the different indicators, mostly marked in the Northern French Alps, which seems to be related to temperature increases at high elevations (concomitant and strongly correlated). Second, there is a bell-shaped pattern between 1975 and 1990 in most of the series, less marked in the Southern Alps and during spring, however, indicating generally higher avalanche activity around 1980. This bell-shaped pattern was not emphasized in Eckert et al. (2010a). More precisely it was hidden in several other cyclic patterns, presumably because of a different data structure (smaller region, aggregation at much smaller spatial scales) and a different methodology (search for a mean effect using hierarchical Bayesian techniques, rough homogenization method to detect missing values, a specific single change-point model not used).

The present analysis has shown that this bell-shaped pattern in avalanche activity corresponds to colder and snowier winters. This is consistent with the climatic patterns discussed by Durand et al. (2009a,b) that have shown that the sharp decrease in snow depths and number of days with snow on the ground between 1947 and 2005 at low and mid elevations and for the northern massifs of the French Alps should be explained by a breakpoint rather than by a linear decrease over the whole period. This breakpoint was also recorded by Marty (2008) in the Swiss Alps, and is therefore relevant for a rather large spatial scale. This exists in other proxies in the French Alps such as

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glacier mass balances (Vincent et al., 2004; Eckert et al., 2011), and it is also clearly marked in snow avalanche runout elevations in France (Eckert et al., 2010b). It may therefore have a climatic relevance and physical reality for different aspects of snow avalanche activity, even if it is definitely much less pronounced for avalanche counts than for runout elevations. For example, it is not sufficient to cluster the years with high avalanche counts and a CI around 1980 since they are scattered throughout the period of study due to the high interannual variability.

This approach also opens the door to the possible evaluation of the future impact of climate change on avalanche activity in the French Alps by combining the regression models obtained with the results of SCM simulations forced by scenarios of climate warming, as in a study conducted by Jomelli et al. (2009) for debris flows in the Ecrins massif. This may complement the results obtained by Lazar and Williams (2008) regarding the evolution of the type of releases by information regarding their numbers in terms of trend and high and low peaks, potentially very useful information for long-term avalanche hazard assessment in land use planning, which continues to be carried out within the debatable assumption of stationarity of the avalanche process.

Finally, in avalanche forecasting, the first attempts at spatiotemporal downscaling that have been undertaken (from the whole Alps to the Northern Alps and the Southern Alps, and the whole year to winter and spring subscales) must now be actively pursued to reduce the gap between this climatological approach that investigates the main effects at large spatiotemporal scales and forecasting models used in an operational context at much smaller spatiotemporal scales, typically one massif or a small group of massifs over a few days. This may help quantify changes already apparent and/or to be expected in the near future: changes in intensity, frequency, and location of major avalanche cycles limited by more gradual changes in their main climatic drivers.

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Table 1. Spearman rank correlation test (p-values) for the 1958–2009 period. Bold values indicate series for which the stationarity assumption is rejected at the 95 % confidence level.

	Alps	Northern Alps	Southern Alps
MEPRA index	**0.046**	**0.046**	0.14
EPA counts	0.087	0.068	0.73
Composite Index CI	0.052	**0.043**	0.31
MEPRA model	0.051	0.055	**0.042**
EPA model	0.054	**0.028**	0.33
CI model	**0.014**	**0.021**	0.15

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Table 2. Avalanche years for which response variables and associated regression models exceed an 80th or a 90th percentile threshold (marked as 80 and 90, respectively).

	Entire French Alps						Northern Alps		Southern Alps		Alps in winter		Alps in spring	
	MEPRA Index	MEPRA model	EPA counts	EPA model	Composite Index	CI model	Composite Index	CI model	Composite Index	CI model	Composite Index	CI model	Composite Index	CI model
1958–1959														
1959–1960									80	80		80		
1960–1961														
1961–1962														
1962–1963	90	90		80	80	80		80	80	90			80	80
1963–1964														
1964–1965														
1965–1966	80	80				80	80	80						
1966–1967														
1967–1968														
1968–1969														
1969–1970		80		80		80	80	90				80	90	80
1970–1971									90	90			90	90
1971–1972														
1972–1973														
1973–1974														
1974–1975													80	
1975–1976														
1976–1977									80	80				
1977–1978	90	90	90	90	90	90	90	90	90	90	90	90		
1978–1979														
1979–1980			80								80			80
1980–1981											80			
1981–1982												80		
1982–1983													80	90
1983–1984			80	80	80	80	80	80			80	90		
1984–1985								80						80
1985–1986	90	90	90	90	90	90	90	90	90	90	90	90	90	90
1986–1987														
1987–1988			90	90	80		80						90	
1988–1989														
1989–1990														
1990–1991														
1991–1992														
1992–1993														
1993–1994			80	80	80		80				80	80		
1994–1995			90	90	90	90	90	80			90	90		
1995–1996														
1996–1997														
1997–1998														
1998–1999	80	80	90	90	90	90	90	90			90	90	80	
1999–2000														
2000–2001	80	80							90	90				90
2001–2002														
2002–2003														
2003–2004														
2004–2005														
2005–2006	90	90	80	80	90	90	90	80	80	80	90		90	80
2006–2007														
2007–2008	90								80					90
2008–2009	90	90	80		80	80			90	90	80	80	80	

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Table 3. Regression models $y_t = \sum_{j=1}^{p} X_{jt}^{\text{norm}} \cdot \beta_j + \varepsilon_t$ at the French Alps scale for the annual anomalies in the three response variables (MEPRA index, EPA activity, and composite index CI). For each explanatory variable retained, X_j, β_j is the weighting coefficient, ρ_j the correlation coefficient between $X_{jt}^{\text{norm}} \cdot \beta_j$ and the response variable, and R^2 the determination coefficient of the model.

	Explanatory variables j	β_j	ρ_j	R^2
MEPRA index	Thickness of wet snow (1800 m, north)	0.40	0.75	0.88
	Snow depth (3000 m, north)	−0.30	−0.45	
	Thickness of wet snow (3000 m, north)	0.29	0.33	
	Thickness of surface recent dry snow (3000 m, north)	0.72	0.86	
EPA counts	T_{min} 1800 m	0.27	−0.34	0.85
	T_{max} 1800 m	−0.71	0.09	
	T_{min} 3000 m	−0.88	0.64	
	T_{max} 3000 m	0.78	−0.15	
	Thickness of wet snow (1800 m, south)	1.12	0.62	
	Snow depth (2400 m, south)	−0.85	−0.50	
	Thickness of surface recent dry snow (2400 m, south)	−0.90	−0.62	
	Thickness of surface recent dry snow (3000 m, south)	1.14	0.62	
CI	T_{min} 3000 m	−0.44	0.60	0.86
	T_{max} 3000 m	0.29	−0.01	
	Thickness of wet snow (1800 m, south)	0.86	0.65	
	Snow depth (2400 m, south)	−0.85	−0.55	
	Thickness of surface recent dry snow (3000 m, south)	0.72	0.75	

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Table 4. Regression models $y_t = \sum_{j=1}^{p} X_{jt}^{\text{norm}} \cdot \beta_j + \varepsilon_t$ at the Northern and Southern French Alps scale for the annual anomalies of the composite index CI. For each explanatory variable retained, X_j, β_j is the weighting coefficient, ρ_j the correlation coefficient between $X_{jt}^{\text{norm}} \cdot \beta_j$ and the response variable, and R^2 the determination coefficient of the model.

	Explanatory variables j	β_j	ρ_j	R^2
CI Northern Alps	Snow precipitation 1800 m	0.39	0.75	0.82
	T_{min} 3000 m	−0.40	0.57	
	T_{max} 3000 m	0.26	−0.12	
	Thickness of wet snow (1800 m, south)	0.75	0.70	
	Snow depth (2400 m, south)	−1.00	−0.59	
	Thickness of surface recent dry snow (3000 m, south)	0.59	0.79	
CI Southern Alps	Snow precipitation 3000 m	−0.16	−0.52	0.91
	Thickness of wet snow (1800 m, north)	0.76	0.87	
	Thickness of wet snow (3000 m, north)	0.24	0.38	
	Thickness of surface recent dry snow (3000 m, north)	0.36	0.86	
	Thickness of surface recent dry snow (1800 m, east)	0.30	0.83	
	Thickness of wet snow (1800 m, south)	−0.46	−0.64	

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Table 5. Regression models $y_t = \sum_{j=1}^{p} X_{jt}^{\text{norm}} \cdot \beta_j + \varepsilon_t$ at the French Alps scale for the winter and spring anomalies of the composite index CI. For each explanatory variable retained, X_j, β_j is the weighting coefficient, ρ_j the correlation coefficient between $X_{jt}^{\text{norm}} \cdot \beta_j$ and the response variable, and R^2 the determination coefficient of the model.

	Explanatory variables j	β_j	ρ_j	R^2
CI Winter	Snow precipitations 1800 m	0.36	0.78	0.80
	T_{min} 1800 m	−0.12	0.27	
	T_{max} 1800 m	0.19	−0.13	
	Snow precipitations 2400 m	−0.24	−0.72	
	Thickness of surface recent dry snow (3000 m, south)	0.19	0.77	
CI Spring	Thickness of wet snow (2400 m, north)	−0.12	−0.07	0.85
	Thickness of wet snow (3000 m, north)	0.07	0.23	
	Thickness of surface recent dry snow (3000 m, north)	0.33	0.75	
	Thickness of wet snow (1800 m, east)	−0.26	−0.59	
	Thickness of surface recent dry snow (3000 m, east)	0.45	0.72	
	Thickness of wet snow (3000 m, south)	0.10	0.18	
	Thickness of surface recent dry snow (3000 m, south)	−0.64	−0.68	
	Thickness of wet snow (1800 m, west)	0.40	0.64	

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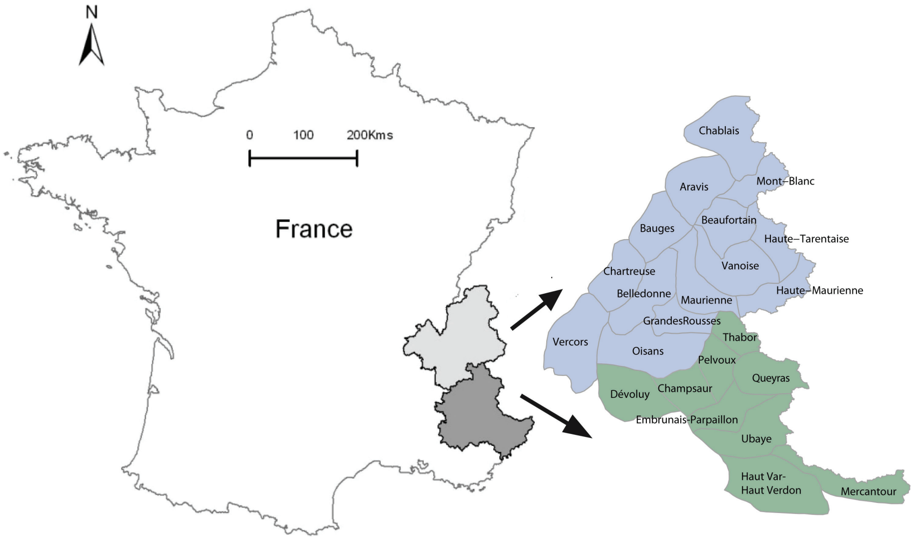

Fig. 1. Area studied. The French Alps are divided into 23 massifs. The Northern French Alps and Southern French Alps are represented in blue and green, respectively.

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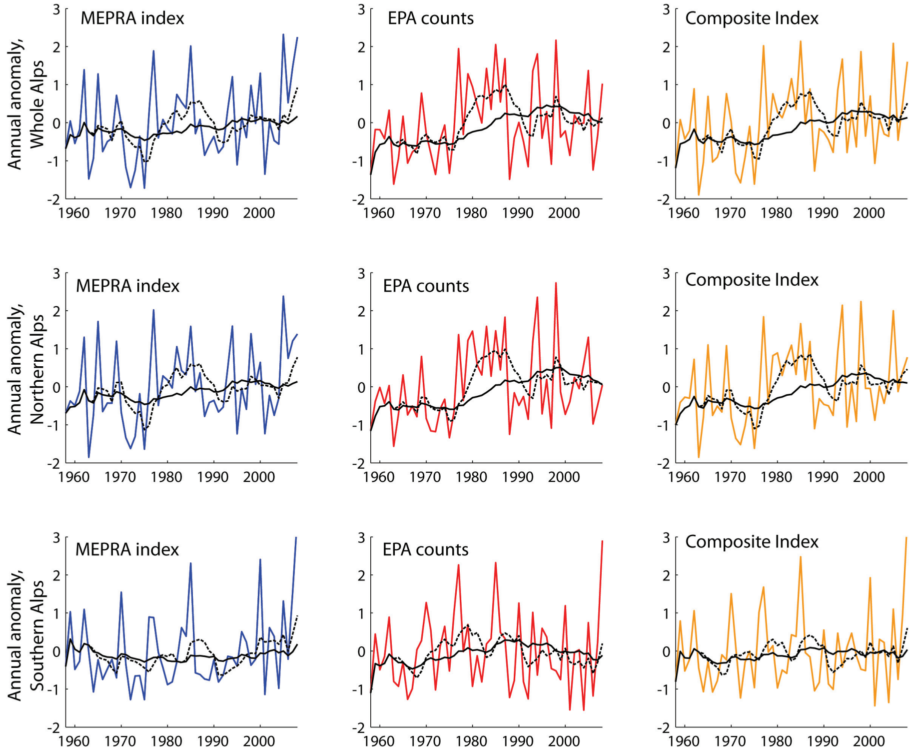

Fig. 2. Variations in annual anomalies of the MEPRA index (in blue), EPA counts (in red) and the composite index (in orange) over the whole French Alps, the Northern French Alps, and Southern French Alps. Moving averages over 20 and 5 yr are represented in black solid and dashed lines, respectively.

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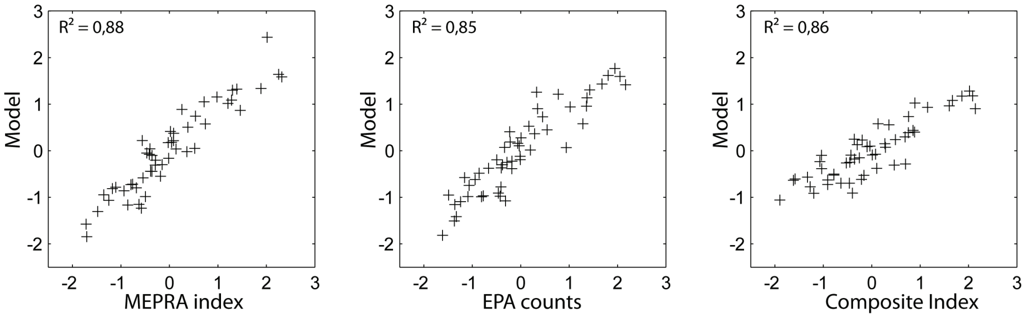

Fig. 3. Scatter plots of regression models versus response variables for the whole French Alps.

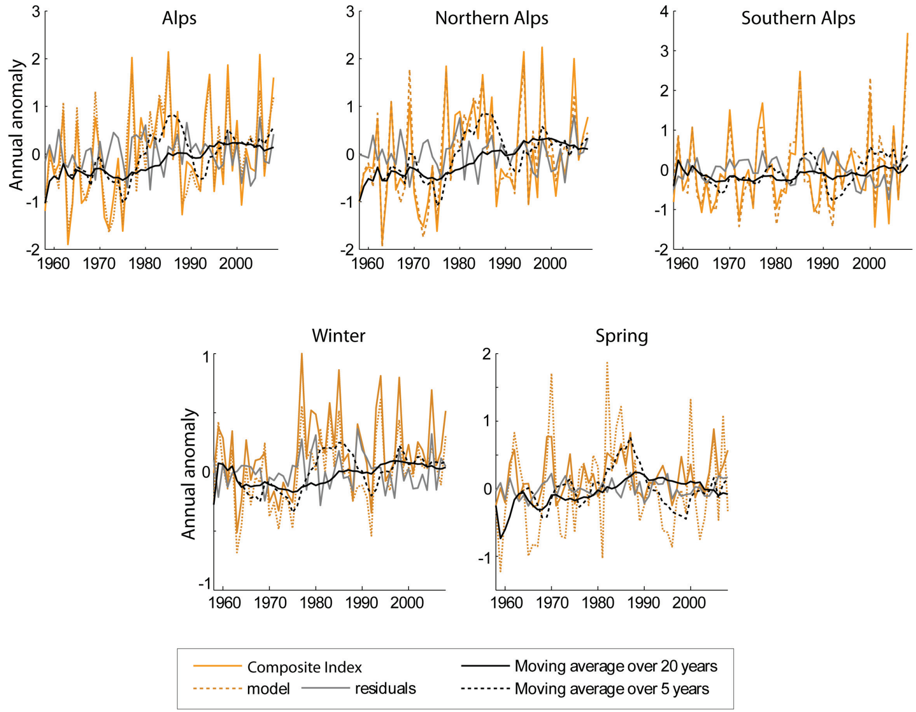

Fig. 4. Composite index (orange solid line) versus regression model (orange dashed line) and model residuals (dashed grey line) for the whole French Alps, the Northern and Southern subregions, and over winter and spring subperiods. Moving averages over 20 and 5 yr for the regression models are represented in black solid and dashed lines, respectively.

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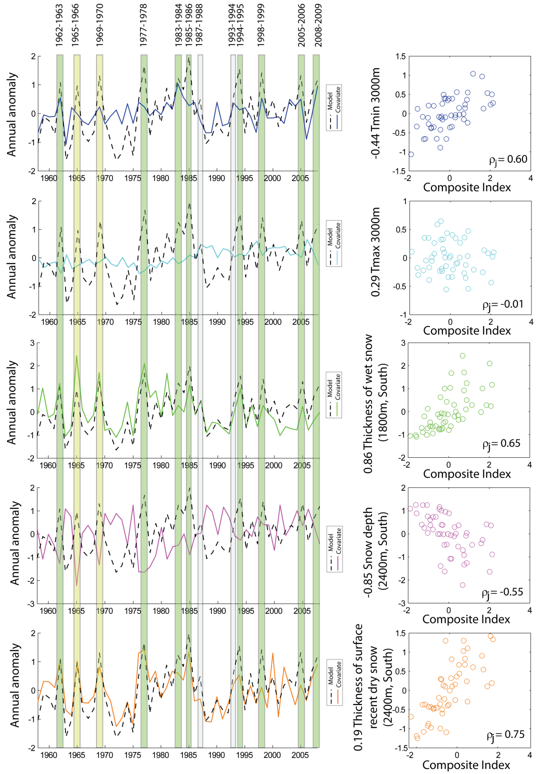

Fig. 5. Temporal evolution of the covariates retained in the regression model of the composite index, for the whole French Alps, and scatter plots between each weighted covariate $X_{jt}^{\text{norm}} \cdot \beta_j$ and the CI. ρ_j is the corresponding correlation coefficient. Green bands correspond to years for which the CI and its regression model exceed the 80th percentile threshold (see Table 2). Yellow and grey bands correspond to years for which only the model or the CI exceeds the threshold, respectively.

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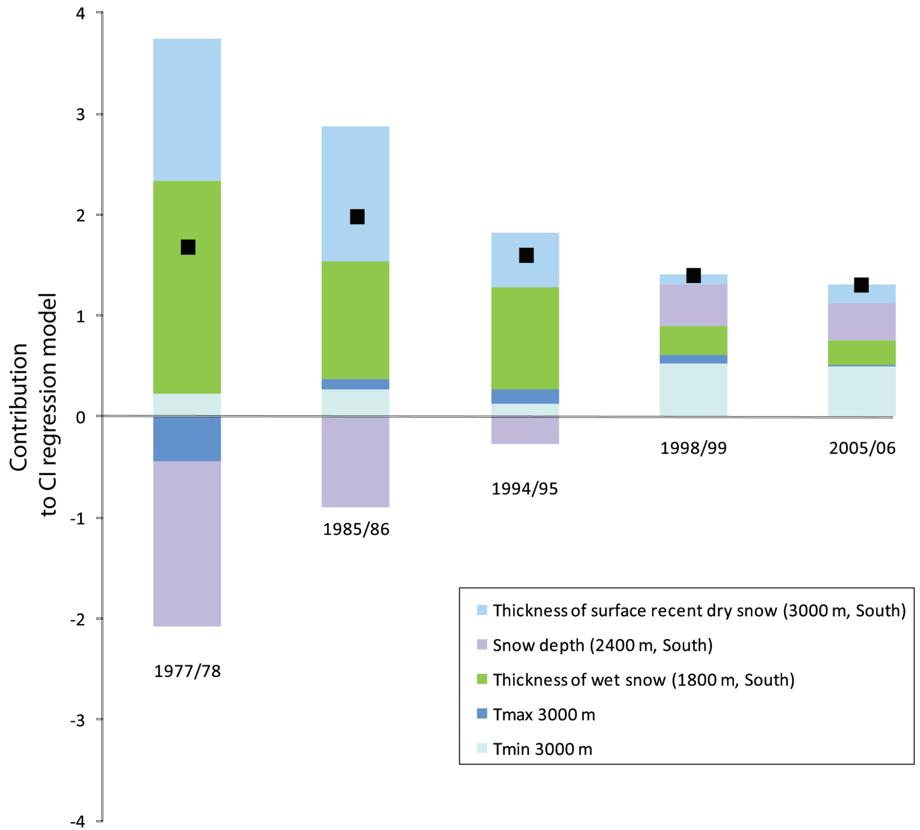

Fig. 6. Contribution $X_{jt} \cdot \beta_j$ of each covariate for years in which both the composite index and its regression model exceed the 90th percentile threshold, for the whole French Alps. Black squares represent the modeled anomalies of CI $\sum X_{jt} \cdot \beta_j$.

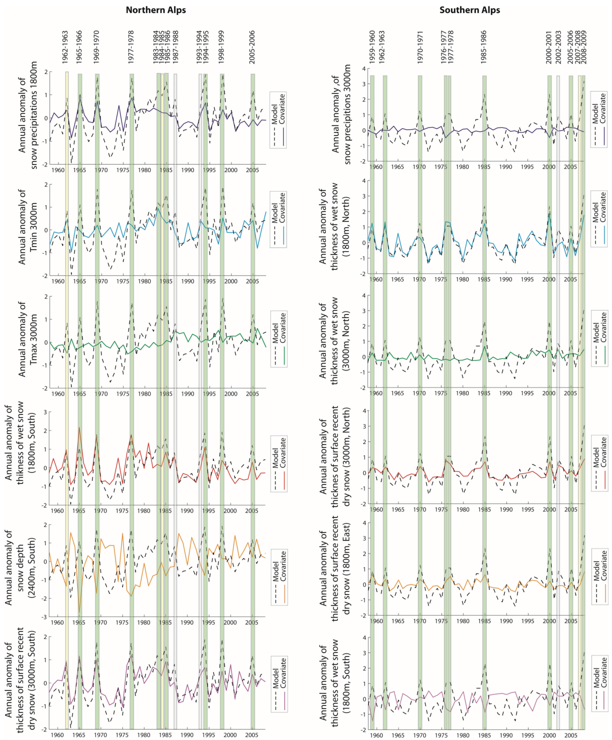

Fig. 7. Temporal evolution of the covariates retained in the regression model of the composite index, for the Northern and Southern French Alps. Green bands correspond to years for which the CI and its regression model exceed the 80th percentile threshold (see Table 2). Yellow and grey bands correspond to years for which only the model or the CI exceeds the threshold, respectively.

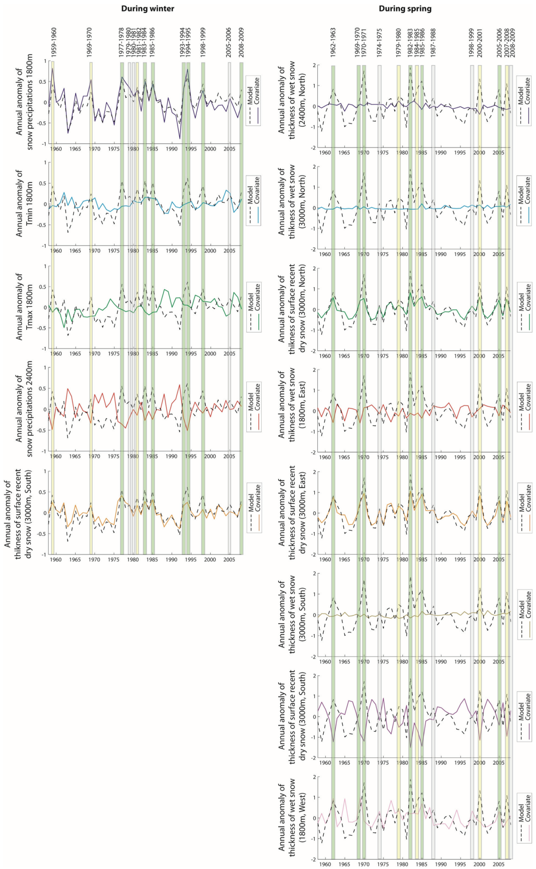

Fig. 8. Temporal evolution of the covariates retained in the regression model of the composite index, during winter (15 December to 14 March) and spring (15 March to 15 June) in the entire French Alps. Green bands correspond to years for which the CI and its regression model exceed the 80th percentile threshold (see Table 2). Yellow and grey bands correspond to years for which only the model or the CI exceeds the threshold, respectively.

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