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RESEARCH ARTICLE

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Influence of snow and meteorological conditions on snow-avalanche deposit volumes and consequences for road-network vulnerability

Hippolyte Kern[1] | Vincent Jomelli[2] | Nicolas Eckert[3] | Delphine Grancher[4] | Michael Deschatres[5] | Gilles Arnaud-Fassetta[6]

[1]Laboratoire de Géographie Physique, Université Paris 1 Panthéon-Sorbonne, Thiais, France
[2]Aix-Marseille University, CNRS, IRD, INRAE, Collège de France, Aix-en-Provence, France
[3]University of Grenoble Alpes, INRAE, CNRS, IRD, Grenoble, France
[4]Laboratoire de Géographie Physique, Thiais, France
[5]University Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE, Grenoble, France
[6]Université Paris Cité, UMR 8586 PRODIG, Paris Cedex 13, France

Correspondence
Hippolyte Kern, Laboratoire de Géographie Physique, Université Paris 1 Panthéon-Sorbonne, CNRS-UMR 8591, 2 rue Henri Dunant, Thiais 94320, France.
Email: hippolyte.kern@lgp.cnrs.fr

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Abstract

Snow avalanches are a major component of the mountain cryosphere that frequently create road obstructions. Deposit characteristics determine the extent of damage to the road infrastructures and the period of disruption of the road network, but the factors controlling snow-deposit volumes remain largely unknown. This study investigates the influence of meteorological and snowpack conditions on snow-avalanche deposits and road-network vulnerability based on 1986 deposit volumes from 182 paths located in two regions of the French Alps between 2003 and 2017: the Guil and Haute-Maurienne valleys. During the period, 195 avalanches impacted the road network in these areas, leading to major disruptions. In the Haute-Maurienne, correlations between deposit volumes and meteorological and snowpack conditions are high in winter. However, the relationships differ with path elevation and orientation. Results do not show any significant relationship between volumes and meteorological or snowpack conditions for the spring season. Focusing on deposits that disturbed the road network in winter and spring reveals a distinct influence of meteorological and snow variables compared to the overall dataset, with snowfall intensity as the predominant control variable of deposit volumes leading to road cuts. When the same analysis is conducted by considering Guil valley separately or by aggregating the Haute-Maurienne with Guil valley area data, results do not show any significant relationship, highlighting the specific local nature of relations between deposit volumes and meteorological and snowpack conditions.

KEYWORDS
avalanches deposit, meteorological control, road network vulnerability, snow avalanches

1 | INTRODUCTION

Avalanches are defined by a rapid movement of snow within a path (Ancey, 2006). Avalanche characteristics are directly related to climatic, meteorological, and geomorphological conditions (Gaume et al., 2012; Mock & Birkeland, 2000; Schweizer et al., 2003). The final avalanche deposit extent and volume are highly variable, driven by several factors, including snow depth, temperature and initial snowpack stratigraphy, modified by the avalanche flow and the path morphology.

Snow avalanches create a menace for people and settlements and create road obstructions (Eckert et al., 2018; Leone et al., 2014; Rheinberger et al., 2009; Sanz-Ramos et al., 2021). Avalanche deposits cause road obstructions, and the volume of snow on the road directly determines the time of disruption and possible associated damages to road infrastructure (Bründl et al., 2004). In order to preserve the accessibility of mountain areas, different protection and warning systems are used (e.g., Stethem et al., 2003; Vera Valero et al., 2016; Zischg et al., 2005).

Knowledge of the factors driving snow deposit volume (SDV) remains limited, despite being an important aspect that helps to define effective protections to avoid reduction of territorial accessibility. Only a few studies have been dedicated to avalanche deposits, and none have examined their relationship with road network vulnerability. Research focused on the sedimentological characteristics of snow avalanche deposits (Bartelt & McArdell, 2009; Jomelli & Bertran, 2001) or differences in the rounded granule structures associated with longitudinal and vertical sorting within the deposit area (Jomelli, 1999; Jomelli & Bertran, 2001). More recently, studies have focused on the relationships between SDV and the geomorphological characteristics of avalanche paths. A weak relationship between path slope, maximum frontal speed and SDV was observed (Kölher et al., 2018; Mc Clung & Gauer, 2018; Sovilla et al., 2015). Additionally, a weak but significant influence of avalanche paths mean elevation and orientation on winter SDV was evidenced (Kern et al., 2020; Kern et al., 2021). However, how meteorological and initial snowpack characteristics, such as snow depth, density, or temperature, drive the volumetric characteristics of avalanche deposits has been rarely explored.

This work aims to examine the influence of meteorological and snow conditions on avalanche SDV. In addition, how this control varies with path orientation, elevation and from one area to another is also investigated using different sub-samples of data. Eventually, specific meteorological and snow conditions favourable to road cuts are analysed. The work grounds on a large record of 1456 natural avalanches and associated SDVs registered in 77 distinct paths in the Haute-Maurienne (Northern French Alps) and 442 SDVs from 86 paths in the Guil valley (Southern French Alps) between 2003 and 2017. Those are related using stepwise linear regressions to their best meteorological and snowpack drivers from SAFRAN and Crocus reanalyses in both winter and spring seasons.

2 | STUDY AREA

The studied paths are primarily located in the upper Maurienne valley (Figure 1). SDVs in the Guil valley were also included (Figures 1, 3). Previous studies have demonstrated that these areas are particularly relevant for studying avalanche activity and risk (e.g., Eckert et al., 2009; Favier et al., 2014; Kern et al., 2021; Viallon-Galinier et al., 2022; Zgheib et al., 2020, 2022).

The upper Maurienne valley is the upper part of the Arc watershed, located in the Savoie department. The Haute-Maurienne valley includes three municipalities: Lanslevillard, Bessans and Bonneval-sur-Arc. These municipalities are sparsely populated, yet tourism is particularly prevalent, notably due to the presence of several ski areas. The valley has a west-southwest orientation and presents a topography typical of glacial valleys: a symmetrical U-shaped valley with slopes that regularly exceed 30°. The valley bottom is located at an elevation between 1500 and 1800 m a.s.l, and the culminating point of the massif reaches 3752 m a.s.l. The vegetation is sparse, and most of the avalanche paths are weakly forested or completely forest-free.

The Queyras massif, located in the Hautes-Alpes department, is mainly part of the Guil watershed. This watershed is divided into several valleys with a dendritic hydrological and topographical structure. The massif surface area is 36,000 hectares and includes 14 communes, including Ceillac and Saint-Véran. Regarding land use, there are several alpine and Nordic ski resorts. The valley bottom is at an elevation ranging from 1500 to 1700 m, a.s.l and the peaks exceed 3000 m a.s.l. The south-facing slopes have been flattened to create relatively moderate slopes, around 30°, whereas the north-facing slopes are much steeper, reaching an average slope of 45° to 50°. The valleys no longer have a U-shaped profile but are rather asymmetrically V-shaped, with more avalanche paths on the steep north-facing slopes. Most of the avalanche paths are largely forested.

3 | DATA AND METHODS

3.1 | Data

3.1.1 | Avalanche-deposit volumes

The analysis is based on SDV estimated from paths monitored by the Enquête Permanente sur les Avalanches (EPA) (Mougin, 1922), a system of descriptive reports on avalanche events. With 0.8 avalanches per path and per year between 1946 and 2005 (Eckert, Parent, et al., 2010), the Haute-Maurienne region exhibits high avalanche activity compared to other regions of the French Alps. The EPA monitors avalanches as exhaustively as possible on more than 3000 avalanche paths in the French Alps since the beginning of the 20th century (Mougin, 1922). For each avalanche, a volume is provided by an estimation of the length, width and mean depth of each deposit. However, to develop a more comprehensive SDV database, further corrections and completions works were completed until 2017 (Kern et al., 2020). Our study only uses data covering the 2003–2018 period (15 full avalanche seasons), for example, since a major update, which considerably increased the reliability of the information (Bourova et al., 2016; Kern et al., 2020). Thus, the study includes 1456 avalanche events and associated SDV registered in 77 paths in the Haute-Maurienne (Figure 3) and 442 SDV from 86 paths located in the Guil valley.

To analyse the possible links between meteorological and snow conditions with SDV, the avalanche year (from 1st November to 31st May) was divided into two seasons. The winter season includes avalanches that occurred between 1st November and 28/29th February,

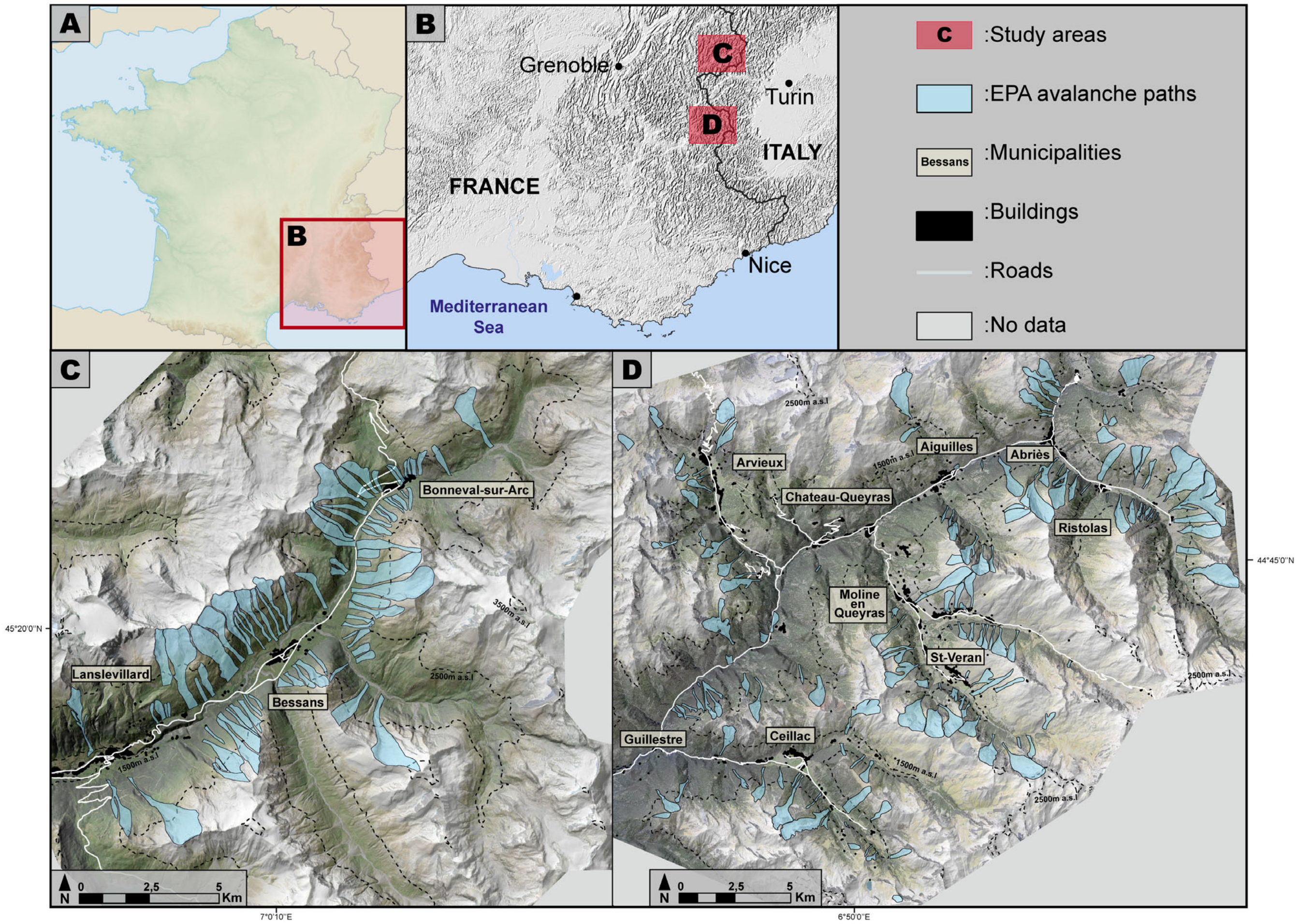

FIGURE 1 Location of the studied EPA avalanche paths located in (a) the Haute-Maurienne Valley and (b) the Guil valley (Queyras massif). [Colour figure can be viewed at wileyonlinelibrary.com]

and spring season includes avalanches that occurred from 1st March to 31st May.

The general path orientations determined via GIS tools from a metric DEM have been used to distinguish different subgroups of homogeneous avalanche paths, considering 8 classes of orientation (Figure 5). Then, the seasonal mean SDV for each subgroup was then evaluated for both winter and spring seasons.

Finally, road disruptions, that is, avalanche deposits obstructing the road network (from 1–10 m^3 to thousands of m^3), frequently occur on the RD902, the only road of the Maurienne valley. It has the particularity to be close to the runout zones of several paths. In winter, the northern part of the road is closed a few kilometres above Bonneval-sur-Arc. Consequently, any road disruption caused by an avalanche leading to a road closure will impact local communities with possible total road isolation. The spatial variability of avalanche-related road disruptions is important (Figure 4). The number of road disruptions per avalanche path over the period 2003–2107 ranged from 1 to 12 with a mean of 2.8. Most of the paths regularly impacting the road are located between Bessans and Bonneval-sur-Arc. This section of the valley is characterised by an important topographic constriction; the valley floor, where the road is located, is only fifty metres wide and is bordered by steep slopes with a strong avalanche activity and important deposit volumes. Between Lanslevillard and Bonneval, there is on average 1 path every 450 linear metres of road that generates deposits affecting the road. Those result from large avalanches (SDV along the road can exceed hundreds of thousands of cubic metres) and are analysed separately. Indeed, the 109 winter deposits and the 61 spring deposits that affected the road network display much larger extreme SDV than the rest of avalanche deposits recorded in the area (Figures 2, 3). Because information related to avalanches impacting the road network in the Guil valley is too limited (Figure 3), only data from the Haute-Maurienne were considered for this specific analysis.

3.1.2 | Meteorological and snow conditions

Meteorological and snow data

The meteorological and snow conditions are from reanalyses produced by the SAFRAN and Crocus modelling chains operated by Metro-France. SAFRAN is an atmospheric analysis system that provides data for atmospheric parameters relevant to snow on the ground over elevations and orientations. SAFRAN has been largely used in French Alpine regions

(Dupire et al., 2017; Durand et al., 1999) and frequently to analyse periglacial processes and their relation to climate (Jomelli et al., 2015; Pavlova et al., 2014). SAFRAN and Crocus reanalyses have also often been used with EPA data (Castebrunet et al., 2012, 2014; Evin et al., 2021; Sielenou et al., 2021), but never to analyse the variability of SDV so far. SAFRAN combines information from numerical weather prediction models and in situ meteorological observations. Crocus is a one-dimensional, multilayer physical snow scheme that simulates the evolution of the snow cover as a function of energy and mass-transfer between the snowpack. Crocus uses SAFRAN outputs to simulate snow variables for each layer (snow mass, density and temperature), and their evolutions (Vernay et al., 2022). Validation of SAFRAN and Crocus reanalyses and some comparisons with other snow models can be found in Etchevers et al. (2004) and Vernay et al. (2022). Used simulations were done for a flat topography and for a 40°, slope considering eight distinct orientations.

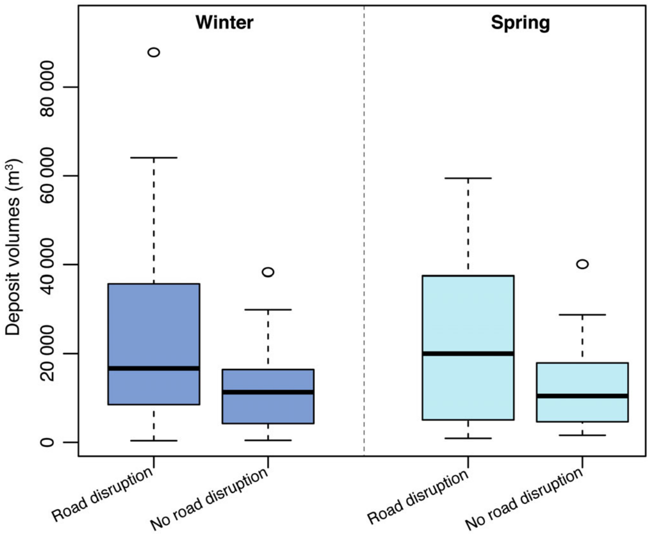

FIGURE 2 Boxplot of mean seasonal SDV per year from avalanches disrupting and not disrupting the road network in the Haute-Maurienne. The median, two quartiles, the 10% and 90% deciles and the extreme values are represented. [Colour figure can be viewed at wileyonlinelibrary.com]

A first expert selection of potential predictors was carried out among the numerous outputs from the reanalyses. We kept 10 daily outputs for the two valleys over the considered period for four elevations: 2100, 2400, 2700 and 3000 m a.s.l. (Table 1), which are listed below: Mean daily air temperature, number of days with an air temperature higher than 0°C, mean daily snowfall (mean snowfall), accumulated snowfall from the start of the avalanche year (accumulated snowfall), number of snowfall days, number of high snowfall days (higher than 75% of the mean intensity), mean snow depth (mean depth), max snow depth (max depth), mean ramsond and max ramsond. As the wind data are not considered, there is no exposure effect on Safran variables. However, an effect of the orientation is reflected through energy balances and consequently different snow metamorphosis effects between each orientation, which leads to different

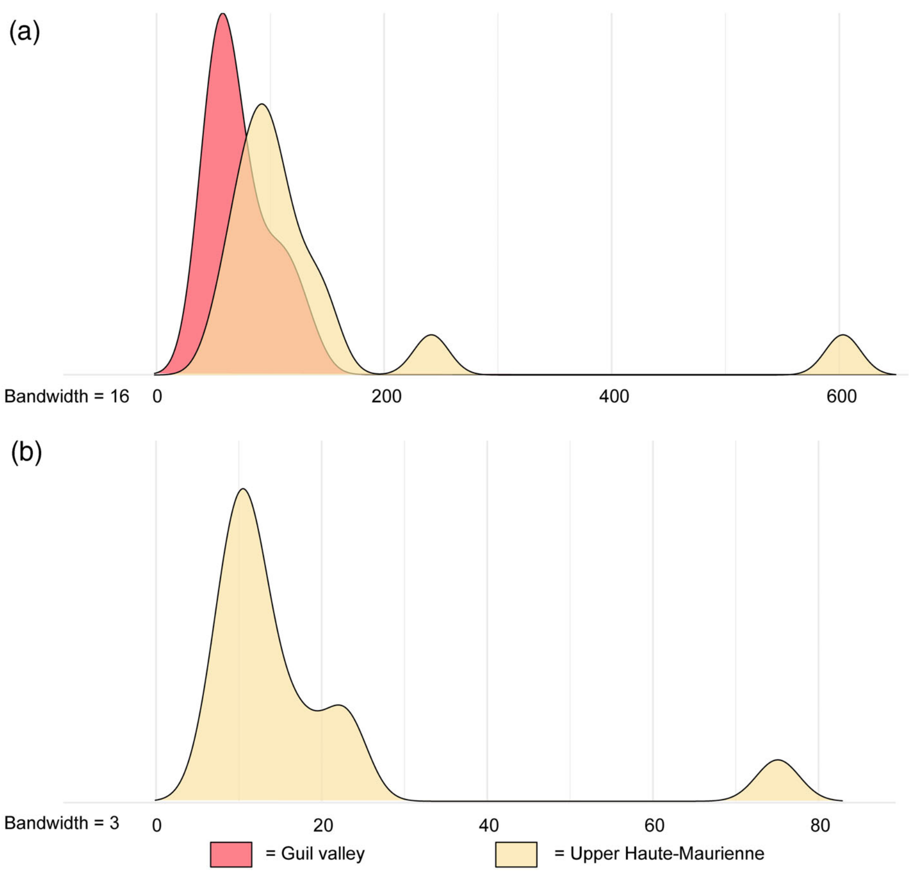

FIGURE 3 Kernel density estimation of (a) annual number of avalanches in the Haute-Maurienne and Guil valleys and (b) annual number of avalanches disrupting roads in the Haute-Maurienne. [Colour figure can be viewed at wileyonlinelibrary.com]

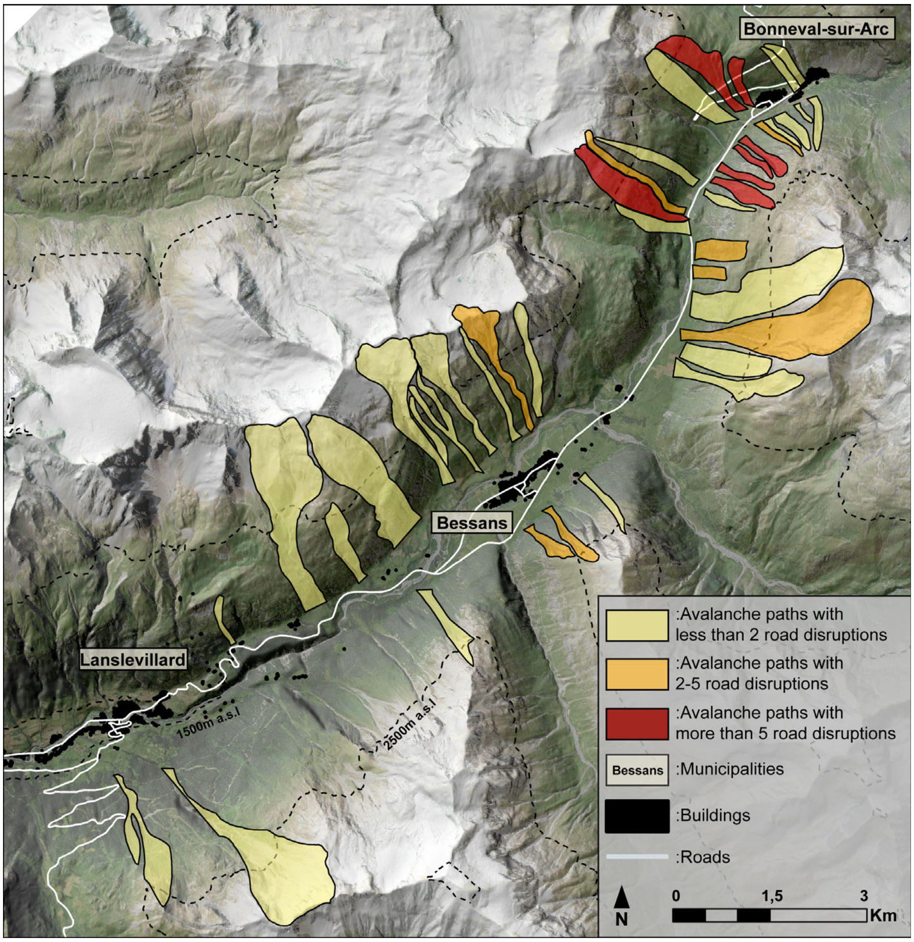

FIGURE 4 Number of road disruptions per avalanche path between 2003 and 2017 in the Haute-Maurienne. [Colour figure can be viewed at wileyonlinelibrary.com]

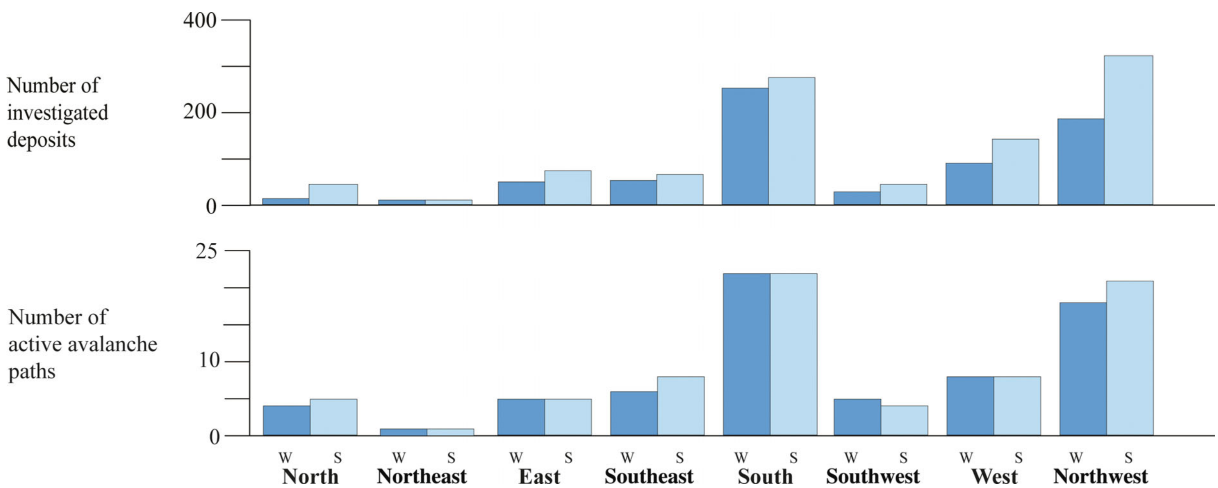

FIGURE 5 Number of investigated deposits and investigated avalanche paths for winter (W) and spring (S) seasons, based on path orientations from the Haute-Maurienne. [Colour figure can be viewed at wileyonlinelibrary.com]

Crocus snowpacks as function of orientation on the 40° slope. Ramsond values from Crocus correspond to a penetration depth of ram resistance sensor measurement and are expressed in metres. Because of a high correlation ($p > 0.98$) with ramsond data, wet snow depth data were not considered in our study.

The full Haute-Maurienne and Guil valleys meteorological and snow data used for this study are detailed in Figures S1–S4.

3.2 | Statistical analyses

First, stepwise linear regressions were undertaken in order to determine the combination of meteorological and snow variables that best explain Haute-Maurienne seasonal mean SDV variability. From the set of potential predictive variables (Table 1), the stepwise procedure selects those that are significant based on the p value of the F tests

TABLE 1 Variables used to infer the influence of meteorological and snowpack conditions on SDV.

Category		Name	Number of variables
Meteo	Air temperature	Mean air temperature (°C)	1
		Number of days with temperature higher than 0°C	1
	Snowfall	Mean snowfall (mm)	1
		Accumulated snowfall (mm)	1
		Number of snowfall days	1
		Number of snowfall days (higher than 75% of the mean intensity)	1
Snowpack		Mean and max snow depth (m)	2
		Mean and max ramsond (m)	2

Note: Mean snowfall is the total seasonal snowfall divided by the number of days during which snowfall occurred.

using forwards and backward selection. Classical 0.05 and 0.01 probability thresholds for forward selection and backward elimination were used, respectively. In order to properly integrate the influence of the same variable at different elevations, we primarily integrated the meteorological and snow mean conditions for the 4 bands of elevations from SAFRAN and Crocus reanalysis altogether. In a second time, each elevation band has been considered separately. This was distinctly done using the 648 winter and the 808 spring SDV. This was primarily done while mixing the data from avalanche paths, whatever their orientation, and relating the corresponding deposits to Crocus snow variables simulated on a flat area (i.e., for which there is no orientation effect, leading to "average" conditions).

We also applied the same methodology on different subgroups relative to path orientation and road network vulnerability. To this aim, we had to define a compromise between the minimal size of each subgroup and the explanatory power of our models. We used the following empirical rationale:

- We only considered producing specific statistical orientation models for SDV from orientations that recorded an adequate number of avalanches from a sufficient number of paths. Therefore, only south, west and northwest orientations with at least 100 deposits from a minimum of 5 paths were considered for both winter and spring seasons (Figure 5). For these regressions, only snow predictors simulated for the same orientation on the 40° slope were considered. For each elevation, there is one value for SAFRAN meteorological variables relative to a flat topography and four values for Crocus snowpack variables, one relative to a flat topography and one for each considered orientation.
- Analyses on the avalanche events that affected the road networks were conducted separately from the rest of the dataset because of their very large volume as mentioned earlier. However, path orientation was not considered at this stage, because of a limited number of events. This causes an overrepresentation of certain orientations affecting the road networks. In detail, 58% of the corridors present a northwest or south orientation.

Finally, in order to test the relevance of the local nature of these results, they are compared and combined with data from the Guil valley that display significant avalanche activity in a different geographical setting. First, the stepwise procedure was applied exclusively to the Guil valley. Second, to combine the volume data with the meteorological and snowpack variables from the two areas, multi-area means, derived from local means, were evaluated for the two seasons. Because differences in avalanche activity between the two areas are important (Figure 3), analyses were conducted using seasonal weighted mean SDV and covariates to address regional disparities for the two seasons as follows:

$$\overline{X}^t_\omega = \omega^t_{HM} X^t_{HM} + \omega_{GV} X^t_{GV}$$
$$\text{with} \begin{cases} \omega^t_{HM} = \frac{N^t_{HM}}{N^t_{HM}+N^t_{GV}} \\ \omega^t_{GV} = \frac{N^t_{GV}}{N^t_{HM}+N^t_{GV}} = 1-\omega^t_{HM} \end{cases} \tag{1}$$

where $X^t{}_{HM}$ and $X^t{}_{GV}$ are the mean seasonal SDV or the seasonal mean of any of the considered covariates for the year *t* in the Haute-Maurienne and Guil valleys, respectively. $N^t{}_{HM}$ and $N^t{}_{GV}$ are the number of SDV for the considered season of the year in the Haute-Maurienne and Guil valleys, respectively.

The path orientations differ widely between the two areas, preventing the consideration of orientation effects in the multi-area analysis. Hence, only the whole set of data, independent of their orientation, is considered. Moreover, some seasons include only data for one of the two areas and are consequently not considered.

4 | RESULTS AND INTERPRETATIONS

4.1 | SDV variability

4.1.1 | Changes in seasonal SDV over the 2003–2017 period in the Haute-Maurienne

Local SDV and avalanche activity show high variability on an inter-annual and inter-seasonal scale. Several years recorded particularly low SDV for both seasons (e.g., 2004 and 2009, mean SDV <5000 m^3 for both seasons). In contrast, 2008 and 2010 recorded large mean SDV for both seasons and up to 31,000 m^3 during the 2010 winter (Figure 6). The avalanche activity is particularly high for 2016 and 2017.

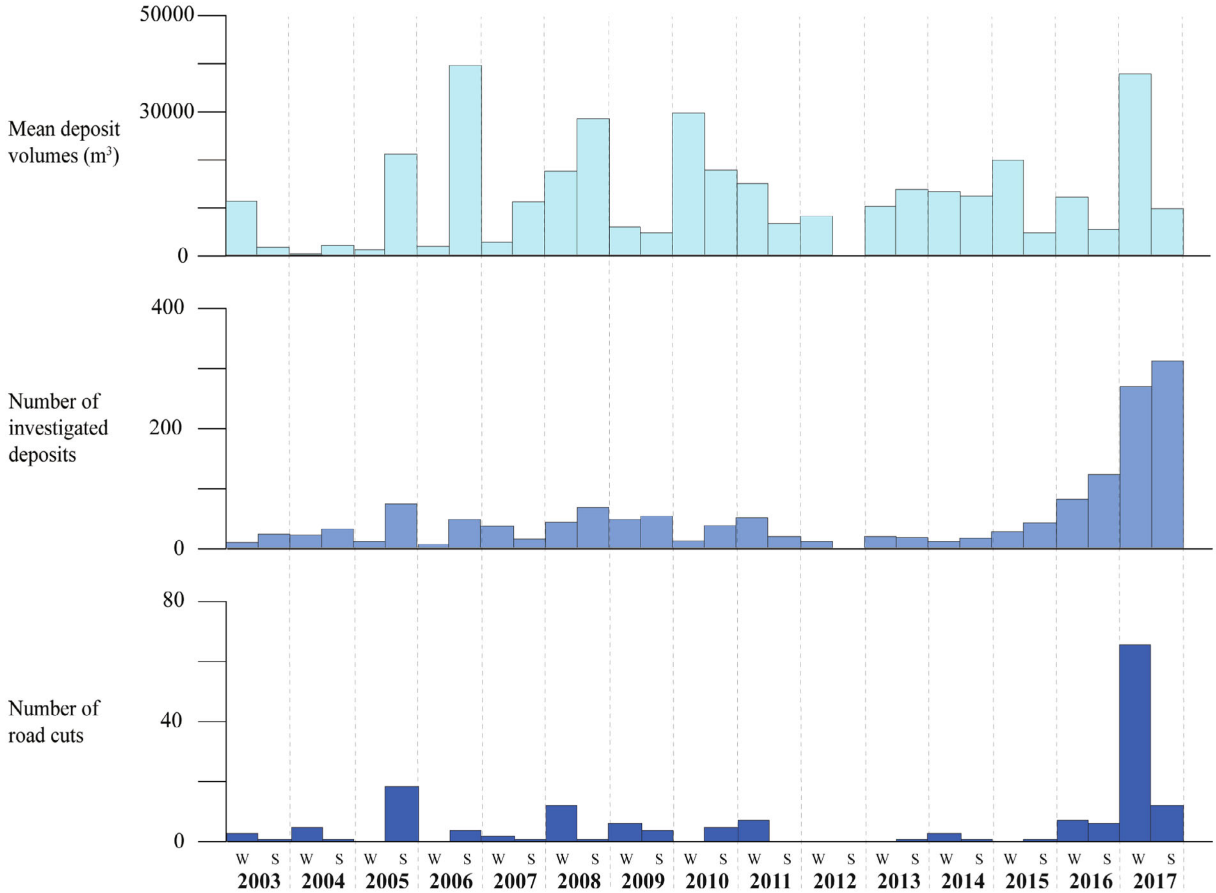

FIGURE 6 Mean inter-annual winter (W) and spring (S) SDV, number of investigated deposits and number of road cuts in the Haute-Maurienne area for the period 2003–2017. [Colour figure can be viewed at wileyonlinelibrary.com]

We also note a significant variability between the seasons. The sample mean is higher for winter SDV (22681m^3) than for spring (12,556 m^3). By contrast, the mean frequency is higher for the spring season (58 avalanches and 0.79 avalanches per spring and per path) than for the winter season (43 avalanches and 0.63 avalanches per winter and per year). Only three winters recorded higher avalanche counts than the associated spring (2007, 2011 and 2013). The high spring avalanche activity may partly explain the differences between winter and spring mean SDV.

Our data reveal that 2017 was an exceptional year for both SDV and avalanche activity with 579 avalanches recorded and a mean winter SDV of 38,300 m^3, respectively. This resulted in significant disruptions to the road network. In 2017 (Figure 7), almost half of the avalanches cutting roads were recorded. Most of the paths located downstream of Bessans were impacted in 2017 only.

SDV data relative to the Guil valley are presented in Figure S5.

4.1.2 | Changes in seasonal SDV with path orientation

We note a significant impact of orientation on mean SDV and avalanche activity. South orientation paths recorded particularly large mean SDV for both winter (22,000 m^3) and spring seasons (18,500 m^3). West-facing paths recorded high mean SDV during winter (21,500 m^3) but low mean SDV during spring (7500 m^3). Northwest-facing paths recorded low mean SDV for both winter and spring (<15,000 m^3) (Figure 8).

In the Haute-Maurienne, the south- and northwest-oriented paths are particularly prevalent and thus have recorded a high number of avalanches between 2003 and 2017. By contrast, the western-oriented paths are less frequent, leading to a lower number of avalanche records. However, despite this variability, the three studied orientations present a strong annual mean activity per path (1.7 avalanches per year and path for south paths, 2.1 for west paths and 1.6 for northwest paths) along with only a few seasons that do not record any activity at all.

4.2 | Relationships between SDV, meteorological and snow conditions

4.2.1 | General influence of meteorological and snow conditions on SDV

We conducted two distinct analyses using the whole set of SDV from Haute Maurienne from both seasons. First, we explored relationships

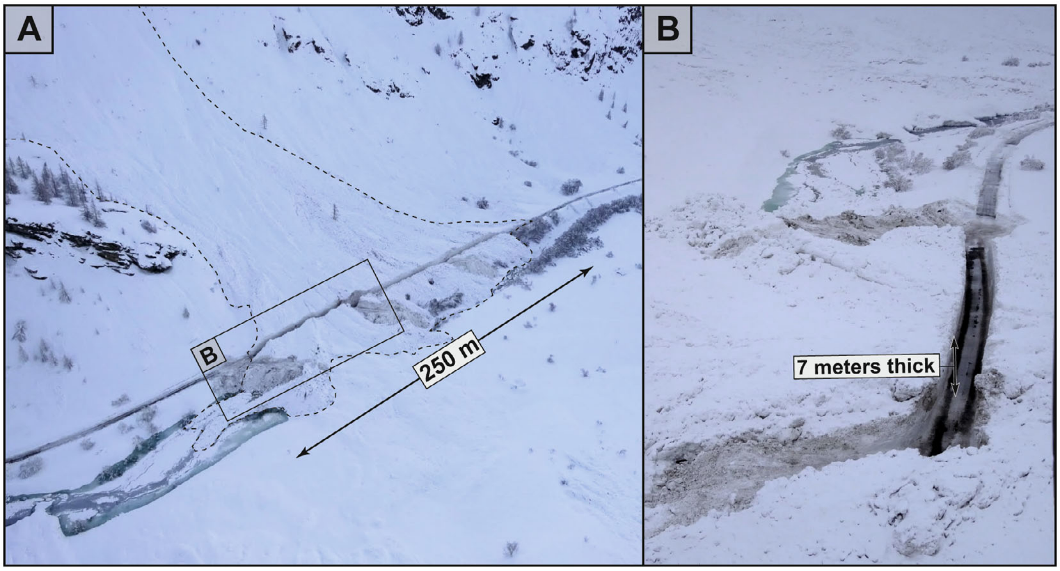

FIGURE 7 Aerial (a) and lateral views (b) of an avalanche deposit that resulted in a major road cut in Bonneval-sur-Arc in January 2018 (RTM 73). The thin black line is RD 902 after partial snow removal. Within the SDV, snow walls on both sides of the road are ~7 m high. [Colour figure can be viewed at wileyonlinelibrary.com]

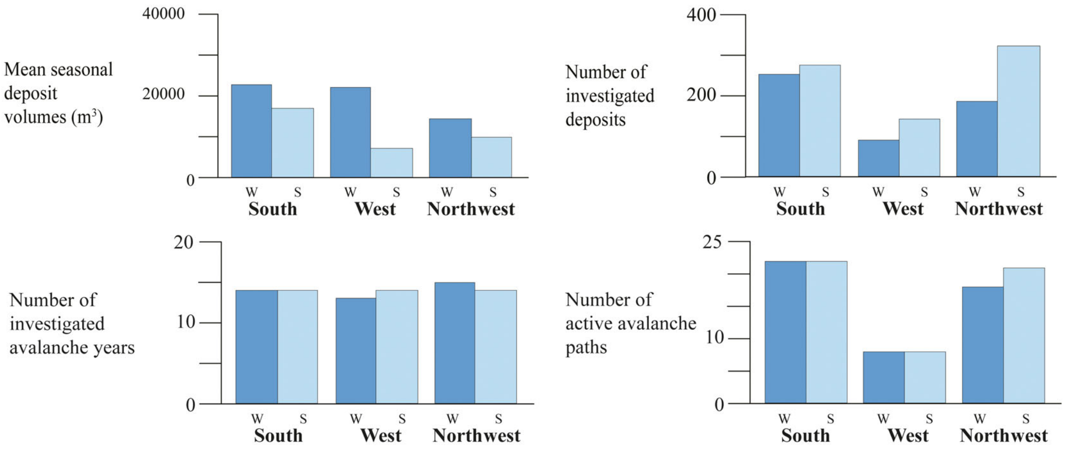

FIGURE 8 Mean SDV for winter (W) and spring (S) seasons, number of investigated deposits, investigated avalanche years and investigated avalanche paths for south, west and northwest facing paths from the Haute-Maurienne. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Statistical summary of stepwise linear regressions performed between mean SDV for an undefined path exposition and meteorological and snow conditions for a flat topography in the Haute-Maurienne considering all elevations and the two seasons.

Orientation	Season	Regression R^2	Retained variables	Number of investigated years	Number of investigated deposit
Undefined	Winter	0.54	Ramsond max 2400 m a.s.l. (+) Depth max 2700 m a.s.l. (+)	15	648
Undefined	Spring	No regression	No significant variables	14	808

Note: The + or − indicates the sign of significant relationships.

between mean SDV variability and meteorological and snow conditions with all variables from different elevations. Then we further investigated relationships between mean SDV and snow-meteo data related to a specific elevation (2100, 2400, 2700 and 3000 m a.s.l.).

Regression models for the two seasons considering all elevations are summarised in Table 2. Model is only significant in winter. SDV variability is positively influenced by max snowpack depth at 2700 m a.s.l. and max ramsond depth at 2400 m a.s.l. ($R^2 = 0.54$)

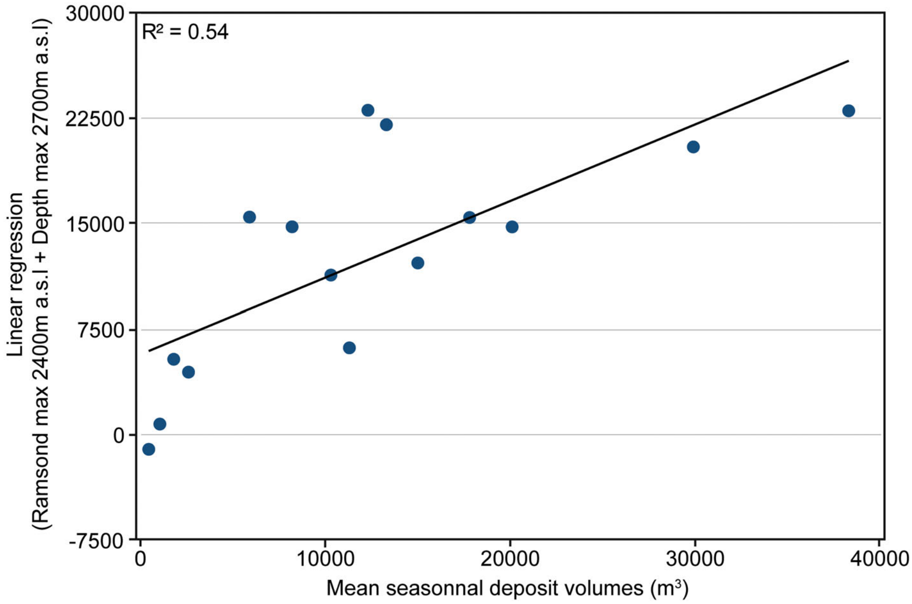

FIGURE 9 Multi-elevations winter linear regression results and observed mean winter SDV evaluated independently of path exposition in the Haute-Maurienne (Table 2). [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Statistical summary of stepwise linear regressions performed between mean winter SDV for an undefined path exposition and meteorological and snow conditions for a flat topography and a given elevation only in the Haute-Maurienne.

	Season	Regression R^2	Retained variables	Number of investigated years	Number of investigated deposits
Maurienne 2100 m a.s.l.	Winter	0.27	Accumulated snowfall (+)	15	648
Maurienne 2400 m a.s.l.	Winter	0.51	Accumulated snowfall (+) Max ramsond (+)	15	648
Maurienne 2700 m a.s.l.	Winter	0.35	Max depth (+)	15	648
Maurienne 3000 m a.s.l.	Winter	0.31	Accumulated snowfall (+)	15	648

Note: The + or − indicates the sign of the relationships.

(Figure 9). This may reflect that the volume of snow in the starting area combined with the volume of the easily re-mobilised snowpack during the flow downslope explains the SDV.

Considering the four elevations separately, the best model to predict observed mean winter SDV is obtained with the 2400 m a.s.l snow and meteorological conditions ($R^2 = 0.51$). In detail, the R^2 is lower at 2100 and 3000 m a.s.l. than at 2400 and 2700 m a.s.l. (Table 3). These best elevations are related to the flowing areas and to the lower part of the release areas and are consequently relevant for the dynamics of the avalanches. All the selected variables show a positive correlation with SDV and are related to the total amount of snowfall (accumulated snowfall) and snowpack (max depth or max ramsond). However, their influence is a bit lower than with the multi-elevation model (Table 2). As the spring multi-elevation model does not retain any variables, spring is no longer considered for the models related to a specific elevation.

4.2.2 | Influence of meteorological and snow conditions on winter SDV according to the orientation of avalanche path

Winter regression models considering different orientations of the paths in Haute Maurienne and all elevations are summarised in Table 4. Three significant models were retained with R^2 values varying from 0.4 to 0.66. The best model ($R^2 = 0.66$) shows a link between mean winter SDV and ramsond mean at 2400 m a.s.l. and mean daily snowfall at 3000 m a.s.l. for the south-oriented paths (Figure 10). Interestingly, the two selected variables in the model are the same as those mentioned earlier (with a difference concerning elevation bands). No model retains variables while considering specific orientation of the spring season.

Significant variables retained for the west and northwest models are also the same as those reported earlier when the orientation

TABLE 4 Statistical summary of stepwise linear regressions performed between winter SDV and meteorological and snow conditions in the Haute-Maurienne for specific orientations (SDV from the considered exposition only and meteorological and snow conditions from the corresponding 40° slope).

Orientation	Season	Regression R^2	Retained variables	Number of investigated years	Number of investigated deposits
South	Winter	0.66	Ramsond mean 2400 m a.s.l. (+) Mean snowfall 3000 m a.s.l (+)	15	91
West	Winter	0.40	Accumulated snowfall 2700 m a.s.l. (+)	14	252
North-west	Winter	0.57	Accumulated snowfall 2700 m a.s.l. (+)	14	186

Note: Snow and meteorological conditions from all elevations are considered. The + or − indicates the sign of the relationships.

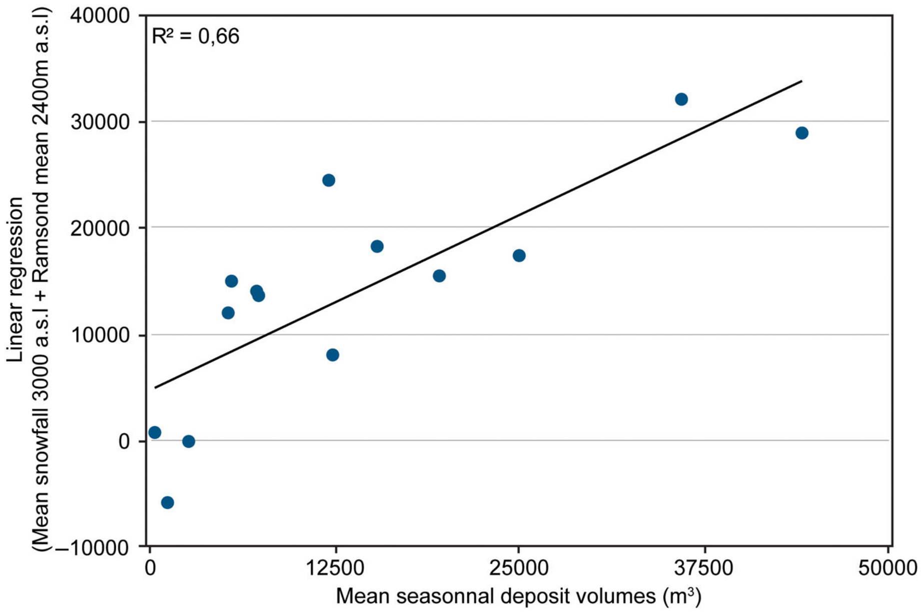

FIGURE 10 Multi-elevations linear regression results and observed mean winter SDV for south-facing paths in the Haute-Maurienne (Table 4). [Colour figure can be viewed at wileyonlinelibrary.com]

effect was not considered. North-west model presents a slightly better R^2 (0.57) than the model that does not account for orientation ($R^2 = 0.54$, Table 2).

Meteorological and snow conditions influence on SDV disrupting the road network

Regression models only considering SDV that caused road disturbances in Haute Maurienne are summarised in Table 5. Statistical analyses show a distinct relationship between meteorological and snow variables compared to the overall sample of SDV. In winter, we notice that the best model ($R^2 = 0.54$) differs partly from the general analysis conducted earlier; it only retains the accumulated snowfall at 2700 m a.s.l. and highlights a higher influence of the accumulated snowfall. In spring, the best model retains mean daily snowfall at 2100 m a.s.l ($R^2 = 0.45$). Such differences with previous results (Table 2) may be due to a specific relationship between large deposits that cause road disturbances and meteo-snow data. But they may also be due to a lower number of avalanches and to the fact that, according to the 2017 data, 59% of winter avalanches and 22% of spring avalanches caused road disturbances. Indeed, even if removing 2017 data does not affect the spring model ($R^2 = 0.46$), the winter model is no longer significant.

4.2.3 | Regional variability in meteorological and snow conditions influencing SDV

Contrary to Haute-Maurienne, there are only two significant models (Table S1) for the Guil valley for all elevations as potential predictors: the winter linear model fitted for southeast facing paths with snow and meteorological conditions retaining the mean and max ramsond at 2100 m a.s.l ($R^2 = 0.91$) and the spring linear model fitted for north facing paths retaining max ramsond at 2100 m a.s.l ($R^2 = 0.35$). This suggests that relationships between SDV and meteorological and snow conditions are specific to a local context. However, we cannot exclude that differences are also related to a much smaller number of SDVsf in the Guil valley. Eventually, the weighted combination of deposit volumes from the two study areas was considered (Equation 1). It does not produce better results, with no significant model identified both for winter and spring seasons (Table S2).

5 | DISCUSSION

Based on the availability of a large record of natural avalanches SDV and refined snow and weather data over 15 years, statistical analyses

TABLE 5 Statistical summary of stepwise linear regressions performed between SDV disrupting roads and meteorological and snow conditions in the Haute-Maurienne during winter and spring seasons.

	Orientation	Season	Regression R^2	Retained variables	Number of investigated years	Number of investigated deposits
Multi-elevations models for paths with road disruptions	Undefined	Winter	0.54	Accumulated snowfall 2700 m a.s.l. (+)	9	109
Multi-elevations models for paths with road disruptions	Undefined	Spring	0.45	Mean snowfall 2100 m a.s.l. (+)	13	61

Note: Snow and meteorological conditions are for a flat topography and all elevations. SDVs are considered altogether independently of path's exposition. The + or − indicates the sign of the relationships.

were conducted to study meteorological and snow factors driving SDV. In the Haute-Maurienne, the influence of meteorological and snowpack conditions on winter deposit volumes is mostly driven by the quantity of snow contained in the snowpack within the starting area, either represented by the accumulated snowfall or by the maximal snow depth. This finding is consistent with previous studies that suggest that large run-outs are linked to large volumes of mobilised snow, themselves dependent on the depth of the snowpack (Bartelt et al., 2012; Eckert, Baya, & Deschâtres, 2010; Legros, 2002). Rather similar results have recently been found in the US where large magnitude avalanche probability is related to the amount of snow (Peitzsch et al., 2021). We show that the meteorological and snow influence on SDV is better evidenced while using variables from different elevations. This reflects the combined effect of initially released snow and entrainment during the flow to explain deposit patterns, in accordance with, for example, Sovilla et al. (2006). SDV control is also better evidenced while considering path orientations. The winter SDV integrates the distinctive evolution of the snowpack conditions between the different considered orientations. Concerning SDV disrupting the road network, we have highlighted a distinct relationship between meteorological conditions and SDV with regards to the overall sample. The Haute-Maurienne valley road network vulnerability is mainly determined by path proximity to the road network. However, our analyses also revealed that road cuts result from important SDV driven by most favourable meteorological conditions only, namely large snowfall. However, due to the uneven distribution of the paths orientations, the result should be considered with care.

However, results do not show any significant relationship for the spring season, during which higher avalanche activity results in lower mean SDV. We suspect that the meteorological and snow conditions indirectly control the high spring avalanche occurrence and mask the varying influence of meteorological and snow variables on spring SDV. Furthermore, comparing or aggregating Haute-Maurienne data with Guil valley does not show any significant relationship, highlighting the nonuniversal nature of the relations between deposit volumes and meteorological and snowpack conditions. Similarly, aggregating/averaging the data over the full avalanche year (i.e., without the winter and spring distinction) lead to few significant relations (Table S3). Here again, we posit that at this scale the control of SDV by snow and meteorological conditions is masked by other factors such as different avalanche activity between paths and seasons.

Another limit of the approach is that pointwise snow data measured on the field were not used. However, reanalysed data from the SAFRAN/Crocus reanalyses, largely validated with comparison to point measurement (Durand et al., 2009), present the advantages of having a spatial resolution that makes it possible to consider several elevation bands, notably high elevations where there are no pointwise measurements but which are the most relevant for avalanche release. In addition, all available meteorological measurements are actually assimilated within these reanalyses. Eventually, a key parameter driving avalanche dynamics, wind, was not considered in our study, which precludes assessing the contribution of snowdrift on our results. Hence, even if Crocus reanalysis integrates an exposition effect within energy balance computations, further analyses should probably even better consider exposition changes (e.g., including snow depth changes with drifting snow).

6 | CONCLUSION AND PERSPECTIVES

SDV shows a discontinuous and nonlinear response to meteorological and snow condition variations. Yet, averaging our data at the seasonal scale, makes it possible to understand the predominant meteorological factors for seasonal SDV evolution with simple linear regression models. These results point to the feasibility of identifying a control based on meteorological and snowpack conditions on SDV. Yet, the nonuniversal nature of this control points to the necessity to consider local meteorological and snow conditions for assessing avalanche dynamics and related hazards.

Moreover, the regression models obtained, even if statistically significant, are only relative to a short period of time (15 years), making the robustness of the obtained relationship questionable, as, for example, some winter models are extremely sensitive to the extreme 2017 year. Further work should consider datasets covering longer time frames to strengthen the findings.

Concerning SDV disrupting the road network, both winter and spring highlight a different influence of variables on snow deposit volumes compared to the overall path sample. It is further speculated that the road network vulnerability is influenced by a complex combination of meteorological and snow conditions, road proximity and path morphological characteristics, which influence both the occurrence and magnitude of road disruptions. Yet, fitted models show distinct control variables for both winter and spring SDV that have led to road cuts, providing a basis for predicting the future intensity and location of major road cuts in the study area by feeding the obtained relations with future local projections of snow and weather conditions (Verfaillie et al., 2018).

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CONFLICT OF INTEREST STATEMENT

The contact author has declared that neither they nor their co-authors have any competing interests.

DATA AVAILABILITY STATEMENT

The whole EPA avalanche data are freely available at https://www.avalanches.fr/static/1public/epaclpa/EPA_listes_evenements/ (INRAE, 2021). The dataset of mean deposit volumes and morphological variables analysed in this study can be requested from Hippolyte Kern.

ORCID

Hippolyte Kern https://orcid.org/0000-0002-4624-4452

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