# PROBABILISTIC ANALYSIS OF RECENT SNOW AVALANCHE ACTIVITY AND CLIMATE IN THE FRENCH ALPS

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ABSTRACT: The characterization of statistical relationships between snow avalanche occurrence and climate can be useful for avalanche prediction. We investigated the relationship between avalanche occurrences between 1978 and 2003 and meteorological parameters for 576 avalanche events from 12 avalanche tracks in the Valloire valley in the French Alps. Probabilities of avalanche occurrence based on logistic regression analyses were calculated at a daily and yearly time scale, by differentiating high- and low-frequency avalanche tracks. For high-frequency avalanche tracks, the daily probability of avalanche depends on the precipitation (water equivalent, i.e. WE) the day before a given avalanche event, along with the mean air temperature the day of the event. For low-frequency avalanche tracks, on the other hand, it depends on precipitation (WE) the day preceding a given event. We also tested the relationship between various meteorological parameters and the type of avalanche. The occurrence of dry snow avalanches is related to total precipitation (WE) on the day of and the day before a given event, whereas that of wet snow avalanches depends on precipitation (WE) the day of a given event, and maximum air temperature during the event. Our results show that for high-frequency avalanche tracks, annual probabilities of high avalanche activity depend on the occurrences of successive days (≥3 days) with high rainfall in winter and above-average air temperature (mean + 1 SD). For low-frequency avalanche tracks, probabilities of high avalanche activity depend on the occurrences of successive days (≥3 days) with high rainfall in winter.

Keywords: snow avalanche, climate, statistic modelling, occurrence probability, French Alps.

## 1 INTRODUCTION

In mountain areas like the Alps, the increase in human activity has resulted in increased risks for natural hazards such as snow avalanches. There is therefore a growing demand for hazard zoning and avalanche protection.

In the Alps, public historical records of avalanches are available for variable periods, up to a century. However, the relationship between avalanche activity and climate is still poorly documented. De Quervain and Meister (1987) found that avalanche activity over the last 50 years in Switzerland showed no trend in frequency or periodicity over time. Laternser and Pfister (1997) compiled historical data covering 2-3 centuries in Switzerland and reported numerous catastrophic avalanche events in relation to specific weather conditions.

In the French Alps, in spite of records tracing avalanches back to the 20th century (1907), studies on avalanche activity in relation to climate were based primarily on physical models developed by Météo France, e.g. SAFRAN-MEPRA-CROCUS (Durand et al., 1999). These models appeared to be very efficient for short-term prediction (5 days) at the regional scale, but less suitable for occurrence prediction on a local level. However, statistical relationships between meteorological parameters and historically documented avalanche occurrences at the local level clearly need to be estimated: 1) to improve our ability to predict high-magnitude avalanche events, 2) establish their centennial frequencies, and 3) characterize the impacts of anticipated climatic change on this process. In France, historical data on avalanche occurrences are available for ~500 settlements throughout the Alps and Pyrenees, which offers a unique opportunity to reach these objectives.

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Statistical analyses aiming to correlate avalanche occurrence with meteorological data were carried out ~40 years ago (Loup and Lovie, 1966; Poggi and Plas, 1969). More recently, the dynamics of dirty avalanches in relation to climate during the Little Ice Age was investigated geomorphologically (Jomelli and Pech, 2004).

The objective of this research is to document the statistical relationship between climate and avalanche activity in the French Alps, which also entails 1) identifying meteorological parameters that affect the initiation of avalanche, and 2) linking annual avalanche frequency with climatic parameters. The dataset used in this study, which included observations on > 500 avalanches and meteorological data over the last 25 years for the Valloire valley in the French Alps, were provided by CEMAGREF. Frequency probability models based on logistic regression will be produced according to the activity in each avalanche track and the type of avalanche.

## 2 STUDY AREA

The Valloire valley is a hanging valley with an east-west orientation in the Massif de la Maurienne (French Alps), north of the Galibier path (Fig. 1). Substrates consist of flysch on west-facing slopes and limestone on east-facing slopes. Summits can reach 3,000 m a.s.l and steep slopes (>30°) may be 500-1,000 m in length. Strong slope gradients may explain the formation of deep gullies after heavy snowfall or rapid snowmelt. With such characteristics, the Valloire valley represents a relatively easy case study with respect to avalanche activity, compared to other mountainous areas. Most precipitation originates from low-pressure (cyclonic) masses coming from the Atlantic, but air advection from Mediterranean lowlands can also bring large amounts of rain or snow in this part of the Alps. At 1,460 m a.s.l, the mean winter precipitation (1978-2000) is about 365 mm (WE), and the mean annual air temperature 0.6°C.

## 3 METHODS

### *3.1 Avalanches Data source*

Data used in this study are from a survey of avalanches called E.P.A. (*Enquête Permanente des Avalanches* - standing investigation of avalanches), which was initiated in the 1900s by foresters. More than 400 forest rangers from the ONF (*Office National des Forêts* - national forestry commission) are involved in avalanche surveys on 538 selected sites throughout the Alps and Pyrenees.

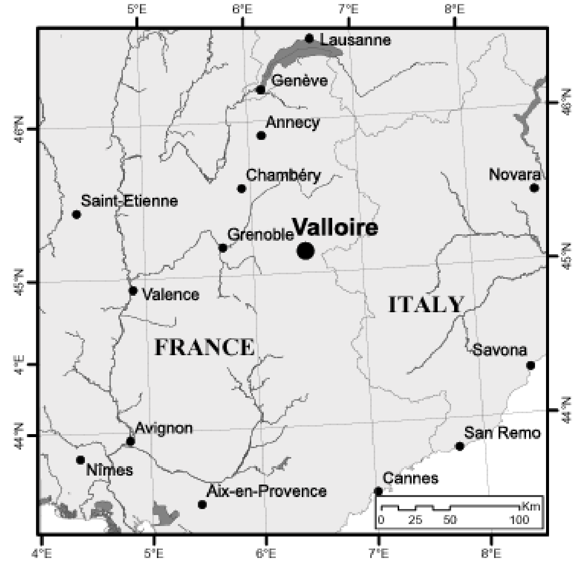

Fig.1: Location map of Valloire valley.

In 1970, when 39 people were killed in a high-magnitude avalanche at Val d'Isère (Savoie, France), the French Government realized the utility of the avalanche database as a tool for risk management. The coordination at the national level and registration of all observations into a database were done by CEMAGREF (ETNA Division: *Erosion Torrentielle, Neige et Avalanche* - erosion due to rain, snow and avalanche) since 1971. This database documents avalanches > 200 m in width. Descriptors of each avalanche event include an identification number for each avalanche track, date and time of the event, elevation of the starting and runout zone, some characteristics defining the type of avalanche, morphometric characteristics of the snow deposit, meteorological observations during and up to 3 days before the event, the presumed triggering factors (e.g. natural vs. anthropogenic), human casualties, and infrastructure damage. However, the quality and reliability of surveys vary from site to site, but the record from Valloire is considered one of the best. Because avalanche survey methods have changed significantly over the years, our statistical analysis was conducted over a 25-year period—1978-2003—which features high-quality records and greater homogeneity of survey methods (Garcia and Jamard, 2002).

Statistical analysis was applied to five months of the snow season, from December of year n-1 to January, February, March, and April of year n. November was not considered because trigger factors for early winter events were mentioned only twice over the 25-year period. Observations on the 1236 avalanches in the Valloire valley were made by two rangers only, between 1978 and 1999, and 2000 and 2003, respectively. Three avalanches that were started artificially with explosives were not considered. A total of 54 avalanche tracks, i.e. those with easy access by road and winter observations spanning the 25-year period, were first retained for analysis. Data from these avalanche tracks were analyzed carefully, particularly the number of avalanches surveyed, the length of the observation period, the presence of any man-made infrastructures that possibly modified avalanche frequencies, and finally, any appropriate remarks made by the ranger. Then, 12 avalanche tracks were selected and classified into two groups: high-frequency (n > 40) and low-frequency (n = 20-40) avalanche tracks over the 25-year period. Variations in frequencies appeared to be related to the dynamics of avalanches at each site rather than the quality of surveys. Wet snow avalanches are the most frequent type. Because of a lack of information on physical (e.g. slope) or ecological (vegetation) characteristics, site parameters were not considered. The triggering zone of these avalanches is between 2400 and 3040 m a.s.l.

### 3.2 _Meteorological data_

Data from the Valloire meteorological station (1,460 m a.s.l) were used. Daily precipitation and temperature data were available for the whole period, whereas data on wind direction and velocity were not. The weather classification at 500, 700, and 850 hPa provided by Météo France (Benichou, 1995) was also used to evaluate the relationship between avalanche occurrence and any special synoptic situation. The NAO Hurell index (1995) (corresponding to the pressure ratio between Reykjavik and Lisbon) was used to test the teleconnection hypothesis. 32 meteorological parameters were tested on a daily basis: precipitation (mm WE) on the day of a given avalanche event, as well as one, two, and three days before a given event cumulated or not; daily mean, minimum and maximum temperatures; and thermal amplitude until 3 days before the event. 12 parameters were tested on an annual basis: winter mean precipitation, and the number of times it rained during two or three successive days in winter or temperature greater or lower than 0.5, 1, 1.5 or 2 standard deviations in winter.

### 3.3 _Statistical analysis_

One of the difficulties in predicting avalanche formation lies in the importance of morphological (e.g. altitude of the starting zone, characteristics of the snow cover) and climatic parameters (snow drift accumulation), which are rarely available over a long time period and a large surface area. Moreover, climatic data, when available, may come from stations away from the exact location of an avalanche event, so that meteorological parameters calculated from any one station are not strictly identical to those at the avalanche location. The probability model used in this study evaluates uncertainties associated with discrepancies between the climate at meteorological stations and at avalanche sites. The effects of climatic variables on avalanche initiation were simulated using a logistic regression model (Aldrich and Nelson, 1984; Hebertson and Jenkins, 2003), which was also used to predict debris flows (Jomelli et al., 2003; Jomelli et al., 2004). A logistic regression model is commonly used to investigate the relationship between discrete responses like event/non-event and a set of explanatory variables. The dependent variable $Y_i$ ranges from 1 to k. The model is based on cumulative probabilities as follows:

$$Logit(p_i) = f\left(Pr\left(Y_i \leq \frac{i}{x}\right)\right) = \alpha_i + \beta' x + e \qquad (1)$$

where *f*(x) is the logistic distribution function, with *i* varying from 1 to k, the intercept $\alpha_i$ from αι to αk-1, *β’* is the slope coefficient and *e* the error. Because of constraints from the logistic distribution, estimated probabilities are between 0 and 1. The cumulative probability *pi* of the occurrence *i* is calculated from the equation:

$$p_i = \frac{e^{Logit(p_i)}}{1 + e^{Logit(p_i)}} \qquad (2).$$

The 32 and 12 variables considered on a daily and yearly basis respectively were systematically tested. All statistically significant variables were retained for further analysis (p ≥

0.05). Finally, bootstrap analyses were performed to test the global sensitivity of our models. Because our data were time series, these analyses were computed on residuals in order to keep the data independent (Efron and Tibshirani, 1994; Anatolyev, 2002). A hundred samples (>100) were extracted randomly from the dataset, logistic models were created using the same climatic factors, and residuals were calculated.

## 4 RESULTS

### *4.1. The daily basis investigation*

We first focused on high-frequency avalanche tracks and tried to identify meteorological factors responsible for avalanche initiation. The analysis was based on 384 avalanches from five avalanche tracks for which the date of occurrence was known. Code 1 or 0 was assigned to days with or without identified triggering factor in the binary logistic regression. Different models were tested using a variety of meteorological parameters. The model fitted well with precipitation the day before a given event. Air temperature has a strong effect on snow metamorphosis and stability of the snow mantle. A good estimate was also obtained with precipitation and thermal amplitude the day of a given event, as well as with precipitation and daily mean air temperature. Finally, tests were performed with atmospheric circulation patterns, but a significant model was obtained for two avalanche tracks only. The independent variables yielding the best fit were the precipitation on the day before an event ($P_{d-1}$ in mm WE+) and daily mean air temperature during the event ($Meant_d$ in degree).

The model is:

$$\mathrm{Logit}(p1) = -2.757 + (0.084 P_{d-1}) + (0.047 \times Meant_d) \quad (3)$$

This model fits well and is statistically significant (Table 1). The estimates are highly significant and the rate of correct prediction was 88.2%. When the mean air temperature is close to 1°C during the day of the event, the probability of avalanche occurrence is > 0.3 when precipitation exceeded 25 mm the day before of the event (Fig. 2), and > 0.5 when precipitation reached 35 mm. When precipitation exceeded 70 mm, the role of temperature was negligible. Lastly, when the analysis was carried out for each avalanche track, the same parameters remained statistically significant.

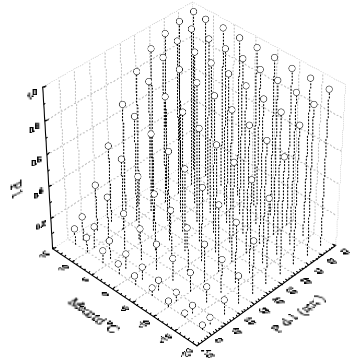

Figure 2: Daily snow avalanche occurrence probability on high frequency paths.

Table 1: Maximum likelihood estimates for high frequency avalanche paths model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -2.757 | 0.086 | 0.000 |
| MeanTd | 0.047 | 0.016 | 0.004 |
| Pd-1 | 0.084 | 0.009 | 0.000 |

The same statistical analysis was conducted on low-frequency avalanche tracks using the same meteorological parameters. The analysis was based on 196 avalanches from seven well-dated avalanche tracks. Code 1 or 0 was assigned to days with or without an identified triggering in the binary logistic regression. Good fits were obtained with precipitation the day of the event, as well as 2 and 3 days before. The independent variable that yielded the best fit was the precipitation the day before the event ($P_{d-1}$ in mm).

The model is:

$$\mathrm{Logit}(p1) = -3.817 + (0.099 P_{d-1}) \quad (4)$$

The model fits well and is statistically significant (Table 2). The estimates are highly significant and the rate of correct prediction is 93%. For these low-frequency avalanche tracks, the probability of avalanche occurrence seemed not to be influenced by the meteorological conditions during the day of the event (Figure 3).

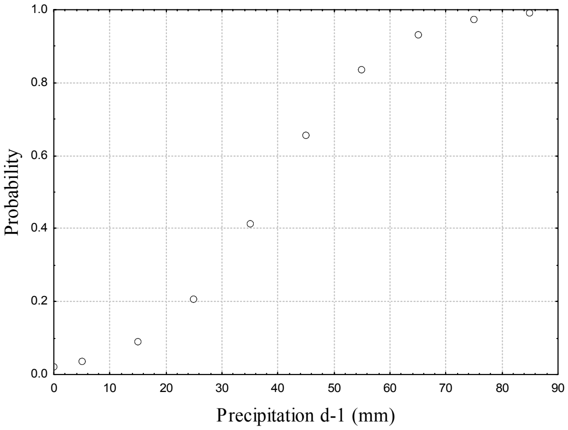

Figure 3: Daily occurrence probability on low frequency avalanche paths.

And this effect is not due to discrepancies of one day between the actual day of any avalanche event and the day of observation because some avalanche tracks selected for this model were very close to the avalanche tracks with the highest activity (99 avalanches). Hence, if an avalanche event occurred in this track on day d, it is clear that the observations of avalanches used in equation 4 were made the same day. The probability of avalanche occurrence was >0.4 when precipitation exceeded 40 mm the day before the event. Moreover, the precipitation effect was not constant. The triggering probability increased strongly when precipitation ranged between 30 and 60 mm the day before the event.

Table 2: Maximum likelihood estimates for low frequency avalanche paths model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -3.817 | 0.148 | 0.000 |
| Pd-1 | 0.099 | 0.013 | 0.000 |

Finally, among high-frequency avalanche tracks, we tested the role of meteorological parameters according to the type of avalanches surveyed, which initially included melt, dry, slab, and mixed avalanches. Two types (melt and dry) were retained because criteria used to define slab avalanches changed over the 25-yr survey period and the type identified as “mixed” was largely dependent on the ranger’s opinion. A total of 378 avalanches were selected from five avalanche tracks. Code 1 or 0 was assigned to days with or without an identified triggering in the binary logistic regression. Specific models were obtained for each type of avalanche (melt and dry) which were both highly significant statistically (Fig. 4, 5; Tab. 3, 4). The rate of correct prediction for melt and dry types was 91% and 89%, respectively.

Snow melts avalanche type

$Logit(p_1) = -4.118 + (0.062P_{\text{d-1}}) + (0.072T\text{max}_{\text{d}})$ (5)

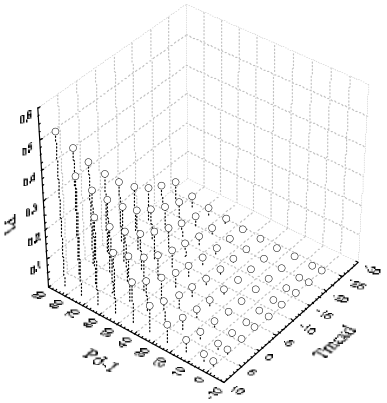

Figure 4: Daily snow melt avalanche occurrence probability on high frequency paths.

Table 3: Maximum likelihood estimates for snow melt avalanche model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -4.118 | 0.183 | 0.000 |
| Tmaxd | 0.072 | 0.011 | 0.000 |
| Pd-1 | 0.062 | 0.021 | 0.000 |

Dry avalanche type

$Logit(p_1) = -4.420 + (0.044P_{\text{d+d-1}})$ (6)

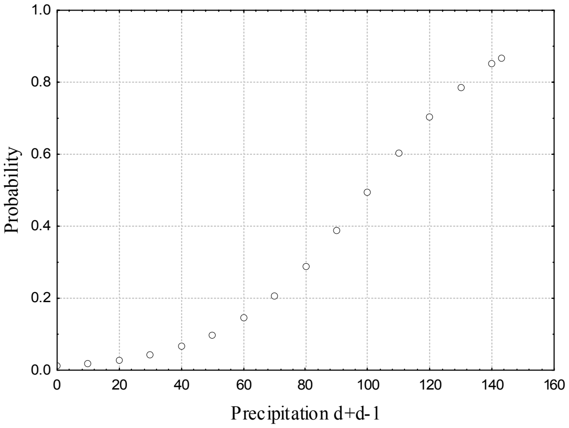

Figure 5: Daily dry avalanche occurrence probability on high frequency paths.

Table 4: Maximum likelihood estimates for dry avalanche model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -4.420 | 0.159 | 0.000 |
| Pd+d-1 | 0.044 | 0.008 | 0.000 |

The probability of occurrence of snowmelt avalanche increased strongly when precipitation exceeded 40 mm (Fig. 4). The effect of temperature became clear when precipitation was > 50 mm, although for dry snow avalanches, this parameter was negligible (Fig. 5). Finally, total precipitation on the day of a given event and the day before were most significant, especially when precipitation totaled 60 mm.

### *4.2. The annual -basis investigation*

On an annual basis, correlation matrices were calculated in order to detect any possible relationships between climatic parameters and avalanche frequency. Calculations included both low- and high-frequency avalanche tracks and were then done for both groups. Avalanche frequencies correlated closely with the number of times in winter that precipitation was recorded during at least three successive days ($r^2 = 0.65$). The relationship was even stronger when calculated for each of the two groups of avalanche tracks (high and low frequency). Different logistic regression analyses were accordingly performed.

We first focused on high-frequency avalanche tracks and explained avalanche occurrence probability by the climatic factors outlined earlier. The statistical analysis was based on 384 avalanches from five avalanche tracks. A binomial logistic regression was made for each year—assigning code 1 to years with < 20 avalanches, and code 2 to years > 20 avalanches. The model fitted best with the number of times there were > 3 successive days with rain in a winter, and the number of times that winter air temperature was > mean + 1 SD (standard deviation), as independent variables (Fig. 6). The model is:

Logit(p1) = -9.342 - (0.369$P_{3d}$) + (0.084$SDT$mean) (7)

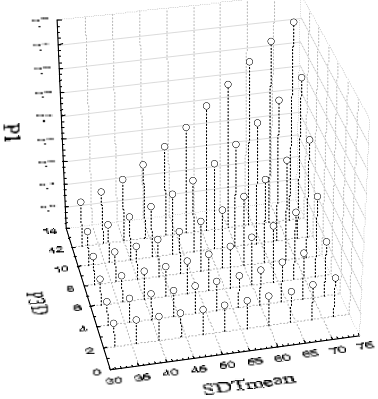

Figure 6: Yearly occurrence probability on high frequency avalanche paths.

The model fits well and is statistically significant (Table 5). The estimates were highly significant and the rate of correct prediction was 91%. The annual probability of high avalanche activity increased strongly with the occurrence of three successive days of high rainfall in winter; especially when six such triplets were counted per winter (Fig. 6).

Table 5: Maximum likelihood estimates for yearly high frequency paths model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -9.342 | 3.023 | 0.002 |
| SDTmean | 0,084 | 0.038 | 0.026 |
| P3d | -0,369 | 0.160 | 0.021 |

The same analysis was conducted on low-frequency avalanche tracks (20 to 40 events in each avalanche track between 1978 and 2000). A binomial logistic regression was calculated using 198 avalanche events from 7 avalanche tracks. A binomial logistic regression was also calculated for each year. Code 1 was assigned to years with < 20 avalanches and code 2 to years with > 20 avalanches. The independent variable that yielded the best fit was a maximum occurrence of 3 successive days with high rainfall per winter (Fig.7).

The model is:

Logit(p0) = -3.625 - (0.443$P_{3d}$) (8)

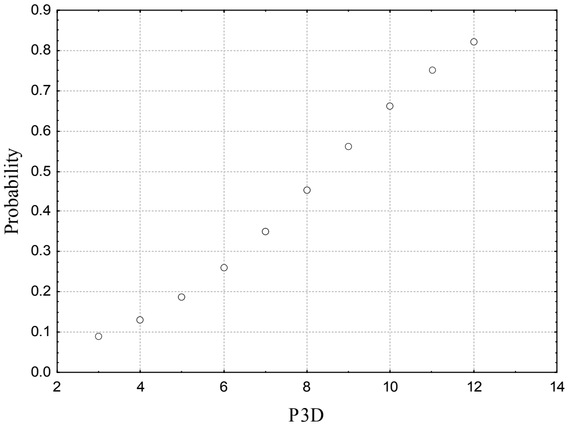

Figure 7: Yearly occurrence probability on low frequency avalanche paths.

The model fits well and is statistically significant (Table 6). The estimates were highly significant and the rate of correct prediction was 86%. The annual probability of high avalanche activity was around 0.5 when the occurrence of 3 successive days with high rainfalls exceeded 8 per winter (Fig. 7). Moreover, the probability of avalanche activity associated with this variable increased linearly.

Table 6: Maximum likelihood estimates for yearly low frequency paths model.

| Parameter | Estimate | S.E. | p-value |
|---|---|---|---|
| Intercept | -3.625 | 1.700 | 0.033 |
| P3d | 0.443 | 0.219 | 0.043 |

## 5 DISCUSSION

### 5.1 *Does the quality of avalanche survey influence the models?*

In the E.P.A., more than 70,000 avalanches were surveyed in the French Alps and Pyrenees. For several reasons, the quality of surveys is extremely variable. Some triggering factors can be underestimated or ignored and the number of avalanches used in this study was thus minimal. However, conditions were best for surveys in the Valloire valley after 1978 because of the proximity of the people who made observations, and the competence and motivation of the observer. Second, discrepancies may exist between the date of any avalanche event and meteorological data computed in the model. This means that the data used for a given avalanche event may be younger than the meteorological data used in the dataset by one or two days. However, by comparing probabilities calculated for dates of avalanche initiation with those calculated for days preceding any avalanche event, we estimated that in most cases (91%), probabilities were lower for the day preceding a given event. Moreover, to test the sensitivity of our models, bootstrap analyses were performed. They showed that the mean of the errors between parameters obtained from each simulated sample and those obtained with the original dataset was low, which demonstrates that these parameters are statistically stable.

### 5.2 *The significance of the meteorological parameters used in the models*

Considering daily activity, all of the models presented here are in close agreement with current data on avalanche dynamics. In Norway (Bakkehoi, 1987), British Columbia (Mc Clung and Tweedy, 1993), the U.S. (Butler, 1986), and the Swiss Alps (De Quervain and Meister, 1987), it was shown that the probability of avalanche occurrence correlated primarily with precipitation and most often with total precipitation for the three days preceding a given avalanche event. Our frequency models for low- and high-frequency avalanche tracks confirmed the key role of precipitation in avalanche initiation. However, in the models presented in this paper, total precipitation for the three days preceding an avalanche event did not appear to be the best parameter explaining avalanche frequencies (Föhn, 1992), which is probably due to the higher number of wet avalanches in the data set. For the high- and low-frequency avalanche tracks, precipitation is a significant variable, but probabilities decreased going back in time from day d to d-3. Moreover, in high-frequency avalanche tracks, air temperature was very rarely considered and the mean temperature on the day of avalanche events seemed a key variable in our models (De Quervain and Meister, 1987). Air temperature has a strong influence on snow metamorphosis and stability of the snow mantle, as it modifies the thermal gradient within the snow cover. Wind direction and speed may also have a strong influence on avalanche occurrence, but these parameters were not tested in the absence of data from field surveys (De Quervain and Mesiter, 1987; Mc Clung and Tweedy, 1993).

In most studies that dealt mainly with wet snow and slab avalanches, meteorological parameters were not differentiated according to types of avalanches. Some studies in the Alps (Loup and Lovie, 1966), in Tibet (Yanlong and Maohuan, 1992), and in Russia (Akkouratov, 1969) found a relationship between high frequencies of wet snow avalanches and heavy precipitations and temperature > 0°C. Our models from high-frequency avalanche tracks confirmed the key role of precipitation and temperature. However, wet snow avalanches may be triggered by rapid variations in air temperature the day before a given event, an indication that the instability of the snow mantle can also develop over a very short period of time.

On the other hand, Poggi and Plas (1969) in the French Alps, and Yanlong and Maohuan (1992) in Tibet found a relationship between dry snow avalanche occurrence and snowfall. Our results are in agreement with their conclusions.

Considering annual activity, causes of avalanche occurrence and variations through time have been debated for years. Total avalanche activity per winter is usually not considered dependent on specific conditions of the snow cover nor on total snow depth (Loup and Lovie, 1966; De Quervain and Mesiter, 1987). However, in several regions where heavy snowstorms (> 50-cm snowfalls in 2-3 days) largely account for the total annual snowfall, years with high avalanche activity may correspond to years with above-average total snowfall (De Quervain and Mesiter, 1987; Dubé, 1999; Hebertson and Jenkins 2003; Boucher et al., 2004).

Avalanche activity may also be related to atmospheric circulation patterns (Hächler, 1987; Birkeland et al., 2001). In this study, we found that avalanche activity in the French Alps was related to rainfall during 3 successive days (or more) preceding a given event and, on a yearly basis, on the number of such triplets that was not correlated with any specific circulation patterns or with the NAO Index. No cyclical trend in the temporal distribution of avalanche occurrences was evidenced in this part of the Alps (Loup and Lovie, 1966; Laternser and Schneebeli, 2002).

## 6 CONCLUSION

Because of increased human activity in mountain areas, it has become imperative to improve avalanche forecasting at the local level (i.e. at the actual site), which is currently difficult using physical models only. This study showed that statistical analysis based on avalanche field surveys could improve our knowledge of the causes of avalanche activity in relation to effective meteorological parameters. In most alpine areas, avalanche surveys are available and the methodology presented in this study can thus be replicated. The models developed in this study were based on logistic analyses and are in agreement with current data on avalanche dynamics. Avalanche activity is one of the many mountain processes that may respond quickly to anticipated changes in climate. In that respect, statistical analyses based on long historical records of avalanche occurrences can be very useful for improving avalanche prediction.

## 7. ACKNOWLEDGMENTS

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