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DEBRIS FLOW OCCURRENCE AND METEOROLOGICAL FACTORS IN THE FRENCH ALPS: A REGIONAL INVESTIGATION

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ABSTRACT

Debris flow (DF) phenomena is at the top of the list of dangerous natural hazards in the mountains areas all over the world. Among factors resulting in a DF triggering, meteorological conditions are considered to be the most relevant. The general objective of this study was to identify meteorological parameters controlling the triggering of DF in one part of the French Alps over the last 50 years.

Major factors are quite well explored at the global scale or contrariwise in very precise territory in particular catchment areas. However for now we have a poor knowledge of those factors at the scale of a medium-sized region (including catchments with different geomorphic characteristics over several km^2) especially in the French Alps. In addition in this region only a few studies focused on relationships with climate.

To understand DF activity and link it with meteorological parameters in the north region of the French Alps, we used a multivariate statistical approach. Regional meteorological parameters (such as mean monthly temperature and precipitation) were first computed from a Principal Component Analysis of observed meteorological data from four weather stations. A binomial monthly logistic regression (LR) probability model was then fitted between the main principal components and DF data base composed of 298 debris flow events triggered between 1971 and 2008. Results revealed that the most successful model including two meteorological predictors (minimal monthly temperature and the number of rainy days between May and September) correctly explains more than 60% of the DF events.

Key words: DF probability, logit, meteorological parameters, regional scale.

INTRODUCTION

Debris flow (DF) is a dominant mass movement process in mountain areas all over the world and is a significant natural hazard. A classical distinction is generally made between a debris flood corresponding to a rapid, surging flow of water, heavily charged with debris in a steep channel, and a debris avalanche corresponding to a rapid or extremely rapid shallow flow of partially or fully saturated debris on a steep slope without confinement in an established channel (Hungr *et alii*, 2008).

In a warming climate in the Alps, for instance, regional climate models generally agree that precipitation would be likely to undergo seasonal shifts and that higher interannual variability could occur and thus cause an increase in extreme precipitation events (Christensen & Christensen, 2004 Déqué, 2007). As it is known that debris flows and debris avalanches are often triggered by intense summer rainy events (Caine 1980; Iverson 1997; Guzzetti *et alii*, 2007), a change in the global climate in the future could have an impact on the magnitude and /or frequency of these processes (Jomelli *et alii*, 2007, 2009). Consequently, a better knowledge of the relationship between debris flow/avalanche and climate is a fundamental issue.

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Over the last few decades several papers have been published on the links between climate conditions and triggering of debris flows. These links were investigated at two distinct spatial scales. Some studies analyzed the climatic causes of debris flow triggered in a few small catchment areas with an accurate documentation of geomorphic characteristics and meteorological stations located in the catchment area (Gorsevski *et alii* 2000; Stoffel and Beniston, 2006; Rupert *et alii* 2008). Other studies investigated the impacts of climate conditions on debris flows at large spatial scale by focusing on a regional trend over a region of several thousand km^2 (Haeberli *et alii*, 1990; Zimmerman, 1990; Rebetez *et alii*, 1997; Guzzetti *et alii*, 2007). Such spatial scale investigations were mainly based on statistical modeling rather than determinist analyses.

In the French Alps, very few studies have been conducted at a large spatial scale (several km^2). Most studies were composed of technical reports that focused on a special catchment area that revealed risks of DF. Jomelli *et alii*, (2003, 2004, 2007) analyzed the relationships between climate conditions and different types of debris avalanches as a function of their lithology or of the nature of the accumulated debris over a part of the southern French Alps. In most cases, extreme precipitation in summer and the number of freezing days were considered as significant parameters.

At a smaller spatial scale, (Remaitre, 2006) analyzed climate conditions responsible for the triggering of 12 debris flows in one valley of the southern French Alps. He did not observe any significant relationship between annual precipitation and the triggering of debris flows. By contrast he identified two causes that may be responsible, namely i) daily total precipitation above 20 mm and ii) monthly mean precipitation above the mean value.

The main goal of this paper is to document the relationships between current climate and DF activity in the northern part of the French Alps, based on a large number of debris flow events selected in a large territory.

GENERAL SETTING

STUDY AREA

The territory considered in this paper corresponds to the department of the Savoie located in the North Alps (Fig.1). It contains two large river valleys (both of which are NW-SE oriented) the upper Isere and Grand Arc valleys and their effluents. These huge principal valley catchment areas cover more than 300 km^2.

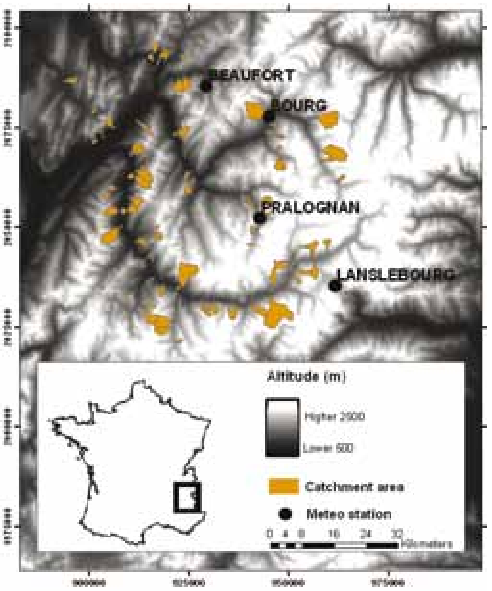

Fig. 1 - DF catchment area and location of the meteorological stations

In between the two valleys there is a huge mountain massif de la Vanoise with Grande Casse peak (3855 m asl) and a mean altitude of around 2 000 m asl.

Geologically, the SE part of this region including the upper part of the valley d'Arc mainly consists of schistes, while the central massive de la Vanoise is a crystalline outbreak and the lowest NW part is covered by sedimentary rocks.

This region is one of the most popular tourist areas of the French Alps with many famous ski resort stations that receive more than one million tourists each season. Buildings and road networks are potentially threatened by debris flows hazards. There is therefore a growing demand for hazard zoning and revision of DF protection.

DEBRIS FLOW EVENTS DATABASE

Data used in this study is from a survey of DF triggering conducted by the service Restauration des Terrains de Montagne (RTM) which was initiated in the 1900s by foresters and covers the entire French Alps. The data is organized by a department and for our study we used the database of Savoie department.

DF data for the Savoie region were collected from scientific and technical journals, monographs by local publishers, technical reports and unpublished documents gathered from the archives of local authorities and state agencies stored at RTM services.

Descriptors of each DF event include an identification number for each DF catchment area, date and time of the event, elevation of the starting and runout zone, some characteristics defining DF morphometrics, meteorological observations during and up to three days before the event, human casualties, and damage to infrastructure.

Although, the quality and reliability of the surveys vary from site to site, the record concerning Savoie department is considered as one of the best by the service RTM. Because DF survey methods have changed significantly over the years, our statistical analysis was conducted over a 37-year period (1971-2008) which features high-quality records and greater homogeneity of survey methods.

One problem was to distinguish DF from other natural hazards like floods. For that reason, we only reviewed the active period for DF from May to September and carefully checked the description of the events made by the forest ranger.

The analysis of old documents was completed by a field trip where the most active DF catchment areas were visited. Since the spring 1971 298 daily dated DF events from 102 catchments have been recorded in the Savoie region.

Mean DF catchment area in the region is around 3 km^2 with talweg length of around 1 km. The DF altitude zone is between 800-2800 m. All the catchment areas selected in this study are quite small with less than 2 km^2 mean surface areas, but very well surveyed because they are located close to the railway road network.

Twenty-eight debris flows that were impossible to date were not taken into account in the analysis. Half of the recorded DF catchment areas had DF triggering event only once in the current period. In the other half, DF event ranged from two to five and only five catchment areas were very active with more than 20 recorded events.

METEOROLOGICAL DATA

To characterize climatic conditions in the studied region, we selected four meteorological stations at different locations and elevations (Table 1). Observed cumulative precipitation and minimal and maximum temperature data at a daily time scale were available for four meteorological stations in the North Alps region for the period 1971-2008. These Météo-France stations are situated in Beaufort, Bourg st Maurice, Pralognan and Lanslebourg villages and are equally distributed over the investigated territory (Fig. 1).

Name	Latitude	Longitude	Altitude, m
Beaufort	45°41' N	6°34' E	1030
Bourg St Maurice	45°36' N	6°45' E	865
Lanslebourg	45°13' N	6°56' E	2000
Pralognan	45°23' N	6°43' E	1420

Tab. 1 - Meteorological stations with daily precipitation and temperature data for 1971-2008 period

For further statistical treatments, additional factors were calculated for each station such as the monthly mean precipitations for instance from May to September. We added monthly number of rainy days and the number of days between May and September during which rainy events were greater than 10, 20 and 30 mm/day. Temperature factors consisted of monthly mean minimal and maximal temperature.

METHODS

REGIONAL CLIMATE CONDITIONS

We used data collected from the four meteorological stations to compute regional climate conditions that were used to document the relationship between climate and debris flows activity. For our purpose we used Principal Components Analysis to extract the main part of the variance of the regional climate signal from the four different meteorological stations.

This statistical analysis also allowed us to reduce data dimensionality (Jolliffe, 2002). By using Principal Components analysis separately for each temperature and precipitation characteristics principal components (PCs) were generated then used for further analysis in logistic regression probability model.

LOGISTIC REGRESSION MODEL

Logistic regression (LR) analysis is often used to investigate the relationship between a set of explanatory variables such as meteorological factors and discrete responses like event/non-event or presence/absence (Hosmer & Lemeshow, 2000).

The logistic regression estimates probabilities of the event and non-event occurrence, conditionally on the explanatory variables. LR is based on the logit function defined as

$$logit(p) = \ln\left(\frac{p}{1-p}\right) \qquad (1)$$

where p is probability to be estimated. The main assumption is that *logit (p)* can be approximated by a linear combination of the explanatory variables:

$$\ln\left(\frac{p}{1-p}\right) = a_0 + \sum_{k=1}^{k} a_k x_k \tag{2}$$

with x_k the k^{th} predictor, a_k the k^{th} linear coefficient and K the number of predictors.

By simply inverting Eq. (1), we have that

$$p = \frac{1}{1+e^{-logit(p)}} \tag{3}$$

or equivalently

$$p = \frac{e^{logit(p)}}{1+e^{logit(p)}} \tag{4}$$

which, based on Eq. 2, can be written as:

$$p = \frac{e^{a_0+\sum_{k=1}^{k} a_k x_k}}{1+e^{a_0+\sum_{k=1}^{k} a_k x_k}} \tag{5}$$

Eq. (5) is used in practice to relate the probability p of an event with the meteorological factors $(x_k)_{k=1,\ldots,K}$

Our objective for the LR probability model at a monthly time scale was to find the best temperature and precipitation parameters that would explain DF triggering in the region.

The LR model was run monthly (from May to September), by assigning the label 1 to months including a DF triggering and the label 0 to months in which DF did not occur. The series of first PCs for each meteorological parameter were tested as independent explicative variables.

To check the quality of the model several verification tests for each LR were computed and then compared to select the most significant model results.

First the probability of the adjusted model was tested against a test model. If this probability Pr > LR is less than the 0.05 significance threshold that was set, then the contribution of the variable to the adjustment of the model is significant. Otherwise, it can be removed from the model.

Next the estimated values is Wald's Chi^2 test, where the likelihood-ratio test is performed in which $(\underline{\theta}-\theta_0)^2/\mathrm{var}(\underline{\theta})$ is compared to a chi-square distribution, where the maximum likelihood estimate $\underline{\theta}$ of the parameter of interest θ, is compared with a suggested value θ_0, which is zero in our case. The best model should have the greatest Chi^2 values.

The table of standardized coefficients was used to compare the relative weights of the variables. The higher the absolute value of a coefficient, the more important the weight of the corresponding variable. When the confidence interval around standardized coefficients is null, the weight of a variable in the model is not significant.

After all different tests, the best compilation of temperature and precipitation parameters was chosen based on the highest LR model coefficients values.

RESULTS

During the period of DF activity (from May to September and from 1971 to 2008), there were 98 months without triggering and 88 months with DF activity in the region.

Primarily parameters used as explanatory factors for the triggering of DF were: mean monthly precipitation, number of rainy days per month, number of rainy days with daily rain cumulative greater than 10, 20 and 30 mm/day, monthly minimal and maximum temperatures.

PCs analysis was then conducted on these parameters to compute independent regional climate parameters. For precipitation parameters more than 70% common signal is documented from the first component (F1) and 90% of common temperature component series. For that reason only this component was retained for further analysis (Tab.2).

The F1variables contribution consisting of data of four chosen meteorological stations is nearly equal (Tab.3). The weight of each meteorological station in PC's F1 is around 25% and only Lanslebourg has lower meanings for precipitation parameters.

We first tested all F1 parameters one by one to

Meteorological parameters	**%cumulated F1**	%cumulated F2	%cumulated F3
Mean monthly precipitation	**72.635**	19.149	5.051
No.rainy days	**63.213**	19.823	8.955
Nrd>10mm /day	**78.633**	12.207	5,232
Nrd >20mm /day	**57.394**	21.875	10.756
Nrd >30mm /day	**47.135**	30.484	13.581
Tn (min temp.)	**95.571**	2.244	1.666
Tx (max temp.)	**95.806**	2.933	1.035

Tab. 2 - PCA functions for meteorological parameters

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Tab. 3 - Weight of four meteorological stations in PC's functions interior distribution of meteorological parameters

Meteorological parameter	Chi² (LR)	Pr > LR	Value	% correct
Model 1: No. of rainy days	9.427	0.002	0.258	60.22%
Model 2: Monthly min. Temp.	9.299	0.002	0.255	62.90%

Tab. 4 - Statistical parameters of two independent logistic models for most significant meteorological parameters

Model parameters	Chi² (LR)	Pr > LR	Value	% correct
No. of rainy days	19.909	< 0.0001	0.430	64.52%
Tn (min. temp.)	19.781	< 0.0001	0.422	

From\ To	To 0	To 1	% correct
From 0	64	34	65.31%
From 1	32	56	63.64%
Total	96	90	64.52%

Tab. 5a (top). LR model output using the best temperature and precipitation parameters: Nrd (number of rainy days) and Tn (minimal temperature). 5b (bottom). Percentage of correct predictions of DF events: presence - 1, absence 0

distinguish the most significant parameters in the temperature and precipitation series.

After trying different combinations two distinct significant models were determined. The LR models that either only used the number of rainy days (*Nrd*) between May and September 1971-2008 or monthly minimal temperature (*Tn*) explained 60 and 62% of triggering respectively (Tab. 4).

Numbers of rainy days with daily rain cumulative greater than 10, 20 and 30 mm/day were expected to be closely correlated with DF events as indicators of extreme precipitation events, but the tests revealed that these extreme precipitation parameters were less or insignificant in our case. Supposing that PCA approach may be less relevant to extreme precipitation events, tests were conducted with observed data but they did not revealed better results.

As the monthly minimal temperature (*Tn*) and the number of rainy days (*Nrd*) between May and September 1971-2008 were the best parameters analyzed separately, we computed another LR model which combined the two best parameters. The model has a greater significance and higher coefficient values than two parameters independently taken (Table. 5a). The percentage of correct predictions for presence/absence of DF event was greater than 60% (Table. 5b). Tests, conducted with other combinations of climate parameters gave less significant results.

The LR probability model linear equation coming from equations (1) and (2) is:

$$\boldsymbol{Logit\ (p1) = -0.14 + (0.44*Tn) + (0.39*Nrd)} \qquad (6)$$

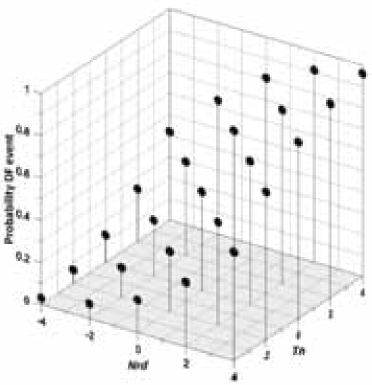

Fig. 2 - DF triggering probability: Nrd= F1 for number of monthly rainy days. Tn= F1 for monthly minimal temperature

Figure 2 shows the probability of a DF being triggered as a function of the monthly minimal temperature (*Tn*) and number of rainy days (*Nrd*) per month between April and October. The probability of a DF increased considerably when bought F1 of number of rainy days and F1 for temperature parameter was positive. The probability of a DF event greater than 0.8 was observed when the F1 of *Nrd* was greater than 0 and the F1 of *Tn* was greater than 2. The lowest probability values (0.2-0.4) were observed with negative F1 of *Nrd* and *Tn*.

DISCUSSION AND CONCLUDING REMARKS

DOES THE QUALITY OF THE DF SURVEY INFLUENCE THE MODELS?

The national natural hazard survey documented more than 900 debris flows in the whole French Alps and 298 were surveyed in the Savoie department over the last four decades. For several reasons, the quality of surveys changed during these last decades and conditions for surveys in the Savoie department were improved after 1971 because of the rise of the competence and motivation of the observers. Nevertheless, the number of debris flows used in this study was kept to the minimum. Second, discrepancies may exist between the date of any debris flow event and meteorological data computed in the model. This means that the data used for a given debris flow 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 the triggering of debris flows with those calculated for days preceding any debris flow event, we estimated that in most cases (86%), probabilities were lower for the day preceding a given event.

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 from the original dataset was low, demonstrating that these parameters are statistically stable.

THE SIGNIFICANCE OF THE METEOROLOGICAL PARAMETERS USED IN THE MODELS

The statistical analysis of debris-flow inventory in the Savoie region allows us to discuss the role of the different climatic parameters in the triggering of debris-flows. The models presented here are in agreement with current data on debris flow dynamics. In Iceland (Decaulne & Saemundson 2007), the U.S. (Cannon *et alii*, 2008), and the Swiss Alps (Haeberli *et alii*, 1990; Zimmermann & Haeberli, 1992; Rebetez *et alii*, 1997; Zimmermann, 2005) it was shown that the probability of debris flow occurrence correlated primarily with precipitation and most often with total precipitation for the 15 days preceding a given debris flow event or intense rainy events. Our model revealed that debris flow triggering in this part of the French Alps underlines precipitation as a significant parameter as well.

It is also interesting to note that our model points to temperature as a significant parameter in the triggering of debris flows. There are several possible interpretations of the significance of this parameter.

Tests revealed that extreme precipitation between 10 and 20 mm/day may be a significant parameter if it is combined with temperature. The probability of DF triggering driven by the number of rainy days greater than 10, 20 mm combined with monthly minimal and maximum temperature explained lower than 50% of triggeringless than the best model presented in the previous paragraph. Tests using the number of days during which rainy events were greater than 20 mm/day resulted in small insignificant correlations. The possible explanation for this relationship with extreme precipitation is quite complex. On one hand, extreme precipitations with high values are quite rare phenomena and they do not occur every month, so there are lots of zero values as input data for LR analysis. On the other hand, in summer such storms occurring during hot days are often very localized and as such are not always recorded by the rain gauges at weather station. Simple comparisons of data concerning DF events and rains recorded by the nearest weather station showed that in less than 50 % cases cumulated rain lower than 10 mm/d was observed the day as the DF was triggered, which may explain why extreme precipitation events only were less or not significant in our analysis. Moreover tests conducted during the hottest summer period did not reveal better results.

It is well known that two conditions required for debris flow to be triggered (Caine, 1980; Johnson & Rodine, 1984; Van Steijn, 1996): heavy rainfall of long duration or high intensity as mentioned above and a large volume of debris. The relationship between the triggering of a debris flow and the minimum monthly temperature may also suggest such a relationships with the stock of rock debris as observed in other parts of the French Alps (Jomelli *et alii*, 2004). The volume of debris is due either to morainic accumulations on a slope (Haeberli *et alii*, 1990) or to debris accumulated in a catchment area or at the apex of a slope deposit (Pech & Jomelli, 2001) by frost weathering or by erosion in the track (Jakob *et alii*, 2005).

The increase in temperatures at high altitudes over the last few decades has clearly demonstrated by different done on homogenized series (Beniston *et alii*, 1997; Diaz & Bradley, 1997; Böhm *et alii*, 2001) as well as at the four stations used in this paper. The mean altitude of the triggering zone of debris flows is about 2200 m in this region close to the 0°C isotherm. The temperature underlined in the model could at least in some cases reflect a possible degradation in the permafrost either in rock walls as has been observed elsewhere in the Alps (Haeberli *et alii*, 1993; Haeberli & Beniston, 1998; Wegmann *et alii*, 1998; Imhof *et alii*, 2000) or in the track. Another possible interpretation is linked to the influence of temperature on snow/rain limit with liquid precipitation as rain occurring at high altitudes. It could also reflect possible changes in the duration of snow cover and expose high slopes to greater temperature variations. Further detailed studies will be conducted to explore these different possible explanations proposed here and analyze possible differences between the northern and the southern parts of the French Alps.

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