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Are Debris Floods and Debris Avalanches Responding Univocally to Recent Climatic Change – A Case Study in the French Alps

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1. Introduction

Debris flow is a dominant mass movement process in mountain areas all over the world and is a significant natural hazard. A classical distinction is made between a debris flood (DF) corresponding to a rapid, surging flow of water, heavily charged with debris in a steep channel, and a debris avalanche (DA) 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, 2005). In mountain areas like the Alps, the increase in human activity has resulted in increased risks of natural hazards such as debris flows. There is thus a growing demand for hazard zoning and debris flow protection. However, debris flows are caused by complex interactions between local topography, weather and sediment properties, making the understanding of debris flow activity very difficult. Because anticipated changes in climate may alter the dynamics of slope processes and the frequency or magnitude of extreme events, understanding the mechanisms that link climate and debris flow activity is the first step in any attempt at forecasting. Consequently, many studies have focused on the meteorological conditions that trigger debris flows in different environmental conditions in northern Europe (Innes, 1985; Rapp, 1995; Nyberg and Rapp, 1998) and in the Alps (Haeberli et al., 1990; Zimmerman & Haeberli, 1992; Rebetez et al., 1997). Triggering thresholds based on analyses of intense rainy events or long duration precipitation have been proposed for different spatial scales (Caine 1980; Guzzetti et al., 2008). An increase in temperatures and changes in the amount and frequency of rainfall have been observed in different mountain regions in the last few decades. Such changes in climate conditions could have an impact on the intensity and/or frequency of debris flows. However, only a few authors conducted detailed analyses of the impacts of climate change on DF activity to check the validity of this hypothesis. In British Columbia, Canada, Jakob & Lambert (2009) predicted an increase in the total number of debris flows by the end of the century due to increases in precipitation. From tree-ring series Stoffel & Beniston (2006) clearly show that the debris-flow frequency at Ritigraben (Swiss Alps) increased in the 1866–1895 period that followed the maximum extent of LIA glaciers and that events occurred most often in the early decades of the 20th century.

Surprisingly few papers have been devoted to debris avalanches and their relationships with meteorological or climatic conditions (Jomelli et al., 2004, 2009). In the French Alps, Pech & Jomelli (2001) underlined the active role of the apical cone of talus slopes in DA activity as the main factor responsible for asynchrony between sequences of heavy rainfall and DA triggering. Jomelli et al., (2007) observed a contrasted response of DA activity to recent climatic change depending on the geomorphic characteristics such as the lithology and the nature of stored debris. However, there are several geomorphic differences between DF and DA. For instance Blijenberg (1998) observed that the triggering of DF and DA is partly controlled by the relationship between slope angle and the intensity of precipitation in the triggering area. DF events occur in confined channels; hence slopes in the triggering zones may differ from those in the triggering zone of DA catchments. Moreover, sediment supply is *a priori* more limited in DA catchments than in DF catchments because most DF events transport sediment temporarily stored inside the channel (Veyrat & Menier, 2006). Consequently these differences in morphometrical and sedimentological characteristics may trigger a different response by DF and DA to climate change.

A natural hazard such as debris flows is defined as the result of a combination of hazards that correspond to the natural event and the vulnerability of elements exposed to this event, linked to human presence (Alexander, 2005). Thus, risk involves the exposure of populations and their infrastructures to a potentially damaging natural event. Concerning the risk of DF, most studies focused on understanding and reducing natural events, whereas vulnerability to DF is both a relatively new and innovative concept. Several studies have been conducted on the structural vulnerability of buildings (Hulsbergern & Carree, 1987; Alexander, 1988; Leone et al., 1996). For instance Fuchs et al., (2007) showed that vulnerability to DF in the Alps is highly dependent on the construction material used for structures exposed to this risk. However, few analyses have been made of the vulnerability of transport networks.

Existing studies on the vulnerability of communication networks focused on seismic risk, particularly following the Los Angeles (1994) and Kobe (1995) earthquakes (Hassani & Takada, 1995; Chang, 2000). However, new assessment methods have been developed for network disturbances, especially the risk of landslides, and these approaches can be transposed to DF hazard. For instance, Leone (1996, 2008) developed a method based on calculations of the rate of damage in order to establish a referential (damage matrix) for the economic assessment of the structural and functional vulnerability of transportation networks. This approach enabled physical damage to be distinguished from the resulting disruptions. Manche (2000) emphasized the latter aspect and developed a method for analyzing functional disturbances in mountainous areas, based on the concept of loss of accessibility. Here the aim was to highlight the fact that consequences may occur far from the affected area. Cleyze (2007) tackled these concepts in more detail, in particular the degree of damage to the physical infrastructures comprising the transportation network, but also the deterioration in the services provided by that network. However, existing studies focus on road networks, while few tackle the vulnerability of rail networks.

The aim of this paper is twofold: 1) to analyze the morphometrical characteristics of DF and DA catchments and to compare the response of these two processes to climatic change in recent decades (since the 1970s) in the French Alps; and 2) because the French alpine economy mainly depends on transportation networks, to compare the vulnerability of rail and road networks to recently documented debris flow activity.

2. Study area

DF and DA catchment areas are widespread throughout the French Alps. For this study, we selected 308 DF in the Arc and upper Isere river valleys close to the town of St Michel

de Maurienne, and 111 DA in the massif des Ecrins around the Durance river close to the town of Briançon (45°00'S, 6°30'E) (Figs. 1-2). The Arc and upper Isere region consists mostly of schist and sandstone, while the Massif des Ecrins is a crystalline formation and mainly consists of granites and metamorphic rocks. Typical geomorphic DA characteristics have the following components: (1) a funnel-shaped debris source area consisting of broad steep granite and metamorphic walls (100-400 m in height), (2) a zone where debris levees are found on both sides of the flow track on scree slopes or transitional deposits (Jomelli & Francou, 2000; Pech & Jomelli 2001); and (3) a terminal part where the levees join to form a frontal lobe or a combination of several lobes (Van Steijn,1991; Van Steijn et al., 1988; Major, 1997). These DA deposits are located between 1 600 and 2 400 m asl which is close to the 0°C annual isotherm. DF catchments consist of steep non-vegetated slopes in the triggering zone, an incised channel with an intermittent water flow that can be eroded by debris flow events, and a gentle deposit zone situated between 450 and 1 900 m asl. In the period 1961–2000, the annual average temperature at Briançon and at Pralognan was respectively 6.1 °C and 5.5 °C, and annual average precipitation was 1 064 mm and 974 mm.

3. Data source

3.1 DF and DA surveys

DF data used in this study came from a survey conducted by the service *Restauration des Terrains de Montagne* (RTM) which was established by foresters in the 1900s and covers the entire French Alps. The organization has a departmental structure and for our study we used the database of Hautes-Alpes and Savoie departments. DF data were also collected from scientific and technical journals, monographs by local publishers, technical reports and unpublished documents from the archives of local authorities and state agencies stored at the RTM.

The inventory and cartography of DA was carried out by analyzing series of aerial photographs starting in 1970 and completed by field observations made every year between 1995 and 2010 (Jomelli et al., 2003). The scale of the aerial photographs ranged between 1: 15000 and 1: 30000. Well-defined debris avalanche deposits showing clear lobes and levees were dated by combining three approaches: analysis of aerial photographs, old documents from RTM, and from department archives. Some DAs were dated by dendrochronology: damage to *Larix deciduas* trees included broken tree trunks, impact scars, and stem tilting leading to the production of reaction wood. *S*amples were processed in accordance with standard methods of dendrogeomorphology (Stoffel et al., 2006).

Descriptors of each DF and DA event included an identification number for each catchment area, the year of the event, the elevation of the starting and runout zone, some morphometrical characteristics such as the difference (δh) in height (m) between the upper limit of the source area and the deposit (fig. 3). The volume of some recent DA deposits was estimated from the length, width, height of the deposit lobe measured in the field. In the case of DF deposits, we used rare documented events in the RTM data base.

3.2 Climate data

Sixteen meteorological stations at different locations (Fig. 1) and elevations were selected to characterize climatic conditions in the study area. Observed cumulative precipitation and minimum and maximum temperature data at a daily time scale were mostly available for 1971-2010 and in a few cases, for a longer period (table 1). Temperatures were analyzed to

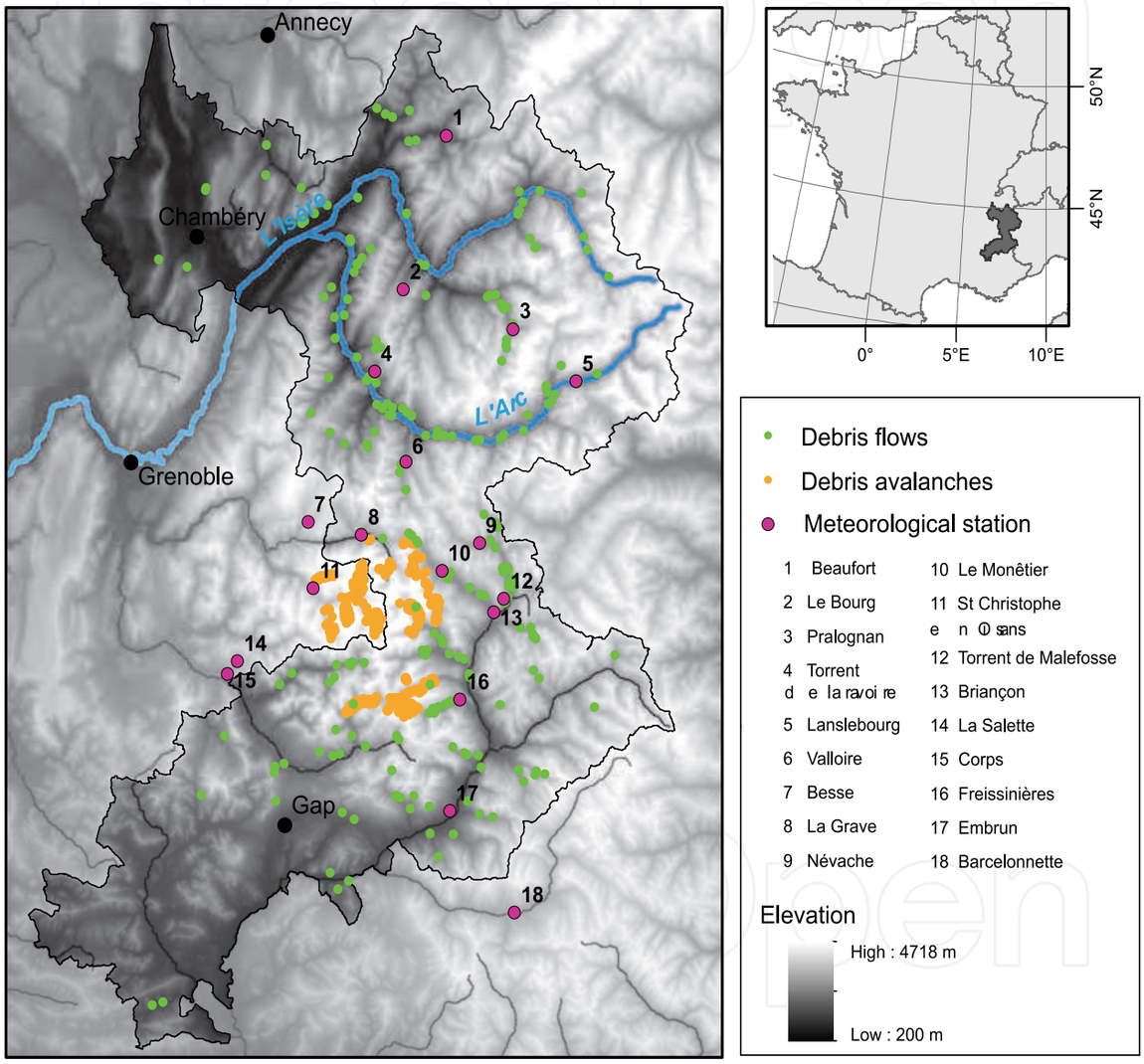


Fig. 1. Location map.



Fig. 2. Debris flood (left) and debris avalanche (right) catchments selected in this study that show different geomorphic and material properties in the triggering, transit and deposit zones.

document possible recent warming using t-tests. Precipitation was analyzed to identify changes in the intensity and frequency of precipitation. First we checked if daily precipitation above a threshold of, for example, 10 mm/d or 21 mm/d or 33 mm/d changed significantly in recent decades. To answer this question, a pertinent threshold had to be determined. For each station the choice of the threshold was determined by a mean residual plot. In a series of precipitation events we tried to identify the lowest threshold (for example 12 mm/d) above which precipitation events are considered as high intensity events i.e. extreme events. The lowest threshold was selected to analyze as many data as possible above it. A specific threshold was computed for each meteorological station. To characterize a possible trend in the intensity of precipitation for a given threshold, we computed the distribution of extreme events above the threshold and compared the parameters of the distribution estimated for the period 1970-1990 with those obtained for the period 1990-2010 for each station. The Generalized Pareto Distribution (GPD) i.e. the distribution of extreme

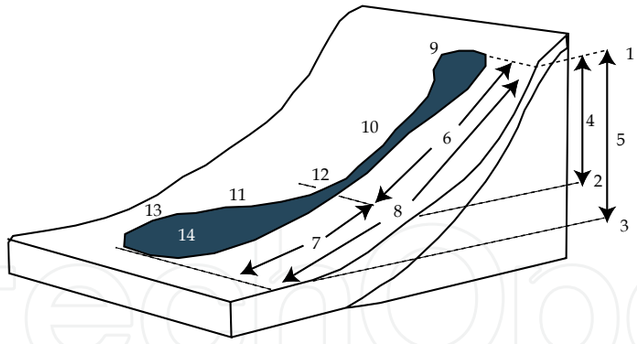


Fig. 3. Parameters measured in the DF and DA catchments (after Lorente et al., 2003 modified). 1: The elevation of the top of the debris flow. 2: the elevation at which debris flow deposition begins; 3: the elevation at the runout deposit ends; 4: difference in height (m) between the top and the transit zone; 5: difference in height (m) between the top and the base; 6: total length (m) of the debris flow between the upper part and the beginning of the deposit; 7: length (m) of the debris flow deposit from end of channel to the front; 8: the total length (m) of the landform; 9: average gradient at the top; 10: average gradient of the channel; 11: average gradient of the deposit; 12: average width of the channel; 13: average width of the deposit; 14: estimated volume of material mobilized by the debris flow.

events above a given threshold (Embrechts et al., 1997) was then fitted to daily precipitation data. The second step involved analyzing changes in the frequency of these extreme precipitation events since the 1970s. To compare the number of intense precipitations per year before and after 1990, we used a Poisson model because the number of intense rainfall events above a given threshold followed a Poisson distribution (Embrechts et al., 1997). This Poisson distribution can be defined as follows:

$$P(x) = \exp(-\lambda)\frac{\lambda^x}{x} \text{ where } x \in N \quad (1)$$

where λ is the parameter of Poisson law and x the number of events.

For each station, we estimated the λ parameter describing the distribution of the rainfall events between two distinct observation periods (1970-1990; 1990-2010). After testing, comparison of the λ parameters obtained for the two periods made it possible to identify significant variations in precipitation. These climate data were also used to link the triggering of debris flows with climate conditions. Different climatic parameters were calculated: mean monthly precipitation, number of rainy days per month, number of rainy days with daily cumulative rainfall greater than 10, 20 and 30 mm/day, monthly minimum and maximum temperatures.

Principal Components Analysis (PCA) was used to extract a common regional climate signal from the different meteorological stations. This analysis enabled us to reduce data dimensionality by performing covariance analysis between factors and to obtain non correlated factors, i.e. linear combinations of values. By using PCA separately for each temperature and precipitation characteristic, we generated new synthetic value of these parameters that combine the common components of the selected meteorological stations. The values of the principal coordinates were then used for further analyses in the logistic regression probability model described below.

4. Statistical method used to characterize factors that trigger DF and DA

To better understand the relationship between climate parameters and the occurrence of debris floods/avalanches, we used a logistic regression (LR) model (Aldrich & Nelson, 1984). LR analysis is often used to investigate the relationship between a set of explanatory variables such as meteorological factors and discrete responses such as event/non-event or presence/absence (Hosmer and Lemeshow, 2000). The logistic regression estimates probabilities of the occurrence of the event and non-event, depending on the explanatory variables. Our objective for the LR probability model at a yearly time scale was to find the best annual temperature and precipitation parameters that explain DF/DA triggering in the region. The first component of Pc values of the different climatic parameters were used as explanatory variables.
The dependent variable Yi is ordered and has values from 1 to k. The model based on cumulative probabilities is:

$$\mathrm{Logit}(p_i) = f\left(\Pr\left(Y_i \le i \middle| x\right)\right) = \alpha_i + \beta' x + e \tag{2}$$

where $f(x)$ is the logistic distribution function, i varies from 1 to k, the intercept α_i varies from $\alpha 1$ to $\alpha k\text{-}1$, β' is the slope coefficient and e the error. The logistic distribution constrains the estimated probabilities to between 0 and 1. The cumulated probability pi of the occurrence i is calculated from the equation:

$$p_i = \frac{e^{\mathrm{Logit}(p_i)}}{1 + e^{\mathrm{Logit}(p_i)}} \tag{3}$$

To check the quality of the model, for each LR, several verification tests were computed and 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 was less than the 0.05 significance threshold that was set, the contribution of the variable to the adjustment of the model was significant. Otherwise, it was removed from the model. Next, the estimated values, the corresponding standard deviation, Wald's Chi^2, the corresponding p-value and the confidence interval were displayed for the constant and for each variable of the model. The best model had the highest 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 greater the weight of the corresponding variable. When the confidence interval around standardized coefficients had a value of 0, the weight of a variable in the model was not significant. We also computed the percentage of well-classified observations for the different explanatory climatic parameters. If the final percentage score was higher than 50%, the model was considered to be significant. After all the tests, the best compilation of temperature and/or precipitation parameters was chosen based on the highest LR model coefficient values.

5. Estimation of transportation network vulnerability

To analyze the impacts of DF on the transportation network, we distinguished physical damage to roads (direct impacts) from functional disturbances i.e. the consequences of the physical damage (indirect impacts). The method consisted in compiling an inventory of disturbances to the transportation network documented by the RTM and the DDE (direction

départementale de l'équipement) responsible for maintenance of the roadway network and SNCF in charge of the railway network. The intensity of these disturbances was then classified using the method proposed by Leone (1996) with modifications, and from a classification of the damage by the SNCF (société nationale des chemins de fer français) (ISRI index) (fig. 4). However, the difference between direct and indirect impacts was difficult to distinguish in the SNCF damage testimonies.

Dpmax	Type of damage to road
SD	No damage described (but functional perturbation)
D	Damage but no details
DP	Damaged bridge (road closed as precaution)
D1	Degradation of pavement
D2	Subsidence of the platform
D3	Obstruction of the roadway
D4	Destruction of the platform without the bridge breaking
D5	Destruction of the platform, bridge broken

PFmax	Functional disturbance due to damage to road
SP	No perturbation described (but physical damage)
P	Perturbation but no details
P1	Limitation of size of vehicle
PP	Traffic interrupted, duration not specified
P2	Temporary interruption of road traffic (some hours)
P3	Prolonged interruption of road traffic (some days)
P4	Long term or permanent interruption of road traffic (weeks, months)

ISRI	Type of incident on the railroad
G4	Simple detection of event
G3	No direct impact, requires repairs
G2.b	Potentially serious incident, requires works
G2.a	Major incident affecting regularity and safety of rail traffic, requires works
G1	Serious risk for rail traffic safety (1.a crash, derailment, 1.b crash, derailment avoided)

Fig. 4. Intensity of road and rail disturbances.

6. Results

6.1 Climatic analysis

In the French Alps, since the nineteen century the temperature has increased by 1 or 2°C (depending on the season and the location (Déqué, 2007). Table 1 shows that since the 1970s and independent of altitude, most meteorological stations recorded a significant increase in temperatures (Mann-Whitney test; 0.05 level) at a yearly time scale. This trend confirms other observations for the whole European Alps using homogenized instrumental time series (Böhm et al., 2001; Beniston et al., 1997). Analysis of seasonal data (results not shown) revealed that in spring, temperatures increased significantly (t-test) since the beginning of

the 1970s at most stations. In summer, the mean value of this increase was around 0.9 °C. In autumn and spring, the increase in temperatures (0.6°C) was also significant (t-test) at most stations. In winter, there was a general significant increase (0.7 °C) over the whole period at all stations. Concerning changes in the number of freezing days since the 1970s, a significant decrease (t-test) in the number of freezing days (between 10-15%) was recorded at different stations.

Analysis of precipitation revealed trends in the intensity of summer precipitation and changes in their frequency above a certain threshold (Table 1). Changes in intensity/ frequency were analyzed over the whole period. At an annual time scale, only the stations at St Christophe en Oisans, Névache and Beaufort presented significant variations in intensity since 1970. The minimum threshold at which changes in the intensity were considered significant was 10 mm at Beaufort station, but 21 mm at Nevache. The frequency of rainfall events increased (Student's test; 0.05 level) at most stations except Corps, Briançon, Freissinière and Lanslebourg (Table 1). The minimum threshold at which changes in the frequency were considered significant was 10 mm at La Grave station, but 30 mm at St Christophe en Oisans. Analysis of seasonal data (results not shown) revealed that in spring the monthly precipitation mean increased significantly (t-test) since the beginning of the 1990s at most stations, whereas in summer, the mean did not reveal any significant change. In fall the increase in the monthly precipitation mean was significant (t-test) at most stations. In winter there was a significant increase in the whole period at all stations. Analysis of variations in the number of rainy days revealed a significant increase over the last decades at Lanslebourg, Pralognan, St Christophe en Oisans and Valloire.

6.2 Geomorphic characteristics

A comparison of the geomorphic characteristics of DA and DF catchments revealed significant differences. The mean value of the gradient where deposition started was 19.8°, with a wide range of gradients (15-27°) in granite DA catchments. This variance can be explained by the conditions under which DA occur. The angle of deposition can be strongly influenced by the presence of break angles in the length profile of the scree slope (Jomelli & Francou, 2000) or by forest patches, and by variations in water content. These values are close to those reported by Lorente et al (2003) in the Pyrenees. By comparison, DF deposition occurred on gentler slopes (< 20°) with the same lithology. The difference in angle between DF and DA can be explained by the fact that slope deposits on which DF and DA flow do not have the same sedimentological characteristics. Most DA deposits were recorded on scree slopes composed of a superficial coarse-grained openwork layer (Jomelli & Francou, 2000) that favors water infiltration, while DF deposits mainly occurred on slope deposits composed of a superficial massive layer, totally or partially filled with a sorted, fine-grained matrix.

The mean length of the DA deposits was 22.1 m with a minimum length of 5.8 m, and a maximum length of 55.6 m, which is much shorter than in DF catchments where deposits longer than 100 m were observed. Relatively large differences in the length of both types of debris flow deposits were observed due to the influence of local topography especially local differences in slope gradient. However, different lengths were also expected due to variations in water content. Another major difference was in the lowest altitude reached by the DF and DA deposits. DF ended at about 1 150 m (standard deviation = 426 m) while DA ended at about 1 820 m (standard deviation = 211 m).

Location	Elevation		Precipitation					Temperature	
		Period of observation	Frequency		Intensity		Period of observation	Yearly time scale	Summer time scale
			Significant trend	Threshold	Significant trend	Threshold		Significant Trend	Significant Trend
St Christophe-en Oisans	1570	1963-2010d	Increase	30 mm	Yes	15mm	1961-2010 m	Increase	Increase
Embrun	849	1950-2010d	Increase	25mm	No		1950-2010d	Increase	Increase
Névache	1600	1961-2010d	Increase	30 mm	Yes	21mm	1978-2010d	Increase	Increas
Valloire	1460	1973-2010d	Increase	10mm	No		1983-2010d	Increase	Increase
Corps	1265	1947-2010d	No		No		No	Not analysed	Not analysed
La Grave	1780	1961-2010d	Increase	10mm	No		1961-2005d	Increase	Increase
La Salette	1770	1970-2010d	Increase	25mm	No		1970-2010d	Increase	Increase
Monétier les bains	1450	1950-2010d	Increase	30mm	-	Not available	1961-2010d	Increase	Increase
Barcelonnette	1155	1970-2010d	Increase	15mm	No		1970-2010d	Increase	Increase
Briançon	1324	1970-2010d	No		No		1970-2005d	Increase	Increase
Freissiniere	1320	1970-2002d	No		No		1970-2010d	Increase	Increase
Beaufort	1030	1970-2010d	Increase	25mm	Yes	10mm	1970-2010d	Increase	Increase
Lanslebourg	2000	1970-2010d	No		No		1970-2010d	Increase	Increase
Pralognan	1420	1970-2010d	Increase	15mm	No		1970-2010d	Increase	Increase
Bourg	865	1970-2010d	Increase	25mm	No		1970-2010d	Increase	Increase
Besse	1416	1950-2001d	Increase	20mm	No	Not available	1961-2010 m	Increase	Increase

Table 1. Analysis of significant variations (0.05 level) in precipitation and temperature since the 1960s for 16 stations in the French Alps (see figure 1); m−d = monthly and daily observation respectively

To estimate runout distance using morphometric parameters we used the simple formula of Vandre (1985), who found that runout distance is about 35–45% of the difference in height between the head of the source area and the point at which deposition starts (δh). The formula is:

$$\text{Runout} = \alpha\delta h \tag{4}$$

where α is an empirically derived fraction parameter expressing the ratio of runout to δh. In the case of DA, the α value was around 0.43 while for DF, it was around 0.605.

A very clear difference was observed in the volume of material mobilized by DF and DA (Brochot et al., 2002). The estimated volume of material mobilized based on 26 DA deposits averaged 130 m^3 and the maximum value was 472 m^3. Thus according to Innes (1983), these cases can be defined as "small scale" debris avalanches. These values are of the same order of magnitude as most debris avalanches cited in the literature (Blijenberg, 1998). Unfortunately, the volume of DF was rarely documented in the database. For 36 documented DF events, the volume averaged 35 000 m^3 with a maximum value of 500 000 m^3.

6.3 Changes in the frequency of DF and DA

The analysis of variations in the frequency of debris avalanches was based on 111 events that occurred since 1970. Debris avalanches are a very common geomorphic process with a

mean recurrence interval of 3.7, meaning that more than one event occurred in one of the valleys every third year. However, recurrence intervals varied considerably between the catchments with a standard deviation of 21.9 for the whole region. We used a Student's t-test to check if changes in the frequency of debris avalanches were significant at a level of 0.125. Some catchments underwent a significant increase in the number of debris avalanches in the last 20 years compared to previous periods. However, in most cases the number of events per catchment was not high enough to reveal a significant change over the study period. We also tested if the number of events changed significantly over the last four decades at the regional scale. Results revealed no significant variation in the occurrence of DA. However this global result masks two different trends in DA activity depending on minimum elevation of the starting zone. At low altitudes (< 2 200 m), the number of DA decreased significantly since the 1990s, whereas at high altitudes (> 2 200 m) it has increased. The data were then classified according to the total length of the DA system. A significant decrease (0.01, Mann-Whitney test) in the number of debris avalanches was observed for the systems less than 600 m in length (Fig. 5). In contrast, there were no significant variations in the number of the debris avalanches longer than 600 m between the two periods (Fig. 5).

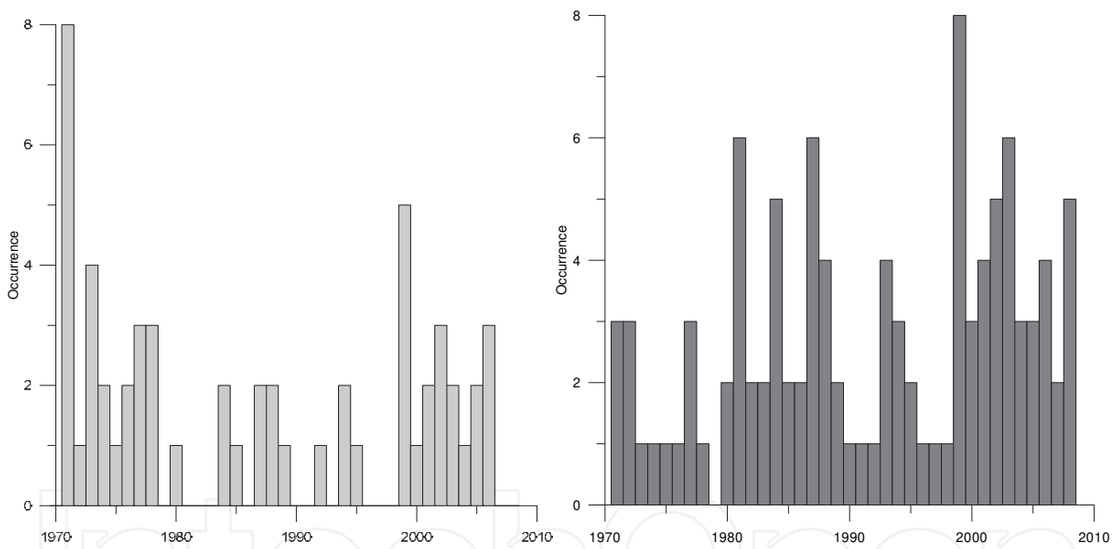


Fig. 5. Occurrence of debris avalanches over the last four decades according to the minimum elevation of the starting zone: left = below 2200 m asl; right = above 2200 m asl.

However, this trend should be interpreted with caution because the inventory of events cannot be considered as complete. Indeed, in a system with a high degree of activity, younger deposits can easily cover or sometimes erode older flows. The overall decadal frequency of debris avalanches is shown in figure 5. On average, two and three events per decade years were identified during the study period. A slight trend towards more debris avalanches was observed in the second 20-year period.

The same analysis was conducted on debris floods. Results revealed the same trend considering that most started at high elevations i.e. higher than 2 000 m asl. There was an increase in the number of debris flood since the end of the 1980s (fig. 6). About 5.8 events were triggered per year between 1970 and 1989 versus 13.3 between 1990 and 2010.

Catchment areas with high altitude triggering zones were more active. Even if there is probably a bias in the inventory (the data reported in the survey represent minimum frequencies) we believe that the higher debris flood activity may not only be the result of sample skewness because this trend was observed in most valleys for which we had a sufficient number of data and in valleys where the people responsible for the observation were the same for the two periods.

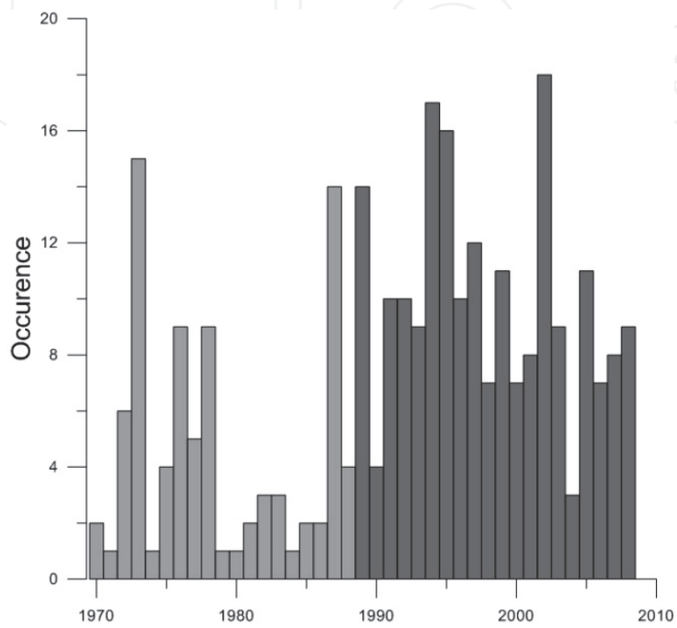


Fig. 6. Changes in debris flood activity since 1970.

6.4 Climate conditions responsible for DA and DF activity

We analyzed the climate conditions responsible for triggering DA. Binary logistic regression was performed yearly. We carried out the annual sum of the number of occurrence observed DA. The result was classified in two groups of equal size (obtained starting from a threshold of three annual releases) giving to the years with less than three occurrences the code 0, and to the years with at least three occurrences the code 1.

We tested all first components of the PAC of different parameters one by one and then combined them to identify most significant parameters in the temperature and precipitation series. After different combinations, the independent variables that gave the best fit were mean monthly temperature and number of daily rainfall events greater than 20 mm/day (*Nd20*) between May and October 1971-2010. The model is:

$$Logit(p_1) = 4.7 - (0.38 \times mean\ TX) - (0.5717 \times Nd20) + e \quad (5)$$

The percentage of correct predictions for the presence/absence of a DA event was higher than 75% (Table 2).

We conducted the same analysis for DF events. The number of occurrence was classified in two groups of equal size (obtained starting from a threshold of five annual releases) giving to the years with less than five occurrences the code 0, and to the years with at least five occurrences the code 1.

The independent variables that gave the best fit were mean minimum temperature (*Tn*) and the number rainy days (*Nrd*) between May and September 1971-2008. The model is:

$$Logit(p_1) = - 0.14 + (0,44 * Tn) + (0,39 * Nrd) + e \quad (6)$$

The percentage of correct predictions for the presence/absence of a DF event was higher than 65% (Table 2).

	Parameter	Value	Wald Chi square	Pr>Chi2	% correct 0	% correct 1	% correct_total
DA	NFR	0.38	2.36	<0.03	66.67	85.71	77.78
	Nd (20)	0.57	5.482	<0.007			
DF	Tn	0.504	5.958	<0.0001	74.81	54.69	69.79
	Nrd	0.476	5.598	<0.0001			

Table 2. Statistics for the two DA and DF models.

6.5 Impacts of DF and DA activity on the transportation network

The analysis of DF and DA events revealed clear differences in impacts on the transportation network. No death was reported for either DF or DA. However, the social impacts of DF were much greater than those of DA mainly due to the fact that the DF deposit zone was located at low altitudes i.e. at an altitude with permanent socio-economic activity. Damage caused by DA was mainly due to the deposition of rock debris on roads. However there were only a few cases and these affected secondary roads used by only a few cars. The indirect consequences of the damage was thus limited. By contrast, DF activity had both direct and indirect impacts on road and rail networks. To illustrate such impacts we selected two catchments that had undergone much DF activity over the last decades. The first DF catchment named "La Ravoire" is located in the Arc valley, south of Savoie department (figs. 1-7-8). The elevation ranges between 2 686 m in the upper part to 499 m at the confluence with the Arc river, with a average slope of 16-17°. The watershed covers 10,5 km² with a highly urbanized debris fan area of 0.2 km² at Pontamafrey village. La Ravoire drainage basin is composed of metamorphic and sedimentary rocks covered by superficial deposits.

The second DF catchment named "Le Malefosse" is located in the northeast of Hautes-Alpes department (figs.1-7). This catchment is rather small with a surface area of 1.8 km² and 0.3 km² for the debris fan. Altitudes range from 2 509 m in the upper part to 1 315 m at the confluence with the Durance river, with a high average slope of 21.8°. The geological conditions at La Malefosse catchment are similar to those at La Ravoire. The transportation networks affected by DF were as following for both catchments:

- the D1006 road in Savoie department linking France and Italy. The traffic is relatively high for this type of highway with 8515 vehicles per day (Conseil Général, 2010).
- the international high-speed train (TGV) linking Paris and Turin, and the regional line which links different towns in the valley, with a total of 71 trains per day (SNCF, 2010).
- the N94 road in Hautes-Alpes department; this is an international transit road linking the main towns in the French Alps (Briançon, Gap, Marseille, Grenoble) with Italy. In 2006, daily traffic was 9346 vehicles (DDE Hautes-Alpes).



Fig. 7. Location map of La Ravoire catchment (left) and Malefosse catchment (right) showing impacted transportation networks.



Fig. 8. View of Pontamafrey village constructed on the debris cone of La Ravoire. La Ravoire channel crosses the village the international line of high-speed train (TGV) which links Paris to Turin and the road way D1006.

The survey of DF conducted by RTM-DDE and SNCF reported that 24 events were triggered since 1970 in the La Ravoire (fig. 9) catchment and that 14 had an impact on the transportation network (43% on the railway and 57% on roads). In the Malefosse catchment nine events were reported (fig. 9) of which 5 damaged roads. In both catchments, the

majority of events that caused damage occurred between June and August. A slight trend towards more DF was observed in the more recent years in the Malefosse catchment while no trend was observed in La Ravoire. Of the events that caused damage in both catchments, 69% were triggered by consecutive rainy days (between 2 and 6 days of rain on average) recorded by the meteorological stations at Saint-Martin and Briançon. Six percent were triggered by a single rainy day with daily cumulated precipitation < 20 mm and 12% of events were triggered but no rainfall event was recorded at the weather stations. This can be explained by localized rainfall such as storms. Finally, no information concerning the weather was available for 13% of the events.

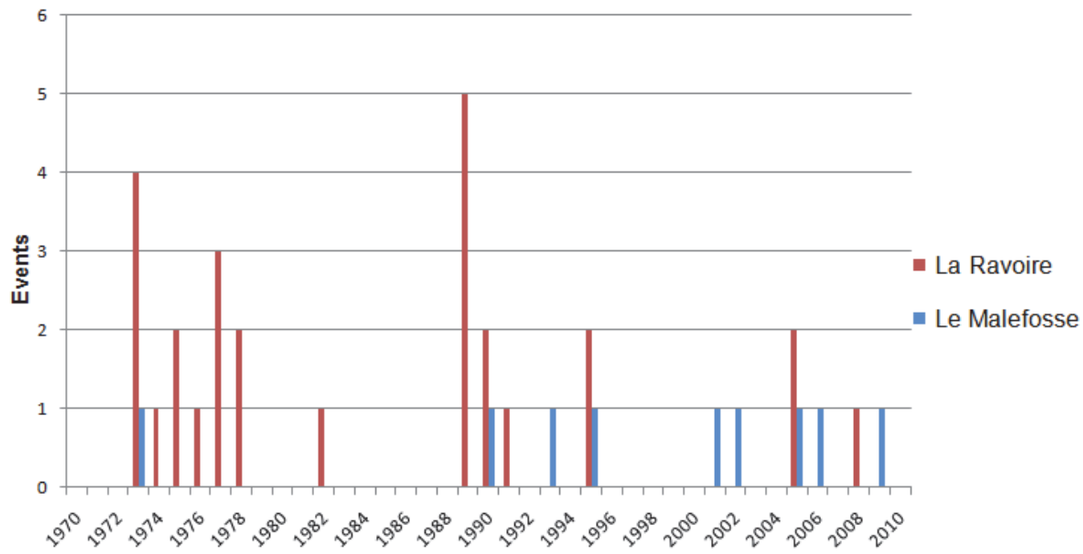


Fig. 9. Debris flow triggering at La Ravoire and Le Malefosse catchments since 1970.

Results of the analysis of damage caused by DF activity is shown in figure 10. In both catchments, the main physical damage was caused by rock debris transported by DF and deposited on roads in around 60% of documented cases in both catchments. The other damage to roads (21%) was reported but no details were given. The PFmax scale highlighted the lack of a precise description of the functional disturbance in about 60% of documented cases. This result can be explained by the fact that the evaluation was made just after the DF was triggered and it is often very difficult to predict the real consequences of impacts over a long period, and thus to quantify functional disturbances. However La Ravoire underwent a large proportion of serious perturbations with an interruption of road traffic of several hours. Finally, the ISRI scale revealed a large proportion of major incidents that affected the rail traffic and safety. Functional disturbances caused by this damage usually involved delays or temporary breaks in rail traffic. The consequences were operating losses and economic losses due to the immobilization of rolling stock. Moreover, in the case of a temporary interruption of rail traffic, the rail network owner (SNCF) must provide alternative means of transport (bus, taxi, transfer to other rail lines, etc.). The rail network thus appears to be the most vulnerable in terms of the intensity of disturbances caused by the La Ravoire torrent, although the number of impacts on the road network was higher.

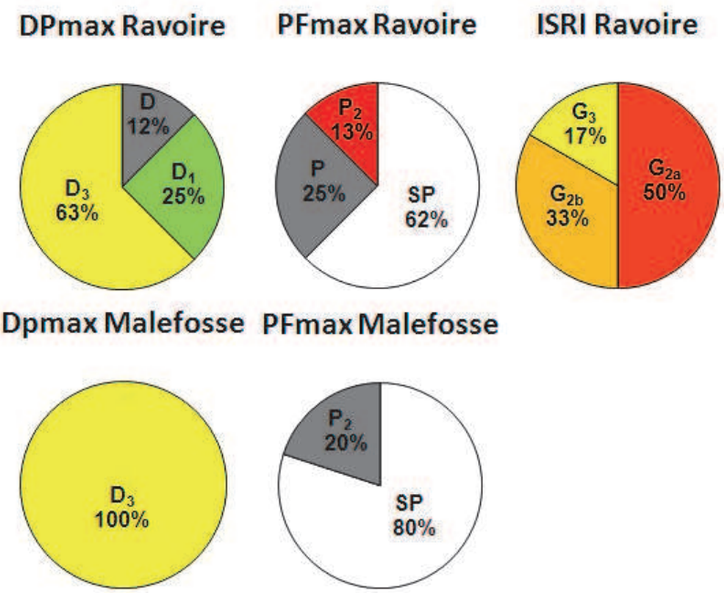


Fig. 10. Distribution of physical and functional damages (La Ravoire and Malefosse catchments) and rail incidents (La Ravoire catchment).

The sudden triggering of DF makes it difficult to manage and forecast the associated risk. Consequently, a large number of measures have been taken to reduce damage to infrastructures caused by DF in high risk areas. Pontamafrey village, which is located on the debris fan of La Ravoire, provides an illustration of possible network protection strategies (fig. 8). The village has a bypass system for the railroad (2.2 km long), with a drawbridge to allow trains to pass in the case of interruption of the normal railroad caused by a DF event. The road is also equipped with a drawbridge that is automatically activated by the torrent detection systems located upstream on the La Ravoire river. The total cost of these installations was 3,774,000 € (Cojean et al., 2002). However, the cost of damage caused by DF before the construction of the protective structures rose to 4,548,000 € ((Cojean et al., 2002). This example highlights the need for assessment and management systems to reduce network vulnerability.

7. Discussion

In this paper, we compared the geomorphic characteristics of debris floods and debris avalanches in the same alpine region and the relationships with climate conditions responsible for their triggering. The climatic trend observed in the French Alps was characterized by analyzing data on extreme summer rainfall events recorded daily at 16 stations located in Hautes-Alpes, Savoie and Alpes de Haute-Provence departments since 1970. According to the generalized Pareto law (GPD) our results showed that extreme summer rainfall events increased significantly in the region. In addition, there was a significant increase in annual and seasonal temperatures in the last 20 years combined with a significant reduction in the number of freezing days. The occurrence of DF and DA exhibited two different trends depending on elevation. At low altitudes (< 2 200 m) the number of DF and DA decreased significantly since the 1980s, whereas at high altitude (> 2 200 m), it increased. Over the same period there was a significant increase in DF activity.

However, despite this common trend in DF and DA activity, modeling revealed that the climatic parameters responsible for the triggering of DF and DA differed. The frequency of triggered DA depends mainly on summer rainy events greater than 20 mm/day and minimum temperatures while that of DF depends on mean summer temperatures and the number of rainy days. The role of intense or long duration precipitation in triggering debris flows has been known for a long time. The data we analyzed do not differ from this rule. However, it is difficult to interpret the fact that DA are mainly caused by extreme events while DF are mainly caused by long duration precipitation. Extreme rainy events were an explanatory factor in DF activity that was less significant than the number of rainy days. In addition, laboratory experiments and model results revealed that the morphometric characteristics of the catchment area (channel confinement for instance) play a significant role in the dynamics of debris flows and depositional structures. In particular, debris flow behavior evolves in response to changing pore pressures that depends on a combination of morphosedimentological characteristics and water infiltration *(*Major & Iverson 1999; Marr, et al., 2001). Consequently it is probable that the differences in slope inclination between DA and DF as well as the confinement/non-confinement of the channel may be an explanation (Hampton, 1975) but the scale at which measurements were made in this study did allow us to check this hypothesis. Indeed, we were unable to measure the local topography which has an influence on the behavior of debris flow initiation (Blijenberg, 1998). Differences between the granulometrical characteristics of DF and DA triggering zones which were impossible to quantify at the large spatial scale considered in this study as well as probable differences in the amount of precipitation between meteorological data collected at low elevations and data collected in the triggering zone may also be relevant. Indeed, summer storms responsible for extreme rainy events are often local and are consequently not always recorded by meteorological station pluviometers. It is also interesting to note that both DA and DF triggering were sensitive to temperature. This parameter is rarely considered as significant in the literature. Some cases studies in the Alps revealed a relationship between the rapid snow melt and/or glacier retreat and permafrost degradation induced by a temperature and the triggering of debris flows (Haeberli & Beniston, 1998; Wegmann et al., 1998; Imhof et al., 2000; Bardou & Delaloye, 2004). Permafrost degradation may be a relevant explanation for the high altitude DF and DA triggering selected in this study. As the mean altitude of the triggering zone of DA is about 2 200 m in this region close to the 0°C isotherm, the significant trend observed for high altitude DA activity (fig. 5) suggests a change in the mobilization of rock debris triggered by warmer temperatures. Such an increase in temperature at high altitudes has been demonstrated in recent decades by different authors working on homogenized series (Beniston et al., 1997; Diaz and Bradley, 1997; Böhm et al., 2001). It may also reflect the influence of temperature on the snow/rain limit with liquid precipitation occurring at high altitudes or possible changes in the duration of the snow cover, which may expose the high slopes to greater temperature variations. However one can wonder if this relationship is only due to the recent increase in temperature observed from the 1990s on. To test this hypothesis, we computed a logit analysis for the 1970-90 period. Results revealed that temperature was less important than rainfall but was nevertheless significant.

Another important aspect is the consequences of these changes in DF and DA activity for society. The analysis of DF and DA data revealed clear differences. No death was reported due to either DF or DA. However, the social impacts of DF were much greater than for DA mainly due to the fact that the DA deposit zone was located at low elevations, i.e. where there is permanent socio-economic activity.

8. Conclusion

The aim of this study was to analyze the morphometrical characteristics of DF and DA catchments and to compare the response of these two processes to climate change in recent decades (since the 1970s) in the French Alps. Two areas the Hautes-Alpes and Savoie regions, were selected. In the two areas, a total of 419 debris floods and debris avalanches occurred since the beginning of the 1970s. Significant geomorphic differences were observed between the two processes. The debris avalanches were "small scale" events according to the definition of Innes (1983). Located at high elevations, they occurred on steep slopes. By contrast, DF were much larger events triggered in larger catchment areas that spread to urbanized areas. A climate analysis was performed using data from 16 meteorological stations located in the area. This analysis revealed a significant increase in annual and seasonal temperatures in the 20 last years combined with a significant reduction in the number of freezing days. Changes in the frequency of summer rains were also observed. The response of debris flows and debris avalanches to this climate change was investigated. There was a significant increase in the occurrence of both processes at high elevations (> 2 200 m). In addition, logistic regression models were used to characterize the relationship between climate and the frequency of debris floods and debris avalanches. Results revealed that different climatic parameters are responsible for the triggering of DF and DA. We showed that the probably frequency of triggered DA depends mainly on summer rainy events greater than 20 mm/day while that of DF depends on the number of rainy days and mean seasonal temperature. Consequently, we observed a univocal response of DF and DA to recent climatic change because for both processes climate parameters responsible for their triggering changed. Finally an analysis of the socio-economic impacts of DF was performed. The results showed that such processes cause direct and indirect damages. By identifying the critical sections of road and rail networks and their strategic value in organizing the territory, this approach allowed us to characterize the types of impacts that are most frequently observed in these networks. Obstruction and degradation of roads with temporary interruption of traffic are the main types of damage. The cost of damage was also estimated. However, evaluating the vulnerability of the network has some limits, such as the lack of visibility and information available on the damage, particularly with respect to functional disturbances whose consequences extend beyond the area of the event.

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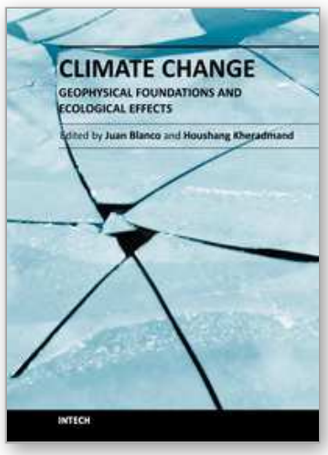
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Climate Change - Geophysical Foundations and Ecological Effects

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This book offers an interdisciplinary view of the biophysical issues related to climate change. Climate change is a phenomenon by which the long-term averages of weather events (i.e. temperature, precipitation, wind speed, etc.) that define the climate of a region are not constant but change over time. There have been a series of past periods of climatic change, registered in historical or paleoecological records. In the first section of this book, a series of state-of-the-art research projects explore the biophysical causes for climate change and the techniques currently being used and developed for its detection in several regions of the world. The second section of the book explores the effects that have been reported already on the flora and fauna in different ecosystems around the globe. Among them, the ecosystems and landscapes in arctic and alpine regions are expected to be among the most affected by the change in climate, as they will suffer the more intense changes. The final section of this book explores in detail those issues.

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