ATMOSPHERIC PATTERNS LEADING MAJOR AVALANCHE EPISODES IN THE EASTERN PYRENEES AND ESTIMATING OCCURRENCE

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ABSTRACT: The occurrence of major avalanche episodes in the Eastern Pyrenees (NE Spain) is estimated by means of the Poisson and the negative binomial distributions, assuming that they are rare events. The differences observed in their spatial distribution along the seven regions in which Eastern Pyrenees have been divided, suggests us to look for spatial variations in the relationship between extreme avalanche episodes and synoptic patterns. Applying principal-component analysis procedure, atmospheric patterns at 500 hPa geopotential height leading major avalanches have been obtained. Looking at their pressure anomalies at 500 hPa, the relation of these patterns respect to the normal atmospheric conditions can be assessed.

KEY WORDS: major avalanches, atmospheric patterns, principal-component analysis, Pyrenees.

1. INTRODUCTION

In the Eastern Pyrenees (NE Spain), the growth of tourism in recent decades, has resulted in an increase in house building, opening of mountain roads during winter and a spreading of associated infrastructures. The policy of territorial planning aims to develop new ski resorts in the Eastern Pyrenees and to build thousands of new lodgings. As a consequence, exposure to natural hazards has increased and so the risk; its trend is to rise. Studies dealing with avalanche situations in Pyrenees are very scarce, usually from a study-cases point of view.

Frequently, the occurrence of rare events in meteorological subjects has been attained by the application of the Poisson and the negative binomial distributions (Thom, 1966; Sakamoto, 1973). This paper applies these models to the annual probability of major avalanches episodes, considering a major avalanches episode as a discrete natural event (Hewit, 1970). Generally, in snow avalanche matter, Poisson distribution has been used to model the arrival rate of avalanches (McCLung, 2000).

Studies for specific sites analysing the relationship between regional atmospheric circulation patterns and avalanche data has been undertaken by Fitzharris (1981) and Mock (1996) as two examples.

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More recently, Birkeland (2001) has emphasized that differences in avalanche activity with distinctive atmospheric conditions can be observed even in sites located in a similar intermountain avalanche climate. His conclusions remark that the local topography explains the different effects of synoptic patterns on avalanches. He also proposes a methodology inspiring the present contribution.

In the Alps, studies taking into account circulation patterns to explain major avalanches in a regional scale have been developed by Hächler (1987) in the Swiss Alps. He differenced circulation patterns responsible of severe avalanches in the Northern and Southern Alps focusing on both geographical factors as distance from the nearest sea, and mountains disposition and dynamic factors as the direction of the upper-level airflow. In the French Alps, Villecrose (2001) showed the difficulty of comparing major avalanche situations when studying the main catastrophic crisis in the French Alps. This study tries to define and to compare extreme situations by means of quantitative avalanche activity, damages, number of fatalities and depth of fresh snow. It concludes that those parameters are not enough and they must be put in relation with the snow and weather context.

There are few works focused on Pyrenees. Some internal reports from the Geological Institute of Catalonia (IGC) (www.igc.cat/allaus) have shown the relative magnitude of each major avalanche winter looking at the intensity and geographical extension of the major avalanches recorded for each winter. Studies focused in relating synoptic conditions and avalanches are very scarce; Esteban et al. (2007) analyze study-cases and

García et al. (2007) proposes one classification of synoptic patterns producing major avalanches, but doesn't use any statistical method to typing.

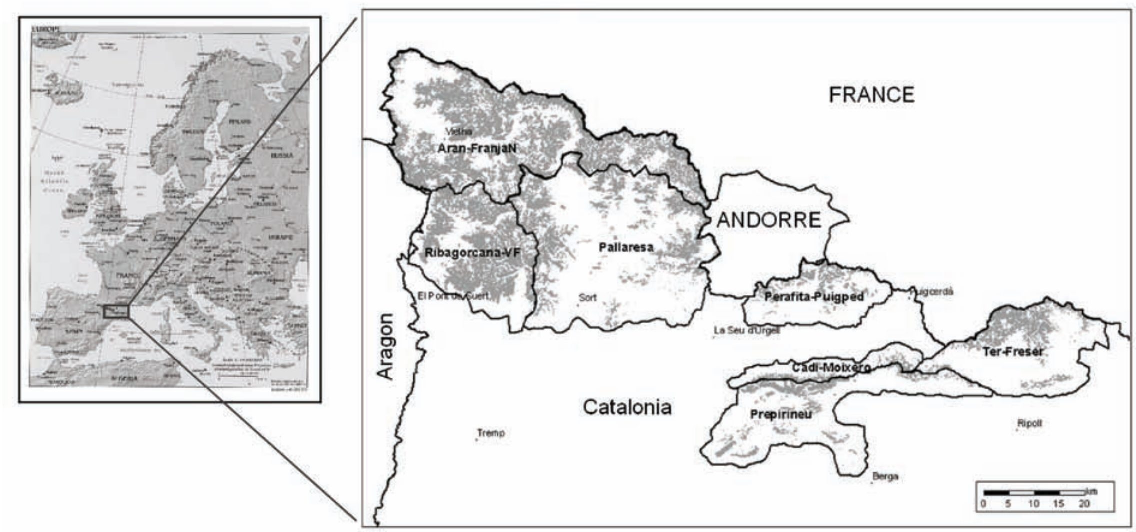

Figure 1. The Eastern Pyrenees location. The range has been divided in seven nivoclimatic regions. Avalanche coverture is also shown.

The purpose of this study is to contribute to better understand the occurrence of major avalanche episodes in the Eastern Pyrenees and their relation with atmospheric circulation patterns. First of all, we have tested if major avalanches episodes might be considered rare events such as hail days or, for instance, snowing days at sea level in the Mediterranean climate context where this study is included. Different models of distribution have been applied to describe the observed distribution of major avalanches episodes in this range. Second, multivariate statistical analyses have been used to determine which synoptic situations are responsible of major avalanche episodes in the Eastern Pyrenees.

2. STUDY AREA

The Pyrenees constitute a mountainous system of about 450 km from the Atlantic Ocean (west) to the Mediterranean Sea (east). They rise from the isthmus that links the Iberian Peninsula with the rest of the Euro Asiatic continent. The study area, Eastern Pyrenees, is located in the eastern half of the range, specifically in the southern side since northern one belongs to France. It spreads 146 km long and ranging from 52 to 19 km wide, diminishing towards the east. Highest elevations reach 3,000 m, but in general they range between 2,500 and 3,000 m. The timber line is located between 2,100 and 2,400 m aprox. The highest mountain villages are located from 1,500 m to lower altitudes. The highest winter opened roads reach 2,300 m and 9 alpine ski resorts spread on altitudes over 1,500 m height. At about 5 million people inhabit at less than 3 hours away by car, what gives an idea of vulnerability.

The Eastern Pyrenees has been divided in 7 regions attending to weather and snow conditions (figure 1). Avalanche coverture is shown too (Oller et al., 2006). These snow and avalanche regions are the empirical result of 15 years of avalanche forecasting and it is not a climatic classification in the stringent sense of the word since long data series don't exist. The singular geographical factors affecting the climate of the Eastern Pyrenees bears three different climatic conditions in a relatively small area (García et al., 2007). The relatively low latitude of the massif becomes the Pyrenees in a boundary range between the humid ocean climate and subtropical dry climate.

Three climatic conditions could be defined. The northwest part of the Eastern Pyrenees shows a humid ocean climate as the main river basin drains to the Atlantic Ocean through France. Precipitations are abundant and show a regular interannual distribution. The total amount of fresh snow at 2200 m height is about 500-600 cm per year. The oceanic influence crosses the range to the south face but diminishing quickly. Regular, moderate snowfalls lead high avalanche activity, being this area where the maximum natural avalanche activity takes place. So, climate gains continental features towards the south and east. Winter precipitation reduces being the winter the driest season and snow precipitation increases in the equinoctial seasons. Interannual variability of precipitation increases. The total amount of fresh snow at 2200 m height exceeds slightly 250 cm per year. Predominant winds come from north and northwest, often with gusts over 100 km/h. Snow cover depth is scarce, unstable structure on shadow slopes persists and wind slabs are frequent. Oceanic influence disappears completely in the most eastern part of the Eastern Pyrenees and Mediterranean Sea influence plays a significant role. It means heavy snowfalls, but seldom, due to lows centred on the Mediterranean Sea blowing very humid, maritime flow from the east. Interannual variability of snowfalls is very high. The total amount of fresh snow at 2200 m height is about 350-450 cm per year. Predominant winds come from north (*mistral*, or locally *tramuntana)* and maximum gusts sometimes exceed 200 km/h at 2200 m height due to the formation of a persistent low in the lee-side of the Alps over the Lion Gulf. Snow pack distribution is scarce and it often coexists with nude terrain above timber line due to the persistent wind. Hard slabs on lee sides are frequent.

The nivoclimatic regions in which Eastern Pyrenees has been divided are, from west to east: “*Aran-Northern border of Pallaresa, AP*” (Oceanic conditions); “*Ribagorçana-Vall Fosca, RF*”, “*Pallaresa, PL*”, “*Perafita-Puigpedrós, PP*”, “*Cadí Moixeró, CM*” (Intermountain conditions); “*Prepirineu, PR*” and “*Ter-Freser, TF*” (Mediterranean influence).

3. DATA AND METHODOLOGY

Major avalanches episodes are counted from 1970-71 to 2007-08 winter seasons, it means a series of 38 years. A major avalanche episode is defined as the occurrence interval of time (minimum one day) of at least one extreme avalanche registered. Episodes of exclusively major avalanches triggered by explosives have been rejected. We have considered major avalanches in a wide sense, as defined by Schaerer (1986), avalanches larger than usual, arriving to the bottom of the valley, destroying mature forest or damaging structures.

The main drawback is the lack of meteorological and avalanche observations in high-mountain in the Eastern Pyrenees, before the avalanche warning service began in 1989. That’s why an essential part of this work is to look for major avalanche events in the past, it means, dating and localizing. So this study builds on the research achieved by Muntán et al. (2004), where a new method based on dendrogeomorphology has been developed to detect evidence from past disturbances and to identify major avalanches episodes and their spatial extension.

In addition to annual resolution, extreme avalanches have been systematically dated in a daily resolution from 1996 till now. In 1996 the Nivometeorological Observers Network (NIVOBS) of the IGC begun a winter surveillance making transects every day to report snow conditions and avalanche events. All the episodes have been dated and mapped due to systematic observations in all the seven regions pointed out, even by means of helicopter flights. Monthly or weekly resolution on avalanche dating prevails from 1986 to 1996. Before 1986, avalanche dating is scarce and without continuity and data comes from enquiries to inhabitants; annual and monthly resolution prevails. To sum up all, major avalanche episodes have been dated by means of population enquiries, historical documentation, dendrochronology and observations from NIVOBS.

To find out the theoretical probability of a major avalanche episode occurrence, a test of hypothesis using the Kolmogorov-Smirnov test of goodness of fit with critical values of the Lilliefors test, at the 0,05 level of significance, is applied to know whether the Poisson or the negative binomial distribution are adequate for the occurrence of major avalanches episodes at year. The probability function for the Poisson distribution is given by:

$$f(x) = \lambda^x \frac{e^{-\lambda}}{x!}$$

where λ is the population mean and x is the number of events.

The negative binomial probability function is more suitable for events which show a certain dependency among them to occur. The negative binomial probability function is given by:

$$f(x) = \frac{\Gamma(x+k)}{\Gamma(x+1)\Gamma(k)} \cdot \frac{p^x}{(1+p)^{k+x}}$$

where x is the number of events at year, and k and p are the parameters of the distribution.

Regarding to the analyse of circulation patterns leading major avalanches episodes, daily atmospheric circulation data at synoptic scale have been selected from the NCEP-NCAR reanalysis data (Kalnay and others, 1996) by using maps of 500 hPa pressure height. The obtained series of pressure values comprises from 1970-71 to 2007-08 winter seasons (Dec. to Mar.). The grid ranges from 70º-30º latitude N and from 30ºW to 20ºE longitude with a spatial resolution of 2,5º per 2,5º, that is the North Atlantic-Western Europe zone. Due to the lack of daily meteorological database recorded on the ground in high-mountain we have decided to analyse the 500 hPa geopotential height for the position of troughs and ridges, general flows, cut-off lows, dynamics and thermal anticyclones, which control the weather at synoptic scale and affects the evolution of the snow cover. Besides this atmospheric level involves a strong inertial component in the time, which usually concatenates certain weather regimes well-known at surface level in the Pyrenees (Romero et al., 1999; Esteban et al., 2005).

We used principal-component analysis (PCA) in the T-mode data matrix, where the variables consisted of the pressure values for the 357 points of the grid and the cases consisted of the days from 1970-71 to 2007-08 winter seasons (Dec. to Mar.). The definitive number of components was decided by means of the Kaiser-Meyer-Olkin's measure of sampling adequacy, Bartlett's test, the explained variance criteria and Scree test. The next step was to rotate the components by a varimax method to aid both in interpretability of the low-variance principal components and in raising their loadings. One component is got by means of the negative phase of some data sets, once they have been put to the parametric ANOVA test which has confirmed no significant statistical differences between them.

Finally, we have mapped the pressure anomalies at 500 hPa level for each principal component respect to the average distribution of pressure for the winter seasons corresponding to the 1970-71 to 2006-07 period. This operation consist of subtracting the standardized values of the average 500 hPa values of each component representing all the extreme avalanche episodes from the daily average of the 1970-71 to 2006-07 period, previously extracting the avalanche episodes dates. The purpose is to observe the relationship between the atmospheric circulation patterns leading extreme avalanches and the average atmospheric conditions. The pressure anomaly maps gives an idea of the role that the North Atlantic Oscillation index (NAOi) plays in the occurrence of extreme avalanche episodes in the Eastern Pyrennees. The NAO, as a low frequency circulation pattern, determines strongly the variability of the temperature and precipitation behaviour in Europe (Osborn and others, 1999; Beniston and others, 1996). The interest of connecting extreme avalanche episodes with NAOi lies in the fact of NAOi for the next winter seems to be predictable at medium term with a reasonable level of confidence (www.cru.uea.ac.uk).

4. RESULTS AND DISCUSSION

Results in figure 2 show that the annual probability of recording at least one extreme avalanche episode in the Eastern Pyrenees is 64% (Poisson model) or 62% (negative binomial model). The best fit with the test Kolmogorov-Smirnov and Lilliefors critical values at the 0.05 level of significance, corresponds to the Poisson distribution; maximum absolute value of the differences between observed and calculated accumulate frequencies is 0.069 for Poisson and 0.087 for negative binomial.

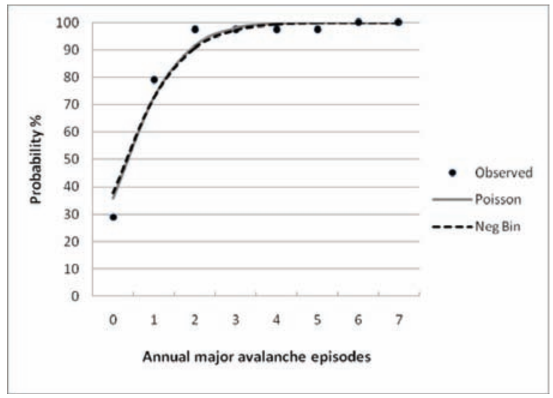

Figure 2. Comparison of the observed cumulative frequencies of annual extreme avalanches episodes with the theoretical probabilities for the Poisson and negative binomial distributions in the Eastern Pyrenees (1970/71-2007/08).

Results in table 1 show that it is more probable to register at least one major avalanche episode than no one. Major snow avalanches in the Eastern Pyrenees are a rare natural event but not exceptional. The maximum observed major avalanche activity took place in the winter 1995-96 when 6 episodes were registered and 144 extreme avalanches were mapped.

Nº Episodes	fi	Obs. Prob.	Calc. Prob.	
			Poisson	Neg. Bin
0	11	0.289	0.358	0.376
1	19	0.500	0.368	0.351
2	7	0.184	0.189	0.179
3	0	0.000	0.065	0.067
4	0	0.000	0.017	0.020
5	0	0.000	0.003	0.005
6	1	0.026	0.001	0.001
7	0	0.000	0.000	0.000

Table 1. Observed and calculated annual probabilities by Poisson and negative binomial models of number of major avalanches episodes in the Eastern Pyrenees (1970/71-2007/08).

The annual frequency of major avalanches episodes varies widely from one region to another in Eastern Pyrenees, in spite of the fact that they are very similar in latitude and distance (Table 2). The region of oceanic climate (*Aran-Northern border of Pallars*, *AR*) shows the highest probability of suffering at least one episode at year (44%). The probability diminishes drastically to the eastern, intermountain climate regions with calculated frequencies less than 15% of having at least one annual episode (*Perafita-Puigpedrós*, *PP*; *Cadí-Moixeró*, *CM*). Extreme avalanches could be considered an exceptional natural event in the region *Prepirineu* (*PR*), where an annual probability of 3% is expected. In this case, topographic features play an outstanding role since summits rarely exceed the timber line. Moving towards the east, close to Mediterranean Sea, the annual probability of at least one annual extreme avalanche episode increases again till 25% (*Ter-Freser, TF*), linked probably to cyclogenetic processes characteristic of Western Mediterranean Sea. This broad regional variability allows us to look for spatial variations in the relationship between extreme avalanche episodes and synoptic patterns.

Nº	Regions						
Epis.	AR	RF	PL	PP	CM	PR	TF
0	0.560	0.692	0.789	0.974	0.854	0.900	0.749
1	0.324	0.255	0.187	0.026	0.135	0.095	0.217
2	0.094	0.047	0.022	0.000	0.011	0.005	0.031
3	0.018	0.006	0.002	0.000	0.001	0.000	0.003
4	0.003	0.001	0.000	0.000	0.000	0.000	0.000

Table 2. Calculated annual probabilities by Poisson model of number of major avalanches episodes for the 7 regions of the Eastern Pyrenees (1970/71-2007/08).

Applying PCA, the extreme avalanche episodes are gathered in six principal components, which explain the 94% of the total variance. The first component, representing the 39% of the total variance, identifies northern and north-western advections over the Eastern Pyrenees. The composite-anomaly map of component 1 shows the minimum anomalies respect to the average atmospheric circulation and it can be considered as a relatively frequent weather situation (Figure 2, upper). It is linked to positive and neutral NAOi. Its spatial extend in terms of major avalanche releasing is the widest, affecting all the regions, but mainly *Aran-Northern border of Pallars* (AR), 34% of the cases (Table 3). Generally, the Azores high pressures are extended in a north-south axis over the Atlantic Ocean, while a deep low pressure is located on the axis Baltic Sea-Italian Peninsula. This configuration pumps either an artic or a maritime polar air mass over the Pyrenees. This pattern generates very low temperatures (-15º to -20ºC at 2200 m height), intense snowfalls, strong winds and very active drift snow processes. A snowfall about 100-150 cm in 24 hours were recorded in *Aran-Northern border of Pallars* (January 2003). Major powder avalanches are frequent, but restricted to this region. Precipitation gradient decreases strongly towards the south and east. In the rest of the regions, major slab avalanches prevail specially located in southern slopes due to the enormous overloading of drifted snow deposited on lee side aspects, but exclusively if fresh snow on the ground previously exists.

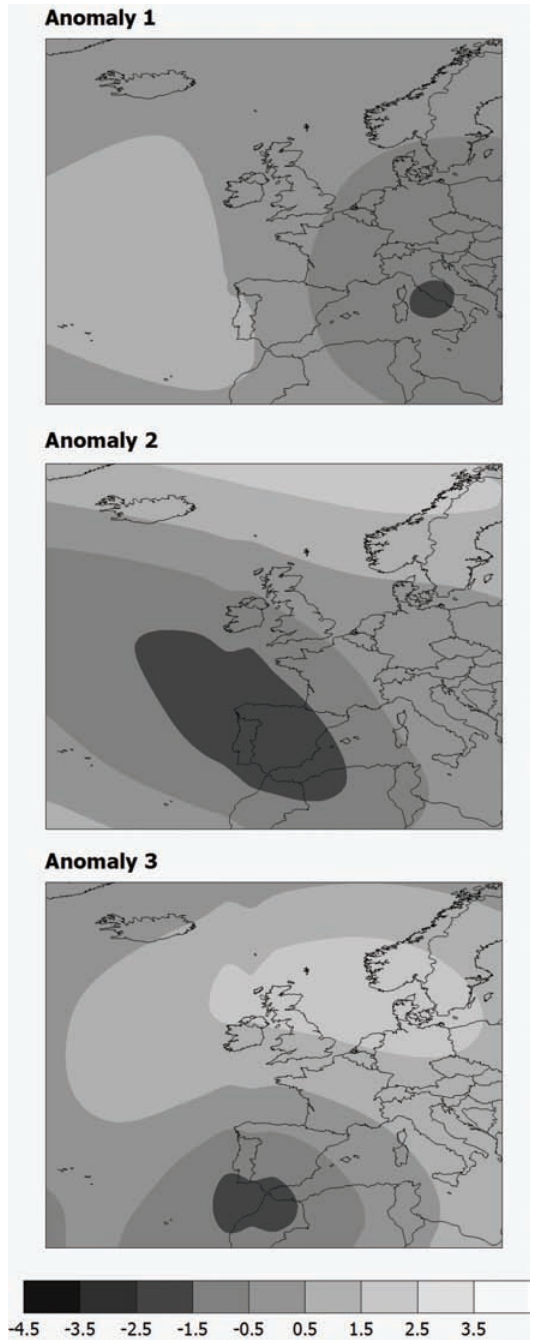

Figure 2. Anomaly maps of pressure at 500 hPa level corresponding to components 1, 2 and 3 (standardized values), respect to average atmospheric conditions.

The next two components gather a 31% of the total variance, sharing a similar weight. These components are the main atmospheric patterns producing major avalanche episodes in the most eastern regions of the study site (*Cadi-Moixeró, Prepirineu and Ter-Freser*). The component 2 is defined by an outstanding negative anomaly in the pressure distribution over the Iberian Peninsula is detected (Figure 2, middle).

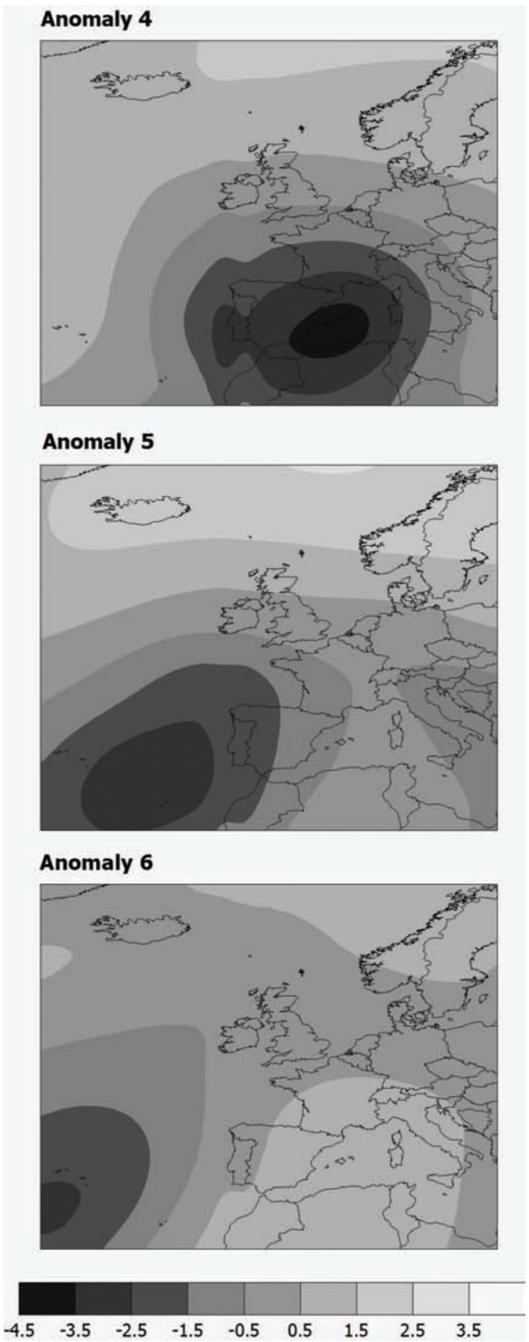

Figure 3. Anomaly maps of pressure at 500 hPa level corresponding to components 4, 5 and 6 (standardized values), respect to average atmospheric conditions.

Atmospheric circulation is characterized by a long trough at 500 hPa exhibiting an oblique axis NW-SE, due to the Siberian high over Europe which diverts troughs to the Mediterranean basin. Normally, it yields a small low at surface level in front of the Eastern coast. Humid, maritime flow on surface produces heavy precipitations in the regions closest to the Mediterranean Sea. Instability is high due to the contrast between cold air at 500 hPa and relatively warm air mass at low levels. The snowpack usually contains weak layers with depth hoar and faceted grains before fresh snow arrives, since low temperatures and strong irradiation has prevailed below the Siberian high pressures influence. So, avalanche activity is favoured due to the surcharge of new fallen snow.The component 3 is explained by a blocking high pressures situation at 500 hPa over Central Europe and a cut-off low centred over the south of the Iberian Peninsula-North of Africa. The composite-anomaly map diverges markedly from the average synoptic conditions (Figure 3, lower), an average anomaly of 1.0 absolute value for each grid point. We want to focus on mesoescalar meteorological phenomena with strong consequences in avalanche dynamic observed in this component. Differences respect to component 2 is that high pressures existed on surface (1015-1020 hPa) over the Pyrenees, but cyclonic circulation rules on upper levels. As component 2, a warm and very humid Mediterranean flow on surface penetrates from the east affecting the regions closest to the Mediterranean Sea, even also distant regions as *Ribagorçana-Vallfosca* well-faced south. Amounts of precipitation about 400 mm (SWE) were recorded during four days in regions of meditarranean influence in December 1991, with snow level around 1800-2000 m height. Extreme avalanches of wet loose snow felt dawn in *Ter-Freser*, the nearest region to Mediterranean Sea. Eastern advection is a synoptic pattern observed usually in September-October giving torrential precipitations in coastal mountain ranges but seldom in winter (Jansà, 1990).

The last three components account for the remaining 15% of total variance. The component 4 shows an exceptional anomaly over the Eastern Pyrenees (Figure 3, upper) so long as a deep, very cold core low at 500 hPa appears. It also reflects a deep low on surface levels. Northern, strong winds and heavy snowfalls affect not only Pyrenees but also the coastal line. Extreme powder avalanches were registered in disparate regions.

The component 5 exhibits the maximum anomaly at 500 hPa (Figure 3, middle) in absolute values (average of 1.3 for all the grid points). A wide low pressure is located at high and low levels in the west of the Iberian Peninsula. From surface to upper levels south and south-western winds flow carrying warm and humid air from Atlantic and even Mediterranean on lower levels over the Pyrenees. The most intense major avalanche episode occurred at the end of 1996 January due to a south-western advection situation. Many major avalanches of fresh, humid and dense snow felt down few hours after the precipitation. Four regions were affected by major avalanches. Timber analysis of died trees by the avalanches indicated ages about 80 years old. A maximum snowfall of 220 mm of snow water equivalent (SWE) in 24 hours was registered and many other exceeding 150 mm of SWE in several regions due to processes of convective cells growth. It means Gumbel recurrence periods exceeding 100 years. As Esteban et al. (2005) have shown heavy precipitations even torrential affect the southern side of the Pyrenees in such synoptic circulation pattern. Nevertheless, snow is registered only in the highest elevations, normally over 2200 m height.

Finally, the component 6 is linked to melting major avalanche episodes. It's the only component reflecting pressures at 500 hPa higher than usual over the Pyrenees. That is why a ridge from the subtropical anticyclonic belt spreads further north over the Western Mediterranean Sea. Usually a warm advection at low levels (850, 700 hPa) gets right into the Pyrenees. Snow cover suffers melting processes suddenly and major avalanches have felt down when the inner layers still contained cold, persistent grains. This component leading major avalanches has been observed in late March after cold winters.

Comp.	Regions							
	AR	RF	PL	PP	CM	PR	TF	Total
1	8	5	4	1	1	1	2	22
2	2	0	1	0	2	2	1	8
3	0	3	1	0	1	1	2	8
4	0	1	0	0	0	0	1	2
5	1	2	1	0	0	0	1	5
6	1	0	0	0	1	0	0	2
Total	12	11	7	1	5	4	7	47

Table 3. Regions affected for every component (one episode can affect more than one region).

Results highlight the differences in the spatial capability of each component in yielding major avalanche activity in the Eastern Pyrenees. Geographical and climatic factors account for the spatial variability. Among the former, the zonal alignment of the axial range lets the retention of humid air masses, both polar and artic from north advections, and tropical air masses from south and southwest flows. The meridian valleys configuration favours the penetration and the placement of the unstable air masses pointed out; the forced lifts by the relief sometimes result on heavy and persistent snowfalls, even stationary convective cells. The proximity to Mediterranean Sea and less to the Atlantic Ocean avoids extreme temperatures as it occurs in inland ranges but surprisingly extensive precipitation shadows exist as well. Among the latter factors, the relatively low latitude of the massif becomes the Pyrenees in a oscillating boundary between the humid ocean climate due to dynamic lows and dry climate associated to subtropical semi-permanent anticyclone belt.

Relationship between winter precipitation and NAOi has been investigated in the Pyrenees (Martín-Vide and others, 1999; Esteban and others, 2001) and results show a negative correlation. The 500 hPa composite-anomaly maps of the principal components leading major avalanches likely suggest more probable major avalanche episodes for negative phase of NAO, since components 2, 3, 4 and 5 occurs when positive anomalies are detected over Iceland and negative over Gibraltar (South of the Iberian Peninsula). These components gather the most part of the total explained variance. It's interesting to note that the 1995-96 winter season, the maximum in major avalanches activity, broke the record of NAOi negative anomaly (-2.35) from 1970 till 2008.

5. CONCLUSIONS

This contribution studied major avalanches activity without long-term snow-climatic database. We have recourse to annual resolution by inquiring into dendro-geomorphological methods and found out daily dating in historical documentation and by means of systematic population enquiring. Thanks to this approach, for the first time values statistically significant of occurrence probability of major avalanches activity is furnished at regional scale for the Eastern Pyrenees. It should promote and reinforce planning actions in forecasting and land-zoning the avalanche hazard in Spain.

Dating extreme avalanches episodes has allowed a classification of related synoptic patterns by means of PCA, which will improve the forecasting tasks. Moreover the calculated anomalies of pressures at 500 hPa level for each principal-component lets know the relationship of this atmospheric types with low-frequency patterns that indicate weather trends at medium-term, as NAO for the Pyrenees.

In spite of being a small geographical area compared to Rocky or Alps, results in occurrence probability and extend of atmospheric patterns reflect also a significant spatial variability, which must be taken into account w applying defence strategies.

However, the challenge is making progress in the accurate identification of the snow structure and stability conditions to assess the effectiveness of each atmospheric pattern associated to extreme avalanches.

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