ABSTRACT: This study investigated the influence of the precipitation and temperature variability during the days before of the occurrence of major avalanche activity in the Eastern Pyrenees. To establish the character of the combined precipitation and temperature, we used four modes (cold/dry, cold/wet, warm/dry and warm/wet) by means of a joint quantile approach. The cold/dry mode showed the highest frequency during the days before the major avalanche episodes in the Mediterranean area, while in the Oceanic area precipitation modes are more linked to major avalanche activity. Thus, winter modes could be a proxy to know snow cover sensitivity to major avalanches in case of lack of stability test on the field. Afterwards, the evolution of the four combined precipitation and temperature categories during the last decades was compared to the observed one into the Swiss Alps.

KEYWORDS: avalanche, climate, Pyrenees, winter modes.

1 INTRODUCTION

The aim of this work is to assay whether combined temperature and precipitation winter modes can be a proxy data to aid in avalanche forecasting when measurements of the mechanical and structural snowpack conditions are not available. Afterwards, the evolution of the winter modes related to major avalanches in the last decades is assessed.

Many studies have shown how the average conditions of mountain snow cover may change in a "warm climate" by the end of the 21st century in the Alps (Beniston et al., 2003; Uhlmann et al., 2009) and in Mediterranean mountains (López-Moreno et al., 2011). However, there is a lack of studies that focuses on the effects of climatic conditions on stability conditions of the snowpack to trigger avalanche activity. This study investigated the influence of the precipitation and temperature variability during the days before of the occurrence of major avalanche activity. Snowpack structure is the result of the effects of the meteorological factors on the snow which are continuously transforming the shape of the snow grains and their mechanical conditions. Meteorological conditions can act as preparatory factors to unstabilize the snowpack conditions in a daily scale contributing to avalanche activity.

Temperature and precipitation variability can develop weak layers day by day, but they also can act as triggering factors in case of heavy snowfalls, rain or heating. A hot point is that meteorological conditions not always act on the same way in terms of avalanche triggering as it depends of the previous state of the snowpack conditions. So temperature and precipitation variability in a temporal scale becomes a stable snowpack into unstable and vice versa.

Joint distributions of temperature and precipitation were used in this study to better understand the evolution of the snowpack structure and they capability of triggering avalanches. Combinations of temperature and precipitation in four modes such as cold/dry (CD), cold/wet (CW), warm/dry (WD) and warm/wet (WW) are identified at a daily time scale to assess the relationship between the major avalanche activity and the weather. This assessment was done not only in the day of the avalanche activity but also during the previous period, when the snowpack is affected by preparatory conditions that can favour avalanche activity. Afterwards, the evolution of the four combined precipitation and temperature categories established in the Eastern Pyrenees will be compared to the observed one into the Swiss Alps.

2 DATA AND METHODS

Climatic data of the Eastern Pyrenees (Figure 1) used in this study has been provided both by the Spanish National Agency of Meteorology (AEMET) and the Meteorological Survey of Catalonia (SMC). Chosen stations range from 1000 m to 2300 m height and stretching from
the western part of the study area where Oceanic climate conditions prevail to the eastern-most part ruled by Mediterranean climate conditions. They consist on 4 stations: Vielha (1002 m) and Bonaigua (2266 m) located in the Oceanic area, La Molina (1704 m) and Vall de Núria (1967 m) sited in the Mediterranean area. They cover the 1970-2012 winter periods from November to April, when the most of the major avalanche activity has been observed.

Figure 1. Map of the Eastern Pyrenees and the study areas.

Tolerance and internal consistence tests have been applied to precipitation and temperature data sets (Esteban et al., 2012). For the Mediterranean area a unique climatic series has been built from 1970 to 2012 by means of a linear regression model. The major avalanches dataset comes from the Geological Institute of Catalonia. This dataset consists on major avalanches episodes registered from 1970-71 till 2006-2007 winter seasons (Nov. to Apr.). A major avalanche cycle (MAC) is defined as the occurrence interval of time under same synoptic conditions (minimum one day is considered) when at least one major avalanche has been registered (artificial triggering events have been rejected) (García-Sellés et al., 2009). 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; all considered avalanches travelled further than 1000 m from the starting zone to the run out zone. Finally, 17 MAC have been treated, 11 occurred into the Mediterranean area and 6 into the Oceanic.

To establish the character of the combined precipitation and temperature during the days before the avalanche episodes occurred, we used the joint quantile approach defined by Beniston and Goyette (2007) and applied by López-Moreno et al. (2011). The 60% and 40% joint quantiles were calculated to define specific winter modes: CD (cold/dray) when the joint quantiles were equal to or below $T_{40}P_{40}$, being the subscript the quantile threshold; CW (cold/wet) $T_{40}P_{80}$; WD (warm/dry) $T_{80}P_{40}$ and WW (warm/wet) $T_{80}P_{80}$. Precipitation quantiles have been calculated only from days with $P>0$ and all the $P=0$ days are considered as dry days. Daily winter modes have been calculated for the period Nov-Apr.

When major avalanches occur, our hypothesis is that internal layering of the snowpack, borne from the past weather conditions, plays a role as decisive as the weather conditions governing the major avalanche activity day. Typical assumed direct causes of major natural avalanches such as heavy snowfalls or intense and persistent rain not always work in the same way due to the sensitivity of the internal conditions of the snowpack, which is modelled by long term weather conditions (García-Sellés et al., 2010). So, the previous 72 h snow height before an avalanche cycle is a main condition but not enough to lead a MAC, as it was stated by Villecrose (2001) when analyzing the catastrophic cycle of February 99 in the French Alps. It is of our interest to know the temperature and precipitation combination during the days before the major avalanche episode since they rule the sensitivity of the snow layers in front of an overload; so, we paid attention to the 30 days previous to a MAC.

3 RESULTS AND DISCUSSION

The winter modes probability distribution functions both in Mediterranean and in Oceanic regimes during the 1970-2011 period are the same (Table 1). WD mode was the highest (Mediterranean-Oceanic: 34%-32%) followed by CD (29%-23%), CW (7%-9%) and WW the lowest (3%-5%). The same distribution was observed in the Swiss Alps, where WD ranged 36% in the period 1960-1991 (Beniston et al., 2011). From here, the occurrence of high precipitation events shows a dependence from the temperature, in the sense of wettest days are linked to coldest days in both climatic areas.

It is interesting to observe that significant differences appears in the 30 days sequences before a MAC with respect to the winter series, following different patterns in both areas (Table 2). So, with regard to the 30 days sequences before a MAC in the Mediterranean area, the thermal feature of the dry days was just the opposite being the cold/dry CD mode the highest daily frequency of occurrence (29%), followed by WD (23%), CW (12%) and finally WW (4%). In the Oceanic area prevails the same order for both series, the winter and the previous 30 days
to a major avalanche cycle, being WD, CD, CW and WW, but there is a quantitative increment of cold/wet days and doubles its percentage in the 30 days sequences before a major avalanche cycle.

<table>
<thead>
<tr>
<th>COMBINED MODES DISTRIBUTION IN THE WINTER SERIES (%)</th>
<th>Oceanic area</th>
<th>Mediterranean area</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD warm/dry</td>
<td>31,5</td>
<td>33,7</td>
</tr>
<tr>
<td>CD cold/dry</td>
<td>22,9</td>
<td>29,2</td>
</tr>
<tr>
<td>CW cold/wet</td>
<td>9,4</td>
<td>6,5</td>
</tr>
<tr>
<td>WW warm/wet</td>
<td>5,0</td>
<td>3,2</td>
</tr>
</tbody>
</table>

Table 1. Frequencies distribution of the combined modes in the winter series (1970-71/2010-11) for the Oceanic and Mediterranean areas.

<table>
<thead>
<tr>
<th>COMBINED MODES DISTRIBUTION IN THE PREVIOUS 30 DAYS OF A MAC (%)</th>
<th>Oceanic area</th>
<th>Mediterranean area</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD warm/dry</td>
<td>31,1</td>
<td>23,0</td>
</tr>
<tr>
<td>CD cold/dry</td>
<td>20,6</td>
<td>29,4</td>
</tr>
<tr>
<td>CW cold/wet</td>
<td>18,3</td>
<td>11,5</td>
</tr>
<tr>
<td>WW warm/wet</td>
<td>6,1</td>
<td>4,2</td>
</tr>
</tbody>
</table>

Table 2. Frequencies distribution of the combined modes in the previous 30 days of a MAC (1970-71/2005-06) for the Oceanic and Mediterranean areas.

Climate behaviour of the 30 days before a MAC is different between Mediterranean and Oceanic areas. CD days prevail in the Mediterranean area and WD days in the Oceanic. Another difference is that CW days have more weight in the Oceanic area than in the Mediterranean; the increment of CD days is lower in the Mediterranean case than in the Oceanic. Probably that is due to the fact that north and northwest advections use to be persistent and to accumulate lots of fresh snow in the Oceanic area, while heavy snowfalls are not so persistent in the Mediterranean area. In this sense, these results agree with the conclusions of previous works on avalanche activity and atmospheric conditions in the Eastern Pyrenees stating that northwest advections are the main cause of MACs in the Oceanic area (Garcia-Sellés et al. 2009).

Winter modes distributions have been put to the non-parametrical Kruskal-Wallis test to prove whether statistically significant differences exist between all the winters and previous 30 days of a MAC series (Kruskal and Wallis, 1952). Mediterranean and Oceanic previous 30 days series have also been compared. Even though quantitative differences exist in orders and percentages that affect snowpack evolution, in no case samples are statistically different among them.

### 3.1 Mediterranean area

From the results, weather conditions to bring a MAC in the Mediterranean area are different from the winter climate conditions of temperature and precipitation. Specifically, along the previous 30 days of a MAC there is an increment of the frequency of cold days (T<40°C) and wet days (P>60) with respect to the average. Considering combined T-P modes, the most notorious is the diminishing of warm/dry days (WD), CW increase slightly and both CD and WW keep steady. The highest daily frequency of occurrence is the CD mode (29%), cold/dry.

It is well known that cold and dry days favour medium and high thermal gradient processes into the snowpack and persistent weak layers build up (Hägeli and McLung, 2007). Depth hoar is also likely to develop in those conditions. Persistent weak layers can wake up in future under stressing conditions such as snowdrift, heavy snowfalls or warm spells.

![Figure 2. Snow profile performed in La Molina (Mediterranean area) on 30th January 2006 (IGC).](image)

The 31st January 2006 is an example of unstable snowpack in Mediterranean area prior to snowfalls triggering major avalanches. Along the first two weeks of January shallow snowpack (50-100 cm) and CD days predominated; faceted grains built up (Figure 2). At the end of the
month, 90 cm of fresh snow in 72 h triggered major avalanches with severe damages in forest (Cadí-Moixeró range). The snowpit (La Molina) just performed the day before the avalanche occurrence few kilometres away from the affected gullies shows large depth hoar grains (3-4 mm), faceted grains in the middle-part of the snowpack and even a tiny layer of surface hoar. In the upper-part fresh snow and decomposed particles show even higher hand hardness than older snow.

Predominance of shallow snowpacks in the Mediterranean area multiplies the effect of cold weather generating faceted grains.

3.2 Oceanic area

In relation to the 30 days sequences before a MAC, unlike Mediterranean area, there are not differences in the Oceanic regime in the mode probability density functions between the 30 days and all the winter series, but the former exhibits a substantial increasing in the frequency of wet modes (CW and WW) prior to a MAC. Attending to combined modes, the most interesting is the increment of CW cold/wet days. The highest mode occurrence corresponds to WD (31%).

More cold/wet days prior to a MAC in the Oceanic area implies more availability of fresh snow that triggers major avalanches by breaking stellar structures, with no dependency of internal weakening. In fact, CW mode ranges 87% in the 5 days prior to a MAC in the Oceanic regime but only 42% in the Mediterranean one.

The 2nd January 2004 is an example of avalanche activity on Oceanic regime, linked to heavy snowfalls and drift processes, regardless of the rest of the snowpack. 135 cm of fresh snow accumulated along 5 days. During the previous 25 days WD mode prevailed beside some CD days. Looking at the snowpit (Bonaigua) performed on the first day of the snowfall event (Figure 3), fresh snow lies over a rather stable snowpack (rounded and bonded grains). Avalanches ran over older snow without being incorporated.

4. TEMPORAL EVOLUTION OF THE WINTER MODES

It is interesting to observe how the modes linked to major avalanche activity have evolved during the last 40 years (Figures 4 and 5). The CD mode which seems to play a role in the weakening of the snowpack layering has suffered a strong diminution in frequency, mainly in the ’70s (43 days on 39 years). Nevertheless, it seems stabilized during the last 20 years. In terms of providing both fresh snow along several altitudinales mountain belts and initiating avalanche activity, CW mode has diminished from the ’80s till now in the Mediterranean area, but it is increasing in the Oceanic area (7 days on 36 years). In spite of that, the high year-on-year variability of this mode assures snowy winters and major avalanche activity in the Mediterranean area (1995-96; 2005-2006), even though
WD steadily increases year by year (13 days in the last decade). Results of trends put to Kendall and Spearman tests with statistical significant in the most of them are shown in the table 3.

![Figure 4. Evolution of the cold/dry number days in the Mediterranean area (1969-70/2011-12).](image)

![Figure 5. Evolution of the cold/wet number days in the Oceanic area (1970-71/2011-12).](image)

Table 3. Observed evolution of the combined modes in the Mediterranean and Oceanic areas. Level of statistical significance: * 95%, ** 99%.

<table>
<thead>
<tr>
<th>Combined Modes</th>
<th>Trends in the Mediterranean area (days by season)</th>
<th>Trends in the Oceanic area (days by season)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>-1.1**</td>
<td>-0.3*</td>
</tr>
<tr>
<td>CW</td>
<td>-0.2**</td>
<td>+0.2*</td>
</tr>
<tr>
<td>WD</td>
<td>+1.3**</td>
<td>+0.5**</td>
</tr>
<tr>
<td>WW</td>
<td>+0.1**</td>
<td>+0.0</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS

The use of winter modes contributes a climatic approach to the major avalanche research since it characterizes the combined behaviour of temperature and precipitation in the period prior to a MAC.

By means of the joint modes approach, weather conditions for major avalanche triggering prove to be different between Mediterranean and Oceanic areas. This point must be taken into account when forecasting, because same meteorological patterns do not lead to same effects in avalanche activity due to different sensitivity of the snowpack.

In this sense, cold and dry days make the snowpack more sensitive and unstable in the Mediterranean regime than in the Oceanic, where this CD mode is not relevant in avalanche activity. Mediterranean snow regime is characterized both by less precipitation than Oceanic and by persistent, strong northern winds. These conditions favour shallow snow packs where high thermal gradient develop weak layers easier than in an Oceanic regime.

On the other hand, avalanche activity in the Oceanic regime seems to be linked to precipitation modes which act as direct agents. Previous state of the snowpack seems to be not so determining for leading major avalanches.

Next step should consist on comparing the results of stability tests between both regimes to check this approach.

On future trends, weather conditions leading major avalanches have diminished in the last decades in the Pyrenees, such as in the Swiss Alps, but the behaviour is different between Oceanic and Mediterranean areas. Nevertheless, the strong interannual variability observed suggest that major avalanches will not diminish at short term.

Hypothesis should be supported by the analysis of new high mountain meteorological series in the framework of climate change projects.

6 ACKNOWLEDGEMENTS

This work was supported by the research project CTP-2010 “Influence of the Climate Change on the Snow Tourism in the Pyrenees”, financed by the Working Community of the Pyrenees.

7 REFERENCES


