SNOWPACK PATTERNS IN THE EASTERN PYRENEES AND THE CASE OF WINTER 2016/17

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ABSTRACT: Regional variability and inter-annual differences in avalanche activity in the Eastern Pyrenees (NE of Spain) are the main problems that the Catalan avalanche forecasting centre must face. This study is intended for advancing in snow climate classification; variability and stability of the snow conditions in time and space are considered among the different avalanche regions of the Eastern Pyrenees. A data set of up to 600 manual snow profiles was analysed over the last 15 years in the Mediterranean and oceanic avalanche regions. Applied methodology is based on determining thresholds and ranges of the snow variables for identifying different snowpack patterns. Unstable conditions such as proportions of faceted grains, size of snow grains and hardness of the layers are analysed. In addition to variables describing weak layers, we also compared the evolution of surface layering in terms of fresh snow deposition and slab formation. As a result, noteworthy differences on faceted grains and melting forms proportions are found between the snowpack structure in the oceanic and Mediterranean avalanche regions. So, two regional snowpack patterns have been defined in the Eastern Pyrenees. As an example, the evolution of the snowpack conditions during the especially unstable winter 2016/17 is assessed under the criteria proposed for classifying snowpack.

KEYWORDS: Snow climate, Eastern Pyrenees, snowpack patterns.

1. INTRODUCTION

In avalanche forecasting is essential the identification of unstable structures of the snowpack, its spatial distribution and its temporal variability, given that it is the structural and mechanical stability levels of the snowpack that will allow weather conditions to activate or not a major avalanche cycle (MAC). The definition of snowpack patterns has been based on parameters of the snow cover structure associated with unstable conditions such as the proportion of persistent grains (faceted crystals), grain size and hardness of the layers. In addition to these variables linked to the existence of internal weak layers, the evolution of the surface layers such as new snow and wind-drifted snow layers have also been compared between the oceanic and Mediterranean climate regions.

The activity of MACs for the two regions has been related to the predominant snowpack. Large avalanches have been considered, in a broad sense, those that exceed 1000 m of length, that have reached the bottom of the valley, or have destroyed forest mass or damaged infrastructures. (Schaerer, 1986).

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The study of the snowpack connects with the definition and identification of snow climates. These are based on the meteorological factors and characteristics of the avalanches (Armstrong and Armstrong, 1987, McClung and Schaerer, 2006). This work provides information on the conditions of the snowpacks typical of the snow climates of the eastern Pyrenees (figure 1) in which the avalanche regions are included. By avalanche region is understood a regionalization according to the characteristics of the avalanches derived from the dominant climate (Mock and Kay, 1992, Mock and Birkeland, 2000). Finally, two snow climates have been clearly defined from the occurrence of avalanches and atmospheric analysis on a synoptic scale: a Mediterranean and an oceanic one (García-Sellés, 2017).

In this work, the structure of the snowpack of both the Mediterranean and the oceanic snow climates has been analysed on a weekly basis, whose knowledge is more useful in the avalanche forecasting than that derived exclusively from the descriptions of the snow climates (Hägeli and McClung, 2007). Used parameters and indexes related to unstable conditions of the snowpack have been treated in avalanche forecasting by Techel and Pielmeier (2014).

Finally, as an example, the evolution of the snowpack conditions during the winter 2016/17 is assessed under the criteria proposed for classifying snowpacks. This winter stands up due to the persistence of internal weak layers and the instability index is of special interest to characterize it.

2. STUDY AREA, DATA AND METHODS

The stratigraphic profiles carried out by the Institut Cartogràfic i Geològic de Catalunya (ICGC) in different areas of the Eastern Pyrenees in the period 1997-98 to 2011-12 (15 seasons), between December and April, have been analysed. This assumes a database of 612 profiles, analysing the physical parameters of 5346 snow layers. We have chosen 10 different locations in the Mediterranean area (TF, PR and CM regions, figure 1) and 12 in the oceanic area (AR, figure 1) to avoid biases due to local topographic conditions. The Eastern Pyrenees means the Pyrenees administratively corresponding to Catalonia.

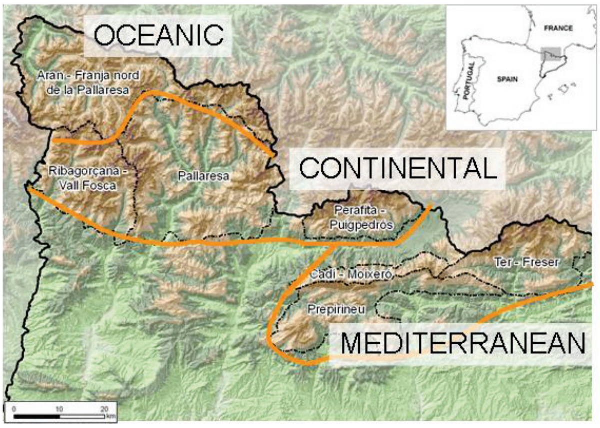


Figure 1: Map of the avalanche regions in the Eastern Pyrenees and snow climates. The northwestern area (Aran-Pallaresa north border, AR) corresponds to oceanic snow climate and the eastern area (Cadí-Moixeró, CM; Prepirineu, PR; Ter-Freser, TF) is affected by Mediterranean snow climate. The central area (Ribagorçana-Vall Fosca, RF; Pallaresa, PL; Perafita-Puigpedrós, PP) probably dominated by continental or transitional snow climate is not analysed in this study due to the lack of enough data.

The methodology consisted of both detecting the weak layers, considered as such in the existing bibliography (McCammon and Schweizer, 2002) from crystallographic criteria, and the calculation of indices associated with unstable conditions of the snowpack (Techel and Pielmeier, 2014). They are those that showed moderate to strong correlation to the mean snowpack structure ranking that is used in avalanche forecasting operative to assess the stability of the snowpack. Variables are: PG_{prop} (proportion (%) of the snowpack which consists of persistent grain type and has a hand hardness ≤3), $SIZE_{prop}$ (snowpack which is coarse-grained, grain size ≥1.25 and has a hand hardness ≤3), $HARD_{prop}$ (snowpack which is very soft, hand hardness ≤1.3). Proportions are relative to the snow depth. It is also calculated the TSA_{layer} (the layer threshold sum, which consists of the accumulative proportions of PG_{prop}, $SIZE_{prop}$ and $HARD_{prop}$). We have also proposed other parameters describing the snowpack structure which define avalanche character (Hägeli et al., 2010; Nairz and Mair, 2013), such as MF_{prop} (melting forms proportion, including crusts) and NPG_{prop} (non-persistent grains proportion which hardness is ≤3). Grain types and their recorded parameters are those from Fierz et al., 2009.

3. RESULTS AND DISCUSSION

The distribution of statistical measures of central tendency for several variables will be used to classify snowpacks. To look for different snowpack patterns, snowpack variables are classified by assessing the probability of exceeding several thresholds. Box plots are used to demonstrate which variables most effectively discriminate snowpack types (figure 2). Those variables showing more variability between both climates will be adopted as criteria to classify them. On the other hand, when the value of one parameter is in the range of 25-75 percentiles from the other zone it does not account as discriminator. Using the box plots, each winter is scored by the number of parameters that exceed the range of variability when comparing snow profiles from oceanic and Mediterranean regions. The chosen variables are those not well correlated to *TSA* in order to avoid redundancy; they are instability index (*TSA*), proportion of persistent grains still observed in March and April ($PG_{Mr\text{-}Ap}$), proportion of melting forms (*MF*) and proportion of non-persistent grains (*NPG*). These snowpack structure criteria are which better split the snowpack profiles between Mediterranean and oceanic treats. Analysed data are the distributions of the annual averages of each variable from 1997-98 to 2011-12. Annual averages are calculated from the weekly samples registered from December to April (n=22).

The average evolution of the *TSA* index throughout the season is similar between the Mediterranean zone and the oceanic one (there are no statistically significant differences, $R = 0.55$, $n = 22$, $p < 0.01$), but there are regional particularities. In general terms, the instability of the snowpack is increasing from the beginning of its formation until mid-February, then decreases until the beginning of April, and increases again until the disappearance of the mantle. The differences focus on: a) greater inter-weekly variability of the *TSA* in the Mediterranean area, b) higher values of *TSA* in the coldest part of winter in the Mediterranean area, c) when instability declines in both sectors, in the period from mid-February to the end of March, the instability values are lower in the Mediterranean area, but in the spring period the *TSA* in the Mediterranean area exceeds the values of the oceanic area. The instability during the coldest part of winter, higher in the Mediterranean than in the oceanic area, is not due to a greater proportion of persistent weak layers (PG_{prop}), but to a greater proportion of $SIZE_{prop}$, grains of larger diameter. Accordingly, the proportion of $HARD_{prop}$ is also higher, a higher percentage of layers of low intergranular cohesion. Between both zones there is a consistent correlation for the variable PG_{prop}, but not for $SIZE_{prop}$, nor especially for $HARD_{prop}$ which remains stable in the oceanic zone while it increases in the Mediterranean. It means that the proportion of weak layers is similar between both snow climates, but they are of greater fragility in the Mediterranean area.

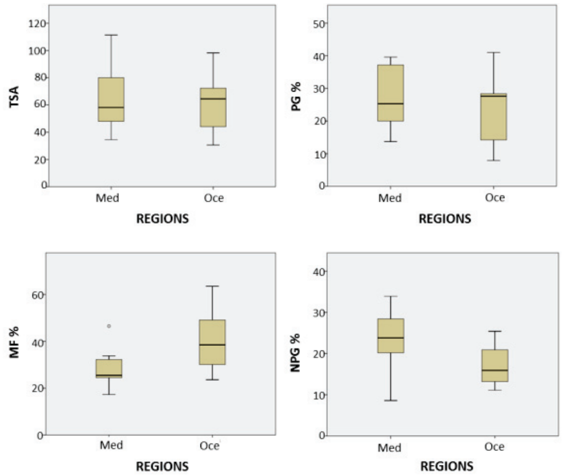


Figure 2. Box plots of several snowpack parameters and snow grain types distributions for Mediterranean and oceanic regions. Data are annual averages from the 1997-98 to 2011-12 seasons. Plotted values are the minimum and maximum of the series, first and third quartile, the median and outliers that exceed the interquartile range.

The second phase in the climatic evolution of the snowpack in both areas consists in a fall of the *TSA* between mid-February and end of April (figure 3). The increase in the stability is due to the reduction of the percentage of persistent weak layers (PG_{prop}) that decays until the end of the season. It is probably due to the progressive insolation of the shady hillsides, the thermal increase of the air, the increase of thickness of the snowpack that hinders the processes of high and medium gradient metamorphism. In this regard, it is noteworthy that the $SIZE_{prop}$ parameter does not change in the oceanic zone, but it declines rapidly in the Mediterranean during the month of March, probably due to the increase in decomposed and fragmented precipitation particles because of spring snowfall episodes, typical of the Mediterranean climate.

The last phase in the evolution of the *TSA* is the change of trend that is registered at the beginning of April in both climatic zones due to the increase of MF_{prop} (it is the parameter that presents less differences between the two zones, R = 0.95, p <0.01). In fact, the melting grains begin to increase in the second half of February but does not imply unstable conditions until the beginning of April when there is an increase in $SIZE_{prop}$, when the melting grains are already sufficiently developed in size due to the increase of the environmental temperatures. Throughout the season, the weekly values of MF_{prop} in the Mediterranean area are systematically smaller than those of the oceanic zone, which is surprising since the Mediterranean area is closer to the sea and at a lower latitude than the oceanic one; at 2200 m the average temperature in winter is 1.2ºC higher in the Mediterranean than in the oceanic region (Oller et al., 2006). The lower presence of wet grains may be due to differences in atmospheric conditions and snowpack stratification processes. The Mediterranean region is climatically affected by strong winds from the northern component, which, after the passage of snow fronts, form plenty of wind-drifted slabs (García-Sellés et al., 2009). This is indicated by the higher percentage of non-persistent grains in the Mediterranean area over the oceanic zone (median of the weekly values of NPG_{prop} = 21 and 16, respectively), and of higher hardness (median of the proportion of $HARD_{prop}$ soft layers equal to 11 in the oceanic area and 7 in the Mediterranean). The highest proportion of hard snowpack that is recorded between February and March in the Mediterranean area can hinder the penetration of liquid water from the surface into the snowpack, resulting in a lower percentage of melting grains.

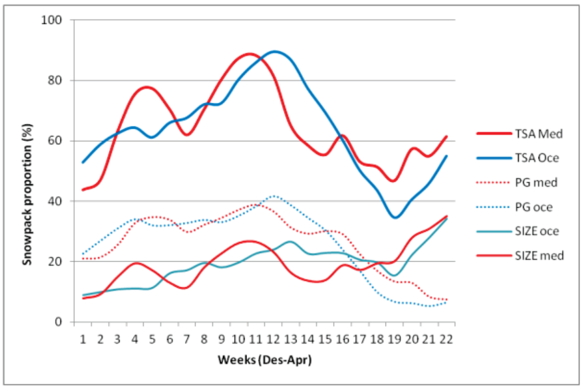


Figure 3: Evolution of the weekly average of different snowpack parameters (15 winters, Dec-Apr; 3 moving mean) for Mediterranean and oceanic areas.

The most notable differences among the parameters of the structure of the snowpack of both nivoclimatic zones are the greater presence of persistent weak layers and larger diameter grains in the first half of winter (December and January) in the Mediterranean area, as well as the greater proportion of NPG_{prop} in the Mediterranean area much of the winter compared to the oceanic. This combination of structures favours patterns of slab avalanches in the Mediterranean area. The most common feature of the snowpack between both zones is the increase of melting grains from mid-February in response to the rise of the positive radiative balance of the snowpack.

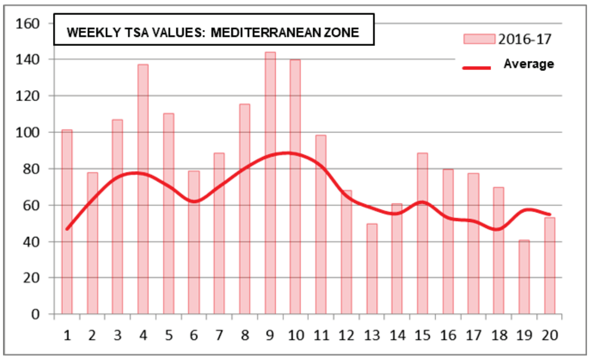
As a result, the Mediterranean snowpack pattern is defined by high values in the proportion (%) of variables associated with conditions of instability (TSA_{layer} >72), moderate percentage of melting grains (*MF*<31), non-persistent grains (*NPG)* >17, presence of persistent weak layers at the beginning of spring ($PG_{Mr\text{-}Ap}$>15). The oceanic snowpack pattern is defined by relatively low values of variables associated with conditions of instability (TSA_{layer}<49), relatively high percentage of melting grains (*MF*>34), low percentage of non-persistent grains (*NPG*<16) and very low presence of persistent weak layers at the beginning of spring ($PG_{Mr\text{-}Ap}$ <10).

Both patterns show low spatial homogeneity since only in 40% of winters the same snowpack pattern has spread over both snow climatic zones of the Eastern Pyrenees (case of extreme pattern). Therefore, the snowpack in the Mediterranean region does not always coincide with the Mediterranean pattern (10 of 15 winters), nor is it always of oceanic pattern in the oceanic snow climate zone (9 of 15 winters). Regarding the temporal variability (table 1), no pattern predominates temporarily over the other, although a concentration of extreme Mediterranean pattern between the 2005-2006 to 2010-2011 winters is observed.

Table 1: Temporal evolution of oceanic and Mediterranean snowpack patterns and their regional distributions. Extreme snowpack winters are shaded.

SEASON	**EASTERN REGION (*n* criteria)**	**WESTERN REGION (*n* criteria)**
1997-98	OCE (3)	OCE (4)
1998-99	MED (3)	*INDETERM.*
1999-00	MED (4)	OCE (4)
2000-01	MED (4)	OCE (3)
2001-02	*INDETERM.*	OCE (4)
2002-03	MED (3)	OCE (4)
2003-04	OCE (3)	OCE (4)
2004-05	MED (4)	OCE (4)
2005-06	MED (3)	MED (3)
2006-07	MED (4)	MED (3)
2007-08	MED (4)	OCE (3)
2008-09	MED (4)	MED (3)
2009-10	OCE (4)	OCE (4)
2010-11	MED (4)	MED (3)
2011-12	OCE (4)	MED (3)
MED.PATTERN	10	5
OCE.PATTERN	4	9
IND. PATTERN	1	1

In addition, the evolution of the variables and indexes of the snowpack could be used to observe snow climate differences among seasons, further than typical sum of fresh snow or daily snow depths. Attending to the *TSA* index, it is possible to compare the instability of the snowpack from one season to another one. So, the snowpack of the winter season of 2016-2017 stands up as one of the most unstable from the nineties in both snow climates. For the Mediterranean region, *TSA* values exceeded the climatic average all weeks but one; for the oceanic region, instability conditions hugely overcome the average till mid-February. Instability conditions were due to a dry season (especially in the oceanic region) matched with cold-normal monthly temperatures. Instability anomaly was more noticeable in the oceanic region, where layers of faceted grains persisted in spring doubling its normal proportion into the snowpack. Snowpack pattern classification of 2016-17 corresponds to a Mediterranean pattern in the Mediterranean region and indeterminate for the oceanic region, where *TSA* index and $PG_{Mr\text{-}Ap}$ were higher than usual (typical values of Mediterranean pattern) but *MF* and *NPG* showed typical values from oceanic pattern.



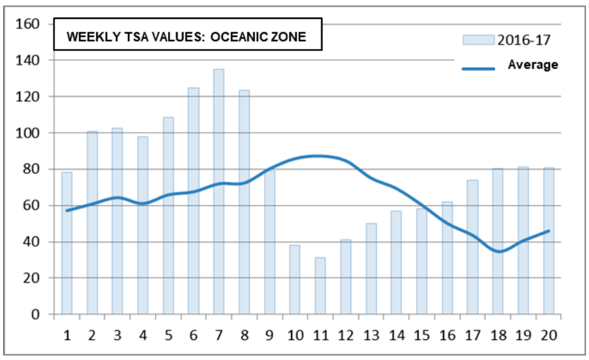


Figure 4: Evolution of weekly values of *TSA* index (bars) during 2016-17 season compared to the mean (line) in the Mediterranean region (up) and in the oceanic one (down).

4. CONCLUSIONS

Regarding the conditions of the snowpack, analyzed 15 years of data, there are no statistically significant differences in the evolution of the snowpack between Mediterranean and oceanic regions from a climatic point of view, but some differences have been observed in some parameters on a weekly scale with different consequences in the snowpack stability between both regions. There are differences in grain type, size and hardness of the snowpack and lack of simultaneity in the occurrence of major avalanche cycles. For this reason, we consider that two regional patterns of snowpack may be defined depending on the evolution of the conditions of instability and the proportion of grain types: an oceanic pattern and a Mediterranean one.

The snowpack of the northwestern area (AR region, oceanic climate) is characterized by lower values of those parameters associated with unstable conditions than in the regions of the eastern area (TF, CM and PR) dominated by Mediterranean climate. The snowpack of the oceanic climatic zone of the Eastern Pyrenees is frequently formed by few persistent grains of low hardness; the stratification consists of low proportions of coarse grains of low hardness, and in general the proportion of very soft layers is also low. The proportions of these parameters are slightly higher in the snowpacks of the Mediterranean climate zone. High values of melting forms are typical from oceanic pattern.

On a seasonal scale, obviously the mantle of oceanic conditions predominates in the north-western area and the Mediterranean conditions in the eastern area, but it is not very frequent as there are winters in which a single pattern, extreme pattern, extends over both climatic domains. A major avalanche cycle (MAC) matching with an oceanic snowpack is more likely to occur (4 MACs have been recorded in 7 oceanic snowpack winters and 2 MACs in 7 Mediterranean snowpack winters). Even a MAC is more likely to occur when the oceanic pattern is extreme, since major avalanche activity has been recorded in all winters that have met this condition. In contrast, only 2 MACs have been observed over 4 winters of extreme Mediterranean pattern.

About the variables to characterize the MACs, the TSA_{layer} index, summation of variables that account for unfavorable conditions of the snowpack, calculated in the profiles carried out in the days prior to a MAC, seems to be a good indicator of what is the state of degradation of the snowpack prior to the triggering of a MAC in the Pyrenean mountain range. It defines well a critical snowpack, easily stressed by an overload.

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