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# SNOWFALL AND SNOW COVER EVOLUTION IN THE EASTERN PRE-PYRENEES (NE IBERIAN PENINSULA)

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**ABSTRACT.** Snow cover has significant impacts on geoecological dynamics as well as on socio-economical systems. An accurate quantification of snow precipitation patterns in mountain regions is needed to better understand the spatio-temporal implications of snow cover. The objective of this work is to characterize the patterns of solid precipitation and snow cover in two high Mediterranean massifs. To this purpose, we analyse instrumental data series of snowfall and snow depth of Port del Comte (2316 m a.s.l.) and Cadí-Nord (2134 m). Both stations are situated in the eastern Pre-Pyrenees and include 14 consecutive snow seasons from November to May, allowing to (i) explore the dependence of the main drivers of snowpack: temperature and snowfall; (ii) find out the most frequent circulation weather types associated with high intensity snowfall events, and finally (iii) investigate the role of the North Atlantic Oceanic (NAO) teleconnection pattern explaining snow cover evolution during the winter season. Data show that snowfall is controlled by similar weather types in both stations that resulted in similar snowfall averages: 205 cm and 258 cm at Port del Comte and Cadí-Nord, respectively. Nevertheless, local factors interfere with the amount of snow depth recorded, which is moderately different between stations. Whereas Cadí-Nord records a seasonal mean of 66 cm, Port del Comte records a smaller quantity of 25 cm with a high interannual and seasonal variability. In fact, snowfall recurrence, snow amount or duration in the ground is considerably variable among years (CV>20). In these stations, snow cover duration is determined by the precipitation in the form of snow falling during the previous months. Snowfalls in moderate to severe episodes (>15 cm in 24 h) are mainly driven by Atlantic flows, mostly from NW. In addition, NAO pattern is negatively correlated with snowfall in November and December months (R>-0.50), showing a weaker and not statistically significant correlation during the rest of the winter season.

## *Evolución de la cobertura nival y la nivosidad en el Prepirineo oriental (NE de la Península Ibérica)*

**RESUMEN.** La presencia de cobertura nival en el Prepirineo es crucial, tanto para la dinámica geoecológica presente como para el sistema socioeconómico, ambos dependientes a partes iguales de este elemento natural. Una precisa cuantificación de los patrones de precipitación nivales son necesarios para entender las implicaciones espaciales de la cobertura nival. El objetivo del presente estudio es caracterizar la precipitación en forma de nieve y la cobertura nival de dos enclaves montañosos de elevada altitud situados en la cuenca Mediterránea. Por este motivo, a continuación, se analizan los datos instrumentales de las estaciones nivometeorológicas del Port del Comte (2316 m. a.s.l.) y del Cadí-Nord (2134 m). Ambas estaciones están localizadas en el Prepirineo oriental, y contienen una cobertura temporal de 14 temporadas nivales desde noviembre a mayo. Con este fin, (i) se ha verificado la correlación existente entre la temperatura y la precipitación nival con el grosor de nieve existente a final de temporada. Además, (ii) se han descrito los patrones sinópticos que se repiten con más frecuencia en los episodios nivales de mayor intensidad, y finalmente (iii) se ha analizado la dependencia de la nivosidad con el patrón de teleconexión principal de la Península Ibérica en los meses invernales, la Oscilación del Atlántico Norte (NAO). Los resultados demuestran cómo ambas estaciones están influenciadas por los mismos patrones sinópticos de precipitación, mostrando una media de precipitación nival por temporada similar: de 205 cm y de 258 cm en el Port del Comte y el Cadí-Nord, respectivamente. No obstante, debido a factores locales, el espesor de nieve registrado por temporada es moderadamente diferente. Mientras que el Cadí-Nord registra una media de 66 cm, el Port del Comte registra una cuantía inferior, de 25 cm con una remarcable variación interanual y estacional. De hecho, tanto la nivosidad, cobertura nival, periodicidad o duración del manto nivoso tienen una considerable variación entre años (CV>20). En estos dos enclaves geográficos, la explicación de la duración nival a final de temporada se encuentra en la precipitación sólida de los meses precedentes. Esta precipitación en los episodios de moderados a severos (>15 cm en 24h) es caracterizada por flujos Atlánticos con un patrón sinóptico de componente noroeste. Además, el patrón de teleconexión NAO está negativamente correlacionado con la precipitación nival durante los meses de noviembre y diciembre (R>-0.50), mientras que la correlación es débil y estadísticamente no significativa los subseque de meses invernales.

**Key words.** Pre-Pyrenees, climate variability, snowfall, snow depth.

**Palabras clave.** Prepirineo, variabilidad climática, cobertura nival, nivosidad.

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## 1. Introduction

Solid precipitation and the consequent accumulation as snowpack is crucial for the stability of the global climate system. Seasonal snow extent, duration or characteristics have large interactions and impacts in the surrounding landscapes. By its own nature, snow albedo delays ground warming (Hall, 2004), provides a protective layer for vegetation when temperatures are severely low, conditions the plant growing season, reduces thermodynamics and affects biogeochemical cycles (e.g., Wipf *et al.,* 2009). Snow is in essence water storage, available for downstream areas. Snow melting determines the temporal distribution of the river flow in mountain areas and supplies nutrients both for the ecological and social systems (García-Ruiz *et al*., 2011). Indeed, snow presence and abundance favours human activities in winter, for example, guaranteeing the opening of ski resorts, a major business in the Pyrenees area, or in springtime, providing hydroelectricity, hydric resources for agriculture or water for settlements and population (e.g., Lasanta *et al.,* 2005). These dependencies will increase in the future, when droughts will be more frequent and severe, and water availability will be more demanding across the Mediterranean basin (García-Ruiz *et al*., 2011).

Future climatic scenarios are expected to impact the timing of snow cover in the ground as well as the frequency and intensity of snowfalls in mid-latitude mountain environments, affecting thus ecological and socio-economic issues (IPCC, 2013). Snowpack is mainly conditioned by the combination of temperatures and precipitation. A long-term warming of ca. 1 ºC has been recorded following the Little Ice Age in the Iberian mountains (Oliva *et al.,* 2018), with temperatures expected to further increase in the next decades. In fact, high elevation areas in mid-latitude mountain ranges are considered to record faster warming rates compared with lowlands (Pepin *et al.,* 2015). On the other hand, annual and winter precipitation in the Iberian Peninsula between 1961 and 2011 years has decreased at a rate of 18.7 mm/decade (Vicente-Serrano *et al.,* 2017). In the Pyrenees, the decrease of precipitation has been more accentuated in the southern slopes of the eastern mountain range (Lemus-Canovas *et al.,* 2019a). Furthermore, several studies pointed to a decrease of snow depth in the mountain range during the second half of the 20th and early 21st centuries (e.g López-Moreno*,* 2005, 2020). However, this trend is variable depending on the time frame analysed, showing a decrease of snow days between 1971 and 2000, and a positive trend between 1985 and 2010 (Buisan *et al.,* 2016). With regards to teleconnection and circulation patterns, numerous studies identified the NAO - often defined as the difference of anomalies of the sea level pressure (SLP) between Ponta Delgada (Azores) and Reykjavick (Iceland) (Hurrell *et al.*, 1995), as the main driver of precipitation in Iberian Peninsula in winter as well as snowfall in the western and central Pyrenees (López-Moreno*,* 2005; Revuelto *et al., 2012*). Additionally, a predominance of NAO positive phases in winter has been found over the 20$^{th}$ century, leading to a reduction of circulation weather types associated with precipitation (López-Bustins *et al.,* 2008).

Nonetheless, an accurate characterization of the snowfall and snowpack in high altitudes of the eastern Pyrenees and Pre-Pyrenees is still missing. Previous works focused on snow stations of the eastern Pyrenees (Salvador Franch *et al.,* 2014, 2016) are now complemented with a detailed characterization of the recent evolution of snow variables. With this aim, this study examines snow data from two stations from the eastern Pre-Pyrenees: Port del Comte (2316 m), located in the massif of Port del Comte, and Cadí-Nord station (2134 m), at the northern foot of the Cadí massif. We analyse snow records of 14 snow seasons examining snowfall records, as well as their frequency and intensity, together with snow cover, thickness and duration. With the objective of providing a better characterization of the spatio-temporal patterns of snow cover in these areas, we will give answer to the following specific objectives: i) Characterise the seasonal snowfall and snow cover evolution in the Pre-Pyrenees, ii) explore the relationship between snow cover, precipitation and temperature, iii) investigate the main weather types associated with snowfall events y iv) analyse the role of NAO teleconnection pattern during the snowfall season.

## 2. Study sites and regional climate

The Pre-Pyrenees mountains are located in the NE of Iberian Peninsula (Fig. 1). This mountain system is aligned W-E along the southern and northern foothills of the Pyrenees, a major mountain system stretching 450 km between the Mediterranean Sea and the Atlantic Ocean. This research focuses on two high elevation meteorological stations from two massifs of the SE Pre-Pyrenees: (i) Port del Comte, situated at 42º18’25’’ N and 1º52’40’’E, SW of the highest peak of the massif (Pedró dels Quatre Batlles, 2378 m), and (ii) the Cadí-Nord snow station, at latitude of 42º29’26’’ N and a longitude of 1º71’49’’E, 20 km NE Port del Comte. It is situated at an altitude of 2134 m, in the northern slope of the Cadí massif and near the Vulturó summit (2648 m) (Fig. 2).

The climate of the Iberian Peninsula is defined by a dominant westerly circulation from November to May, and prevailing anticyclone conditions during summer (Cortesi *et al.,* 2013). In the Pyrenees, the larger geographical differences generate a wide range of sub regional climate types, mainly caused by the distance to the Atlantic Ocean or Mediterranean Sea, and the altitude and aspect which also condition relief barrier effects (Xercavins, 1985). Throughout December to March, precipitation in mid-altitude areas (around 1500 m) is regionalized in three different zones: (i) the western Pyrenees, with an average of precipitation >600 mm; (ii) central axial of the range, with <400 mm; and (iii) eastern fringe, with high interannual variations and <200 mm recorded (Buisan *et al.,* 2016); herein, both studied snow stations are located. According to precipitation criteria, the study area corresponds to the Mediterranean eastern Pyrenees (SMC, 2008). Annual precipitation totals around 1050 mm at the summit of the Port del Comte and 1100 mm at 2100 m of the Cadí-Nord (SMC, 2008). During the warm season, and due to adiabatic heating forced by orography and high elevations, convective rainfall is frequent. This explains a higher precipitation in summer and spring, followed by lower values in autumn and winter. The mean annual air temperature is 3ºC at Port del Comte and 4ºC at Cadí-Nord (SMC, 2008). Between 2100 and 2300 m, the annual air temperature amplitude exceeds 14ºC, with the coldest and warmest months averaging -3ºC (February) and 12ºC (August), respectively. Moreover, nuanced thermal inversions are observed between the culmination zones and the valley bottoms. Temperature elevation gradients in the eastern Pyrenees are slightly lower (0.52ºC/100 m) than the average due to the maritime influence of the Mediterranean Sea (Xercavins, 1985). The wind shows different patterns in these two stations, particularly during the cold semester of the year (November-May), when WNW winds prevail at Port del Comte station with maximum speeds of >20 m/s, whereas at Cadí-Nord station WSW are most frequent, rarely exceeding 10 m/s (SMC, 2019).

The mountain landscape in these two regions is controlled by the presence of the prevailing limestone lithology that has favoured the development of a wide variety of karstic landforms, such as dolines, caves and deep gorges. Soils are thin and poorly developed, which constraints a scarce vegetation cover dominated mostly by alpine meadows at the summit level with above the tree line (2200-2300 m) drawn by small pines *(Pinus uncinata).* Additionally, part of the study area is under regional and Nature 2000 protection figures. The combination of low temperatures with moderate and high precipitation in the winter makes possible the practice of tourism related with snow in several ski resorts established in the surroundings.

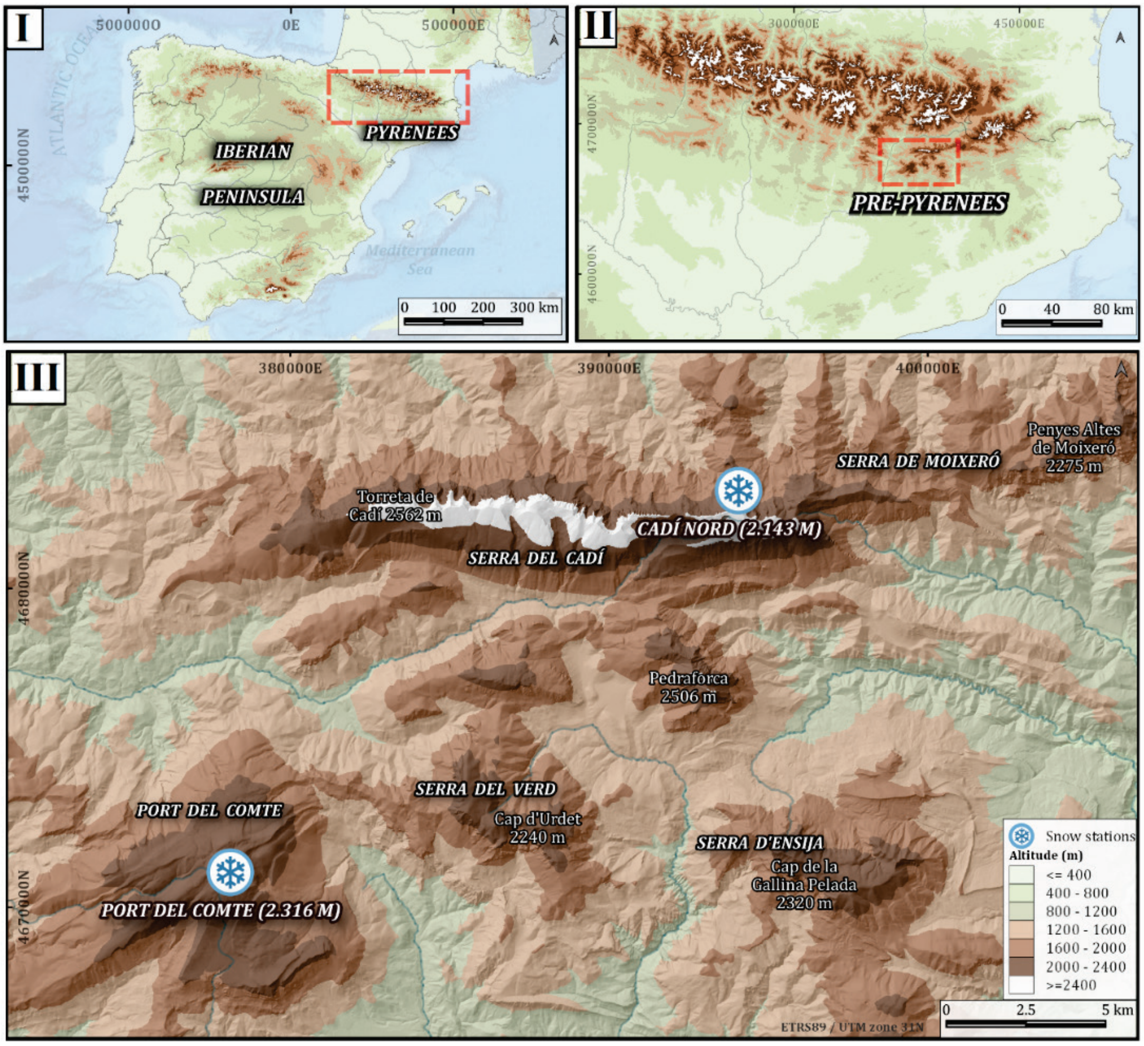


*Figure 1. Location of the Pyrenees within the Iberian Peninsula: (I) Eastern Pre-Pyrenees; (II) Distribution of the stations in the study area (III).*

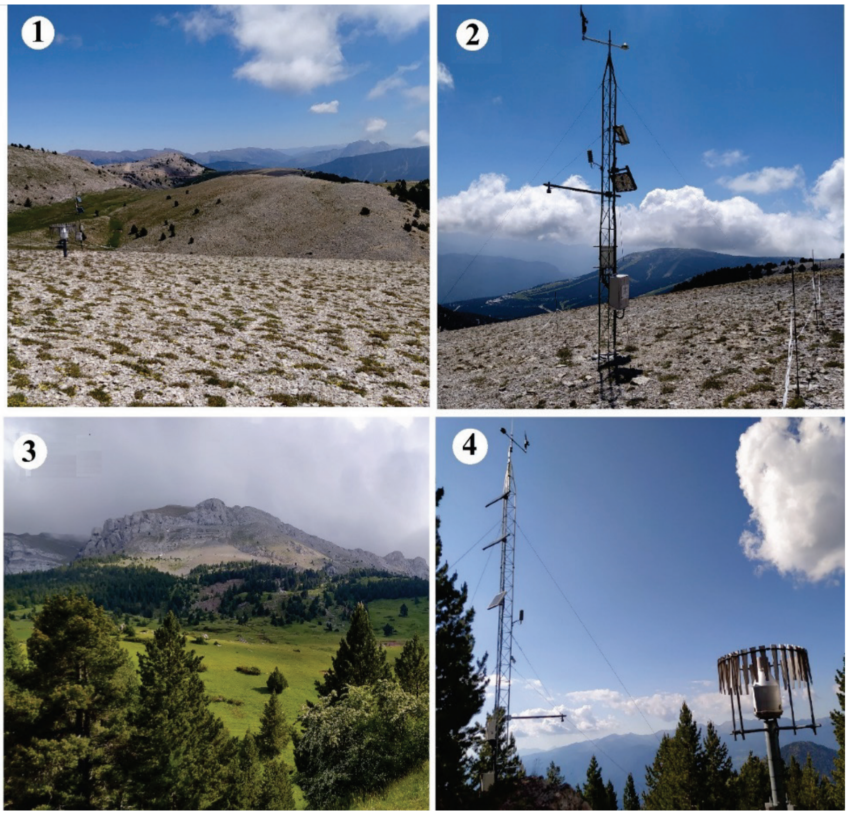

*Figure 2. Several pictures of: (1) Panoramic view of Port del Comte massif, near Pedró dels Quatre Batlles peak (2378 m) towards the Cadí massif;(2) meteorological and snow station of Port del Comte; (3) View of Prat d'Aguiló, a meadow close to Cadí-Nord station; (4) meteorological and snow station of Cadí-Nord.*

## 3. Data and methodology

### *3.1. Instrumental data*

The instrumental meteorological records provided by the Meteorological Service of Catalonia include daily records of temperature, precipitation and snow depth. All analysed data have passed a quality control and homogeneity test. For the purposes of this work, we considered the snowfall season from November to May including two consecutive years of the Gregorian calendar. Port del Comte snow data cover a total of 16 seasons (2002 to 2018) whereas the Cadí-Nord station encompasses data from 15 years (2004 to 2019). In order to compare patterns in both stations, we examine snow seasons from 2004 to 2018.

### *3.2. Snowfall characterization*

Daily snowfall was calculated by the difference with the maximum snow depth of the previous day, assuming that the increase corresponds to snowfall. From the whole dataset, missing data occurred in 0.9% of the total cases at Port del Comte and only 0.2% at Cadí-Nord. For such cases, we compared both snow stations and if there have been any snowfall events; we assumed the mean of snow depth between the last and the following day. The average of snow depth and duration calculated include only days with >0.1 cm of snow depth. Finally, monthly snowfall anomalies (Fig. 3) are the result of the difference between the monthly average and the corresponding monthly value of the season.

To determine whether snowfall or temperature are the main drivers of the variations in the snow depth in late snow season, we followed a previous approach carried out in the western and central Pyrenees (López-Moreno, 2005). A Pearson's correlation was performed between the snowfall and temperature recorded in the preceding months - January, February, March and April - and the last month with measurable snow depth, April. We considered April as the melting month due to the general lack of snow in May, particularly at Port del Comte station (Fig. 3).

### *3.3. Weather types for snowfall events*

The synoptic classification of the major snowfall days (>15 cm in 24 h) was based on the SynoptReg R package (Lemus-Canovas *et al.,* 2019b). This method was successfully implemented at the Pyrenees (e.g., Esteban *et al.,* 2005; Lemus-Canovas *et al.,* 2019a). It uses a principal component analysis applied a to spatial mode matrix, where the days are the observations and the grid points (latitude and longitude) are the variables. Then a clustering method is implemented, and the number of components retained are decided by a Scree test (Cattell, 1966). We selected 12 clusters (CL), which explained 90% of the variance. Subsequently, the principal components were rotated by means of Varimax rotation (Kaiser, 1958) and the extreme scores method (Esteban *et al.,* 2005) was applied. This method uses the scores (>2 and -2) determining a positive and negative phase for every principal component. The extreme scores established the number of groups and centroids for the K-means method. Further details of SynoptReg package are described at Lemus-Canovas *et al.* (2019b). The Database used was Daily SLP (Sea Level Pressure) and Geopotential Height at 500 hPa obtained from NCEP/NCAR Reanalysis 2 (Kalnay *et al.,* 1996) for 30ºN-60ºN by 30 ºW-10ºE with 2.5 resolution.

### *3.4. NAO and snowfall*

In order to detect the relationship between NAO and snowfall during the season, a linear regression was undertaken between monthly snowfall records and monthly NAO values. NAO was calculated by the difference of sea-level pressure in Reykjavik (Iceland) and Ponta Delgada (Azores), and is provided by the Climate Research Unit (CRU), University of East Anglia (https://crudata.eua.ac.uk/cru/ data/nao/)

## 4. Results

We present an accurate characterization of the snowfall and snow depth at Port del Comte and Cadí-Nord over 14 consecutive seasons, together with an analysis of the relationship between snowpack during the late season and the main meteorological drivers and the role of the NAO.

### *4.1. Snowfall and snow depth*

#### *Port del Comte*

From November to May, the total measured snowfall averages 205 cm at Port del Comte, which represents 21% of annual precipitation. Late season snowfall is sometimes beyond the monthly average (for instance 2008-2009 season, when 78 cm were recorded in April). Occasionally, about once in every two seasons, there is a snowfall episode in early summer. There is a considerable interannual variation (CV=41%) and snowy years (i.e. 2009-2010) alternate with snow-poor seasons (2011-2012). The maximum snowfall season was recorded in 2017-2018, with a total accumulation of 411 cm. On the opposite site, minimum peaks occurred in the 2014-2015 season, with a solid precipitation of only 89 cm (Table 1 and Fig. 4). On average, the frequency of snowfall days during a season is 51. The higher recurrence of snowfall days was recorded in the 2008-2009 season (70 days) and a minimum in the 2016-2017 season (30 days). The amount of snow accumulated in 24h is on average 26 cm, with a minimum of 11 cm (2004-2005). The most intense snowfall episode was recorded on 26th of January of 2018, when 41 cm of fresh snow accumulated in less than 24 hours.

*Table 1. Basic parameters of snowfall and snow depth at Port del Comte and Cadí Nord stations.*

| | Snowfall (cm) *P. Comte / Cadí* | | Max. 24h (cm) | | Frequency (days) | | PPt year* (%) | | Snow depth Thickness (cm) | | Duration (days) | | Duration ≥10 cm (days) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 205 | 258 | 26.2 | 38 | 51 | 50 | 21.5 | 26.2 | 25.5 | 66.3 | 148 | 175 | 108 | 151 |
| **Max.** | 411 (17-18) | 431 (17-18) | 41.8 (17-18) | 62 (17-18) | 70 (08-09) | 70 (10-11) | 29.7 (08-09) | 33.1 (04-05) | 59.8 (17-18) | 117 (08-09) | 191 (08-09) | 206 (08-09) | 190 (08-09) | 205 (08-09) |
| **Min.** | 89 (14-15) | 135.5 (14-15) | 11 (04-05) | 12 (04-05) | 30 (16-17) | 32 (16-17) | 8.6 (14-15) | 13.0 (14-15) | 5.1 (14-15) | 24.7 (04-05) | 83 (11-12) | 131 (11-12) | 18 (14-15) | 54 (11-12) |
| **CV** | 38.6 | 29.5 | 28.6 | 51.6 | 24.7 | 27.7 | 28.6 | 23.3 | 59.4 | 50.7 | 22.8 | 10.8 | 48.6 | 26.0 |

( ) = Years; PPt year*(%): Percentage of annual precipitation corresponding to snowfall (cm).

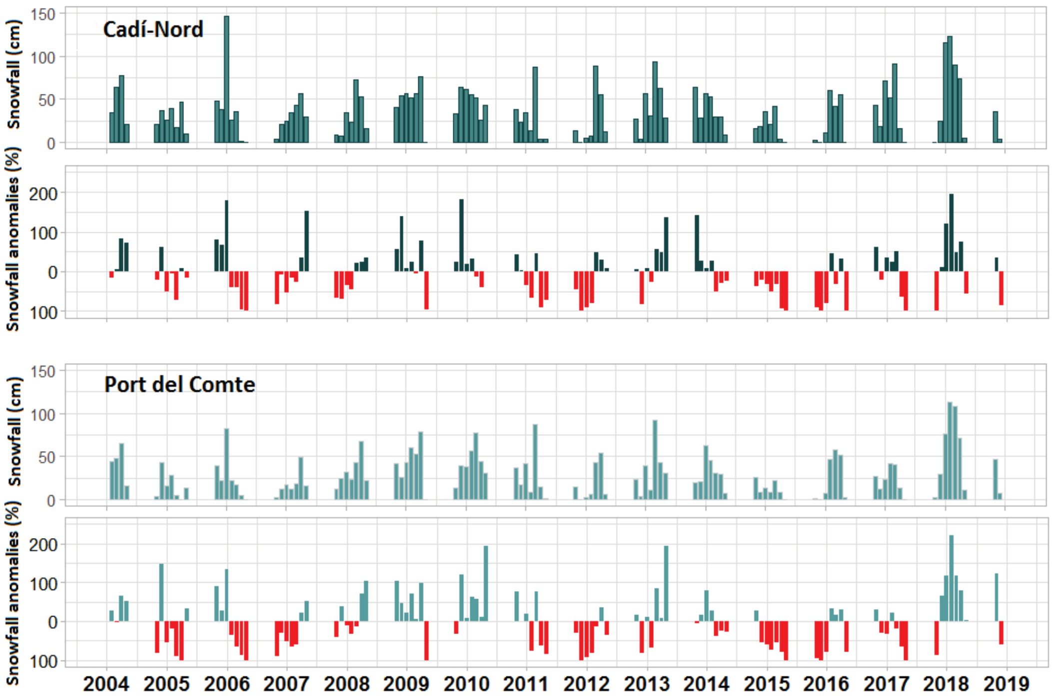


*Figure 3. Time series of monthly snowfall and snowfall anomalies at Cadí-Nord and Port del Comte during the snow season.*

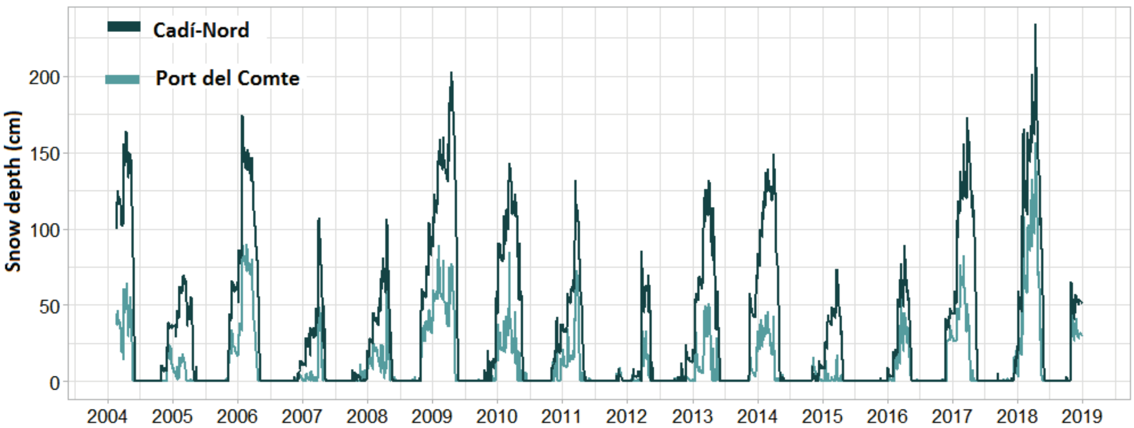


*Figure 4. Annual evolution of snow depth (cm) at Cadí-Nord and Port del Comte.*

Snow persists on the ground during 148 days on average, with maximum values in 2003 and 2004 years, when 211 days of snow were recorded. On the other extreme, the minimum snow persistence occurred in the 2011-2012 season, with only 83 days. If we only consider the days when snow cover was higher than 10 cm, the mean duration of snow depth decreases to 108 days. The minimum was recorded in 2014-2015, with a snow thickness exceeding 10 cm only during 18 days. Snow cover thickness (>10 cm) shows also a high interannual variability as shown by its high CV (48%). When the ground is snow-covered, the average thickness is 25 cm, with peaks in 2017-2018 (59 cm) and a minimum in 2014-2015 with 5 cm. The maximum snow depth normally occurs in February at Port del Comte (Fig. 5), although the highest monthly values were recorded in April 2018, when 114 cm were measured.

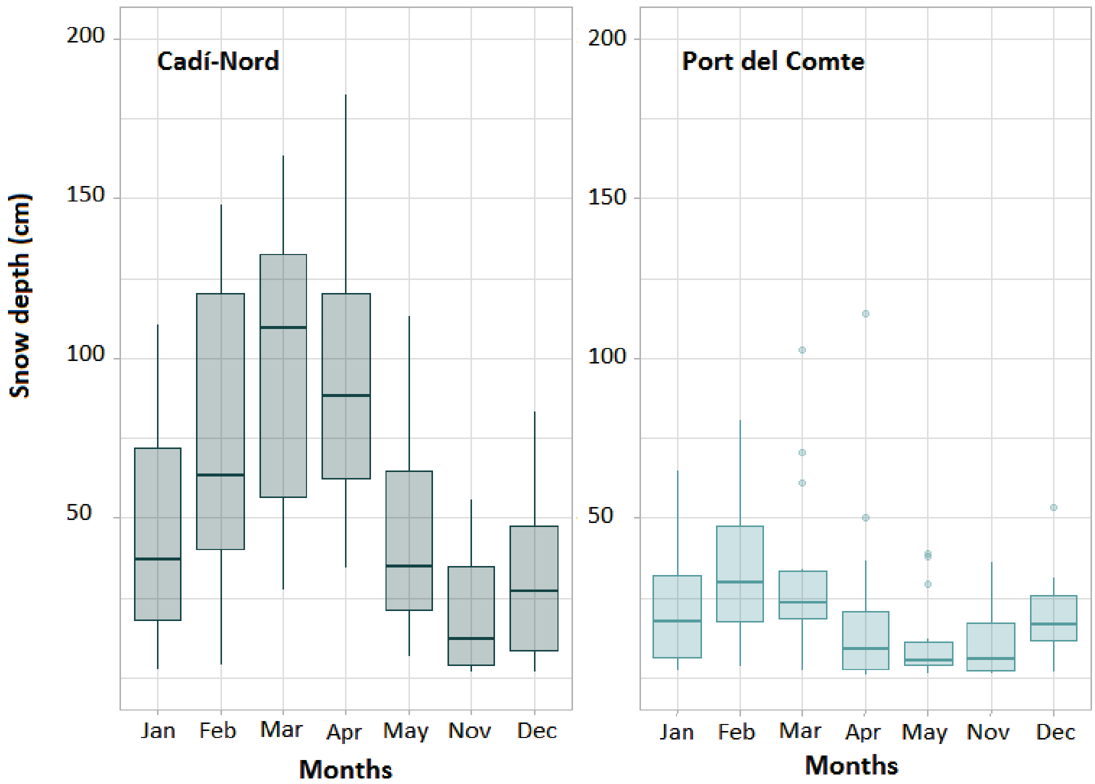


*Figure 5. Monthly distribution of snow depth (cm).*

## *Cadí-Nord (2143 m)*

Over these 14 snow seasons, the average snowfall at Cadí-Nord was 258 cm. In comparison with the annual precipitation, snow accounts for 26% of the total recorded at Cadí-Nord. From November to May, snowfalls represent almost half of the total precipitation (42%). There are seasons above the mean, such as 2013-2014 (213 cm), followed by two snow-poor seasons (89 and 166 cm). The 2017-2018 period was extraordinary in terms of snow as it reached a maximum accumulation of 431 cm, three times higher than the minimum snowfall recorded during the 2014-2015 season (135 cm) (Fig. 4). As well as at Port del Comte, high interannual variability is a common characteristic of snowfall at Cadí-Nord (CV=29.5%). On average, there are 50 days of snowfall at Cadí-Nord, with maximum snow days in 2010-2011 (70 days) and minimum in 2016-2017 (32 days). Intensity record on a snow day is on average 38 cm, with maximum peaks in the 2017-2018 season (62 cm) and minimum in 2004-2005 (12 cm).

In terms of snow cover, snow is present more than 80% of the days between November and May at Cadí-Nord station. The maximum duration took place in the 2008-2009 season, with 206 days. Taking into account only the days with >10 cm of snow, there were 151 days with snow covering the ground. In both cases, the 2011-2012 season recorded minimum values, with 131 days with snow cover and 54 of these with more than 10 cm of snow. Considering days with snow depth >0.1 cm, the snowpack is on average 66 cm. Snow depth (>10 cm) at Cadí-Nord showed also moderate interannual variations, with a CV around 26%. This explains maximum years when snow thickness exceeds 1 m in punctual dates (2008-2009 and 2018-2019, among others) and years with values lower than 30 cm (i.e., 2006-2007 or 2015-2016). Seasonally, March is the month with the highest mean snow depth, although the highest values were measured in April of 2018 (182 cm) (Fig. 5). Usually, snow cover lasts from November to May but it persisted until June in three years (2008, 2013 and 2018).

## *4.2. Climatic parameters affecting snow cover*

### *Temperature*

Figure 6 shows evidence of the control of winter temperatures on spring snow depth. Results show that grouped months have stronger correlation for both stations, however, at a non-significant level of confidence (*p*>0.05). The influence of temperature on the snow depth persisting in April is weak at Cadí-Nord (R=-0.30) as well at Port del Comte (R=-0.27). The occurrence of snow in April is more influenced by temperatures at Cadí-Nord than at Port del Comte because of its lower elevation. In detail, mean monthly temperatures from January to April have a moderate negative correlation with snow depth (R= -0.34 at Cadí-Nord and R= -0.28 at Port del Comte). Similar negative correlations are found from January to March. In March, temperature effects are weaker at Cadí-Nord (R= -0.13) but moderate at Port del Comte (R=-0.43). Finally, April mean temperature is not related to snow depth variations, R=-0.18 at Cadí-Nord and R=-0.1 at Port del Comte.

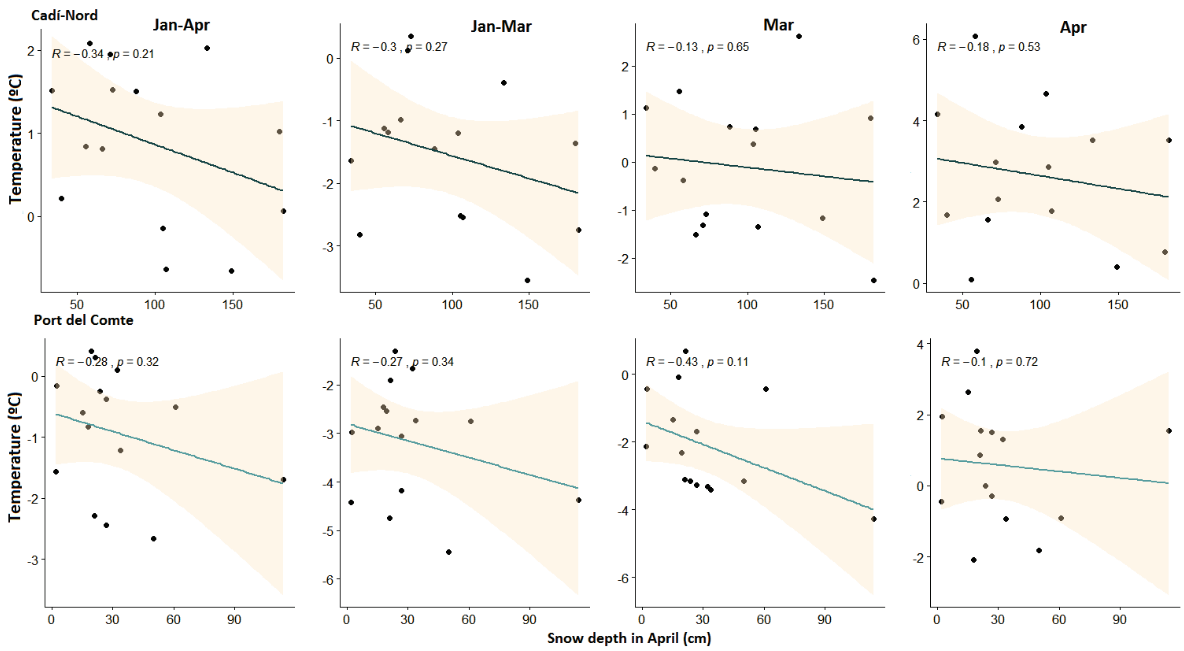


*Figure 6. Correlation between snow depth in April (cm) and mean temperatures (ºC).*

### *Snowfall*

The effect of mid to late season snowfall over late season snow depth at Cadí-Nord and Port del Comte is significant (Fig. 7). For both stations, snowfall is the key factor that controls the thickness of snow in April. In fact, a robust positive correlation is found, stronger at Port del Comte than at Cadí-Nord. Snowfall from January to April shows a higher correlation at Port del Comte (R=0.84) than at Cadí-Nord (R=0.79) with a significant level of confidence ($p$<0.05). Correlations are lower if we consider less months (Fig. 7). While at Cadí-Nord the correlation in March is weak (R=0.35, $p$>0.05) at Port del Comte is higher (R=0.58, $p$<0.05). Lastly, April snowfall is strongly correlated with snow depth at Port del Comte (R=0.67, $p$<0.05), more than Cadí-Nord (R=0.49) but at a non-significant level in the later ($p$=0.06).

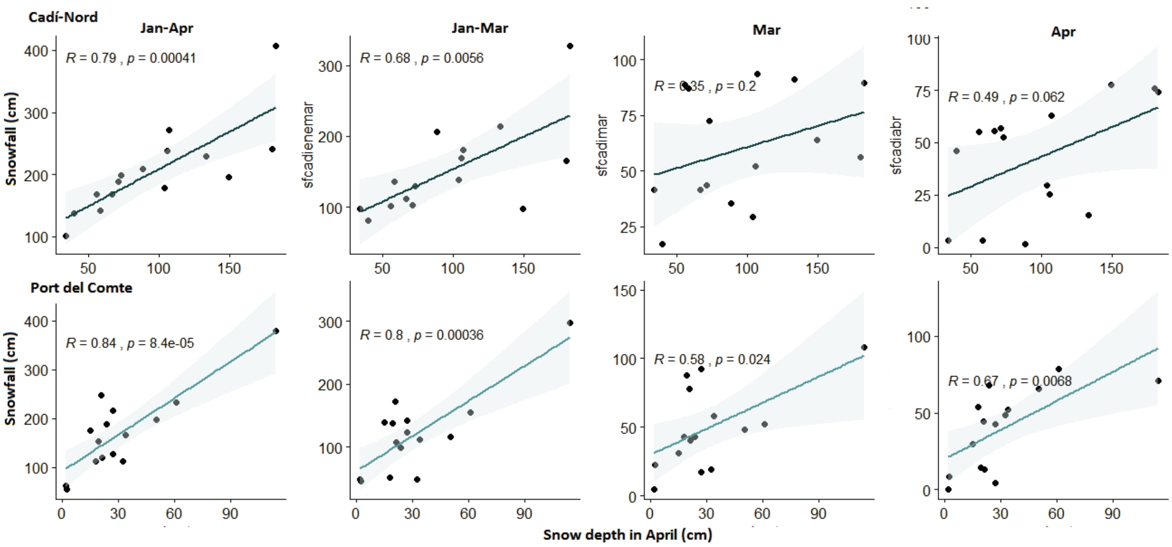


*Figure 7. Correlation between snowfall (cm) and snow depth in April (cm).*

## *4.3. Types of weather associated with major snowfalls*

The synoptic classification of the most frequent weather types revealed 12 CL more usual in the study area grouped in stable or unstable air masses at 500 hPa. The first category corresponds with CL 1, typified as high pressure in Azores and low pressures around Great Britain; CL 2, a zonal situation and high pressure in NW Europe; CL 3, an anticyclone situated over Iberia, a typical situation in January month; CL 4 low pressures with the advection of a polar maritime air mass, CL 5 high pressures over NW Iberian and low pressures circulating in central and North Europe; CL 6 Northern Europe anticyclone; CL 7 high pressures over NW Iberia, blocking northern and mid Mediterranean depressions; CL 8 an extended continental high pressure; CL 9 advection of a depression situated over Gulf of Genoa; CL 10 an anticyclone over western Europe and low pressure around Great Britain; CL 11 high pressures affecting NW Iberian and Bay of Biscay; CL 12 low pressure affecting western Europe from NW origin (Fig. 8).

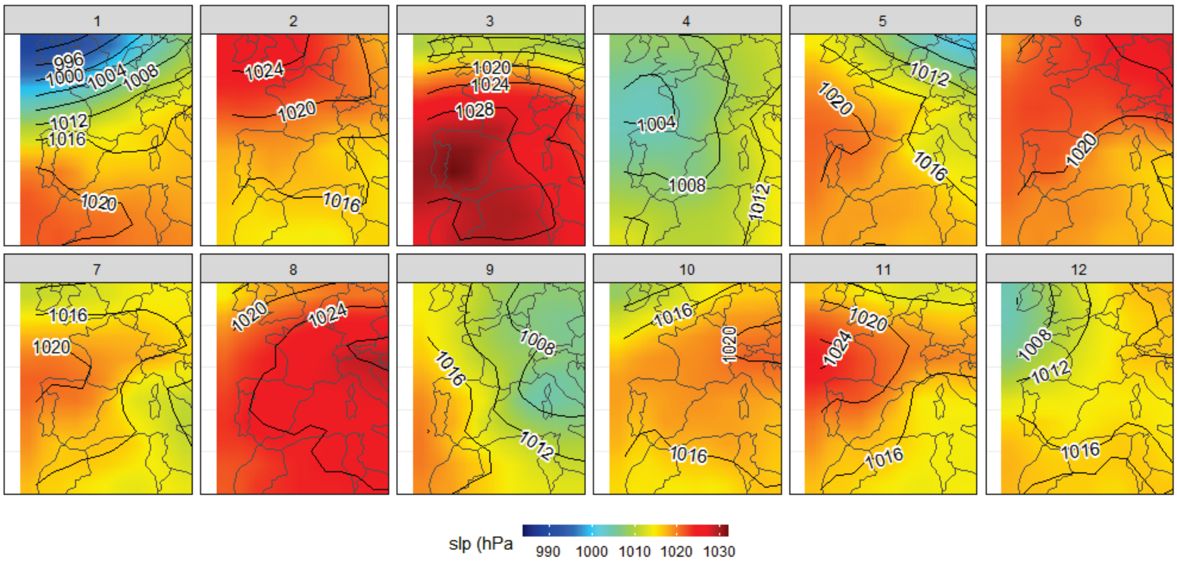


*Figure 8. Mean SLP of the main CL in the study area.*

Nevertheless, there are 5 CL more recurrent categories explaining heavy snowfalls (>15 cm) in the eastern Pre-Pyrenees that concentrate more than 80% of such events. These large snow events are more frequent at Cadí-Nord (n=74) than at Port del Comte (n=36). During the snow season they are concentrated mainly in March, both at Port del Comte (32% of the total) and at Cadí-Nord (27%); followed by April (20 and 18%, respectively) and January (15 and 20%). The NW pattern (CL 4) is the synoptic configuration explaining the most frequent snowfalls (40% of the total). It is characterized by low pressure systems from a polar maritime origin, associated with wet and cold unstable air masses that generate SW air flow over NE Iberia; it is a frequent pattern in winter and the preceding and subsequent months. The second type of situation that led to more intense snowfalls was associated with the advection of a cold polar continental air mass (CL 8). Mediterranean cyclonic activity, formed by the interaction between cold-dry continental and warm-wet air masses from the Mediterranean Sea, characterize CL 9 and 11. These situations are mainly present at the beginning and final months of the season, and bring notable snow events at Cadí-Nord.

## *4.4. The role of NAO teleconnection pattern*

Practically the same correlation indexes between snowfall and NAO are observed at Port del Comte and at Cadí-Nord (Fig. 9). NAO is negatively correlated with snowfall in November at Port del Comte (R=-0.51) and in December at Cadí-Nord (R=-0.61), with a significant level of confidence in both cases. NAO also shows a high negative correlation in November at Cadí-Nord (R=-0.41) and in December at Port del Comte (R=-0.49), although at a non-significant level ($p$>0.05). During the next months, the correlation is weak, with the exception of April (R=0.3, $p$=0.2). For example, in January and February we found positive correlations with NAO (R=0.16, $p$=0.58 at Cadí Nord and R=0.03, $p$=0.89 at Port del Comte), while in March is negative at Port del Comte (R=-0.23, $p$=0.28) and slightly positive at Cadí-Nord (R=0.06, $p$=0.2). In April the correlation is moderately negative, but at a not significant level (R=-0.35, $p$=0.2 at Cadí-Nord and R=-0.29, $p$=0.28 at Port del Comte). Finally, snowfall in May shows no correlation with the NAO (R=-0.075, $p$=0.79 at Cadí-Nord and R=-0.07, $p$=0.8 at Port del Comte).

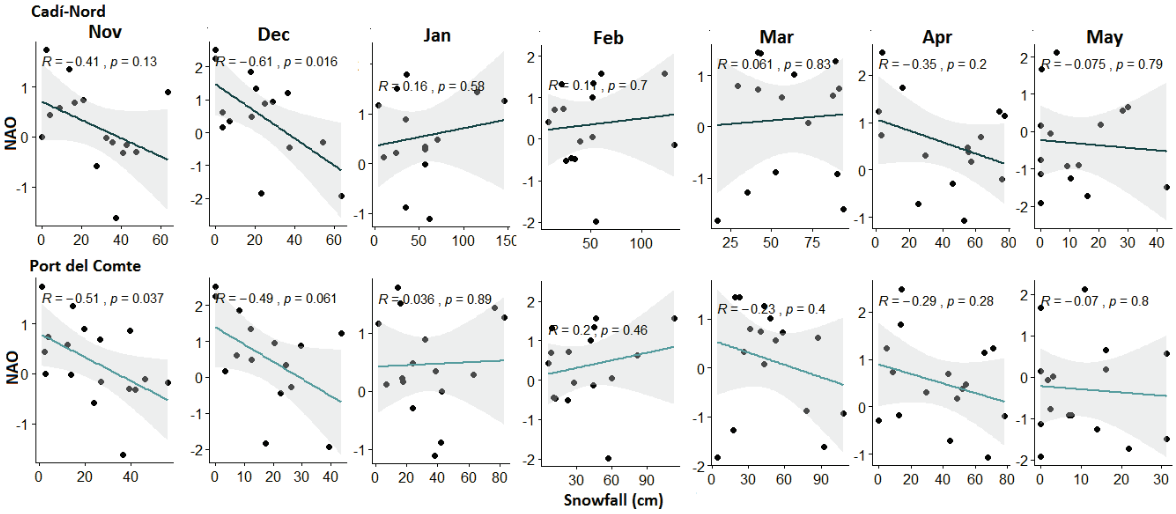


*Figure 9. Correlation between mean monthly snowfall (cm) and NAO.*

In conclusion, data confirm that the NAO plays a prominent role in determining frequency and amount of solid precipitation during the early snow season (November and December). The negative correlation indicating a negative NAO phase suggests that snowfall during these months is driven by low pressure systems located in the southern position, with a weakened Azores anticyclone. In this case, W and SW flows are active, with cyclonic genesis in the western sector of the Iberian Peninsula that favours snow precipitation in the eastern Pre-Pyrenees. During the rest of the season, the relationship with NAO and snowfall is inexistent or weaker and non-statistically significant.

## 5. Discussion

The proximity between Port del Comte and Cadí-Nord snow stations explains that the climate regime is mostly ruled by the same regional factors that determine a similar snow cover evolution. Nevertheless, local factors introduce some singularities at each site; Cadí-Nord snow station is located in a place affected by weak WSW winds that do not favour snow drift, whereas Port del Comte snow station is situated in an open area, exposed to WNW air flows that affect effectively the redistribution of the snow cover.

### *5.1. Snowfall and snow depth patterns*

A high correlation between snowfall and snow depth is found between the two stations (R=0.86). Snowfall events from December to April include ca. 85% of the total events at both sites. Port del Comte, despite being located almost 200 m higher, records ca. 20% less snow depth than Cadí-Nord. Xercavins (1985) showed that precipitation in the southern slopes of the eastern Pyrenees is strongly influenced by the W-E alignment of the mountain range, the distance to moisture sources (Atlantic vs Mediterranean) and the massifs distributed in the surroundings. While the northern face of Pyrenees intercepts the Atlantic low pressures – precisely the most frequent in high snow episodes (Fig. 10) –, the eastern sector of Pyrenees intercepts Mediterranean flows (Xercavins, 1985). Probably for this reason, Port del Comte massif is rain shadowed and climatologically isolated by the orographic in the surrounding. Therefore, instead of altitude, the lesser precipitation recorded at Port del Comte can be explained by its geographical setting, showing also slight continental influences. By contrast, the northern face of Cadí massif is slightly more exposed to the Mediterranean flows channelled through the Tet and Segre valleys, as shown by the higher frequency of heavy snowfall episodes associated with CL 9 and 11 (Fig. 10).

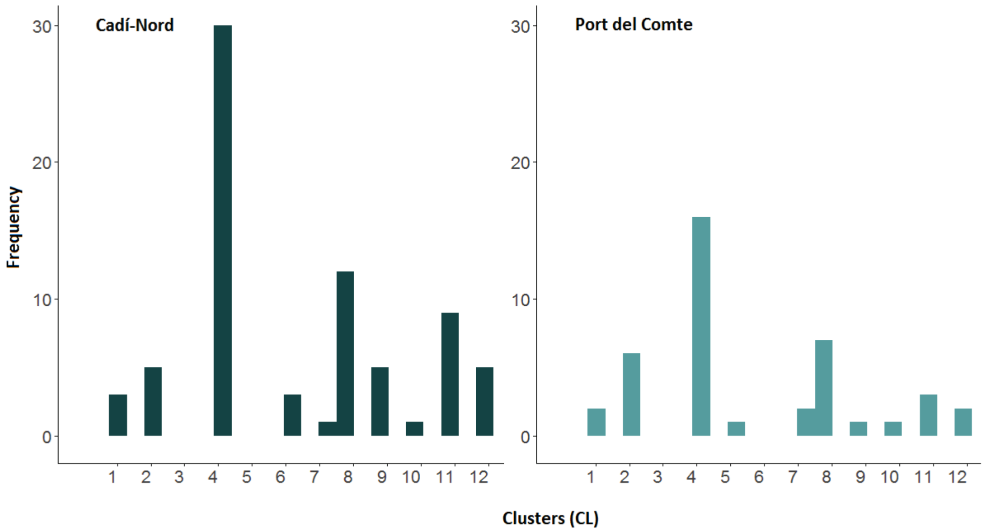


*Figure 10. Frequency of days with >15 cm of snowfall in both stations grouped by CL.*

Our results are in agreement with Vigo *et al.* (2003), who showed an increase of drier conditions in the Pre-Pyrenees moving from the Mediterranean Sea towards NW, particularly in low elevations. The annual snowfall at Cadí-Nord is practically the same than in La Molina (251 cm; 1703 m); just 20 km NE (Salvador-Franch *et al*., 2016). Patterns of precipitation in both regions are driven mostly by wet advections from the Mediterranean Sea uplifted with the first foothills of the eastern Pyrenees (Xercavins, 1985). The number of snowfall days in both stations is constrained by the lower elevation of La Molina station (50 vs 39). In La Molina, snowfall events can be more intense due to shorter distance to Mediterranean Sea, but tends to rain in ca. 20% of the episodes when at Port del Comte and at Cadí-Nord is snowing, because of the altitude difference.

The eastern Pre-Pyrenees show an alternation of snow-rich years with snow-poor years as detected in both stations. However, Port del Comte tends to have greater interannual variability (CV=41%) than Cadí-Nord (CV=29%). Snow-poor seasons (i.e. 2007-2008, 2014-2015) recorded less than half snow precipitation than the snowiest years (i.e. 2008-2009 or 2017-2018). This high interannual variability is linked with the Mediterranean climate of the eastern Pre-Pyrenees that is much reduced in the western fringe of the range where interannual variability is lower (CV ~25%; Navarro-Serrano *et al.*, 2017). Port del Comte and Cadí-Nord share approximately the same snowfall days, around 50 per season. Nevertheless, Cadí-Nord records higher snowfalls every season (38 cm) in comparison with Port del Comte (26 cm). Therefore, snowstorms are usually more intense at Cadí-Nord.

Generally, snow accumulation started in late November, reaching a maximum in February (Port del Comte) or in March (Cadí-Nord). The melting season is faster at Port del Comte, beginning mainly in April until late May in most cases. Along this period, snow cover at Cadí-Nord was thicker and more persistent on average than at Port del Comte. Snow thickness contrasts between both stations, with a thicker snow cover at Cadí-Nord (66 cm) and a thinner one at Port del Comte (25 cm). It also persisted for a longer duration at Cadí-Nord, 175 days and 148 days at Port del Comte. Yet, if we consider only days with notable snow cover, the difference is still greater for the Cadí-Nord. Even so, compared with nearby snow stations, Cadí-Nord station records higher snow depths than in the eastern Pyrenees, such as Núria snow station (1970 m), with 50 cm of snow depth per season, or La Molina (1703 m) with 21 cm (Salvador-Franch *et al*., 2014, 2016). Nonetheless, these differences are apparently related to the higher altitude of Cadí-Nord, the northern slope aspect and the low exposition to the prevailing winds. Snow accumulation in the eastern Pre-Pyrenees is fairly low compared with the snow amount measured in the western Pyrenees, which exceeds 600 cm in mountain areas above 2000 m (Navarro-Serrano *et* *al*., 2017). Nonetheless, snow covers the ground at ca. 40% of the year at Port del Comte and 47% at Cadí-Nord. These values are similar to other Iberian mountains: Alonso-González *et al*. (2020) demonstrated that the landscape in the Pyrenees was snow-covered above 2000 m ca. 40% of the days between 2000 and 2014, decreasing to 37% in the Cantabrian Mountains and 27% in the Central Iberian Range.

### *5.2. Climatic factors affecting snow cover and weather types associated with snow accumulation*

The correlation between snow cover and temperature decreases gaining altitude, and vice versa (López-Moreno *et al*., 2005). For this reason, at the altitude where both stations are placed, the snow depth at the end of the snow season showed a high correlation with snowfall, and a weaker influence of temperatures. The accumulation of snowfall between January to April is the main driver of April snowpack followed by snowfall occurred in the same month. In comparison, Cadí-Nord showed a weaker relationship with snowfall in aggregated and isolated months, and a stronger correlation with temperature than at Port del Comte. In the western Pyrenees above 2200 m the correlation between January to April snowfall and the snow depth in April to May is very high (R=0.72; López-Moreno, 2005), similarly to Cadí-Nord (R=0.79) and Port del Comte (R=0.84). This difference between Cadí-Nord and Port del Comte could be explained by the higher altitude of the last one.

The broad regional climatic influences existing across the Pyrenees from W to E, and N to S, explain the range of synoptic patterns that determine snowfall events in the Pyrenees. In the case of the eastern Pre-Pyrenees, medium to high (>15 cm) snow storms are usually recorded by a few circulation weather types, namely NW and N flows. Results from the eastern Pre-Pyrenees are in accordance with those observed in other areas of the Pyrenees. In high elevation areas of western Pyrenees (>1800 m), heavy snowfall episodes were linked also with NW, N and W air masses (Navarro-Serrano *et al.*, 2017). Similar results were found in the central-eastern Pyrenees (Andorra), where NW and N advections are the situations that record more snow episodes, followed by NE advections (Esteban *et al.,* 2005). Navarro-Serrano *et al*. (2017) pointed out the increasing influence of NE and E advections towards the E in the Pyrenees. Nonetheless, in the eastern Pre-Pyrenees the snowfall recorded by Mediterranean patterns (CL 9 and 11) are less frequent in medium to high snowfall episodes. Indeed, this frequency of this weather configuration driven by a low-pressure system centred around the Gulf of Genova has decreased between 1960 and 2010 (Lemus-Canovas *et al.*, 2019a).

As regards to weather types associated with precipitation events over the Iberian Peninsula, W weather types, consisting of a high pressure system in the W of Canary Island and a low in the W of Ireland records the highest amounts of precipitation from September to March (Cortesi *et al.,* 2013). In the lowlands of the NE Iberian Peninsula, between November and January the highest precipitation episodes correspond also with W weather types (Martin-Vide *et al*., 2008). These periods during the early snow season supply more solid precipitation in the eastern Pre-Pyrenees, statistically significant in November (Port del Comte) and December (Cadí-Nord), R=-0.51 and R=-0.60, respectively. These findings are in accordance with previous studies that identified December as the month with strong and significant negative correlation with precipitation and NAO in NE Iberia (Esteban *et al.,* 2001). In the spring season, as expected by the dynamics of the general atmospheric circulation, the relation between snowfall and NAO is weak or inexistent. During winter, NAO takes an NW to SE alignment above the North Hemisphere, and lower than normal SLP around Azores leads the entrance of northern depressions to Iberia. In boreal spring, has less capacity of explanation, due to the NW to SE alignment and the fewer than winter extension and SLP amplitude (Hurrell *et al.*, 1995). The lack of NAO influence in snowfall in the rest of the months at eastern Pre-Pyrenees is in accordance with previous studies on rainfall in the eastern fringes of the Iberian Peninsula. As well as negative NAO phases are strongly correlated with precipitation in the western Iberia, in the eastern parts of the Iberia there is a weak link between autumn and winter precipitation and the NAO pattern probably due to orographic factors, such as high altitudes or steep slopes (Martin-Vide *et al*., 2006). Indeed, an opposite influence between NAO and snow has been detected depending on the aspect and surrounding topography (Alonso-González *et al.,* 2020). In addition, NAO negative phases are more significantly correlated with precipitation in SW-exposed valleys in the NE Iberia (Esteban *et al.*, 2001).

The impact of the NAO on winter precipitation shows marked spatial differences over Iberian mountain ranges. Robust negative correlations of winter precipitation (and snowfall) and NAO were found in Sierra Nevada (R=-0.7), Cantabrian Mountains and the Central Iberian Range (R=-0.6) (López-Moreno *et al.*, 2011). In other mountain systems such as the Alps, positive NAO values are correlated with years with a thin snowpack; a negative correlation (R=- 0.3) between NAO and snow depth was detected between 1931 and 1999 (Scherrer e*t al.,* 2006). Lastly, the temporal evolution in the last half of the 20th century has shown a trend to increase positive phases of NAO, high pressures in central Europe and anticyclone patterns over IP in winter, translated in a reduction of the WT associated with precipitation (López-Bustins *et al.*, 2008).

## 6. Conclusions

There are still significant gaps on spatio-temporal patterns of snowfall in high mountain areas, such as the eastern Pyrenees, where snow cover plays a critical role for socio-economic activities. Here, the distribution of tens of ski resorts in elevations slightly below 2000 m, together with the high interannual variability of the snow cover characteristic of this range, shows evidence of their critical future in the warming scenario projected by international reports. Changes in the spatio-temporal regime of precipitation, including snow, may also affect water availability in this Mediterranean area where droughts are recurrent and where major cities depend on water supply from the neighbouring mountains. A better characterization of snowfall and snow cover evolution is therefore needed to assess future changes of snow regime in the Pyrenees.

This work characterizes recent patterns of snowfall and snow depth evolution in two high altitude snow stations of the eastern Pre-Pyrenees (Port del Comte and Cadí-Nord) since the early 2000s. Snow cover has shown to be highly variable, with values ranging from 5 to 60 cm at Port del Comte, and from 24 to 117 cm at Cadí-Nord. The presence of snow on the ground at the end of the season is highly controlled by previous months snowfall. Snowfalls are mostly associated with NW weather configurations driven by negative NAO phases during November and December.

Snow cover in both areas is therefore close to limiting climatic conditions for snow ski resorts. A warming scenario or an increase of snowfall variability could impact the feasibility of these activities, or they should be adapted to the new climatic setting.

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