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SPATIO-TEMPORAL ANALYSIS OF SNOWFALL EVENTS IN THE SPANISH PYRENEES AND THEIR RELATIONSHIP TO ATMOSPHERIC CIRCULATION

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ABSTRACT. *In this study we analyzed the annual and seasonal variability of snowfall events in the Spanish Pyrenees, and the relationship between different weather types and normal (between P30 and P80) and intense (> P80) snowfall events. Data for the hydrological years 2008-2013 were obtained from 10 telenivometers (TNMs) managed by the ERHIN Program network. The TNMs were classified and clustered using principal component analysis (PCA) and k-means classification procedures. The results indicated that there was significant variability in annual snow depth amongst both TNMs and years, with the eastern TNMs showing the most inter-annual variability. The western TNMs recorded most annual accumulation in the winter months (December, January, February), whereas those located eastward showed more homogenous accumulation over winter, spring, and late autumn. Analysis of the frequency and intensity of snowfall did not show clear spatial patterns. No relationship was found between geographical variables (elevation, longitude, latitude) and the frequency of snowfall greater than 5 cm. However, a relationship between longitude and snowfall greater than 25 cm was found, showing that western areas are more likely to receive heavy snowfall. Snowfall of medium intensity (P30-P80) was associated with weather types from the northwest, north, and west, while for heavy snowfall events (> P80) the dominant types were from the northwest, followed by the north, and to a lesser extent the west. The western TNMs recorded that Atlantic Ocean weather types brought the most frequent snowfall, while the eastern TNMs showed that Mediterranean weather types were more important. This study indicates that snowfall differs among Pyrenean valleys, with weather types responsible for much of the variability, particularly with respect to normal and extraordinary snowfall events. However, the elevation of the TNMs may have had an effect, necessitating further research to enable quantification of the effects of snowfall gradients in the Pyrenees.*

Análisis espacio-temporal de los eventos de nevadas en el Pirineo español y su relación con la circulación atmosférica

RESUMEN. *Este estudio analiza la variabilidad interanual y estacional de los eventos de acumulación de nieve en los Pirineos Españoles, así como la relación entre diferentes tipos de tiempo y los episodios de nevadas normales ($P_{30} < x < P_{80}$) e intensas ($x > P_{80}$). Los datos fueron tomados para los años hidrológicos 2008 a 2013 a partir 10 telenivómetros de la red gestionada por el Programa ERHIN (Evaluación de los Recursos Hídricos Procedentes de la Innivación). Estos se analizaron mediante un Análisis de Componentes Principales (PCA) y una clasificación por K-medias. Los resultados indican que existe una variabilidad importante en los acumulados de espesor de nieve anual entre telenivómetros y años de estudio, mostrándose los telenivómetros orientales como más variables. Los telenivómetros occidentales tienen la mayor parte de su acumulado anual en los meses de invierno (DEF), mientras que los orientales tienden a homogeneizar más sus acumulados entre el invierno, la primavera y el otoño. El análisis de la frecuencia e intensidad de las nevadas no mostró un patrón espacial claro, aunque los telenivómetros de Quimboa (N001) e Izas (N002) mostraron buena capacidad de registrar nevadas de gran intensidad. No se encontró relación entre variables geográficas (altitud, longitud y latitud) y la frecuencia de episodios de nevadas superiores a 5 cm, pero sí entre longitud y nevadas superiores a 25 cm, mostrando que las estaciones occidentales son más proclives a nevadas de gran intensidad. Las nevadas normales (entre P_{30} y P_{80}) son provocadas, principalmente, por los tipos de tiempo noroeste (NW), norte (N) y oeste (W); mientras que para las nevadas intensas ($>P_{80}$) la componente dominante es la noroeste (NW), seguida por norte (N) y, en menor medida, oeste (W). En los telenivómetros occidentales son las componentes de procedencia atlántica las generadoras de las nevadas, mientras que en los telenivómetros orientales las componentes mediterráneas ganan importancia. Este estudio sugiere que el comportamiento de los distintos valles pirenaicos no es idéntico, sino que existen factores, como los tipos de tiempo, que generan grandes diferencia entre ellos, que pueden verse si diferenciamos las nevadas normales de las extraordinarias. Sin embargo, no debemos desdeñar el efecto que puede causar la altitud de los telenivómetros, con lo que son necesarias nuevas investigaciones que nos permitan cuantificar los efectos de los gradientes pluviométricos en las montañas pirenaicas.*

Key words: weather types, Pyrenees, snowfalls, snow days, telenivometers.

Palabras clave: tipos de tiempo, Pirineos, nevadas, días de nieve, telenivómetros.

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1. Introduction

Study of the spatial and temporal variability of snow cover is of great importance because it is key to explaining ecological, geomorphological, and hydrological processes in mountain areas (Barnett *et al*., 2005; Mellander *et al*., 2007; Jonas *et al*., 2008a, 2008b). In addition, episodes of snow accumulation can influence processes including erosion (Birnie and Gordon, 1980; Gauer and Issler, 2004), avalanches (López-Moreno *et al.,* 2010; Esteban *et al*., 2009) and floods (Lopez-Moreno *et al*., 2002; Pino *et al*., 2016). The spatio-temporal variability of this phenomenon also influences human activities including power generation, water resources management, and winter tourism (Beniston, 2003; Barnett *et al*., 2005; Lasanta *et a*l., 2007; Alvares *et al*., 2009; Uhlmann *et al.,* 2009; López-Moreno *et al*., 2013a). For this reason, various studies have investigated the factors that influence the patterns of spatial distribution of snow cover (López-Moreno *et al*., 2006, 2016; Grünewald *et a*l., 2013; Revuelto *et al*., 2014), the temporal variability of snow cover in response to regional and hemispheric atmospheric circulation (Esteban *et al*., 2005; López-Moreno and Vicente-Serrano, 2007; Buisan *et al.*, 2015), and the likely response of the snowpack to global warming processes (López-Moreno *et al.,* 2009, 2013b, 2014). These studies have shown that since the middle of the last century there has been a decrease in snow accumulation in the Pyrenees (López-Moreno, 2005; Buisan *et al*., 2015), and that this is mainly attributable to changes in the patterns of weather types affecting the Iberian Peninsula (López-Moreno and Vicente-Serrano, 2007). However, the effects of changes in atmospheric circulation over the peninsula can vary because of its complex topography and exposure to air masses from different sources (Esteban *et al*., 2005; Vicente-Serrano and López-Moreno, 2006). Simulations using future climate scenarios calculated using regional models indicate that the trend of decrease in snow cover will be exacerbated in coming decades, and be more obvious at lower elevations (López-Moreno *et al*., 2008, 2009; Maris *et al*., 2009).

Most of the studies noted above have been undertaken using limited snow data. Until recently, the only daily snow depth information was from the Spanish Meteorological Agency (AEMET) for populated areas below 1500 m a.s.l. (Buisan *et al*., 2015), or short data series available from mountain refuges and ski resorts. However, the observation network of the ERHIN Program (*Estudio de los Recursos Hídricos Invernales:* Study of Winter Water Resources) has, since 1985, recorded three snow depth measurements per year at more than 100 snow poles distributed in the Pyrenees, constituting the only long-term dataset on snow depth in the Pyrenees (Arenillas *et al*., 1990; López-Moreno, 2005; Arenillas *et al*., 2008; Morán-Tejeda *et al*., 2013). Under the ERHIN Program, 29 automatic snow monitoring instruments (telenivometers: TNMs) have been installed in the main Spanish mountain types, with the purpose of obtaining systematic, homogeneous, and high temporal resolution (15 min) data on snow depth and snow water equivalents (SWEs). Eleven of the TNMs are in the Pyrenees, and are accessible through the SAIH (*Sistema Automático de Información Hidrológica*: Automatic Hydrological Information System) system of the CHE (*Confederación Hidrográfica del Ebro:* Ebro River Hydrographic Authority). Unlike the older meteorological network, the TNMs in the Pyrenees are located in high mountain areas, all above 1800 m a.s.l. These provide detailed and precise information enabling almost real time study of novel aspects of the snowpack in the Pyrenees.

In this study we used information from the TNMs installed in the Pyrenees to analyze the intensity of snowfall events in those mountains, and to identify their relationships to weather types. Weather types are a function of the synoptic situation in the atmosphere, the occurrence of disturbances, and the predominant wind directions. The high temporal resolution of the data and the longitudinal distribution of the TNMs enabled us to analyze the intensity of snowfall in relation to the occurrence of various weather types, and consequently to identify those synoptic conditions favoring the accumulation of snow in different locations in the western and central Pyrenees.

2. Study area

The ERHIN TNM network covers an area of approximately 180 km long and at least 50 km wide in the Spanish western and central Pyrenees (Fig. 1). This is a main headwater area on the left bank of the Ebro River, and forms a natural border between France and Spain. Elevations in this region tend to increase from west to east, reaching more than 3000 m a.s.l. (Aneto Peak, 3404 m a.s.l.). In the entire mountain range, 5768 km^2 are above 1500 m a.s.l., 3523 km^2 are above 2000 m a.s.l., 735 km^2 are above 2500 m a.s.l. and 5 km^2 are above 3000 m a.s.l. The TNMs are located between 1800 and 2700 m a.s.l., providing good representation among the most highly elevated area in the Pyrenees.

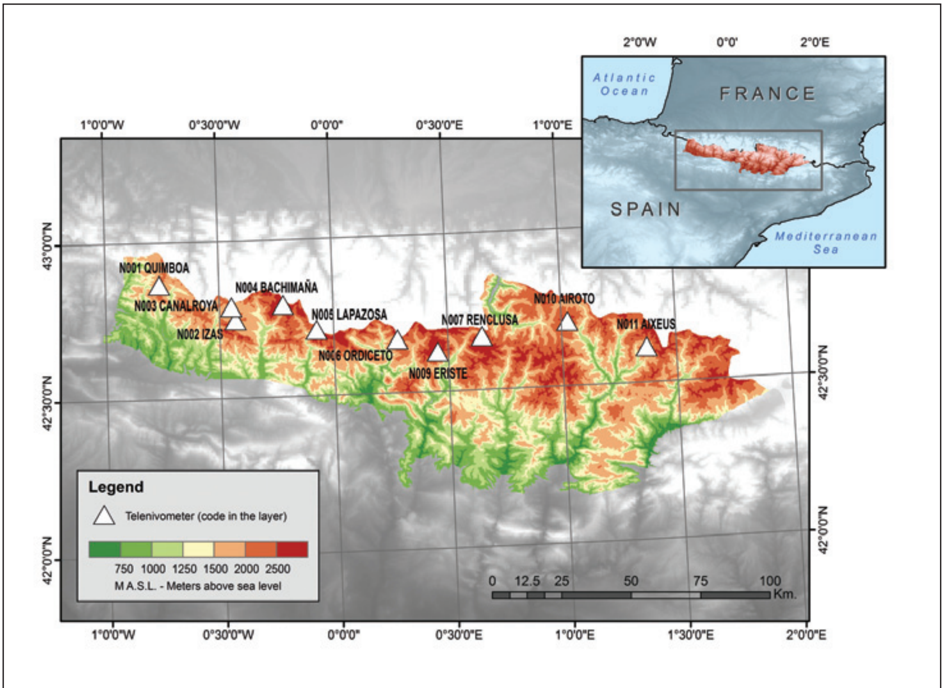

Figure 1. Study area and location of TNMs.

The climate of the Pyrenees is influenced by its proximity to the Atlantic Ocean and the Mediterranean Sea, on its west to east axis. However, the abrupt relief causes great spatial variability in the distribution of precipitation and temperature. Close to the main divide and the Pyrenean summits, precipitation exceeds 1000 mm per year, and can reach more than 2000 mm per year in some areas (Cuadrat *et al*., 2007); however, it generally follows a pattern of decrease from west to east and from north to south (Buisan *et al*., 2016). In areas dominated by Atlantic Ocean conditions (approximately up to the headwaters of the Gállego and Ara rivers), most precipitation occurs between December and March, while to the east in areas having a Mediterranean climate influence, the precipitation peaks occur in spring and autumn (April-June, September-November) (López-Moreno *et al*., 2009). Precipitation usually falls as ice or snow from late autumn to early spring above 1500-1600 m a.s.l. (López-Moreno and García-Ruíz, 2004).

The temperature in this region primarily follows an altitudinal gradient of approximately 0.63°C per 100 m (López-Moreno, 2006). In the cold months the 0°C isotherm is at approximately 1600 m a.s.l. (García-Ruiz *et al*., 1986), and this represents the general limit for persistent snow cover. Below this limit a snowpack occurs only during the coldest months in winter (December to February). Below 1300 m a.s.l. the snowpack is generally ephemeral, even though snowfall events occur frequently in winter (López-Moreno *et al*., 2011).

3. Data and Methods

3.1. Snow Data

Snow depth data for the study area where obtained from the TNMs managed through the ERHIN Program and the CHE. The TNMs are intended to continuously record the snow depth (using an ultrasonic sensor) and the snow water equivalent (SWE), by measuring the snowpack attenuation of gamma rays that pass through the atmosphere and reach the ground.

The study period covers the hydrological years 2008/09 to 2013/14, and the datasets were analyzed for each month of the year other than those in summer (July to September). This period was selected because the TNMs were installed in 2008, enabling us to take advantage of the available data. The hydrological year 2014/15 was excluded because it included numerous data gaps. The data series for the remaining years were of good quality, with < 5% data gaps; these were filled by linear regression using near TNMs and highly correlated ($r > 0.8$) observations. Data from the "Salenques-N008" TNM were also excluded because of the large number of data gaps (> 25% data), as gap filling was not possible.

While the database involved a relatively short period (6 years), it was a period of high climate variability, which enabled analysis of the inter-annual variability in the occurrence of snowfall events, and the frequency of occurrence of different weather types affecting the Iberian Peninsula.

The TNM snow depth data is recorded with a vertical resolution of 1 cm and a temporal frequency of 15 min. We used the snow depth value measured at the end of each day (23:45 h), which enabled snowfall to be related to weather types during the previous 24 h. We only considered snowfall events that accumulated 2 cm or more of fresh snow, thus avoiding sensor noise resulting from temperature fluctuations that affect the spread of ultrasound signals (Ryan et al. 2008). Table 1 shows geographical and locational characteristics for each of the TNMs used in the study.

Table 1. Geographical and locational characteristics of the ERHIN TNMs.

	Name	**Longitude**	**Latitude**	**Elevation**	**Distance to the Atlantic Ocean (km)**	**Distance to the Mediterranean Sea (km)**
N001	Quimboa	-0.76	42.87	1810	93	295
N002	Izas	-0.43	42.75	2080	122	265
N003	Canal Roya	-0.45	42.79	1971	118	269
N004	Bachimaña	-0.22	42.79	2220	133	253
N005	Lapazosa	-0.07	42.71	2140	148	238
N006	Ordiceto	0.28	42.67	2380	175	212
N007	Renclusa	0.65	42.67	2180	202	189
N009	Eriste	0.45	42.63	2350	190	198
N010	Airoto	1.03	42.71	2380	229	172
N011	Aixeus	1.37	42.61	2400	259	147

3.2. Weather System Classification

The daily weather types affecting the Iberian Peninsula were determined using the method of Jenkinson and Collison (1977). This involves sea level barometric information from 16 locations forming a grid of 5 x 5° latitude/longitude resolution that covers the Iberian Peninsula and the Balearic Islands (López-Moreno and Vicente-Serrano 2007), in the region 50-30°N and 20°W-10°E. The sea level barometric data were obtained from the "Reanalysis" NCEP/NCAR database (http://www.esrl.noaa.gov), which is based retrospective analysis of observed atmospheric data, and recalculation of the atmospheric pressure values.

This method has been successfully used to classify 26 winter weather types affecting the Iberian Peninsula (Goodess and Palutikof, 1998; Spellman, 2000). We simplified the results following the method proposed by Jones *et al.* (1993) and Trigo and Da Camara (2000). This reduced the number of weather types to 10 through the elimination of hybrid weather types using a frequency of 0.5 to the types cyclonic (C) and anticyclonic (A), and another 0.5 to the corresponding directional types, which included north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). This method has been successfully used in several studies of the climate of the Spanish Pyrenees (López-Moreno and Vicente-Serrano, 2007; Esteban *et al*., 2009; Buisan *et al*., 2015). To relate the intensity of snowfall to the various weather types, we normalized the number of snowfall events in relation to the days with each weather system. This enabled calculation of the occurrence of particular weather types as a function of snowfall extent, and consequently identification of those synoptic situations favoring snowfall events of differing intensities.

3.3. Statistical Analysis

The data were analyzed using descriptive statistics, with the objective of characterizing the snowfall at the various TNMs on the basis of average snowfall, inter-annual and intra-annual variability, standard deviation, and coefficient of variation (standard deviation divided by the average). The generation of histograms and frequency boxplots enabled us to graphically represent the intensity of snowfall at each TNM.

Two criteria were used to define snowfall intensity. (1) To analyze the relationship between the snowfall intensity and geographic variables (latitude, longitude, elevation), snowfall exceeding 5 cm and 25 cm were used as thresholds for the most common and the heaviest snowfall events, respectively. These values approximately correspond to the 30th (P30) and 90th (P90) percentiles, respectively, for most of the TNMs. (2) To analyze the relationship between the intensity of snowfall and the various weather types we used the specific P30 and P80 values for each TNM, with the aim of characterizing for each location the weather types causing particular snowfall intensities.

Principal components analysis (PCA) was used to classify the TNMs according to: (1) the temporal distribution of snowfall over the various months of the year, to identify those TNMs making similar contributions to total snow accumulation in each month; and (2) the relationship between weather types and snowfall events ranging from P30 to P80, and for snowfall events exceeding P80. This type of PCA enabled grouping of those stations where different weather types had a similar influence on the occurrence of normal and heavy snowfall. PCA is a statistical multivariate technique for synthesis of information, and in this study was used to group the effects of a wide range of variables (the months of snowfall, the weather types, the TNMs) without significant loss of the original information. In this analysis the variables are compressed, and redundant information is eliminated using correlation and variance-covariance matrices. In this study PCA was conducted using the correlation matrix method, with components rotated using the Varimax method (Richman, 1986). Subsequently, non-hierarchical k-means were used to group the locations in a set of k-clusters; this technique has been used in other studies (Esteban *et al*., 2005). The Ward method was used to detect the number of clusters (Calmanti *et al*., 2015). The k-means classification enabled the closest cluster (in terms of the centroid) to be assigned to each TNM, usually based on the Euclidean distance.

4. Results

4.1. Inter-annual and Seasonal Variability

Table 2 shows that there was high inter-annual variability in snow accumulation. Some years were associated with high levels of accumulation; for example, in 2012 and 2013 most TNMs recorded accumulation exceeding 700 cm. In other years (e.g. 2011) the accumulation of snow barely reached an average of 450 cm.

Table 2. Inter-annual total snow accumulation variability (cm) amongst years and TNMs (October to September).

YEAR	N001	N002	N003	N004	N005	N006	N007	N009	N010	N011	R	A	CV
2008	644	768	506	588	576	643	445	363	255	339	513	513	0.30
2009	751	903	314	745	777	622	497	839	469	412	589	633	0.30
2010	572	686	333	603	465	361	381	663	358	420	353	484	0.26
2011	432	480	374	454	349	347	383	743	353	542	396	446	0.26
2012	884	885	647	867	649	670	500	935	529	882	435	745	0.21
2013	912	898	541	728	601	615	547	885	784	572	371	708	0.20
Range (R)	480	422	333	413	428	323	166	572	529	543			
Average (A)	699	770	452	664	569	543	459	738	458	528			
CV	0.24	0.20	0.27	0.20	0.24	0.25	0.13	0.26	0.37	0.34			

There were also years in which there were very large spatial differences in snow accumulation (e.g. 2009), when major differences were found between the snow accumulation levels recorded at the eastern and western TNMs. The year 2013 was the most spatially homogeneous, with an average snow accumulation of 708.4 cm and a coefficient of variation of 0.20 among TNMs. We usually found a high degree of variability among TNMs. For example, the annual accumulation average at the N002-Quimboa TNM was 770.1 cm, but was only 452.4 cm at the N003-Canal Roya TNM. In terms of inter-annual variability in snow accumulation amongst TNMs, we found most variability for the N010-Airoto (CV = 0.37) and N011-Aixeus (CV = 0.34) TNMs, and least variability for the N007-Renclusa (CV = 0.13) TNM.

Figure 2 shows the importance of each month in terms of annual snow accumulation, most of which occurred in the colder months (on average, 67% of the total accumulated occurred from November to February). Snow accumulation began to gradually decrease in spring, and fell to a minimum in June.

Figure 2 shows that despite the general patterns noted above, there was marked variation among TNMs and seasons. The winter months provided a greater proportion of the snow accumulation at the western TNMs, while the spring months favored a greater proportion of the snow accumulation at the eastern TNMs. This observation was corroborated by the PCA, which grouped the TNMs based on the weight of each month with respect to total snowfall. The PCA identified 3 principal components that together explained 87% of the total variance (54%, 17%, and 16% for PC1, PC2, and PC3, respectively). PC1 grouped TNMs for which June and October were important in terms of snow accumulation (0.904 and 0.864, respectively), and February was least important (-0.749). PC2 grouped TNMs for which March and May were important for snow accumulation (0.949 and 0.647, respectively), and January was least important (-0.821). PC3 grouped TNMs for which April was the month showing most accumulation (0.833), and the accumulation in November was below normal

(-0.945). The factor scores for each TNM are shown in Table 3. This shows that for PC1 the maximum correlation was with the N010-Airoto TNM, and the minimum was with the N006-Ordiceto TNM. For PC2 the maximum correlation was with the N007-Renclusa and N011-Aixeus TNMs, and the minimum was with the N002-Izas. For PC3 the maximum correlation was with the N006-Ordiceto and N009-Eriste TNMs, and the minimum was with the N001-Quimboa TNM.

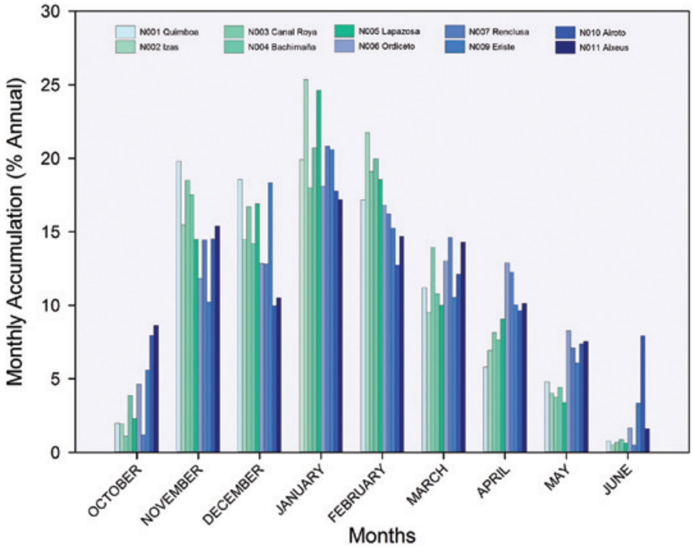

Figure 2. Monthly snow accumulation at each TNM, as a percentage of the annual total. The different colors represent the various TNMs.

Table 3. PCA components for monthly snow accumulation at the various TNMs.

TNM	PC1	PC2	PC3	Cluster	Distance to centroid
N011-Aixeus	0.76	1.14	-0.03	1	1.08
N010-Airoto	2.25	-0.07	-0.26	1	1.34
N009-Eriste	0.69	-0.79	1.19	1	1.65
N001-Quimboa	-0.03	0.05	-1.65	1	1.74
N004-Bachimaña	-0.28	-0.39	-0.82	2	1.06
N005-Lapazosa	-0.61	-1.38	0.31	2	1.34
N002-Izas	-0.73	-1.45	-0.01	2	1.41
N006-Ordiceto	-0.11	0.75	1.34	2	1.54
N007-Renclusa	-1.07	1.16	1.02	2	1.58
N003-Canal Roya	-0.86	0.98	-1.08	2	1.61

The k-means analysis generated two TNM clusters, based on PCA scores (Table 3). Cluster 1 included the eastern TNMs, with the N011-Aixeus TNM being the best representative (distance, 1.08) and Cluster 2 included the western TNMs, with the N004-Bachimaña TNM being the most representative (distance, 1.05).

Figure 3 shows the monthly distribution of snow accumulated at the Bachimaña and Aixeus TNMs, which were the most highly correlated to clusters 1 and 2, respectively. Most of the total annual snow accumulation at the Bachimaña TNM occurred during the winter months (December to February; 54.9%), with only 22.8% occurring from March to May (spring). A very different distribution in monthly snow accumulation occurred at the easternmost TNM, N011-Aixeus, where 42.5% of the total accumulation occurred in the winter months (December to February), while 32% occurred in the spring months (March to May).

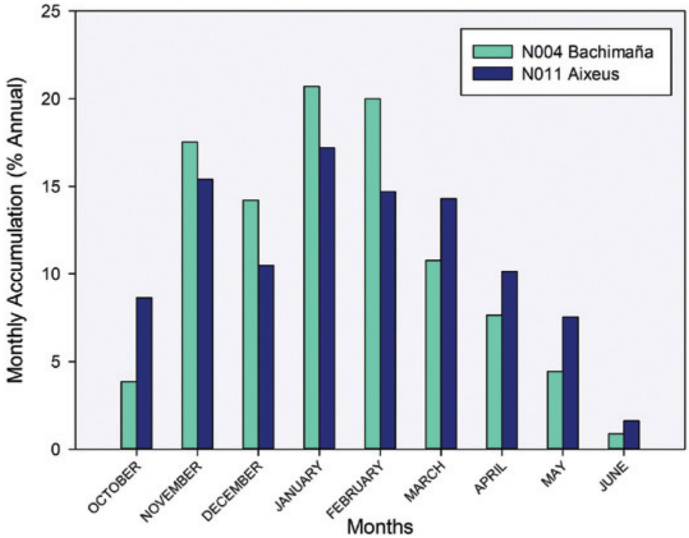

Figure 3. Monthly contributions to annual snow accumulation (%), recorded at the N004-Bachimaña (cluster 1) and N011-Aixeus (cluster 2) TNMs.

4.2. Frequency and intensity of daily snowfall events

The TNMs recording the most snowfall events (> 2 cm) were N009-Eriste (61 days per year), N011-Aixeus (54 days), and N005-Lapazosa (53 days), while those where least snowfall events were recorded were N003-Canal Roya (44 days) and N007-Renclusa (45 days). In general, the eastern TNMs recorded more snowfall days than those located in the west.

In Figure 4 the TNMs are ordered from west to east (see Table 1). This shows that the N001-Quimboa and N002-Izas TNMs commonly recorded snowfalls events exceeding 25 cm, while at the other TNMs this threshold was rarely exceeded. This is also evident from the statistics in Table 4, which show that snowfall at the two most western TNMs frequently exceeded P80>20 cm. while those located eastward rarely reached this level. Thus, at the eastern TNMs the snowfalls were generally more frequent than those TNMs located to the west, but accumulated less snow. The most obvious cases were the N004-Bachimaña (P80: 22 cm) and N010-Airoto (P80: 13 cm) TNMs. The N004-Bachimañana TNM was representative of PC1 (most snow accumulation occurred in winter), while the N010-Airoto TNM clustered in PC2 (marked spring contribution to total snow accumulation). Exceptions to this pattern were the N009-Eriste and N003-Canal Roya TNMs, where local conditions (including aspect and elevation) confounded the west to east pattern.

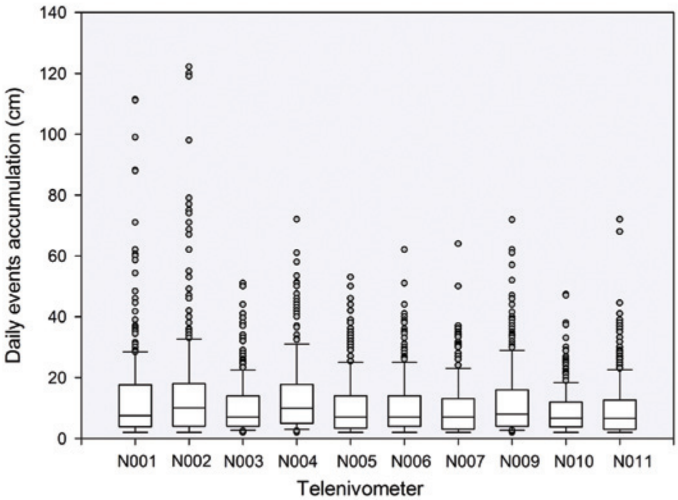

Figure 4. Distribution of daily snowfall events (> 2 cm). The lines in the boxes indicate the mean values, the boxes encompass the 25th and 75th percentiles, the upper and lower bars show the 10th and 90th percentiles, respectively, and the dots are all the events exceeding the 90th percentile.

Table 4. Daily snowfall events exceeding 2 cm recorded at each of the study TNMs.

Percentile	Quimboa N001	Izas N002	Canal Roya N003	Bachimaña N004	Lapazosa N005	Ordiceto N006	Renclusa N007	Eriste N009	Airoto N010	Aixeus N011
P25	4.0	4.0	4.0	5.0	3.0	4.0	3.0	4.0	4.0	3.0
P30	4.0	5.0	4.0	6.0	4.0	4.0	4.0	5.0	4.0	4.0
P50	8.0	10.0	7.0	10.0	7.0	7.0	7.0	8.0	6.5	7.0
P80	20.4	21.0	15.8	22.0	17.0	17.0	16.0	19.0	13.0	14.0
Minimum	2	2	2	2	2	2	2	2	2	2
Maximum	111	122	51	72	53	62	64	72	47	72

Figure 5 shows the relationship of days having snowfall > 5 cm and > 25 cm to the longitude and altitude of their locations. Snowfall > 5 cm (Fig. 5, left panel) showed no clear spatial pattern among TNMs. However, snowfall events exceeding 25 cm (Fig. 5 right panel) decreased eastward. The N003-Canal Roya TNM again appeared to be an exception; it is located in the west but recorded few days having daily snow accumulation > 25 cm.

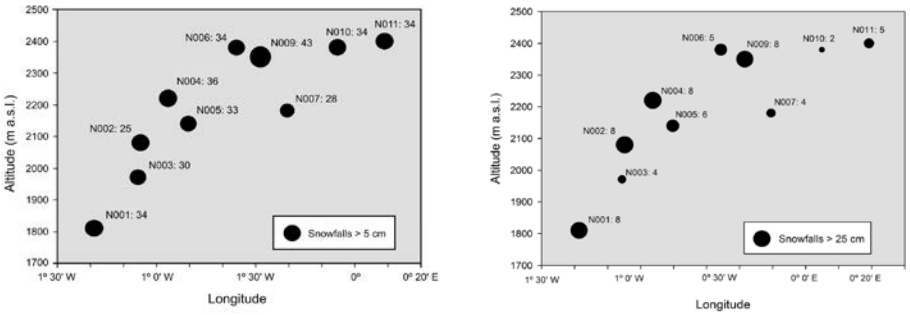

Figure 5. Frequency of daily snowfall events exceeding 5 cm (left) and 25 cm (right) for various TNMs, and the relationship of this to altitude and longitude.

The correlation (r = 0.64) between snowfall events > 5 cm and > 25 cm registered for various TNMs also highlights that there was a mismatch between TNMs recording the largest number of precipitation events, and where the events were most intense.

4.3. Relationship between weather types and snowfall intensity

Table 5 shows the frequency of occurrence of various weather types during the snow season on the Iberian Peninsula. During this period anti-cyclonic types (29.5%) dominated (cyclonic: 22.5%). The N, NE, and NW weather types occurred at frequencies of 8-9%, while the frequencies of E, SW, W, and S types ranged from 2.6 to 6.2%.

Table 5. Weather system frequency during the snow season (October to June).

Weather system	N	NE	E	SE	S	SW	W	NW	C	A
Days / year	25.3	21.8	17.0	12.3	7.3	13.7	12.6	21.3	61.5	80.5
%	9.2%	7.9%	6.2%	4.5%	2.6%	5%	4.6%	7.8%	22.5%	29.5%

4.3.1. Frequency of normal snowfall events associated with different weather types

Figure 6 shows the frequency distribution of weather types during >P30 and <P80 daily snowfall events. It shows that those producing most snow were the NW, W, and N weather types. Although there were differences amongst TNMs, these types produced up to 15% more snow (20% in the case of NW) than the others. The next most productive was the SW weather system, which was responsible in average of the 5% of normal snowfall events, but it exceeds the 10% in several TNMs.

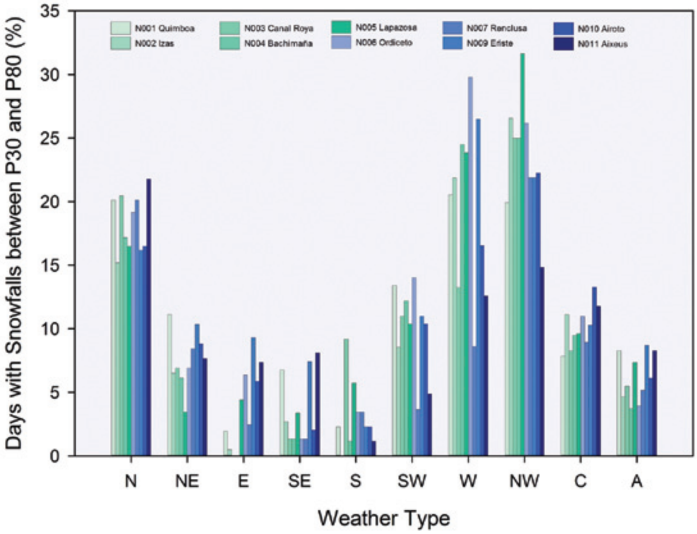

Figure 6. Percentage of normal snowfall days (>P30 and < P80) associated with each weather system.

The recorded effect of weather types varied among TNMs. The TNMs located to the west recorded that the N and NW weather types produced most snow, while for those in the east showed that the NE, E, and SE weather types were most productive. In all cases the N and NW weather types explained the occurrence of most normal snowfall. The PCA grouped the TNMs on the basis of the percentage of days that each weather system generated snow of this intensity. We identified three PCs that explained 77% of total variance (38%, 26%, and 13%). PC1 grouped the TNMs that recorded more influence from Mediterranean weather types (SE, NE, E), PC2 grouped those TNMs that recorded more influenced from Atlantic flows (SW, W, and NW), and PC3 grouped TNMs that recorded the occurrence of snowfall events that were influenced by advections from the south and north.

The PCA scores (Table 6) show that PC1 was highly correlated with the records from the N009-Eriste and N011-Aixeus TNMs, but weakly correlated with the data from the N005-Lapazosa TNM. The TNM having data most highly correlated with PC2 was N006-Ordiceto, while the weakest correlations were recorded at the N007-Renclusa and N011-Aixeus TNMs. The TNM recording the data most highly correlated with PC3 was N003-Canal Roya, while the lowest data correlation with PC3 was from the N002-Izas TNM.

The k-means analysis generated two TNM clusters based on the PCA scores (Table 6). With a few exceptions, Cluster 1 grouped the western TNMs, with the data from the N003-Canal Roya TNM being the most highly correlated. Cluster 2 grouped the eastern TNMs, with the data from the N011-Aixeus TNM being the most highly correlated. However, although the N001-Quimboa and N002-Izas TNMs were grouped in Cluster 2, their distances from the cluster centroid in the PCA implies that they were also correlated to Cluster 1.

Table 6. Factorial scores for the PCA relating normal snowfall events (between P30 and P80) and weather types.

TNM	PC1	PC2	PC3	Cluster	Distance to centroid
N003-Canal Roya	-0.84	-0.07	2.16	1	0.0
N006-Ordiceto	-0.01	1.35	0.35	1	2.44
N005-Lapazosa	-1.21	0.65	-0.19	1	2.48
N004-Bachimaña	-0.76	0.32	-0.57	1	2.75
N011-Aixeus	1.34	-1.48	-0.06	2	0.0
N007-Renclusa	-0.42	-1.80	0.24	2	1.82
N010-Airoto	0.12	-0.09	-0.45	2	1.90
N001-Quimboa	1.24	0.51	0.79	2	2.17
N009-Eriste	1.41	0.93	-0.68	2	2.49
N002-Izas	-0.86	-0.32	-1.59	2	2.92

Figure 7 shows the percentage of snowfall days associated with different weather types for the N003-Canal Roya and N011-Aixeus TNMs, which recorded data most highly correlated to clusters 1 and 2, respectively. This shows that while Atlantic weather types (NW, N, W) were the most productive with respect to normal snowfalls events at the N003-Canal Roya TNM, at the N011-Aixeus TNM these weather types were dominant, but Mediterranean weather types (NE, E, and even SE) also made substantial contributions. The S and SW weather types also made substantial contributions at the N003-Canal Roya TNM.

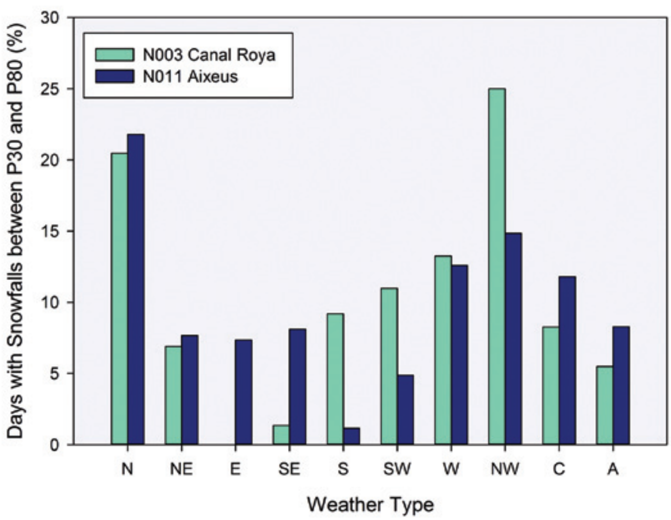

Figure 7. Frequency of normal snowfall events (between P30 and P80) at the N003-Canal Roya and N011-Aixeus TNMs in relation to different weather types.

4.3.2. Frequency of heavy snowfall events associated with different weather types

Figure 8 shows the frequency of days having heavy snowfall events associated with different weather types. This shows that these mostly occurred during advections associated with N and NW weather types (average approximately 10%, respectively). Advections related with W weather types were also associated with the occurrence of heavy snowfall events (ranging from 3 to 5% of days among TNMs). In contrast to normal snowfall, the SW and NE weather types were much less important in explaining heavy snowfalls events.

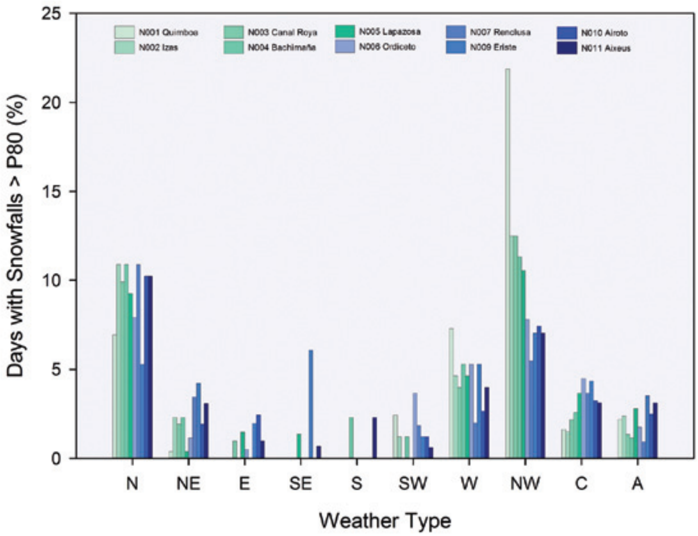

Figure 8. Percentage of days having heavy snowfall (>P80), as a function of different weather types.

Figure 8 also shows that there were marked differences among TNMs with respect to the effect of weather types on heavy snowfall. Thus, the occurrence of the NW weather system explained much of the occurrence of heavy snowfall at the western TNMs (e.g. the N001-Quimboa TNM recorded > 20% of heavy snowfall days associated with the NW weather system), but this correlation declined eastward (< 7-8% of heavy snowfall days associated with the NW weather system). The N weather system had a more homogeneous effect across the study area, with the frequencies of heavy snowfall days associated with this weather system ranging from 7 to 11%. Advections from the Mediterranean (SE, E, NE weather types) also had a marked influence on heavy snowfall events at the TNMs located in the east, but had little influence on the westernmost TNMs.

The PCA applied to heavy snowfall events grouped the TNMs on the basis of the percentage of days that each weather system generated snowfall of P > 80. Four PCs (PC1-PC4) explained 89% of the total variance (34%, 28%, 14%, and 14% respectively). PC1 grouped TNMs where the NW and N weather types were most associated with heavy snowfall, and the NE weather system had little influence. PC2 grouped TNMs where advections from the Mediterranean (SE) caused heavy snowfall, and the N weather system had little influence. PC3 grouped TNMs where frequent heavy snowfall occurred in association with SW weather types (0.93), and the E weather system had little influence. Finally, PC4 grouped TNMs where heavy snowfall occurred in association with S weather types.

The PCA factorial scores for each TNM are shown in Table 7. PC1 showed maximum and minimum correlations with the N001-Quimboa N007-Renclusa TNMs, respectively; PC2 correlated the distribution of heavy snowfall most highly with the N009-Eriste TNM, and least with the N007-Renclusa TNM. PC3 correlated the distribution of heavy snowfall most highly with the N006-Ordiceto TNM, and least with the N005-Lapazosa TNM; and PC4 correlated the distribution of heavy snowfall most highly with the N004-Bachimaña TNM, and least with the N010-Airoto TNM. In this case the k-means analysis was not able to generate groups, indicating that despite a west to east gradient in the factorial scores, especially for PC1, the spatial relationships between weather types and heavy snowfall is much more complex than that observed for normal snowfall events.

Table 7. Factorial scores for the PCA of the relationship between heavy snowfall events (> P80) and weather types.

TNM	PC1	PC2	PC3	PC4
N001-Quimboa	2.12	0.41	0.86	-0.70
N002-Izas	0.17	-0.62	0.28	-0.21
N003-Canal Roya	0.34	-0.50	-1.01	-1.23
N004-Bachimaña	0.30	-0.40	0.18	-0.82
N005-Lapazosa	0.72	-0.10	-1.42	-0.31
N006-Ordiceto	-0.10	0.09	1.79	-0.27
N007-Renclusa	-1.51	-0.88	0.94	-0.01
N009-Eriste	-0.81	2.64	-0.23	0.07
N010-Airoto	-0.69	-0.55	-0.85	1.58
N011-Aixeus	-0.55	-0.10	-0.51	1.89

5. Discussion and conclusions

We analyzed the characteristics of daily snowfall events in the Pyrenees, and their relationship to weather types over the Iberian Peninsula. The results showed that the annual accumulation of snow varied among years and TNMs, and that it was possible to discriminate east-west differences in the characteristics of snowfall events. The TNMs having greater exposure to the Mediterranean area tended to record data that were more variable because of the greater variability of precipitation associated with the Mediterranean climate compared with oceanic climates.

Analysis of principal components and k-means enabled the distribution of snowfall throughout the year to be classified in two groups in relation to the TNMs analyzed. A first cluster grouped the western TNMs, where most snow accumulation occurred during the winter months (December to February). A second cluster grouped the eastern TNMs; in addition to winter snow, these TNMs also recorded marked snow accumulation during spring and autumn, which can be explained by the polar jet stream oscillation (Ramos et al. 2015).

Snowfall frequency analysis showed that there were spatial differences in the distribution of the annual average number of snow days. While some positive bias in the eastern TNMs was detected, this may have been because of the higher elevations of these TNMs, which compensated for the fewest precipitation days occurring in the eastern area of the Pyrenees (Buisan *et al*., 2016). In terms of snowfall intensity, two TNMs (N001-Quimboa and N002-Izas) showed differences from the others in the study. Both these sites showed that there were days when snow accumulation clearly exceeded 50 cm, whereas the others did not record marked differences attributable to spatial patterns. The proximity of these two TNMs to the Cantabrian Sea (93 km to N001, 122 km to N002), could result in very heavy snowfall because of the greater humidity of the air masses reaching the Pyrenees. The number of days when the accumulation of snow exceeded 5 cm but was < 25 cm was not clearly correlated with altitude or longitude. However, the number of snow days recorded at TNMs in this study was generally 30-35 per year (exceptions were the N007-Renclusa TNM: 28 days; and the N009-Eriste TNM: 43 days), which clearly exceeds those reported by Buisan *et al.* (2015) for observatories located in the valley bottoms. This indicates that the snow dynamics at the elevation where TNMs are located (above 1700 m a.s.l.) differs from that at lower elevations, where the snowpack is generally ephemeral (López-Moreno *et al*., 2011). Heavy snowfall events were more commonly detected at the western TNMs (> 8 times per year), while for those in the east < 5 heavy snowfall events were recorded per year. Elevation had no significant influence on the occurrence of heavy snowfall events ($R^2 = 0.08$).

During the study period, anti-cyclonic and cyclonic weather types occurred most frequently over the Iberian Peninsula, which is a finding consistent with previous research covering longer periods in the same region (Vicente-Serrano and López-Moreno, 2006; García-Valero *et al*., 2012; Cortesi *et al*., 2014). In part, this is an artifact of the use of the adaptation proposed by Jones *et al.* (1993) and Trigo and Da Camara (2000), which gives greater relative weighting to these two weather types. During the months of the study the frequency of weather types varied because of major displacement of the Jet Stream towards southern latitudes, which favored successions of different synoptic conditions at the study latitude over short periods of time, as has been reported by Cortesi *et al.* (2014).

The occurrence of normal snowfall events was closely correlated with particular weather types. However, orographic effects and the distance to the Atlantic Ocean explain the differences among TNMs. This has been reported by Buisan *et al.* (2015), who found that the frequency of snow days decreased with increasing distance to the

Atlantic Ocean, but that the orography also caused large differences among neighboring areas (Corte-Real *et al*., 1998; Esteban *et al*., 2005; Vicente-Serrano and López-Moreno, 2006). Advections associated with NW weather types were the most conducive to the occurrence of normal snowfall events, although N and W weather types were also associated with normal snowfall events. The NW types bring polar maritime air masses associated with cool temperatures, high moisture content, and atmospheric instability (Ramos *et al*., 2015). The N weather types generally bring drier air masses than those of NW origin, but are colder and so are also associated with normal snowfall events. In contrast, W weather types bring wet and less cold air masses to the Spanish Pyrenees, leading to high levels of snow accumulation at elevations where the temperature remains < 0°C (López-Moreno and Vicente-Serrano, 2007). The PCA and k-means analyses gave comparable results to those reported by Buisan *et al*. (2015). Thus, western TNMs were grouped because they responded primarily to W and N weather types, while the TNMs located eastward were grouped because they were also heavily influenced by Mediterranean (E, SE, NE) weather types.

The number of heavy snowfall events (> P80) was also closely correlated with the occurrence of particular weather types (Esteban *et al.,* 2005). Overall, NW weather types were most associated with the occurrence of heavy snowfall events, and N types also brought frequent heavy snowfall; in contrast, W weather types were rarely correlated with heavy snowfall events. The PCA showed that the NW and W weather types explained many of the heavy snowfall events recorded at the western TNMs, whereas in the east the greatest influence was from Mediterranean weather types.

This study highlights the need for proper monitoring of the climate and snow processes at high elevations. In the case of the Pyrenees, the network of TNMs has provided additional information to that available through previous studies based on more conventional observations made in the valley bottoms. Thus, it was confirmed that the effect of weather types on snowfall events can differ markedly depending on the elevation, as the effectiveness of some weather types associated with wet but mild air masses is also evident in areas well below the winter 0°C isotherm. We also identified several TNMs that demonstrated the occurrence of west to east gradients in terms of the frequency and magnitude of snowfall events, and their relationship to different weather types. Such anomalies can be explained by the complex topography modulating the response of local climate to dominant air masses (Vicente-Serrano and López-Moreno, 2006; Buisan *et al*., 2016). Such complexity must be taken into account. This will necessitate further research based on high-resolution snow data, and availability of a denser network of observation stations.

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