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Impact of weather type variability on winter precipitation, temperature and annual snowpack in the Spanish Pyrenees

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ABSTRACT: The annual frequency of the occurrence of 10 discriminated weather types were summarized using a principal component analysis that revealed 4 different prevailing winter conditions affecting the Spanish Pyrenees. Northeasterly and easterly flows lead to dry and cold winters where snow only accumulates on northern slopes and mainly in the central Pyrenees. North and northwesterly flows favor wet and cold winters and an increase of snow accumulation in the western Pyrenees and on the northern slopes at lower elevations. Cyclonic and westerly flows favor an increase in precipitation and snow accumulation in all the Pyrenees at lower elevations and cold winters. Finally, southerly flows are associated with milder conditions and high precipitation in the central sector of the Pyrenees, where snow only accumulates at high elevations. For most stations, there were no significant trends in precipitation or temperature during the current reference climatic period (1981–2010), which was in agreement with the lack of observed principal component trends during the same period. Focusing on the shorter 1985–2010 period for which snow data were available, snow depth at mid-March demonstrated significant positive trends associated with an increase in westerly, southwesterly and cyclonic weather during this period. The results demonstrate that the changes in precipitation, temperature and snow accumulation are clearly related to changes in circulation patterns, which are the main driver of temporal fluctuations in the considered climatologies.

KEY WORDS: Snowpack · Winter precipitation · Winter temperature · Weather types · Temporal trends · Pyrenees · Spain

1. INTRODUCTION

The study of the spatial and temporal variability of snowpack and winter precipitation is of great interest because it plays an important role in the ecology and hydrology of mountainous areas and cold regions (López-Moreno & García-Ruiz 2004, Barnett et al. 2005, Jonas et al. 2008a,b). Winter precipitation and snowpack also influence economic activities such as winter tourism, agriculture, and hydropower generation (Barnett et al. 2005, Abegg et al. 2007, Lasanta et al. 2007, Gilaberte-Búrdalo et al. 2014). Furthermore, the inter-annual variability of snowpack is directly related to the climatic condi-

*Corresponding author: sbuisans@aemet.es tions occurring throughout the winter, and annual snowpack accumulation is therefore a good indicator of climate variability and climate change in areas where climate monitoring is generally scarce (Walsh 1995, Nesje & Dahl 2000, Carrivick & Brewer 2004). However, to properly use snowpack as an indicator of climate change, the effects of elevation on temperature and precipitation as predictors of snowpack must be taken into account (Marty 2008, Pederson et al. 2011, Morán-Tejada et al. 2013a, Scherrer et al. 2013).

At the regional level, the inter-annual variability of the dominant atmospheric circulation is associated with significant spatial variability in precipitation and temperature anomalies, and this variability is caused mainly by topography and distance to the sea (Black & Sutton 2007, Fernández-Montes & Rodrigo 2012, Huntingford et al. 2013, Rutgersson et al. 2014). In the Iberian Peninsula, the assessment of this impact has been the subject of numerous studies (Martin-Vide & Lopez-Bustins 2006, Muñoz-Díaz & Rodrigo 2006, Vicente-Serrano & López-Moreno 2006, López-Moreno & Vicente-Serrano 2007, López-Moreno et al. 2008a,b, Gimeno et al. 2010, El Kenawy et al. 2012, Cortesi et al. 2014, Buisan et al. 2015). From these studies it can be inferred that the occurrence of the same weather types can lead to different climatic conditions in the different regions of the Pyrenees.

Decreases in snow accumulation and winter precipitation have been detected in the Pyrenees during the second half of the 20th century (López-Moreno 2005, López-Moreno et al. 2009, Morán-Tejada et al. 2013b). This decrease in precipitation has been partially attributed to changes in the frequency of weather types that are also responsible for increasing winter temperature over the Iberian Peninsula (López-Moreno & Vicente-Serrano 2007). These studies were based on the analyses of regional time series and interannual climate anomalies for the central Pyrenees. However, the spatial variability of these winter precipitation and snowpack time series remains unstudied so far. In addition, most of the available studies for the Pyrenees do not include the most recent years, which have been characterized by a high inter-annual variability and include very wet years with large snowpack accumulations. These years have been associated with the North Atlantic Oscillation (NAO), which moderated the slope of the long-term increasing trend of the NAO index observed for the 20th and early 21st century (Vicente-Serrano et al. 2011, Añel et al. 2014). These recent changes in atmospheric circulation have resulted in a slight increase in snowfall events in the Spanish Pyrenees and the Alps in the last decade (Scherrer et al. 2013, Buisan et al. 2015).

The main objective of this study is to assess the impact of the inter-annual variability of atmospheric conditions on winter precipitation in the valleys of the Spanish Pyrenees, where long-term meteorological records exist, and to relate these results to the observed variability in annual snowpack in March at higher elevation. The study also considers the role of temperature and elevation in the analysis. In addition, the links between weather type and regional precipitation and temperature trends will be used to help explain the temporal evolution of snowpack.

2. STUDY AREA

The study area encompasses the Spanish Pyrenees, and extends from the Atlantic Ocean to the Mediterranean Sea (Fig. 1). The Pyrenees range is ~400 km long and <100 km wide. Elevation increases from sea level to the central Pyrenees, with maximum elevations >3000 m above sea level (a.s.l.).

Valleys in the Pyrenees are typically oriented perpendicular to the main axis of the range, which runs following a west–east direction. This main axis or divide separates the Spanish Pyrenees from the French Pyrenees. In this way, during north and westerly flow, the blocking effect of the mountains in the western Pyrenees explains much of the spatial variability of winter precipitation, which follows north–south and west–east gradients.

Snowfall in winter is more frequent in the high elevation stations in the western Pyrenees, with 20 snowfall days on average at 1000 m a.s.l., whereas at the same altitude in the central Pyrenees, the number of snowfall days is <13 on average, with snowfall accounting for <35% of the total precipitation (Buisan et al. 2015). Also, the high inter-annual variability of precipitation in the Pyrenees leads to alternating snow-poor and snow-rich years (Añel et al. 2014, Buisan et al. 2015).

The 0°C isotherm from November to April is at ~1600–1700 m a.s.l. (García-Ruiz et al. 1986), and it is a good indicator of the level above which snowpack normally remains intact throughout this same period. A thick snowpack of 2–4 m in depth normally exists above 2000 m a.s.l., and lasts until the end of May or until June on upper and shaded slopes (López-Moreno 2005, López-Moreno & Vicente-Serrano 2007).

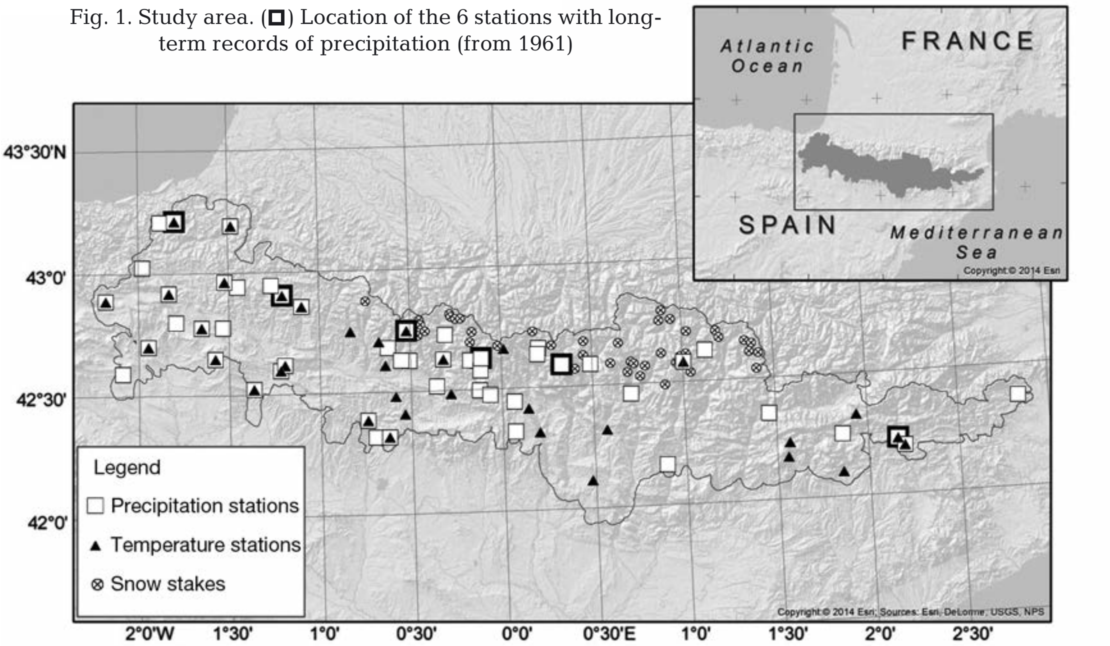

Fig. 1. Study area. (□) Location of the 6 stations with long-term records of precipitation (from 1961)

3. DATA AND METHODS

Precipitation and temperature measurements were recorded at meteorological stations managed by the Spanish State Meteorological Agency (AEMET). The main study period was from 1981 to 2010, and was restricted to winter months from December to March. This period was selected because: (1) it spans the last 30 yr climate standard reference period of time (normal period) as recommended by the World Meteorological Organization (WMO 1989); (2) it contains the largest number of stations with long time series of temperature, precipitation, and snow depth measurements in recent years; and (3) this period was characterized by high variability in the frequency of weather types over the Iberian Peninsula, and therefore facilitates analysis of the importance of weather type on winter precipitation and other climate variables.

Precipitation amount in a 24 h period, as well as maximum temperature and minimum temperature were measured daily at 07:00 h UTC. These data were quality controlled and corrected manually by AEMET staff prior to being recorded in the AEMET database.

Despite its importance, an accurate measurement of winter precipitation remains challenging, especially in mountainous environments (Nitu et al. 2012, Rasmussen et al. 2012). In the Spanish Pyrenees, long-term snow accumulation measurements are mainly based on snow depth measurements, which are taken regularly 3 times each year (mid-January, mid-March, and late April) at a number of snow stakes distributed among different valleys and elevations (López-Moreno et al. 2006). In the valley bottoms, long-term precipitation records are based mainly on Hellman rain gauge measurements, which are less accurate than some newer automated gauge measurements, such as weighing gauges with wind shields, especially in below-freezing temperatures and windy conditions (Nitu et al. 2012, Rasmussen et al. 2012, 2014, Wolff et al. 2014).

A total of 45 stations measuring precipitation were selected from the AEMET homogenized precipitation database (1981–2010) and 36 long-term temperature series were selected from the AEMET homogenized temperature database (1981–2010) (Botey et al. 2013). The selected stations were located in towns in the valley bottoms at <1500 m a.s.l., with the exception of 4 stations at elevations >1700 m a.s.l. The maximum station elevation was 2200 m a.s.l. Snow depth data were obtained from 106 snow stakes that were initially installed in 1985. The snow stakes are managed by the ERHIN Programme (Estudio de los Recursos Hídricos INvernales, Study of Winter Water Resources), and are used to help quantify water resources in the Spanish Pyrenees. They are only located in the Central Spanish Pyrenees >1750 m a.s.l., where seasonal snow cover typically persists from mid-November to late April or early May.

As mentioned above, measurements were taken regularly 3 times each year, with weather conditions occasionally causing minor changes in the measurement dates. We only used the snow depth measurement from mid- or late-March because it is the best indicator of temperature and precipitation occurring throughout the December to March focus period of this study (López-Moreno 2005). Snow depth measured at the end of April or early May is highly dependent on the variable April climate, and the prevailing climate of the entire winter is better represented by the more cumulative March snow depth (López-Moreno 2005).

From the original database, we only analyzed measurements from snow stakes where the data availability within the 30 yr study period was >22 yr, as this selection process resulted in a good balance between using the most complete series and maintaining a high spatial density of measurement locations. The final database contained 42 locations ranging from 1840 to 2450 m a.s.l.

For weather type classification in the Iberian Peninsula we used a method that has been successfully used in previous studies (Jones et al. 1993, 2013, 2014, Goodess & Palutikof 1998, Spellman 2000, Cortesi et al. 2014). This uses the objective weather typing system of Jenkinson & Collison (1977) and is based on the Lamb classification. The 26 classified weather types were reduced to 10, following the approach suggested by Jones et al. (1993) and Trigo & DaCamara (2000). When a hybrid type was found, 0.5 was added to the frequency series of cyclonic (C) or anticyclonic (A) types, and 0.5 to the correspondent directional types series (N: north, NE: northeast, E: east, SE: southeast, S: south, SW: southwest, W: west, and NW: northwest). Weather types that were unclassified due to very low pressure gradients (Fowler & Kilsby 2002) were assigned to anticyclonic or cyclonic types if the mean pressure was above or below the 1020 hPa threshold, respectively (Rasilla Álvarez 2002).

Gridded sea level pressure data were obtained from the daily NCEP/NCAR reanalysis dataset. We used 16 points at 5° of resolution over an area defined rom 40° W to 25° E and from 20° to 70° N, which comprises the Iberian Peninsula. We chose this reanalysis because the resolution was the same during the whole study period (from 1960) and it has been used in other studies in the Iberian Peninsula (Trigo & DaCamara 2000, López-Moreno & Vicente-Serrano 2007).

A principal component analysis (PCA) was performed to summarize the annual frequency of the occurrence of discriminated weather types. The factorial loadings for each principal component (PC) were determined (Table 1), indicating the relationship between each PC and the inter-annual variability of the different weather types. We selected the first 4 PCs, which accounted for 71% of the total variance. The total variance explained by the other PCs was <8%.

4. RESULTS

4.1. Elevation and the spatial distribution of precipitation and temperature

During the study period of 1981–2010, the western Pyrenees received, on average, >600 mm of precipitation during the winter months (December to March), stations in the central Pyrenees received <400 mm, and stations in the eastern and the southernmost Pyrenees received <200 mm (Fig. 2a). Annual winter precipitation was also more variable in regions receiving less winter precipitation, with the inter-annual coefficient of variation increasing eastwards from 30% in the westernmost stations up to 70% in the easternmost stations, and likewise increasing from the north to the south with differences of up to 30% (Fig. 2b).

Winter mean temperature varied with elevation from 8°C at 200 m a.s.l. to –0.5°C at 2000 m a.s.l. The mean winter temperature showed a highly significant and negative correlation ($r = -0.91$, $\alpha < 0.01$) with elevation and a lapse rate in the region of 5°C km^{-1}.

Table 1. Factorial loadings of the obtained principal component analysis (PCA), inter-annual variability of weather types and correlation between principal components (PCs) and weather types. $^{*}\alpha < 0.05$, $^{**}\alpha < 0.01$. Weather types: A: anticyclonic; C: cyclonic; N: northerly; E: easterly; S: southerly; W: westerly. CV: coefficient of variation

Weather type	PC 1	PC 2	PC 3	PC 4	CV (%)
A	0.10	–0.06	–0.94**	–0.01	28.6
C	–0.07	–0.12	0.82**	0.00	52.2
N	0.18	0.70**	–0.20	–0.29	35.5
NE	0.78**	0.35	0.05	0.08	145.3
E	0.64**	–0.38*	0.03	–0.27	75.9
SE	0.09	–0.86**	–0.02	–0.14	210.8
S	–0.03	–0.15	0.06	0.90**	69.4
SW	–0.59**	0.16	0.37*	0.36*	41.0
W	–0.71**	0.23	0.38*	–0.15	46.8
NW	–0.27	0.59**	0.12	–0.27	29.7
% Variance	27.7	20.2	12.8	10.4	
% Accumulated	27.7	47.9	60.7	71.1	

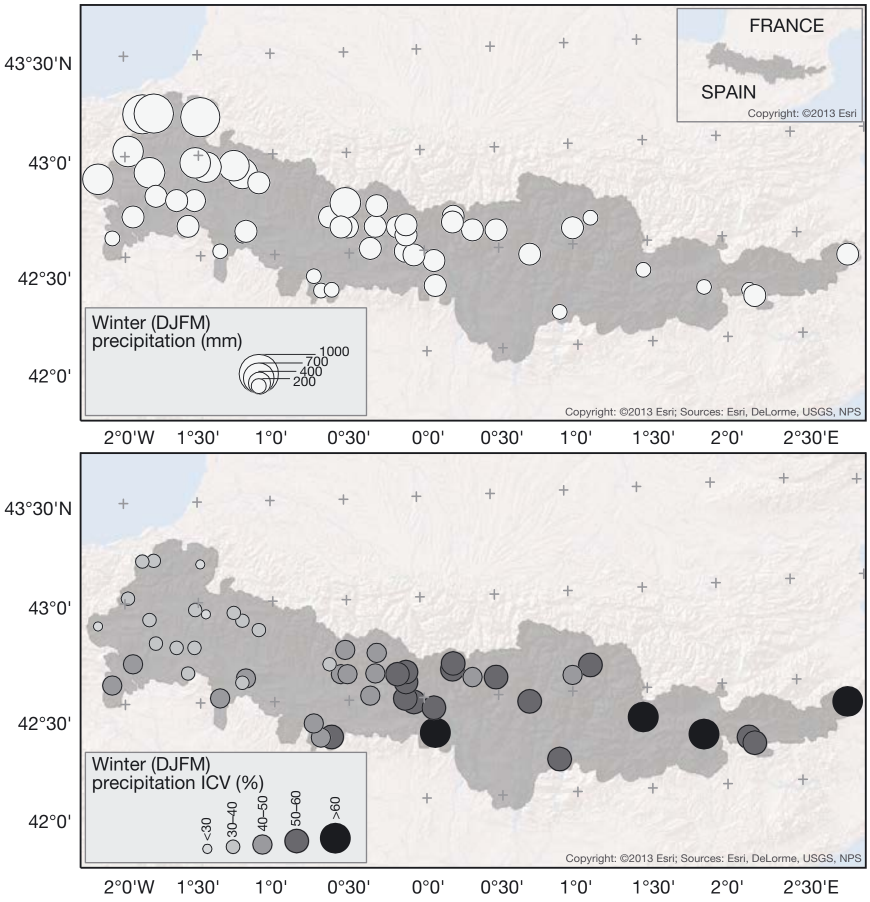

Fig. 2. Winter precipitation (DJFM: December to March) (a) average and (b) inter-annual coefficient of variation (ICV)

4.2. Inter-annual variability and temporal trends of weather types and PCs over the Iberian Peninsula

PC 1 accounted for 27.7 % of the total variance and showed a significant positive correlation with NE and E weather types, but a significant negative correlation with SW and NW weather types. PC 2 accounted for 20.2 % of the total variance and showed a significant positive correlation with the frequency of N and NW weather types and a significant negative correlation with SE weather types. PC 3 accounted for 12.8 % of the total variance and showed significant positive correlations with C, W, and SW weather types and a significant negative correlation with the frequency of A weather type. PC 4 accounted for 10.4 % of the total variance and showed a significant positive correlation with S and SW weather types, whereas it was negatively correlated with the frequency of N and NW weather types.

The inter-annual coefficient of variation for each weather type was also determined (Table 1). High variability was associated with NE, E, and SE weather types, with values >75 %. The A, N, and NW weather types showed the lowest variability with values <40 %, which is still a high value. The remaining weather types reached values between 40 and 70 %.

For the 1981–2010 study period, positive trends in PCs 1 and 3 were detected (Table 2) and the trend for PC 1 was significant, whereas no temporal trends were found for PCs 2 and 4. A positive trend in PCs 2 and 3 was detected during 1985–2010, and the PC 1 trend was weaker than during 1981–2010. During the 1961–2014 period, PC 4 exhibited a statistically significant negative trend, and PCs 2 and 3 also decreased in frequency, whereas no trend was found for PC 1.

4.3. Relationship between weather types, winter precipitation, temperature, and snow depth

To examine the relationship between precipitation and weather type, the Pearson's correlation coefficient between the PCs and the inter-annual variability of winter precipitation was calculated. Fig. 3a–d shows the spatial distribution of these correlations. PC 1 was negatively correlated with the inter-annual variability of winter precipitation for all stations. Correlations were statistically significant for those located in the central Pyrenees. PC 2 showed positive correlations for most stations, except for some in the eastern Pyrenees. These correlations were significant for stations in the western Pyrenees. PC 3 was positively correlated with winter precipitation variability for most stations, with the exception of some in the westernmost Pyrenees. These correlations were significant

Table 2. Temporal trends (Spearman's rho) of frequencies of principal components (PCs). *$\alpha < 0.05$

PC	1981–2010	1985–2010	1961–2014
1	0.41*	0.36	0.02
2	−0.01	0.1	−0.1
3	0.12	0.26	−0.13
4	−0.04	0.01	−0.29*

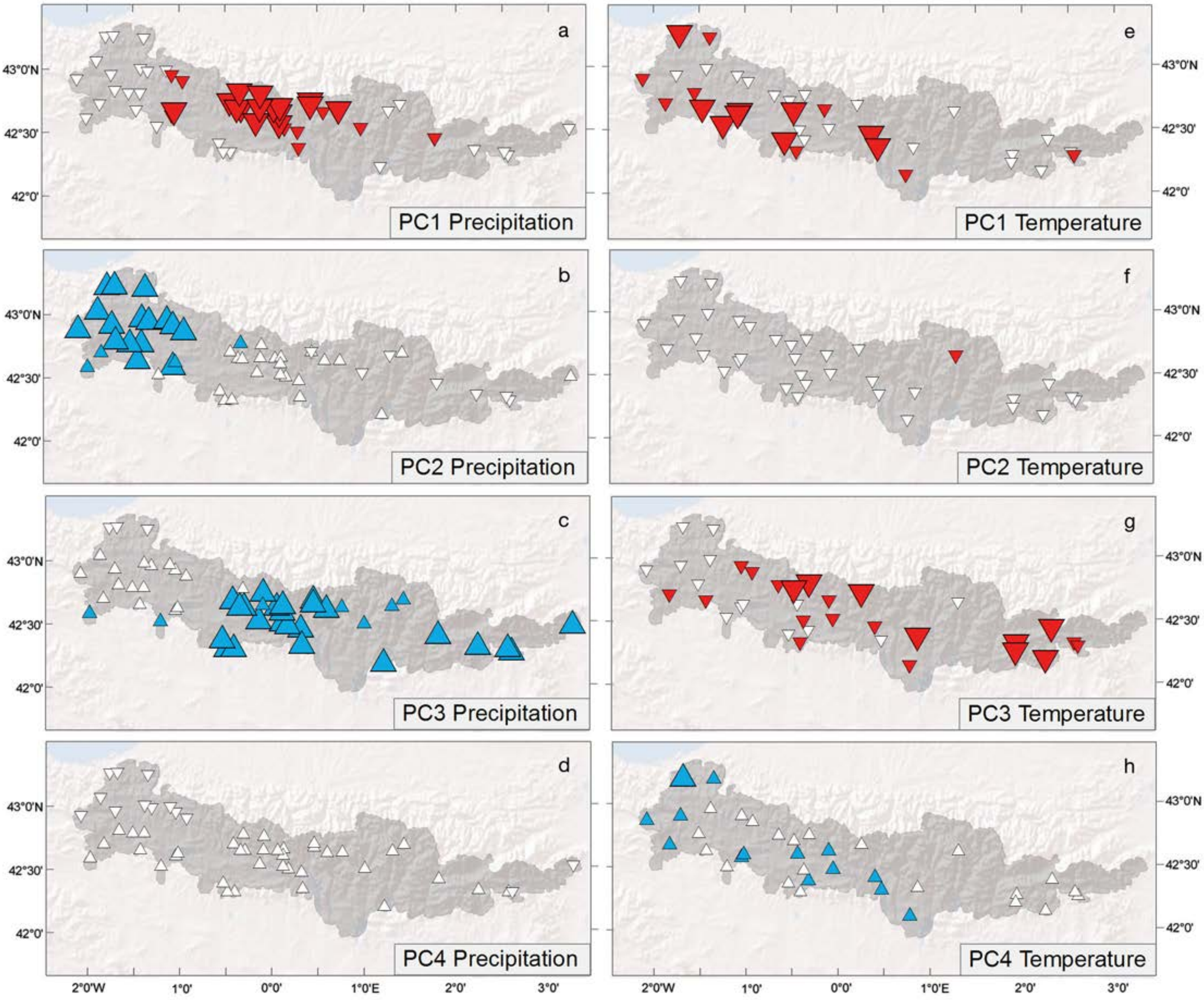

Fig. 3. Spatial distribution of Pearson's correlation coefficient between (a–d) winter precipitation and (e–h) temperature and the different principal components (PCs). △: positive correlation; ▽: negative correlation. Colours show significance for blue: positive and red: negative correlations; small triangles: $\alpha < 0.05$; large triangles: $\alpha < 0.01$

for stations in the eastern and central Pyrenees, with the exception of the northernmost part of the central Pyrenees ($\alpha < 0.05$). PC 4 exhibited some negative correlations in the western Pyrenees and positive correlations throughout the rest of Pyrenees. However, these were not statistically significant for any of the meteorological stations.

The results revealed that the N and NW weather types were strongly correlated with increased annual winter precipitation in the western Pyrenees, whereas the C, SW, W, and NW weather types were strongly correlated with increased annual winter precipitation in the central and eastern Pyrenees.

The spatial distribution of the correlation between the annual winter (December to March) temperature and the PCs was also determined (Fig. 3e–h). PC 1 was negatively correlated for all stations and was significantly correlated for stations located at lower elevations. PC 2 showed negative correlations for all stations, but these correlations were not significant. PC 3 showed negative correlations for all stations and most of these correlations were significant, with the

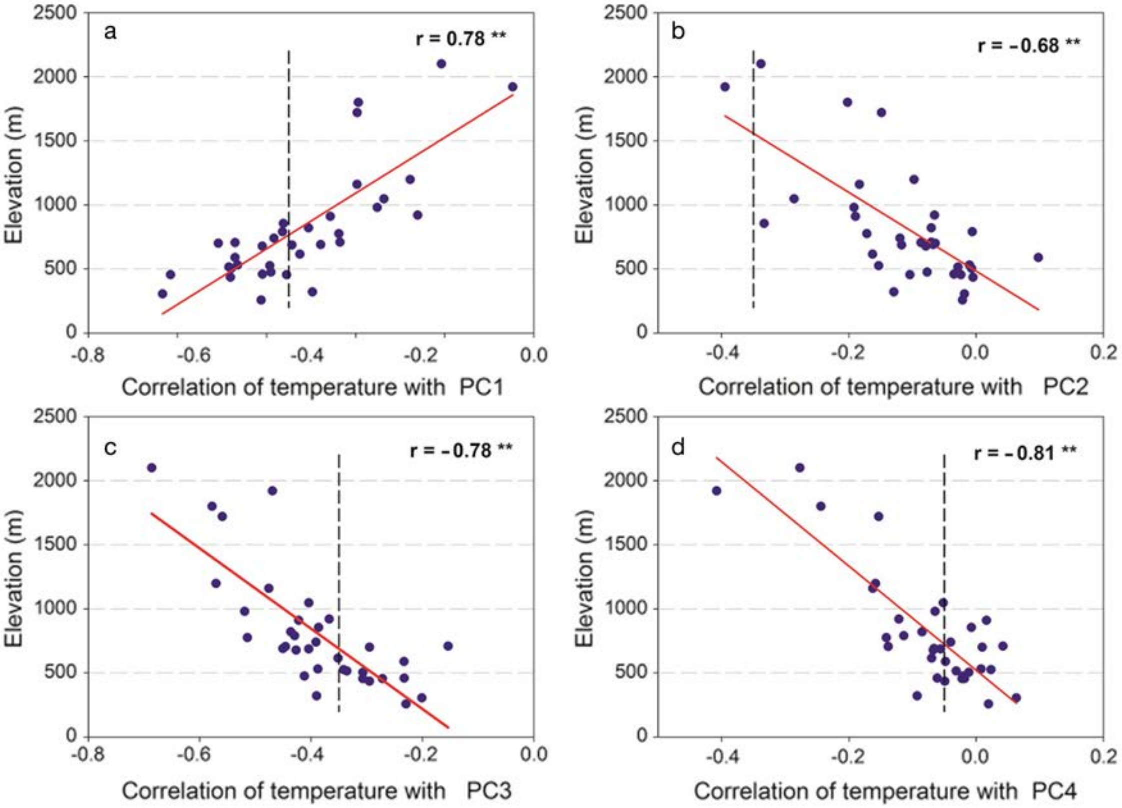

Fig. 4. Elevation-dependence of the correlation coefficients between winter mean temperature and principal components (PCs). Red line: linear fitting; vertical dashed line: level of significance ($\alpha < 0.05$) of the correlation between temperature and (a) PC 1, (b) PC 2, (c) PC 3, and (d) PC 4. $^{**}\alpha < 0.01$

exception of a few stations located in the westernmost Pyrenees. These PC 3 correlations were highly significant for some stations located near the main divide and at higher elevation, and also at locations in the eastern Pyrenees. PC 4 showed statistically significant positive correlations in stations located far from the main divide and at lower elevations in the central and western Pyrenees.

The correlation coefficient (r-value) between the PCs and winter temperature was highly dependent on elevation (Fig. 4). The correlation values between PC 1 and winter temperature (Fig. 4a) showed a highly significant positive dependence on elevation ($r = 0.78$, $\alpha < 0.01$). PC 1 was better correlated with decreasing winter temperature at low elevation stations, and the level of significance ($\alpha < 0.05$) was located below 500 m a.s.l. Fig. 4b,c shows that the correlation values for PCs 2 and 3 were highly significant and negatively correlated with elevation (r-values of –0.68 and –0.78, respectively, $\alpha < 0.01$), which indicates that the influence of these weather types on temperature was more evident at high elevation. The level of significance ($\alpha < 0.05$) for PC 2 was located above 1500 m a.s.l., whereas it was located above 1000 m a.s.l. for PC 3. The correlation values for PC 4 (Fig. 4d) were highly significant and negatively correlated with elevation ($r = -0.81$, $\alpha < 0.01$). PC 4 had more impact on increased mean winter temperature in low-elevation areas, with the level of significance ($\alpha < 0.05$) located below 500 m a.s.l.

According to previous results, and taking into account the spatial distributions shown in Fig. 3, high frequencies of C type and low frequencies of A type showed highest correlation with high-elevation stations, above ~700 m a.s.l. or near the main divide, whereas high frequencies of A, N, NE, and E types showed highest correlation with low-elevation stations and those far from the range axis, below ~700 m a.s.l., especially in the western Pyrenees.

For each winter, the prevailing PC was selected, and the average altitude of the 0°C isotherm was calculated. Fig. 5 shows that this level was located around 1700 m in winter seasons dominated by PC 1. For PCs associated with more precipitation, such as PCs 2 and 3, this level was located at 1700 and 1500 m a.s.l., respectively. The 0°C isotherm can be considered the level above which a continuous winter snowpack can develop. Finally, in winter

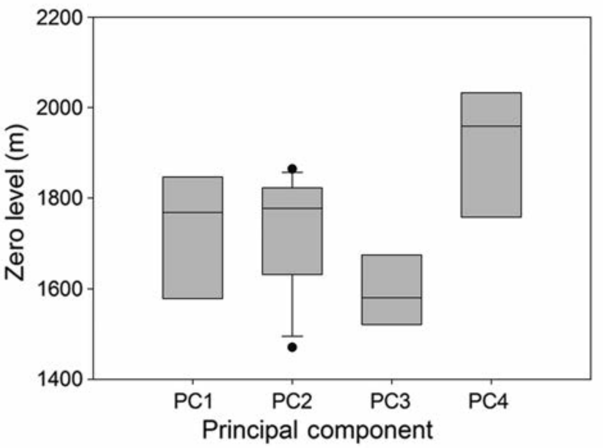

Fig. 5. Boxplot showing the average altitude of the annual 0°C isotherm associated with the prevailing annual principalcomponent (PC). Central line: mean, box: 75th and 25th percentiles, bar: 90th and 10th percentiles, dots: outliers

seasons characterized by PC 4, the altitude of the 0°C isotherm increased to >2000 m.

The spatial distribution of the correlation (r-values) between the inter-annual variability of March snow depth and the PCs was determined (Fig. 6). PC 1 experienced both negative and positive correlations that were significant for 3 locations on north-facing slopes near the main divide. PC 2 displayed positive correlations for all snow depth measurement locations. These correlations were significant for the few stations located near the range axis on north-facing slopes. PC 3 showed positive correlations for all measurement locations. These were significant for most of the locations, but mainly on south-facing slopes. PC 4 showed positive correlations for measurement sites in the central sector and on south-facing slopes of the Pyrenees, whereas it showed negative correlations westward and in areas close to the main divide. However, these correlation coefficients were not generally high (<0.3) and lacked statistical significance.

The results revealed that the C, SW, W, and NW weather types showed the highest correlation with the March snow depth measured at each station, except for 6 north-facing locations at the highest elevations and near the main divide.

4.4. Trends in winter precipitation, temperature, and snowpack in March

To detect significant trends, temporal series were tested against a linear time evolution (1981–2010) using the nonparametric Spearman's rank correlation statistical test. Temperature and precipitation did not demonstrate statistically significant temporal trends for the majority of the studied meteorological stations during the reference period (1981–2010) (Fig. 7a). However, Fig. 7b shows that precipitation trends were mostly negative in the westernmost Pyrenees and mostly positive in the central and eastern Pyrenees, which is consistent with the slight increase in PC 3 (Table 2). Fig. 7c shows no clear spatial pattern in the temperature trends within the study area; however, 2 stations located in the westernmost part showed a significant negative trend in

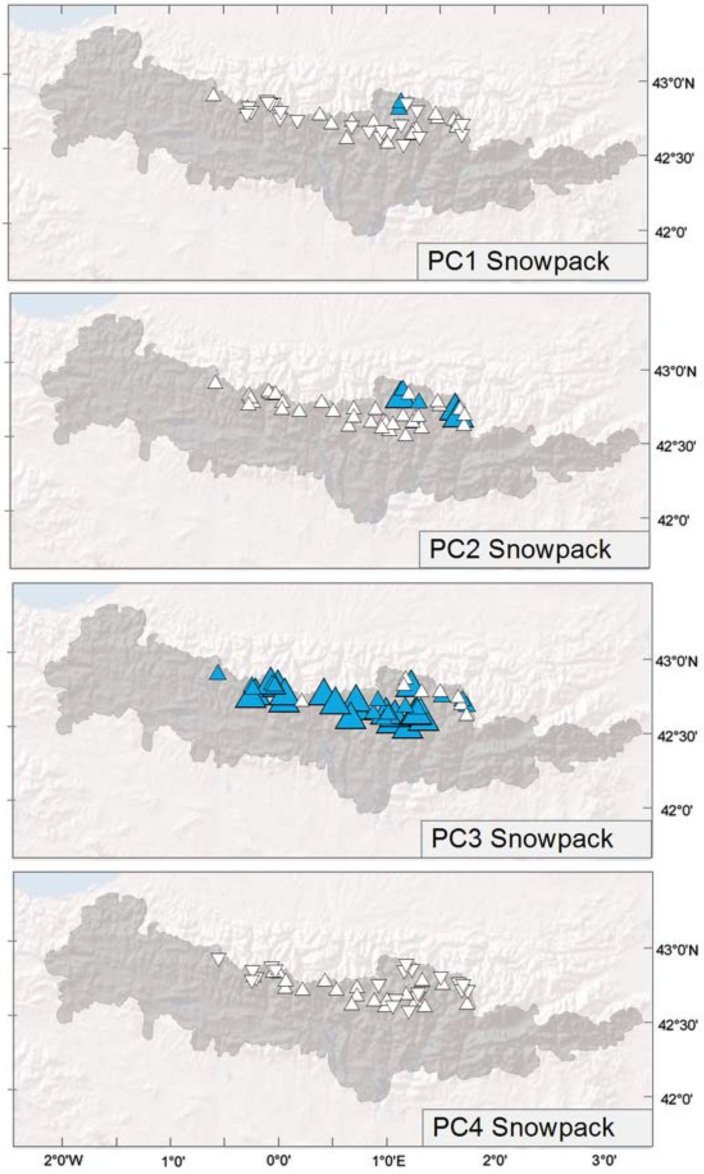

Fig. 6. Spatial distribution of Pearson's correlation coefficient between snow depth and the different principal components (PCs). △: positive correlation; ∇: negative correlation; small blue triangles: α < 0.05; large blue triangles: α < 0.01

temperature during the study period. This is consistent with the increase in PC 1 (Table 2), which was the PC negatively correlated with temperature for all stations, and particularly for low elevation stations in the western Pyrenees.

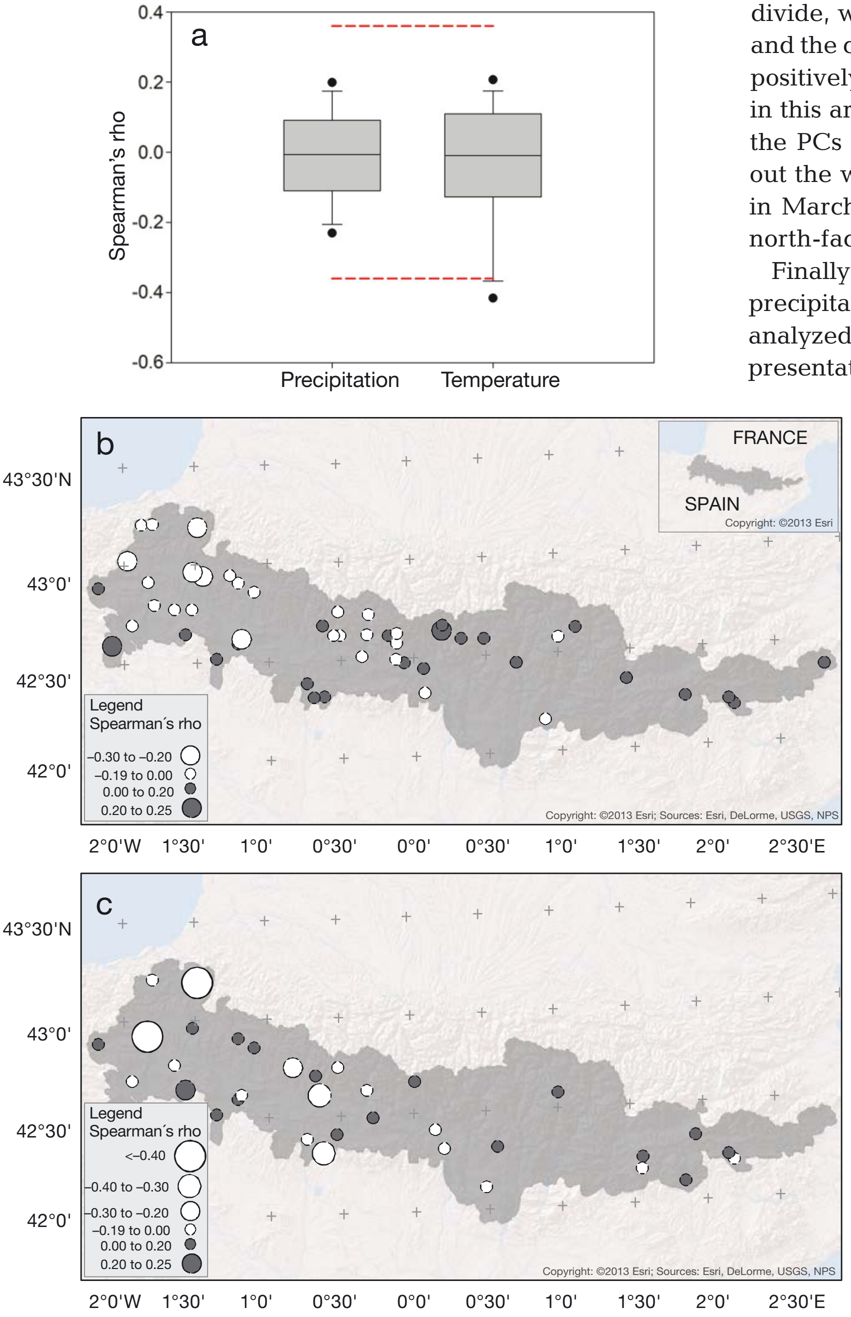

Fig. 7. (a) Boxplot of the temperature and precipitation trends at every station for the 1981–2010 period. Red dashed lines: limit of significance of the Spearman's rho statistic (α < 0.05). Central line: mean, box: 75th and 25th percentiles, bars: 90th and 10th percentiles; dots: outliers. Spatial distribution of winter (b) precipitation and (c) temperature trends for each station, with circle sizes and shading describing the magnitude and sign of the Spearman's rho statistic, respectively

During the 1985–2010 period, 72% of the snow depth measurement locations showed positive and statistically significant trends ($\alpha < 0.05$) in snow accumulation (Fig. 8a). Fig. 8b demonstrates that trend coefficients were higher in the central area of the Pyrenees and in locations near the range's main divide, which is consistent with the increase in PC 2 and the clear increase in PC 3, components that were positively correlated with snow depth measurements in this area. This high sensitivity of the snowpack to the PCs indicates that additional snowfall throughout the winter can significantly affect the snowpack in March at elevations >2000 m, and especially on north-facing slopes.

Finally, for a broader temporal perspective, 6 winter precipitation records for the 1961–2014 period were analyzed. These 6 stations were considered representative because they were distributed throughout the study area; i.e. 2 were located in the western Pyrenees, 3 in the central Pyrenees and the last 1 in the eastern Pyrenees (Fig. 1). Table 3 shows temporal trends in the winter precipitation at these stations for the entire period available (1961–2014) and for the more recent period of 1981–2010, which was studied in more depth in this study. Winter precipitation showed negative but not statistically significant trends for all stations during 1961–2014. This was consistent with slight decreases in PCs 2 and 3, which were associated with precipitation across the study area, and also with the significant decrease in PC 4 (Table 2) that affected the central sector of the study area. Table 2 shows a slight increase in PC 3 during the 1981–2010 period, which is also consistent with the slight increase in precipitation in the central and eastern Pyrenees.

5. DISCUSSION

In this study, we analyzed the influence of weather types on winter precipitation, temperature, and snowpack in the Spanish Pyrenees. A PCA summarized the annual occurrence of 10 weather types. The discriminated groups were associated with winter precipitation, temperature, and snowpack anomalies, and the role of elevation was also considered in the analysis.

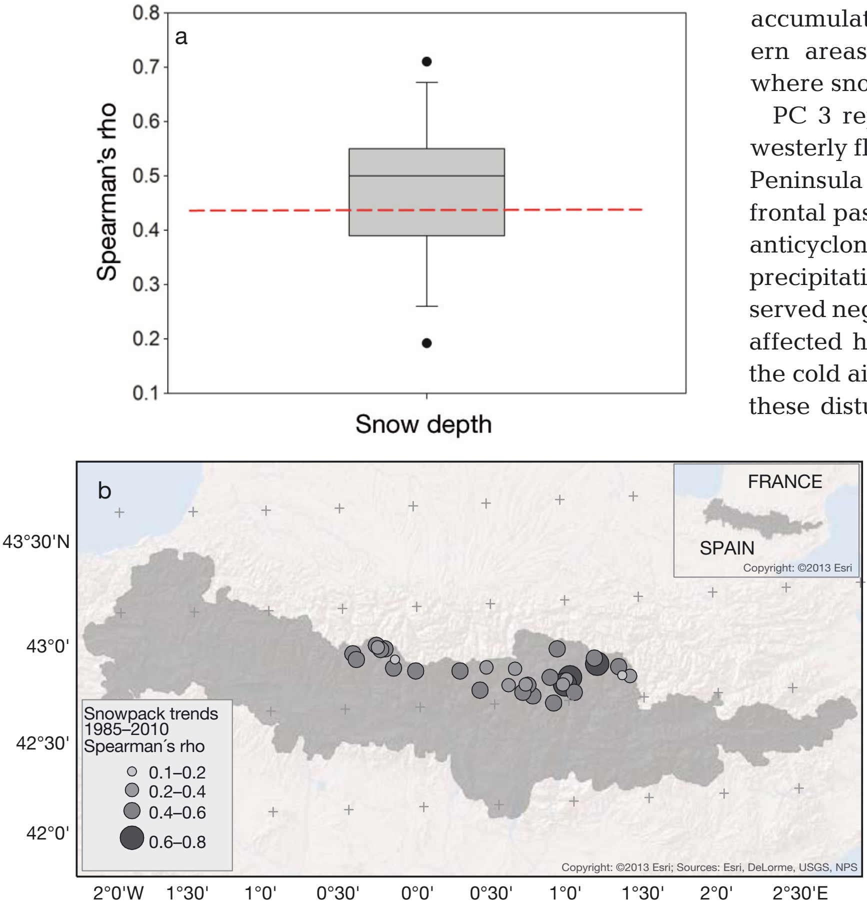

Fig. 8. (a) Boxplot of the snow depth trends at each station for the period 1985–2010. Red dashed line: limit of significance of the Spearman's rho statistic ($\alpha < 0.05$). Central line: mean, box: 75th and 25th percentiles, bar: 90th and 10th percentiles, dots: outliers. (b) Spatial distribution of snow depth trends for each station

PC 1 represented weather types associated with northeasterly and easterly flows, which were mainly characterized by dry and cold continental air and an absence of precipitation. This component was also associated with a higher frequency of anticyclonic weather that favored the development of thermal inversions and temperature anomalies that were strongest in the valley bottoms. These weather conditions were unfavorable for snow accumulation within the entire study area, with the exception of some locations on northern slopes and close to the range axis where snow could persist longer after snowfall events.

PC 2 described weather types associated with northerly and northwesterly flows that led to cold winters and a clear increase in precipitation in the western Pyrenees, the westernmost sector of the central Pyrenees, and also in locations close to the French side of the Spanish Pyrenees, i.e. north-facing slopes. These conditions were favorable for snow accumulation in the mountains, especially in western areas and areas exposed to northerly flows where snow accumulated at lower altitudes.

PC 3 represented weather types associated with westerly flows and disturbances crossing the Iberian Peninsula from the Atlantic Ocean, i.e. cyclonic and frontal passages and also the noticeable decrease in anticyclonic conditions, which led to an increase of precipitation within the whole study area. The observed negative temperature anomaly, which mainly affected high-elevation areas, can be explained by the cold air in the upper atmosphere associated with these disturbances that helped maintain the snowpack in mountainous areas. These conditions were favorable for snow accumulation especially on all south-facing slopes of the Pyrenees and in the central and eastern Pyrenees.

PC 4 represented weather types associated with southerly and southwesterly flows and an increase in precipitation that mainly affected the central Pyrenees. These conditions were also associated with mild temperatures and an increase in the elevation of the rain-snow line during precipitation. A noticeable snowpack only developed at higher elevations because the temperature anomaly was positive for all stations, especially in low-elevation areas.

Although snow stakes were absent in the westernmost area, the fact that northerly and northwesterly flows favored snowfalls above 800 m a.s.l. (Buisan et al. 2015) indicates that PC 2 should be strongly correlated with increased snow depth in the western Pyrenees as well as on north-facing slopes of the Pyrenees due to the topographic blocking effect.

Table 3. Temporal trends ρ (Spearman's rho) of winter precipitation for 6 selected stations for 1981–2010 and 1961–2014. Stations are ordered from west to east

Stn	Elevation (m a.s.l.)	1981–2010	1961–2014
Articutza	305	–0.10	–0.20
Abaurrea Alta	1047	–0.09	–0.11
Canfranc Los Arañones	1160	0.00	–0.13
Torla	1053	0.02	–0.17
Gistain	1422	0.19	–0.16
Campdevanol	738	0.04	–0.17

W and SW weather types, associated with PCs 3 and 4, produced high winter precipitation in the central Pyrenees and favored snow accumulation in that area. This has already been suggested by López-Moreno & Vicente-Serrano (2007) and Cortesi et al. (2014). However, precipitation is dominated by the presence of the N and NW weather types associated with PC 2 in the western Pyrenees, which agrees with the results of Buisan et al. (2015). In contrast, cyclonic weather associated with PC 3 correlated best with increased precipitation in the eastern Pyrenees. These results confirm the significant spatial variability in winter precipitation amounts, with marked westward or southward gradients depending on the prevailing winter weather conditions.

The role of elevation in the relationship between the 4 PCs and temperature was also assessed and helped reveal the physical links between weather type and snow accumulation. Weather conditions represented by PCs 2 and 3 best explained snow accumulation anomalies above the 1700 and 1500 m a.s.l. thresholds, respectively. Also, this level was likely to be lower in the western sector under PC 2 conditions. However, it increased under PC 4 above 2000 m a.s.l. This level is very likely to vary within the study area depending on exposure to radiation, topographic features of the valley, and prevailing winds. In the Swiss Alps, different elevation levels have been identified in which the snowpack responds differently to weather conditions (Morán-Tejada et al. 2013a). These authors showed that precipitation was the best predictor of snowpack above 1450 m a.s.l., and temperature was the best predictor below this threshold. The elevation bias between the 2 mountain ranges is easily explained by the difference in latitude.

There were no significant trends in winter precipitation over the 1981–2010 period. However, an increase in precipitation over time (not statistically significant) was observed in the central and eastern portions of the study area. This was associated with a slight increase in the frequency of westerly flows and the cyclonic weather types associated with PC 3. The trend in the frequency of the different weather types over the Iberian Peninsula was highly variable, and dependent on the selected study period. Thus, studies that have used longer series and did not include data from the last decade indicate a decreasing frequency in western circulations linked to a positive trend of the NAO index (López-Moreno et al. 2011, Vicente-Serrano et al. 2011), which caused a decline in winter precipitation (López-Moreno et al. 2009) and a reduction of the snowpack in the Pyrenees (López-Moreno 2005, Morán-Tejada et al. 2013b). These results agree with ours when the 1961–2014 period is considered. It was possible to detect a decrease (not statistically significant) in winter precipitation during the 1961–2014 period in the Pyrenees, mainly in the central and eastern areas, which was associated with a decrease in westerly, northwesterly, cyclonic, and southwesterly flows. The last years of the period studied in this work were characterized by an increase in winter precipitation snowpack, leading to deeper than normal snow cover. This explains the loss of the statistical significance in the previously reported decline in the Pyrenean snowpack (López-Moreno 2005).

Temperature trends during the 1981–2010 period experienced a decrease that was only statistically significant for 3 stations, and which was associated with a significant increase in PC 1 that mainly affected the valley bottoms. The temperature trend was also associated with an increase in PC 3, which mainly affected high-elevation areas. This indicates that temperature variability was also closely connected to variations in atmospheric circulation patterns (Quadrelli et al. 2001, López-Moreno & Vicente-Serrano 2007, El Kenawy et al. 2012). A winter temperature decrease in Spain (El Kenawy et al. 2012) and a trend reversal for snow indicators such as snow days have also been detected in the Pyrenees and in the Swiss Alps (Scherrer et al. 2013, Buisan et. al. 2015), which is supported by the results of this study.

The positive snow accumulation trend linked to the increase in weather types favoring winter precipitation was noticeable for the 1985–2010 period. The sensitivity of the snowpack to PCs 2 and 3 showed that individual snowfall events during the winter months can result in sustainable increases in snowpack at elevations higher than 2000 m a.s.l., especially on north-facing slopes.

These results demonstrate the potential importance of determining the expected frequency of the weather types affecting the Iberian Peninsula in advance. Improvements in seasonal forecasting could enable advanced warning of the likelihood of winters having above- or below-average precipitation, temperature, and snow accumulation, and also their spatial distribution in the Pyrenees. Recent research has provided promising results on the long-range prediction of European winters and the predictability of the NAO (Folland et al. 2012, Smith et al. 2012, Scaife et al. 2014). These studies should be verified with observed weather conditions in the Pyrenees in order to assess the suitability of seasonal forecasting for planning and adaptation to extreme winter conditions.

6. CONCLUSIONS

The results of this study suggest that winter climate variability (temperature and precipitation) and the spatial distribution of snow accumulation in the Spanish Pyrenees are driven by the inter-annual variability of the different weather types affecting the Iberian Peninsula. These weather types can be effectively summarized into 4 groups by means of a PCA.

The main driver in snowpack variability in high-elevation areas of the Spanish Pyrenees is the presence of weather types leading to precipitation, because under these conditions the interaction between altitude, temperature, and precipitation always favors increased snow accumulation, especially above 1500 m a.s.l. The only exception to this is southwesterly flows, where temperature still plays an important role in snowpack variability above 1500 m a.s.l.

According to the previous result, the winter climate and snowpack trends are linked to the inter-annual variability of weather type. However, trends are highly dependent on the study period considered because of the high inter-annual variability observed.

Regarding precipitation, the results did not show strong significant trends during the 2 study periods (1961–2014 for only 6 observatories and 1981–2010 for 50 observatories). However, during the longer study period (1961–2014), and despite the recent extreme winter seasons of 2012–2013 and 2013–2014, a decrease was found in PCs associated with precipitation, and this decrease was reflected in negative trends in precipitation for all stations. PCs associated with increased precipitation were associated with increases in snow accumulation in March (López-Moreno 2005, López-Moreno & Vicente-Serrano 2007). A decrease in annual snowpack can therefore be inferred, despite the absence of actual snow depth measurements prior to 1985. Most significantly, these results demonstrated that the relationships between PCs and precipitation were valid throughout the study period, independent of the specific period of study.

One limitation affecting these results is the absence of daily snow depth measurements. More frequent measurements would provide an opportunity to study the relationship between intra-annual precipitation and climate variability (Trujillo & Molotch 2014). However, in snow studies, annual measurements recorded at a fixed date (often in early April) are frequently used to study inter-annual climate variability and the net effects of climate fluctuations occurring over the preceding months (Mote 2003, Howat & Tulaczyk 2005, Clow 2010). This approach has been used satisfactorily in the Pyrenees (López-Moreno 2005, López-Moreno & Vicente-Serrano 2007), and the results of this work confirm that March snow depth measurements are a good indicator of the general behavior of snowpack distribution associated with the temperature and especially with the precipitation during previous months (December to March).

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