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ORIGINAL ARTICLE

Evolution and frequency (1970–2007) of combined temperature–precipitation modes in the Spanish mountains and sensitivity of snow cover

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Abstract Snow cover in Spanish mountains is crucial for ensuring water availability in spring and summer months, for the success of winter tourism or for the maintenance of biodiversity in mountain ecosystems. A changing climate may affect the volume of snow cover even in high mountains, where weather conditions are usually favorable for snow accumulation. In this paper, we aim to investigate the evolution (1970–2007) of combined precipitation–temperature modes in the Spanish mountains, and the sensitivity of the snowpack to their occurrence. The climatic database "Spain02" and snow thickness data for Spanish mountains were used for this purpose. Results showed that the frequency of dry-warm and wet-warm days has increased over time in all mountain ranges, while the frequency of the "cold" modes has decreased. The thickness of the snowpack in the Pyrenees has also decreased and its evolution is negatively correlated with the frequency of dry-warm days, and positively correlated with the frequency of dry-cold and wet-cold days. This work constitutes the first approach that relates the evolution of climatic conditions favorable or unfavorable for snow accumulation and the evolution of the snowpack in Spanish mountains.

Keywords Precipitation · Temperature · Joint-quantile indices · Spain02 · Snow · Mountains · Iberian Peninsula

Introduction

Snow cover in mountains is a natural resource that is of high ecological, socio-economic and scientific value. The mountain snowpack constitutes the primary source of water in many areas, ensuring water supply to the lowlands even during the dry season (Barnett et al. 2005; Knowles et al. 2006). But snow cover in mountains has many other implications, including the functioning of alpine and subalpine ecosystems (Pauli et al. 2003; Keller et al. 2005) or the financial success of ski resorts (Elsasser and Bürki 2002). In the mountains of the Iberian Peninsula, under the predominant influence of Mediterranean climates, the environmental and economic role of snow can in some years be critical. This is due to the highly variable thickness of the snowpack related to the characteristic inter-annual variability of precipitation (López-Moreno 2005).

The accumulation of snow cover is a process that is highly dependent on particular weather conditions. These clearly include the combination of precipitation and below-zero temperatures for triggering the snowfall and the persistence of low temperatures during a reasonably long period that enables a sustained snowpack (Beniston et al. 2011; López-Moreno et al. 2011). These conditions are characteristic of mountains. Their topography favors the gradients of temperature such that the zero-degree isotherm can be reached at certain elevations, as well as enhanced precipitation due to the uplift of moist air (Barry 2005). Knowledge of the type of meteorological conditions that prevail in mountains during the snow accumulation and melting seasons is therefore essential to predict the

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accumulation of the snowpack as well as the subsequent availability of water resources. However, snow-prone weather conditions might be threatened in mountain regions as a result of greenhouse gas induced warming (Beniston 2003). There is wide agreement that mean temperatures have increased globally during the last 40 years, in relation to the observed increases in radiatively active greenhouse gases (IPCC 2007; Solomon et al. 2007). Global warming is responsible for the retreat of glaciers in different parts of world, as well as for the reduction in the snowpack in mountains (see examples in Beniston 2003). In Europe, the Alps have been extensively studied in terms of the effects of climate variability on snow cover (Beniston et al. 2003, 2011; Uhlmann et al. 2009), and most studies highlight a reduction in the snowpack due to warmer conditions, both in the past and projected for coming decades. Similar conclusions were drawn for the mountains of the western US and Canada, where snow also constitutes a primary source of water resources (Hamlet et al. 2005; Knowles et al. 2006).

There is a clear need for research in other mountains of Europe, due to their role as "climatic islands," such as those in the Mediterranean basin (López-Moreno et al. 2011). In the Iberian Peninsula, various studies highlighted changes in the seasonality of mountain river flows, which have been attributed to reduced snowpack (López-Moreno et al. 2008; Morán-Tejeda et al. 2011). Contrary to temperature, precipitation has not exhibited a homogeneous trend signal around the world. Some regions, including the Mediterranean, are expected to experience drier conditions on the future decades (Milly et al. 2005; IPCC 2007). To date, however, there has been no clear trend toward more or less precipitation in Mediterranean countries (Bladé and Castro-Díez 2010).

Given the specific meteorological conditions for snowfall, that are seasonally dependent in mid-latitudes, studies pertaining to the behavior of snow can be placed within the study of climatic extremes, that is, the values of the climatic variables located within the tails of the frequency distributions. Much effort has been made in recent years to characterize the behavior of extremes, as exemplified by the number of indices recommended by the World Meteorological Organization Commission for Climatology (CCl) jointly with the World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) (see examples in Alexander et al. 2006). These indices are derived from series of daily precipitation and temperatures, and in general, they characterize one single variable (e.g., warm days, heavy precipitation days, etc.), but their statistical calculation also enables different variables to be combined. Beniston (2009) demonstrated that the use of joint-quantile indices can provide new insights for the understanding of climate variability, due to the mutual feedbacks that both temperature and precipitation may exert upon each other. This approach was shown to be useful as a proxy for predicting the evolution of snowpack in the Alps (Beniston et al. 2011), because particular combinations of temperature and precipitation are closely related to the synoptic circulations favorable (or not) for snowy winters. We believe that this method can also be applied to the mountains of southern Europe and thus its performance when applied to Spanish mountains will be examined in this work.

Based on the above considerations, the objective of this paper is to study the evolution and trends of combined precipitation and temperature quantile-based indices in the mountain ranges of the continental Spain during the last three decades. The underlying hypothesis is that long-term changes of moisture and temperature in mountains may trigger significant changes in thickness of the snowpack. We thus also seek to examine the relation of the observed evolution in climate indices with that of the snowpack during winter and spring seasons. This work constitutes the first assessment of climate evolution in Spanish mountains in relation to snow accumulation. The results will then form the basis for understanding the future evolution of the snowpack in the Iberian mountains in a changing climate.

Study area

The areas of research are the main mountain chains in continental Spain. The most important mountain ranges, with elevations generally over 2,000 m, are the Pyrenees, the Central System, the Cantabrian Range, the Iberian System and the Baetic System (Fig. 1a). The latter range is the one with the highest altitude of the Iberian Peninsula, namely the Mulhacen Peak (3,478 m). The geographical disposition of the Iberian Peninsula, located between the Atlantic and the Mediterranean, together with the complex topography, induces a notable variety of climates throughout the territory. A northwest–southeast gradient of precipitation and temperature is observed, with Atlantic climate conditions (precipitation over 1,000 mm/year and cool temperatures) in the northwestern quadrant, semi-arid conditions (precipitation less than 300 mm/year and warm temperatures) in the southwest and variants of Mediterranean climates in between. Precipitation is concentrated mainly in winter (DJF with about 40 %), when minimum temperatures usually drop to 0 °C or below, depending on the elevation. Thus, snowfalls are frequent especially in the mountainous areas where a deep snowpack usually accumulates. Warmer conditions in spring trigger the melting of the snowpack, with a lag in time for different mountain systems, ranging from late March to early June depending on the elevation and latitude.

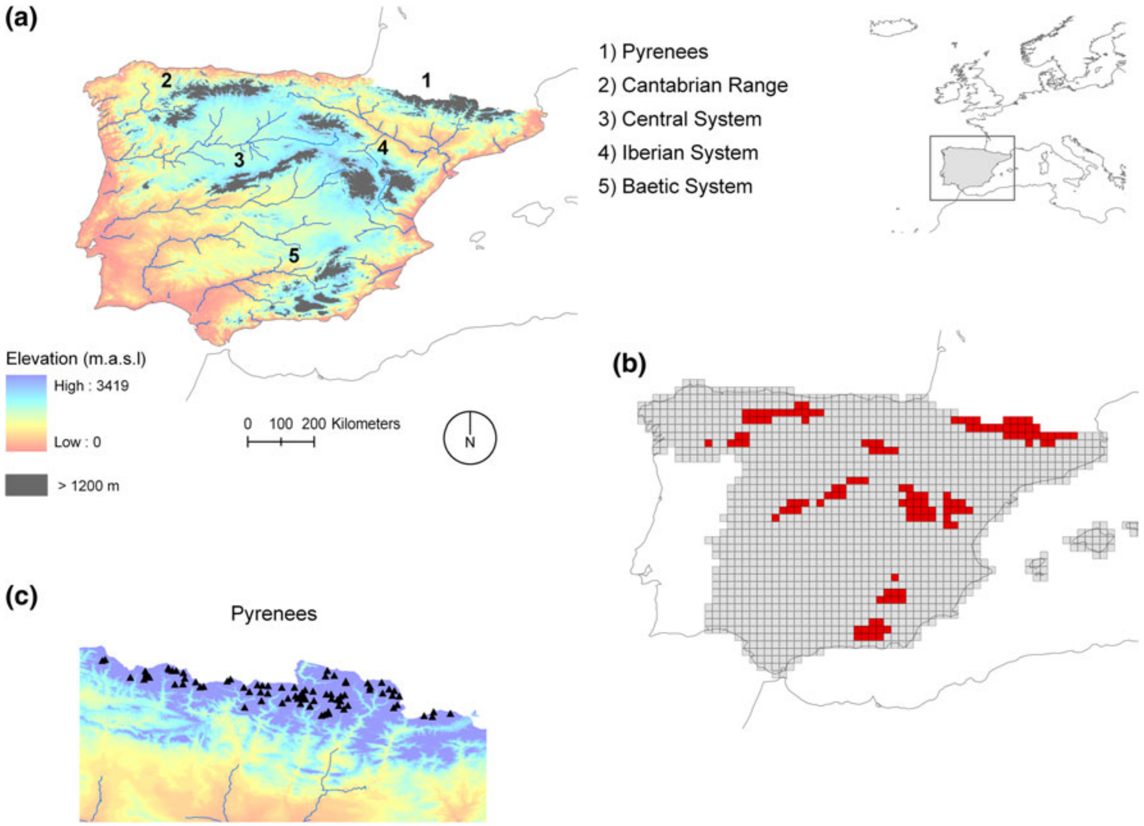

Fig. 1 **a** The Iberian Peninsula and the location of the mountain ranges considered in the study. **b** Grid resolution of the Spain02 database showing pixels with average altitude >1.200 m (*red*). **c** Location of snow poles in the Pyrenees for the study of snow-depth evolution

Data and methods

The "Spain02" database

The climatic data—precipitation and temperature—used in this study was extracted from Spain02 (Herrera et al. 2012). This is a regular 0.2° latitude/longitude (approximately 20 km) daily gridded data set containing precipitation, maximum and minimum temperatures, obtained from quality-controlled surface stations from the *Agencia Estatal de Meteorología* (AEMET, Spanish Meteorological Agency), covering continental Spain and the Balearic Islands during the period 1950–2007. A particular elevation threshold needs to be defined in order to restrict the analyses only to mountain areas. For this, we had to ensure that the entire area of the mountain chains was analyzed, thus avoiding taking into account too many isolated pixels; but also it was necessary that the capability of the database to reflect specific climate characteristic of mountains was guaranteed. The threshold of 1,200 m for this study has been considered to be an optimal level, and as a consequence all pixels with an average elevation higher than 1,200 m were considered for the subsequent analyses (Fig. 1b). As stated by the authors of Spain02 (Herrera et al. 2012), the number of stations used in the construction of the database varies on time and this could lead to erroneous results when using the database for regional trend analyses. To overcome this problem, we only considered the period 1970–2007, for which meteorological stations used to construct the database were evenly distributed in space.

Validation against observations

In order to analyze the capability of Spain02 to reproduce weather conditions in the main mountain ranges of the Iberian Peninsula, a validation of the grid data against observations was performed. For this, we considered 91 precipitation stations and 52 temperature stations from AEMET with heights ranging from 1,210 to 2,507 m. Then, we compared the observations with the nearest grid box of Spain02 whose average height is located above the selected threshold of 1,200 m.

Figure 2 shows the validation results in terms of the bias and Pearson correlation (the same analysis was developed using the Spearman correlation with similar results). Figure 2a shows the height of the AEMET stations used for validation and the corresponding grid points of Spain02.

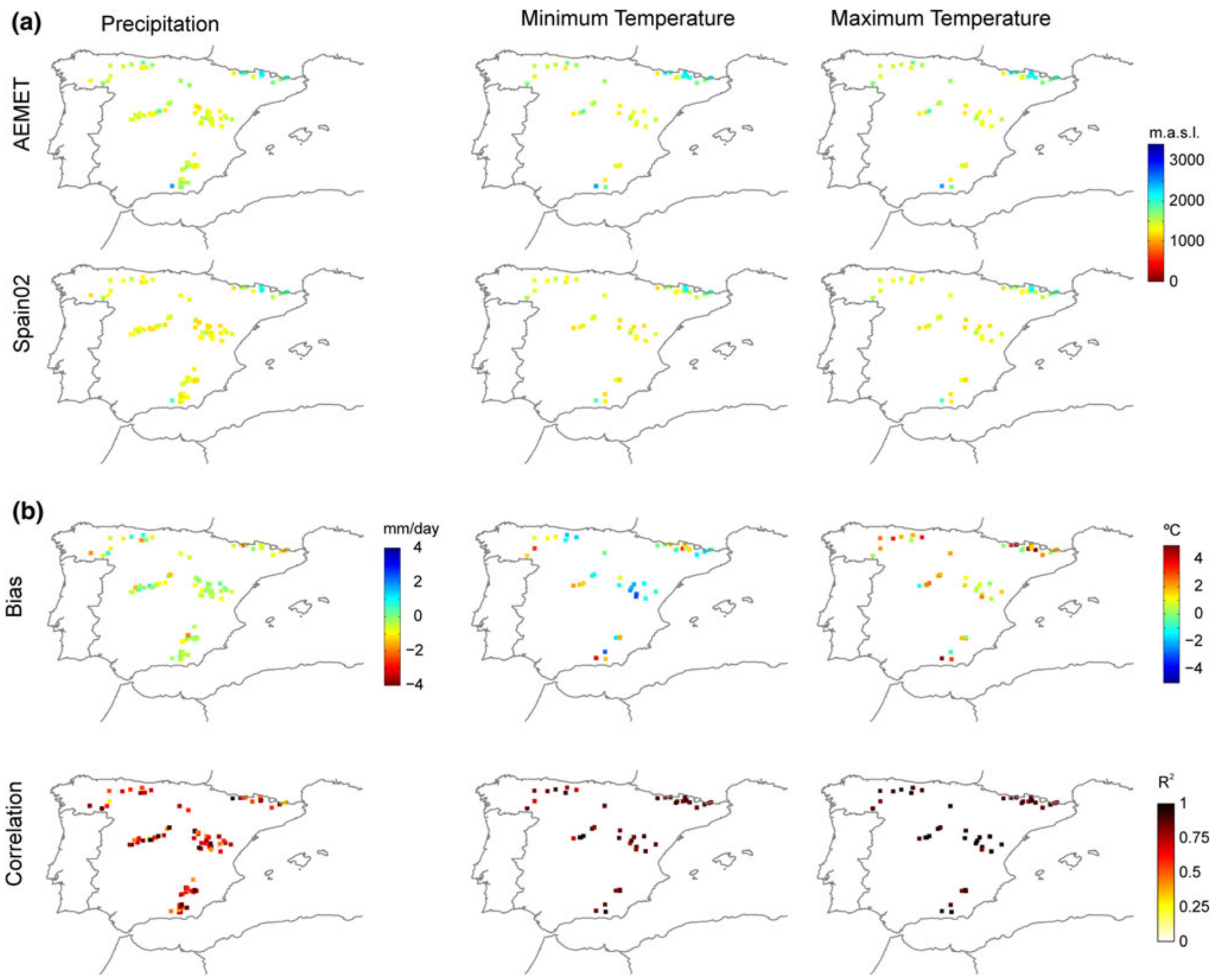

Fig. 2 Validation of Spain02 against observations. **a** Elevation of AEMET stations and corresponding grid points of Spain02. **b** Bias and Pearson correlation between observed and gridded precipitation and temperatures

There is clearly a negative bias for altitude, that is, Spain02 grid points are generally lower than the selected AEMET stations. The consequence is a general positive bias in the temperatures (Fig. 1b). Despite this bias, both temperature and precipitation displayed correlations (Fig. 1b) $R^2 > 0.6$ in all points, indicating that Spain02 reproduces reasonably well the daily variability of the three variables considered.

Moreover, we have compared the temporal evolution of the indices considered in this study (defined in Table 1) for the observations (blue line) and for the Spain02 data set (red line) for the period 1970–2007 (Fig. 3). High correlations are observed in all cases ($R^2 > 0.75$) between observed and estimated series. The variability is therefore well reproduced by Spain02, although it tends to systematically overestimate the number of dry-cold days in winter and dry-warm days in the spring. This systematic bias does not affect, however, the robustness of the trend analyses to be undertaken.

Precipitation–temperature joint quantiles and statistical analyses

The daily resolution of Spain02 database enables the behavior of far-from-normal events to be investigated. In this study, we have computed a series of indices that combine moisture and heat conditions based on the tails of the frequency distributions of daily precipitation and mean temperature series. This approach, proposed earlier by Beniston and Goyette (2007), provides a deeper understanding of the behavior of climate, due to the mutual feedbacks of precipitation and temperature that cannot be revealed when these variables are studied independently from one another. In this case, the resulting indices are representative of the weather conditions that favor or hamper snow accumulation and melting.

The different nature of the frequency distributions of daily precipitation (skewed) and temperature (normal)

Table 1 Definition of the indices considered in the study

Thresholds	Description	Units
$p0$	$P < 0.1$ mm	mm
$p25$	Value of the 25th percentile of the P-$p0$ series	mm
$t25$	Value of the 25th percentile of the T_{mean} series	°C
$t75$	Value of the 75th percentile of the T_{mean} series	°C
Exceedance series		
DW (dry-warm)	Days with $p0$ and $T > t75$	Number of days year^{-1}
DC (dry-cold)	Days with $p0$ and $T < t25$	Number of days year^{-1}
WW (wet-warm)	Days with $P > p25$ and $T > t75$	Number of days year^{-1}
WC (wet-cold)	Days with $P > p25$ and $T < t25$	Number of days year^{-1}
Spells		
A_DW	Average duration of dry-warm spells	Number of consecutive days year^{-1}
A_DC	Average duration of dry-cold spells	Number of consecutive days year^{-1}
A_WW	Average duration of wet-warm spells	Number of consecutive days year^{-1}
A_WC	Average duration of wet-cold spells	Number of consecutive days year^{-1}
M_DW	Maximum duration of dry-warm spells	Number of consecutive days year^{-1}
M_DC	Maximum duration of dry-cold spells	Number of consecutive days year^{-1}
M_WW	Maximum duration of wet-warm spells	Number of consecutive days year^{-1}
M_WC	Maximum duration of wet-cold spells	Number of consecutive days year^{-1}

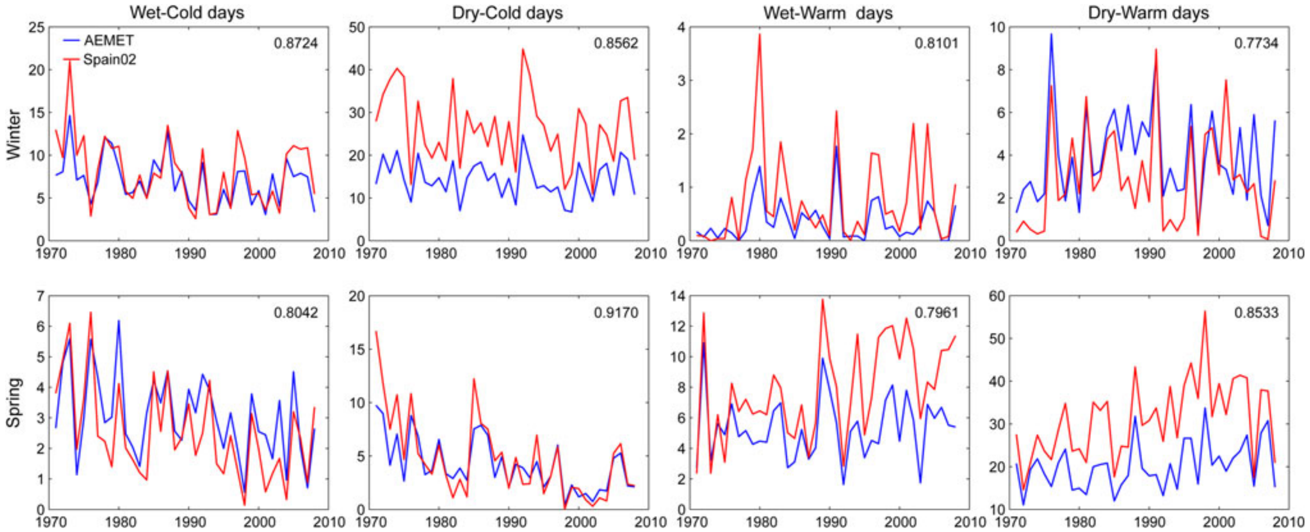

Fig. 3 Comparisons of the evolution of average (by mountain range) precipitation–temperature indices (Table 1) for observations and grid points

required the use of different thresholds for defining the indices to be considered. Calculation of the indices, for 1970–2007 and December-to-May period, involved:

- Separation of dry days ($P < 0.1$ mm) from the precipitation series and computation of the 25th percentile ($p25$) of the $P > 0.1$ mm series. Days with $P < 0.1$ mm ($p0$) were considered "dry days" and days with $P > p25$ mm were considered "wet days"
- Computation of the 25th ($t25$) and 75th ($t75$) percentiles of temperature series. Days with temperature $<t25$ °C are considered "cold days" and days with temperature $>t75$ °C are considered "warm days."
- Combination of thresholds to obtain the precipitation–temperature indices: DW (dry-warm), DC (dry-cold), WW (wet-warm) and WC (wet-cold).

Yearly series of the exceedance of these joint thresholds were calculated separately for winter (DJF) and spring (MAM), resulting in the number of days per year and season belonging to any of the combined classes. Moreover, spells of precipitation–temperature modes, that is, the number of consecutive days of each class, were computed. For the purposes of trend analyses, we calculated the average duration of spells per year and the duration of the longest spell per year on a seasonal basis. Table 1 summarizes the indices of exceedance series and duration of spells, and Table 2 shows the minimum, mean, median and maximum values of the thresholds of precipitation (*p*25) and temperature (*t*25 and *t*75), for each mountain range considered in this study.

The exceedance series and the series of duration of spells per year and season were then checked against monotonic trends. On the one hand, linear regressions (least squared method) were fitted against time to obtain the values of the linear trend and to calculate the change between the end and beginning of the studied period. Furthermore, the Mann–Kendall non-parametric test was used for detecting the statistical significance of trends. (Kendall 1975; Berryman et al. 1988; Yue et al. 2002). A significance P level <0.05 (95 % of confidence) was set to reject the null hypothesis of the test, that is, no trend in data.

Snowpack thickness data

Snow thickness measures were provided by the ERHIN program (*Evaluación de los Recursos Hídricos procedentes de la Innivación* – assessment of water resources from snow) of the Spanish Ministry of Environment. The ERHIN program has been taking snow measurements in the Spanish mountains since mid-1980 with fixed snow poles; three measurements were carried out for every year: the first in late January or early February, the second in March and the third in mid-April or early May. Quality criteria, including a maximum number of 3 data gaps were set up to obtain reliable snow data series. The data period was set from 1986 (first year of snow sampling) to 2007 (to make it coincide with the last year of the climatic series). Unfortunately, snow data for the Cantabrian, Central, Baetic and Iberic systems exhibited many gaps and did not allow obtaining entire series for the defined period; as a result, only snow measurements for the Pyrenees were considered for the study. Some of the selected series still had few data gaps, and only those with less than 15 % of missing data were filled using the results of linear regressions with the best correlated series (i.e., those where $R^2 > 0.7$). A total of 84 series of snow depth in April–May, covering most of the Pyrenees area, were finally selected (location of snow stakes in Fig. 1c) and related to the annual frequency of the different temperature and precipitation modes.

Results and discussion

Evolution in the frequency of days and duration of spells with combined precipitation–temperature conditions

Figure 4a shows the Mann–Kendall coefficients for the exceedance series of the different combined indices for winter and spring seasons in each pixel of elevation >1.200 m, and Fig. 4b summarizes the results by mountain range. Dry and warm (DW) days showed an inhomogeneous signal in winter among mountain ranges. Negative coefficients (although mainly not significant) predominated in the Iberian, Cantabrian, Pyrenees and northern Baetic systems, and positive and significant trends in Central System and southern Baetic. During spring, on the contrary, the signal is strong and homogeneous with positive

Table 2 Minimum, median, mean and maximum values (per mountain range) of the thresholds (*p*25, *t*25 and *t*75) set to obtain the combined indices

Threshold	Pyrenees	Cantabrian range	Central system	Iberic system	Baetic system
*p*25 (mm)					
Min	0.73	1.39	0.75	0.89	0.95
Median	1.40	2.24	1.83	1.63	2.12
Mean	1.73	2.29	1.94	1.73	2.05
Max	4.69	3.57	3.85	3.05	2.80
*t*25 (°C)					
Min	−2.48	0.24	0.30	1.07	2.45
Median	0.20	1.68	2.29	2.13	4.19
Mean	0.00	1.80	2.15	2.13	4.47
Max	2.12	3.18	3.17	3.72	6.31
*t*75 (°C)					
Min	3.96	5.42	6.70	6.74	8.28
Median	6.13	7.16	8.19	8.02	10.41
Mean	6.20	7.24	8.04	7.91	10.18
Max	8.79	8.99	8.87	9.18	11.85

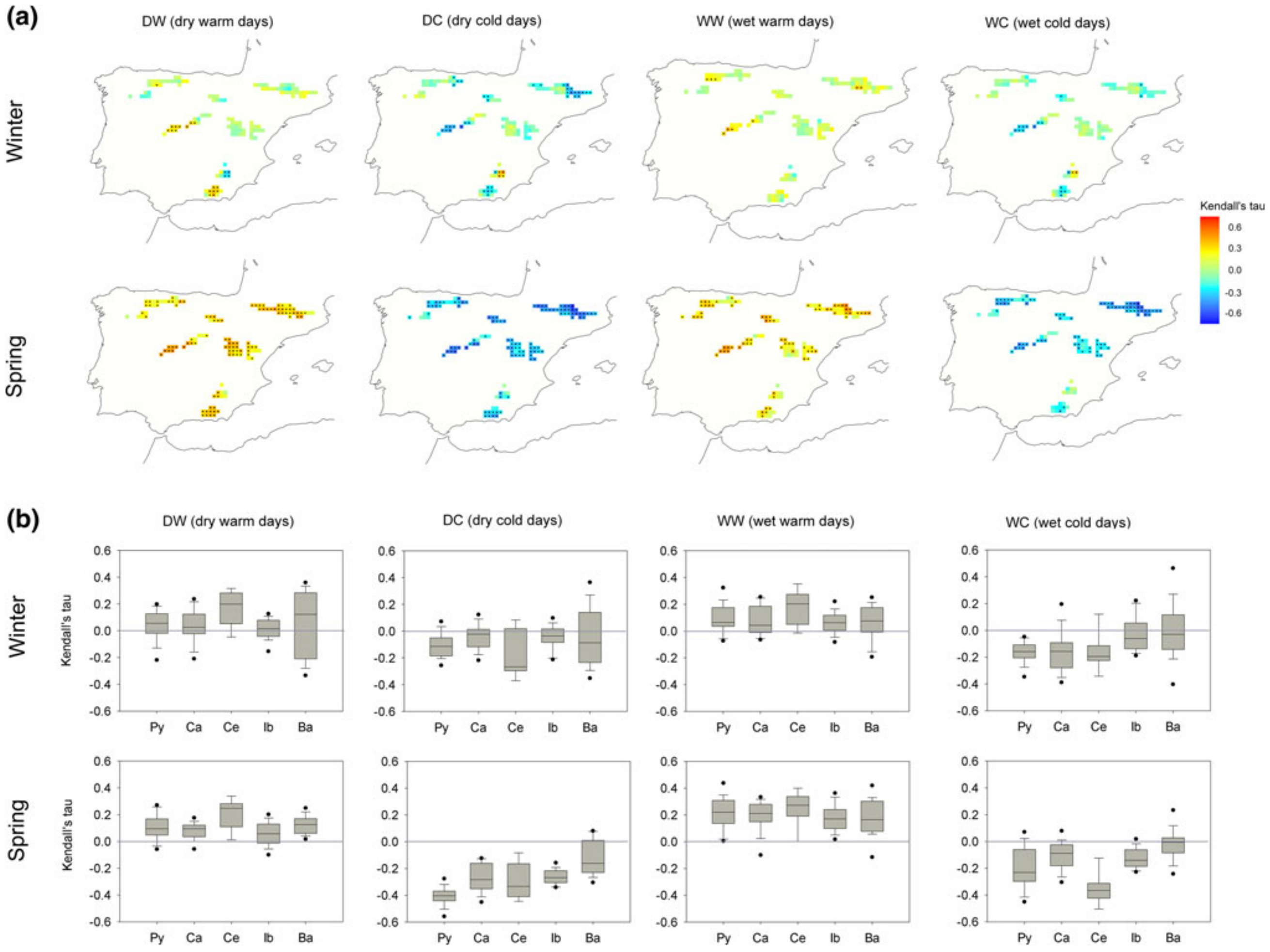

Fig. 4 Trends (Kendall's coefficient) in the joint-quantile indices in winter and spring. **a** Warm (cool) *colors* correspond to positive (negative) trends. *Black dots* indicate significant trend at the 95 % confidence level

significant trends in all mountain systems, indicating a sharp increase in the number of days with combined dry and warm conditions. Dry and cold (DC) days showed a similar behavior, but with trends in the opposite direction. The behavior of the wet modes is pretty similar to that of the dry modes, especially for the wet and warm (WW) days, with weak and inhomogeneous signals in winter and strong positive trends in spring. In the case of wet and cold (WC) days, a negative signal is observed for most mountains, although trends are more pronounced and significant in spring than in winter. Spatially, the Pyrenees, Central System and western Cantabrian range recorded the most pronounced decrease in wet and cold conditions. The Iberian and Baetic systems show, in contrast, more attenuated signals of change.

We calculated as well the amount of change in the indices derived from the linear trend. Two coefficients were extracted from this analysis: the difference in the number of days of each index between the end and beginning of the period (n) and the fold change (f), which is the ratio between the values at the end and at the beginning of the period, and provides insight about the relative magnitude of the change. In Table 3, a summary with the averages n and f for the pixels corresponding to each mountain system is shown. The greatest change is found in the Pyrenees for the cold modes, especially in spring, with a decrease in nearly 10 days in DC and 4.6 days in WC, and a 91-fold (this excessive amount of change is derived by dividing a value of 9.3 days at the beginning of the period by 0.1 days at the end of the period; these data are not shown) and 16-fold change, respectively. The decrease in DC days in spring is the greatest among the indices in all the mountain systems, with a 7-fold decrease in the Cantabrian range or an 8.6-fold decrease in the Iberian System. Wet-cold days have also experienced substantial decreases especially in spring, with less than half (fold change <-2.0) days with WC conditions at the end of the period with respect to the beginning in all mountain systems except in Baetic system (-1.7-fold change).

The homogeneous signal of increase in the two "warm" modes and decrease in the two "cold" modes a priori

Table 3 Change in the average (by mountain range) exceedance series of the combined precipitation–temperature indices

Index	Pyrenees			Cantabrian range			Central system			Iberian system			Baetic system		
	n	*f*	Sig	*n*	*f*	Sig	*n*	*f*	Sig	*n*	*f*	Sig	*n*	*f*	Sig
DW															
Winter	−0.2	−1.1		−0.1	−1.0		3.2	3.5		0.0	1.0		0.8	1.2	
Spring	15.3	1.7	*	9.9	1.4	*	17.8	1.8	*	12.6	1.5	*	18.2	1.7	*
DC															
Winter	−10.2	−1.5	*	−2.8	−1.1		−11.7	−1.6	*	−5.2	−1.2		−3.9	−1.1	
Spring	−9.2	−91.6	*	−5.6	−7.0	*	−7.5	−6.2	*	−7.8	−8.6	*	−6.5	−4.3	*
WW															
Winter	0.2	2.0		0.4	1.3		0.5	2.5		0.0	−1.1		0.1	1.6	
Spring	6.0	1.9	*	5.4	1.9	*	6.2	2.5	*	4.5	1.8	*	3.0	2.5	*
WC															
Winter	−1.6	−1.2		−0.1	−1.0		−3.1	−1.5		−1.0	−1.1		−1.8	−1.2	
Spring	−4.6	−16.2	*	−2.2	−3.6	*	−2.0	−2.5	*	−2.8	−3.2	*	−1.3	−1.7	

n = number of days (absolute); *f* = fold change (relative)

* indicates significant with 95 % of confidence

indicates that the temperatures are the driving factor of change in climatic conditions. Brunet et al. (2007) found that the increases in temperature in Spain from 1973 onwards was more pronounced in spring than in winter which is consistent with our findings. A number of studies have previously explored the trends in extreme quantiles of the temperatures and precipitation for different time periods during the twentieth century for Europe. Although most studies differ in the period or weather stations analyzed, most of them report significant and spatially consistent trends in the extreme temperatures, while for precipitation more uncertainty is observed (e.g., Klein and Können 2003; Moberg and Jones 2005; Alexander et al. 2006). A recent study by Beniston (2009), in which the "joint-quantile" technique was applied for various European sites for the twentieth century, showed a similar signal to that observed in this work, with increasing (decreasing) trends in the warm (cold) modes of the studied indices. The author, however, analyzed in depth the internal behavior of temperatures and precipitation when the different modes were exceeded and concluded that the observed trends were not only explained by the evolution of temperatures. He demonstrated, in fact, that the average amount of precipitation had decreased during the wet-cold modes and increased during the wet-warm modes, while overall the mean annual amount of precipitation remained stationary. The extended geographical scope of the cited work, covering the Iberian Peninsula, suggests that this could be the most likely behavior for our selected areas. Further research should, however, verify this hypothesis.

The averaged series of the different indices for every mountain chain were plotted to visualize the inner characteristics of the detected trends (Fig. 5). It is observed that the evolution of the indices exhibited similar dynamics in most mountain ranges. Some common features that can be observed include: the sustained increase in spring DW that peaked in the late 90s and the later decrease until the end of the series; or the change points in the middle of the 1980s and the middle of the 1990s for DC days. In general, there is an appreciable change of tendency during the last years of the record, namely a decrease in warm modes (while the general trend is to increase) and an increase in the cold modes (while the general trend is to decrease). These similarities suggest that the specific weather conditions that lead to each particular mode are similar over most of the continental Spain. This is somehow controversial: it is well known that climate conditions in the Iberian Peninsula are generally governed by the position and strength of the Azores High, allowing/impeding the penetration of disturbances associated with Atlantic fronts, which are closely related to the behavior of the North Atlantic Oscillation (NAO) (Martín-Vide and Fernández 2001; Hurrell et al. 2003; Trigo et al. 2004); however, recent research has highlighted that especially for the eastern half of the Iberian Peninsula, other atmospheric patterns such as the Western Mediterranean Oscillation (Martin-Vide and López-Bustins 2006) also contribute significantly to regional weather patterns. Recently López-Moreno et al. (2011) concluded that the NAO is a sound indicator of the variability of winter types favorable/unfavorable for snow accumulation in the west-Mediterranean mountains. In this work, spatial homogeneity is seen, but it is evident that the Pyrenees and the western sector of the Central System show the strongest signal of change. These spatial differences leave some open questions that merit to be further explored, such as the weather/synoptic conditions

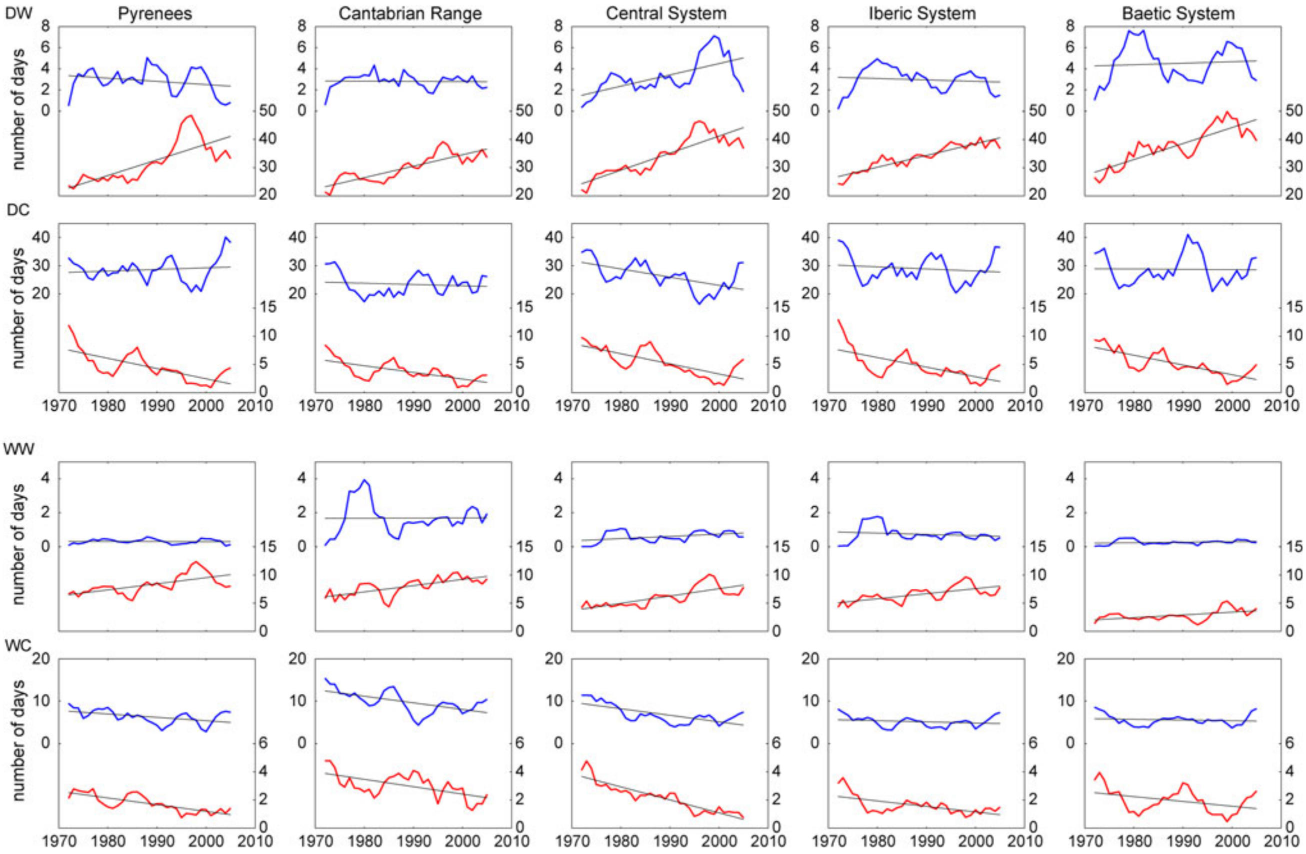

Fig. 5 Plots of the average evolution of the combined indices in winter (*blue line*) and spring (*red line*), for each mountain chain. The time series were smoothed with a 5-year moving average in order to reduce noise and enhance possible cycles

associated with the occurrence of the different precipitation–temperature modes studied here, or the relationship of the studied indices with the various teleconnections affecting the Iberian Peninsula, not only with the North Atlantic Oscillation (NAO), but also the Eastern-Atlantic Pattern (EA), the Scandinavian Pattern (SCA) or the Western Mediterranean Oscillation (WEMO).

Trends in the evolution of the average duration of spells and of the spells of maximum duration per year were as well calculated (Fig. 6). In general, the pattern of increase (decrease) in warm (cold) modes is also observed for the duration of spells, although in this case trends are not as robust as for the case of the evolution in the number of days. The most significant and generalized trends are observed for DC (negative) and WW (positive) spells in spring. The Pyrenees experienced once again the greatest trends, especially in DC. The general negative evolution in the duration of spells with WW conditions is also noticeable.

Influence of climatic evolution on snow accumulation

The second objective of the study was to assess the evolution of the snowpack in the studied mountains and its sensitivity to the evolution of the climatic indices. Various drawbacks related with data quality made this objective difficult to achieve, although the results next presented enabled conclusions to be drawn.

Spring snow depth in the Pyrenees has decreased between the time in which measurements began and recent years (Fig. 7a). The average series constructed with data from the 84 snow poles shows a variable evolution in snow depth, but a negative linear trend is superimposed to this variability. The negative evolution seems more pronounced in the first decade, whereas from 1997 onwards, there is no clear tendency. This is a first sign of coincidence with the evolution of the climatic indices, which in general presented a change of tendency in the last decade of the studied period. In spite of this general evolution, large variability among cases exists, as expressed by the amplitude of the inter-quartile range throughout the period. A principal component analysis with the 84 snow-depth series as input variables allowed us to obtain the most common patterns of evolution of snow depth, therefore reducing the initial inter-cases variability (Fig. 7b). We thus observed the first two components (which together explain about 60 % of the original variance) with a clear decrease in snow depth, although with different dynamics in the

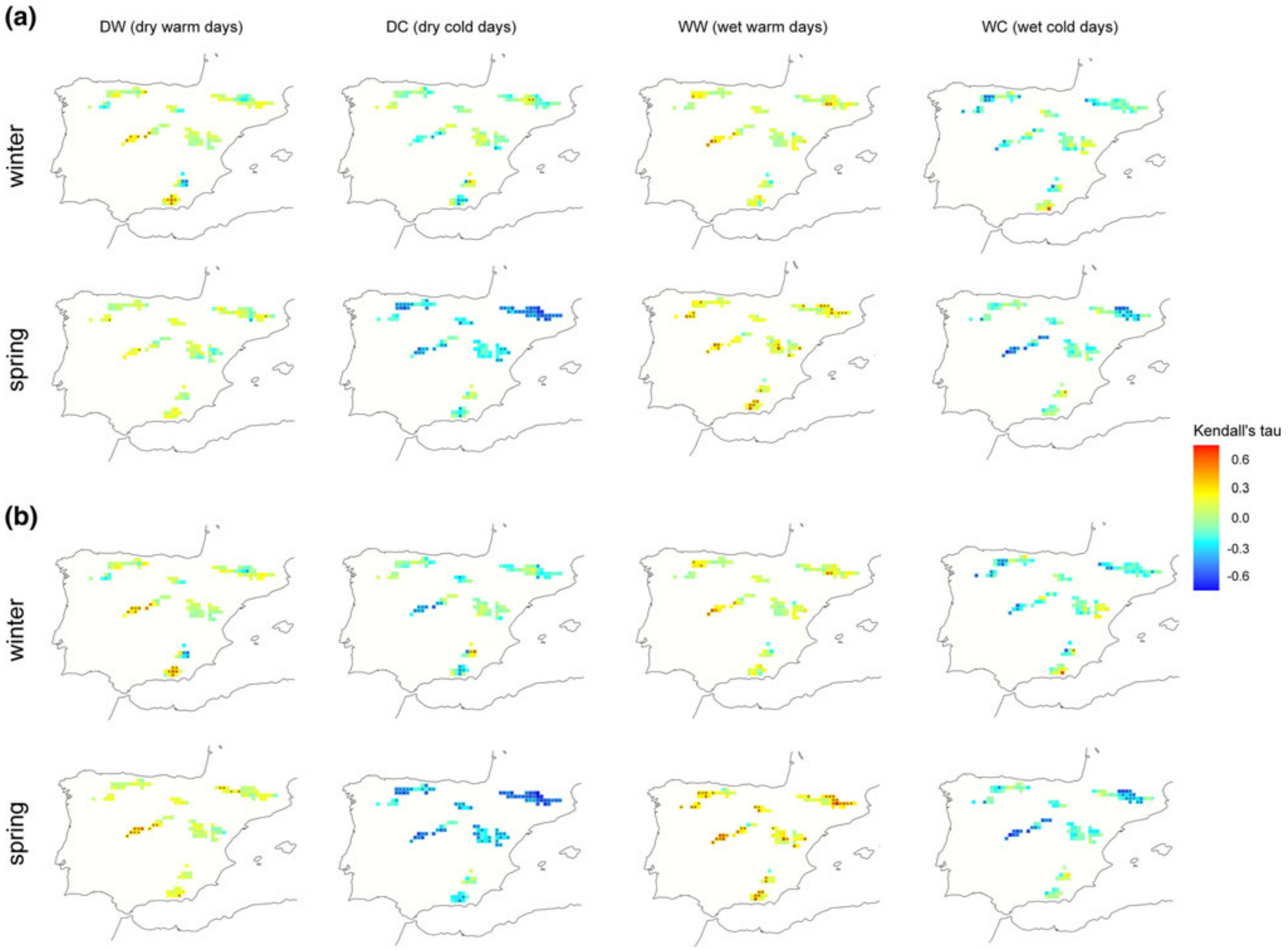

Fig. 6 Trends (Kendall's coefficient) in the mean duration of spells **a** and in the duration of the longest spells **b** with combined climatic conditions. Warm (cool) *colors* correspond to positive (negative) trends. *Black dots* indicate significant trend at 95 % of confidence

evolution of snow. In contrast, the last two components (with quite a smaller proportion of the explained variance) showed no clear signal of trends.

In order to asses to what extent the snow-depth evolution is sensitive to the evolution of the studied climatic indices, we have performed Pearson's correlations between each index in each of the 0.2° resolution pixels of the Pyrenees ($n = 31$), and the standardized (factorial scores) series of snow depth resulting from each principal component, for the common period 1986–2007. Results (Fig. 8a) show that the first principal component (PC1) is mostly anti-correlated with the evolution of DW days in spring and, to a lesser extent (and mostly not significantly), correlated with the evolution of DC days in spring. Otherwise, indices were seen to lie within the non-significance intervals. The evolution of snow depth for PC2 shows a significant and generalized correlation with DC in spring and also with the evolution of WC days in spring. The third and fourth principal components (which represent a minority of snow poles) do not show, in general, any significant correlations with the evolution of the climatic indices. Only the PC4 shows a pattern of negative correlations with the "warm modes" and positive correlations with the "cold modes," but in the majority of cases correlations are not statistically significant. Local particularities of each sampled site (e.g., topography, solar radiation, wind, exposure) may determine these differences in the sensitivity of the snowpack to climate conditions. Figure 8b graphically shows that abundant (sparse) snow springs coincide with the years of low (high) frequency of DW days for PC1 and with years of high (low) frequency of DC days for PC2, although the latter are less evident.

These results are in agreement with those by Beniston et al. (2011) in the Alps, where the snow depth correlated negatively with the evolution of dry-warm days, that is, with the conditions that favor the disappearance of snow in spring. It must be highlighted that the coefficients of correlation obtained, when significant, were not of great magnitude in the majority of cases. We believe that the explanation for the low correlation coefficients has to do

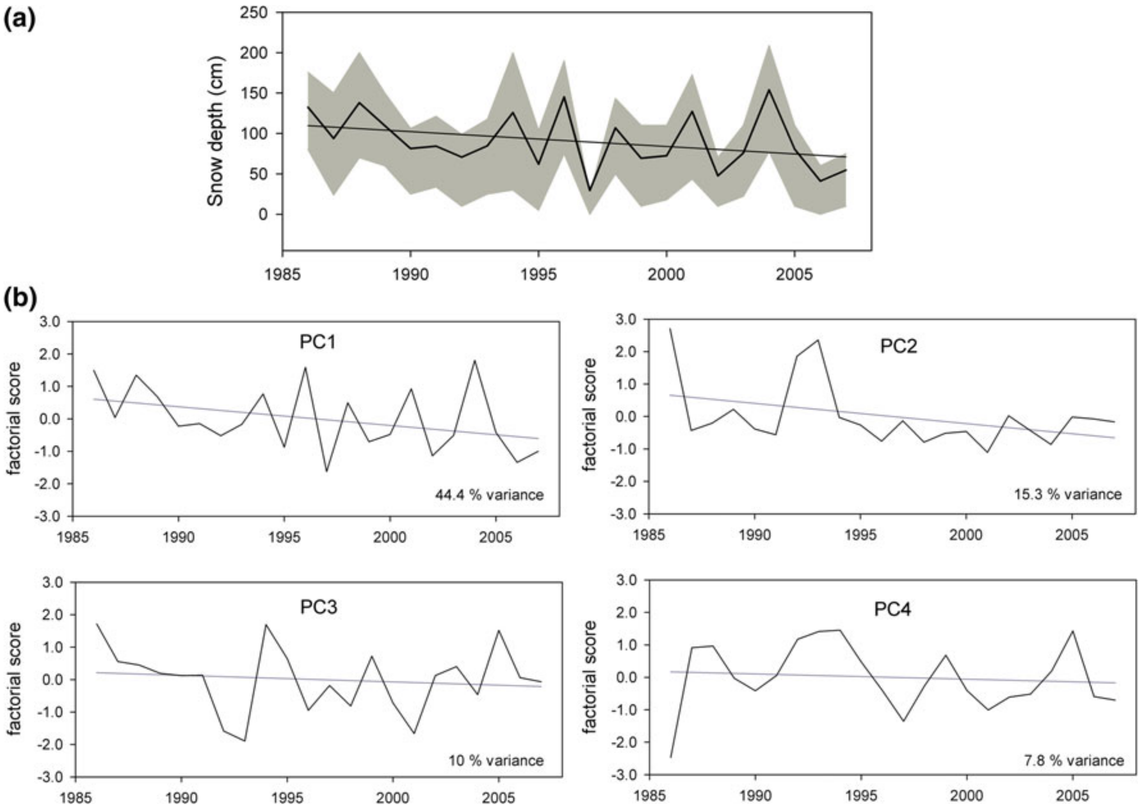

Fig. 7 Evolution of the snow depth in the Spanish Pyrenees (1986–2007). **a** Regional series of snow depth showing the average (*black line*) and the inter-quartile range (*gray shade*). **b** Series of the four first principal components

with the characteristics of the snow-depth data. As explained before, the series of snow depth used in the study correspond with a measurement per year, taken in late April/early May. This value of snow depth is representative of the accumulated snow along the winter/spring, but may be as well masking a history of accumulation/melting related to the specific weather conditions during the year at the sampled site. This might be the explanation, as well, for the fact that snow depth is basically controlled by temperature conditions in spring, whereas the precipitation appears not to be a limiting factor. Daily snow series, such as those used by Beniston et al. (2011) for the Alps, would probably provide better results, as they allow computing statistics such as the mean or standard deviation of snow depth, as well as the duration of the snowpack. Having into account these limitations, we find that the patterns of correlation found reproduce a signal of sensitivity of the snowpack to the evolution of the studied indices. Although snow data in the other studied mountains did not enable a similar analysis, it is expected a similar sensitivity of the snowpack to that observed in the Pyrenees.

A reduction in the snowpack in a warmer climate is likely to take place, given the displacement in altitude and latitude of the 0 °C isotherm. This is, however, difficult to demonstrate directly, due to the lack of continuous monitoring systems of climatic variables and snow depth in mountainous areas. To overcome this, the use of climate indices as proxies has been proven to yield reliable results in several parts of the world. In the western US and Canada, Hamlet et al. (2005) observed downward trends in the snow water equivalent (a measure of the quantity of water contained in a given volume of snow) during the twentieth century, which were in the long term explained by warming temperatures and, on a decadal time scale, by the variability of precipitation. In a study of snow evolution in the Pyrenees, López-Moreno et al. (2005) demonstrated that precipitation of previous months explained the evolution of the snowpack in winter and spring, whereas temperatures partly explained the evolution of snowpack only in spring. They also found that temperatures correlated better with snow depth at low elevations (1,700–2,200 m) than at higher elevations, which implies that there is a certain threshold of elevation for which the observed warming does not yet influence the evolution of the snowpack. Moreover, Pons et al. (2009) demonstrated that the decrease in the occurrence of "snow days" in northern Spain during 1950–1999 was related to increasing temperatures, although precipitation played a role as well, especially at high elevation sites.

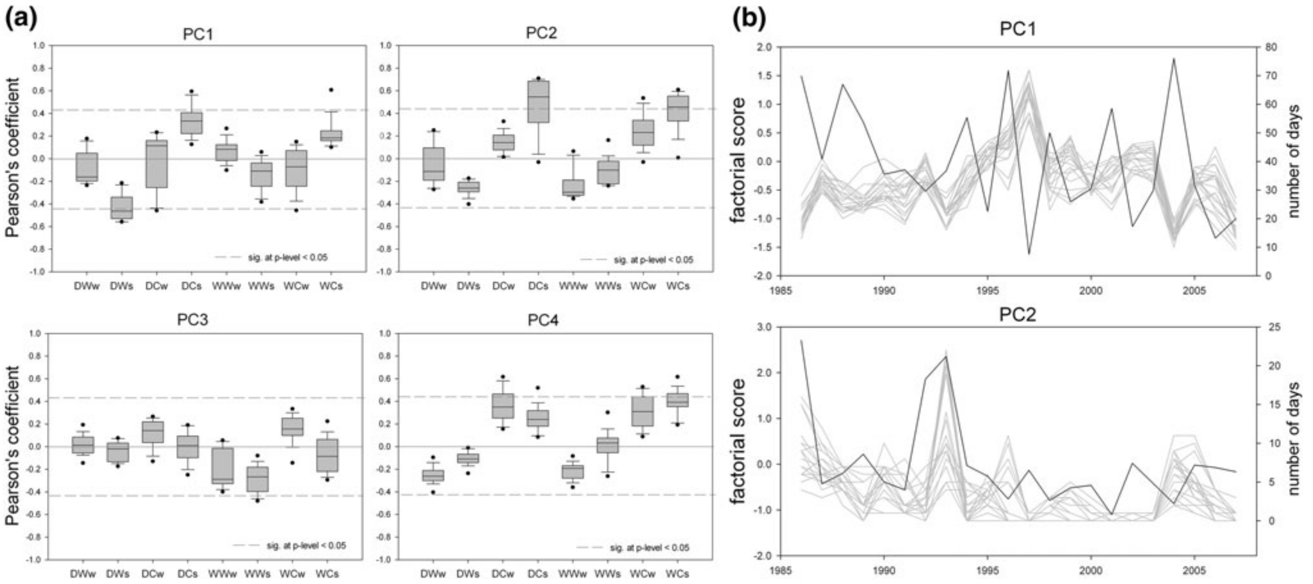

Fig. 8 Correlation between climatic indices and snow depth (1986–2007). **a** Boxplots showing the variability in the Pearson coefficients between the indices in each of the pixels of the Pyrenees and the series of each of the four principal components displayed in Fig. 7b). Series of the two first principal components of snow evolution (*black line*) and the index in the Pyrenees pixels that best correlates with snow evolution (*gray lines*), that is, DW days in spring for the PC1 and DC days in spring for PC2

These observations highlight the need for an in-depth understanding of the relationships between snowpack and climatic variables, in order to better simulate future projections of snow evolution in a "greenhouse climate." For the Swiss Alps, Uhlmann et al. (2009) and Beniston et al. (2011) projected a reduction in the snowpack and a much lower frequency of snow-abundant winters in the course of the twenty-first century in an enhanced greenhouse climate; López-Moreno et al. (2011) predicted a dominance of "warm" winter modes, with a rare occurrence of "cold" winters, for a moderate warming scenario (A1B1, IPCC 2007), in Mediterranean mountains between 2010 and 2100. Based on these precedents, it is reasonable to believe that a reduction in the snow cover is likely to take place in the Iberian mountains under conditions of climatic warming over coming decades.

Conclusions

A noteworthy change in climatic conditions was detected throughout the different mountain systems during the 1970–2007 period. This involved a significant increase in the number of dry-warm and wet-warm days, and also in the duration of spells with identical conditions, particularly in spring, and the respective decrease in the cold modes. The increase in temperatures is therefore the main driver of change in these climatic conditions. The signal of change was homogeneous in the territory, but the magnitude of trends was greater in the Pyrenees and smaller in the Baetic System.

Snowpack in the Pyrenees showed a reduction in depth during the last two decades and in the majority of sampled sites the snowpack evolution was negatively correlated with the frequency of dry-warm days, that is, with the conditions favorable to snow melting. There was in addition, for other cases, a significant correlation with the frequency of wet-cold and dry-cold days, that is, conditions that favor the snowfall and snow persistence. These results confirmed the hypothesis of the sensitivity of the snowpack to changes in the joint precipitation–temperature modes.

This work constitutes the first approach that relates the evolution of climatic conditions favorable or unfavorable for snow accumulation, and the evolution of the snowpack in Iberian mountains. Although results provide evidence of a change in climatic conditions and a certain sensitivity of the snowpack to these, a series of questions have arisen out of the present research that include: the uncertain role of precipitation in the change of joint-quantile modes; the synoptic conditions leading to each particular mode, and the relation with large-scale teleconnection patterns that affect the Iberian Peninsula; or the future evolution of the studied indices and the snowpack during the course of the twenty-first century, in an enhanced greenhouse climate. Such topics would justify future work to attempt to clarify many of these issues.

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