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THE INFLUENCE OF ATMOSPHERIC CIRCULATION AT DIFFERENT SPATIAL SCALES ON WINTER DROUGHT VARIABILITY THROUGH A SEMI-ARID CLIMATIC GRADIENT IN NORTHEAST SPAIN

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ABSTRACT

This paper analyses the spatial and temporal variability of winter droughts in a semi-arid geographic gradient in Northeast Spain, from the Pyrenees in the north to the Mediterranean coastland in the south. Droughts that occurred between 1952 and 1999 were analysed by means of the Standardised Precipitation Index (SPI). The influence of the weather-type frequency and of the general North Atlantic atmospheric circulation patterns was analysed. The results indicate that winter droughts show an important spatial variability in the study area, differentiating three well-defined patterns. These correspond to the Pyrenees, the centre of the Ebro Valley, and the Mediterranean coastland. General negative trends in winter SPI have been found, which are indicative of the increase in winter drought conditions in the study area. Nevertheless, important spatial differences have also been recorded. Dominant north–south gradients in the influence of weather types are shown. Moreover, the negative trends in winter-SPI values agree with the negative trend in the frequency of the weather types prone to cause precipitation, such as the C, SW and W weather types and the increase in the frequency of A weather types. Nevertheless, in the Mediterranean coastland, the positive trend in SPI values agrees with the increase in the frequency of weather types of the east (E, SE), which are prone to cause precipitation in this area. Interannual variations in the frequency of the different weather types have been highly determined by different general atmospheric circulation patterns, mainly the North Atlantic Oscillation (NAO). Nevertheless, the correlation between the time series of weather-type frequency and the winter SPI is higher than that found between the SPI and the NAO. Thus, although the interannual NAO variability explains a high percentage of the interannual differences in the frequency of different weather types, it is not sufficient to explain the spatial and temporal variability of droughts, which respond better to atmospheric variability at more detailed (synoptic) spatial scales.

KEY WORDS: synoptic climatology; weather types; North Atlantic Oscillation; drought; Standardised Precipitation Index; winter season; Ebro Valley; Spain

1. INTRODUCTION

Drought is one of the main climatic hazards that affect arid and semi-arid regions. It can essentially be considered a climatic phenomenon (Palmer, 1965; Beran and Rodier, 1985), since droughts are usually related to an abnormal decrease of precipitation. Although high temperatures, wind flows and low air moisture can reinforce water shortages, it is usual to consider only precipitation data when recognising and analysing droughts (McKee *et al*., 1993; Guttman, 1998; Keyantash and Dracup, 2002).

Several negative effects are associated with drought in the Iberian Peninsula: (1) losses in agriculture (Austin *et al*., 1998; Molinero, 2001); (2) damage to natural ecosystems (Vicente-Serrano, 2004; López-Bermúdez and Alonso, 2001); (3) an increase in forest fire risk (Pausas, 2004); (4) degradation of soils and desertification (López-Bermúdez, 1985); and (5) social alarm (Morales *et al*., 2000).

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Drought studies have received special attention in recent years because of climate change. The atmospheric causes of droughts have been analysed widely in order to improve drought prediction (Cordery and McCall, 2000; Lloyd-Hughes and Saunders, 2002a). In the Mediterranean region, climatic models indicate an important decrease in precipitation (higher than 30%) for the twenty-first century if CO_2 levels continue to rise (Houghton *et al*., 2001). Thus, it is necessary to improve our understanding of the atmospheric factors that determine the spatial and temporal variability of droughts in these regions to determine in greater depth the possible consequences of climatic change.

The influence of synoptic atmospheric circulation on the frequency and intensity of precipitation is very important (Yarnal and Frakes, 1997). For this reason, efforts have been dedicated to the development of classification methods based on different catalogues of weather types (Yarnal *et al*., 2001). The synoptic spatial scale has been widely used for regional precipitation modelling (Romero *et al*., 1999; Phillips and McGregor, 2001; Svensson *et al*., 2002; Santos *et al*., 2005). Moreover, in different regions, evidence has been provided about relationships between weather-type frequency and general atmospheric circulation patterns (Wilby, 1993; Fraedrich, 1994; McCabe and Muller, 2002; Stefanicki *et al*., 1998; Sheridan, 2003). In fact, it could be said that the general atmospheric circulation variability is driven regionally by means of a series of weather types, which would explain in physical terms the intensity and spatial distribution of precipitation.

Different studies have analysed the influence of weather-type frequency on precipitation in different Mediterranean regions, mainly for intense precipitation events (Romero *et al*., 1999; Kahana *et al*., 2002, 2004; Esteban *et al*., 2005). Nevertheless, a few studies on the influence of the frequency and persistence of weather types on droughts in this region have been published (Delitala *et al*., 2000; Olcina, 2001; Brunetti *et al*., 2002). The persistence of blocking-anticyclone cellules is the general condition that causes absence of precipitation in the western Mediterranean region (Delitala *et al*., 2000). In this area, Maheras and Kolyva-Machera (1990) indicated that humid periods are related to meridian circulation modes, whereas the dry periods are related to zonal circulation.

Several papers have indicated that interannual precipitation variability and drought occurrence in Spain are related to changes in the main atmospheric circulation modes on global and hemispheric spatial scales (von Storch *et al*., 1993; Rodríguez-Puebla *et al*., 1998; Rodó *et al*., 1997; Pozo-Vázquez *et al*., 2001, 2004; Martín-Vide and Fernández, 2001). Other papers have analysed the influence of weather types on precipitation (Trigo and DaCamara, 2000; Goodess and Palutikof, 1998; Martín-Vide, 2002; Goodess and Jones, 2002; Corte-Real *et al*., 1998; Esteban *et al*., 2005). Nevertheless, at present there is no joint analysis of the relationship between the general atmospheric circulation modes in the North Atlantic region, the weather-type frequencies and the intensity and spatial differences of droughts, nor have detailed spatial scales been considered by means of a high density of weather stations, a method that would make it possible to accurately determine spatial and temporal patterns in a region of strong precipitation variability.

The present study considers a north–south gradient in Northeast Spain to take into account different climatic and geographic environments, from mountains in the north (the Pyrenees) to the coastland Mediterranean area. The objectives were to determine the role of atmospheric circulation at different spatial scales on spatial and temporal variability of droughts. The study was carried out between 1952 and 1999 with a homogeneous and dense network of weather stations. Winter season (December–February) was selected for the analysis because the influence of atmospheric circulation variability on precipitation is higher (von Storch *et al*., 1993; González-Rouco *et al*., 2000), and winter precipitation is the most important factor in this region to explain the interannual variability of reservoir storages (López-Moreno *et al*., 2002, 2005), river flows (López-Moreno and García-Ruiz, 2004), crop productions (Austin *et al*., 1998) and vegetation activity (Vicente-Serrano *et al*., 2004a).

2. METHODS

2.1. Analysis of the temporal variability of the winter atmospheric circulation

2.1.1. Weather-type classification. Different subjective weather-type classifications have been developed for the Iberian Peninsula (Linés, 1981; Capel, 2000; Ruiz, 1982). However, automatic methods of classification make it possible to maintain homogeneity over time and to create daily series of weather types for long periods. Automatic classifications are based on statistical techniques such as k-mean clustering (Matyasovszky *et al.*, 1993), correlation (Yarnal, 1993), principal component analysis (PCA, Kutzbach, 1970; Deser and Blackmon, 1993; Wallace and Gutzler, 1981) or fuzzy rules (Pesti *et al.*, 1996). Romero *et al.* (1999) used a PCA in T-mode for weather-type classification in the Iberian Peninsula and, in the same region (Corte-Real *et al.* (1998); Rasilla (2002) and Esteban *et al.* (2005), used an algorithm that combines the k-mean clustering and the PCA for the same purpose.

Other methods are based on catalogues of atmospheric circulation type. The most widely used method is the one formulated by Jenkinson and Collison (1977), based on the Lamb catalogue (Lamb, 1972). This has been applied in several regions such as the United Kingdom (Hulme *et al.*, 1993; Wilby *et al.*, 1995; Jones *et al.*, 1993), USA (Wilby and Wigley, 1997), Scandinavia (Linderson, 2001) and Japan (Wilby *et al.*, 1998). In the Iberian Peninsula, it has been widely used to classify weather types (Martín-Vide, 2002; Goodess and Palutikof, 1998; Goodess, 2000; Goodess and Jones, 2002; Trigo and DaCamara, 2000; Rasilla *et al.*, 2002; Spellman, 2000a,b).

A precise description of the classification method can be found in Jenkinson and Collison (1977) or in Jones *et al.* (1993). Jones *et al.* (1993) and Linderson (2001) used a sea-surface pressure grid of 16 points centred over Great Britain and Denmark, respectively, to perform the classification. Rasilla *et al.* (2002) transposed this grid to the Iberian Peninsula (Figure 1). From daily pressure data at these points between 1951 and 1999, and using the Jenkinson and Collison method, we calculated the direction of surface wind and its vorticity in geostrophic units (hPa). These parameters indicate the type and direction of winds (cyclonic/anticyclonic, directional and hybrid), which later allows classification of weather types. We used the NCEP-NCAR daily surface pressure data set for this analysis (http://dss.ucar.edu/catalogs/gridlists/sel_gslp.html#a, Trenberth and Paolino, 1981; Basnett and Parker, 1997).

Martín-Vide (2002) indicated that Jenkinson and Collison's method for weather-type classification in the Iberian Peninsula has some shortcomings. A proportion of 18.4% of the days are not classified in any group. Nevertheless, Martín-Vide indicates that this fact is recorded mainly in summer and autumn owing to the low-pressure gradient that characterise these months in the Iberian Peninsula. Rasilla *et al.* (2002) reclassified the non-classified days according to the mean surface pressure: days with over 1020 hPa are classified as anticyclonic and those under 1020 hPa as cyclonic. We followed the same approach and eliminated the non-classified days. Another problem of Jenkinson and Collison's method for weather-type classification in the Iberian Peninsula is related to the absence of pressure data at other levels (i.e. 500 hPa). This causes a high number of cyclonic days during the summer months to be obtained as a consequence of frequent low pressures at surface level (thermic) during this season (Capel, 2000). Nevertheless, this problem does not affect the present study as it was carried out in the winter.

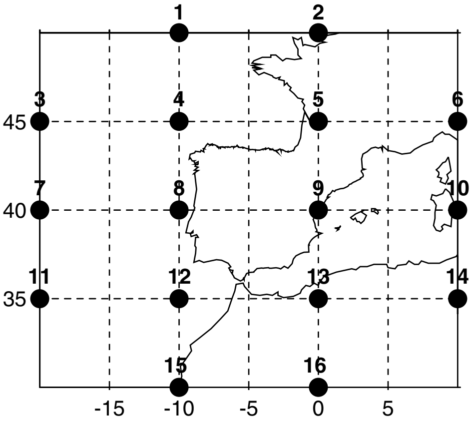

Figure 1. Pressure grid used for weather type classification

Usually, droughts are quantified monthly because this phenomenon needs prolonged precipitation shortages over the course of long periods to be identified. Fowler and Kilsby (2002) analysed the persistence and intensity of droughts as a function of weather-type frequency in the east of England. These authors obtained quantitative monthly series from the daily weather types by means of the sum of the number of weather types of each class during the month. Corte-Real *et al.* (1998) used the same approach to summarise the monthly frequency of weather types in Portugal. In this paper, we followed this approach to create numerical monthly series of the frequency of each weather type. The 26 weather types obtained by means of Jenkinson and Collison's method were summarised by means of the elimination of hybrid types, which were reclassified at 50% to cyclonic (C), anticyclonic (A) or directional weather types (N, north; NE, northeast; E, east; SE, southeast; S, south; SW, southwest; W, west and NW, northwest) (Jones *et al.*, 1993; Trigo and DaCamara, 2000).

2.1.2. General atmospheric circulation patterns. The general atmospheric circulation patterns show less temporal variability than weather types. Although some studies show changes around 8–10 days in the phase of the general atmospheric circulation patterns (Feldstein, 2000), the persistence of general conditions can be maintained for periods of months or years. Hurrell (1995) indicated that the North Atlantic Oscillation (NAO) shows a persistence of negative or positive phases for years. Therefore, the temporal variability of weather types would be set within the general atmospheric circulation patterns, which are more general and less variable in time and space. Barnston and Livezey (1987) showed, in the Northern Hemisphere, nine general atmospheric circulation patterns in winter and three in summer, spring and autumn, and also identified a pattern (NAO) throughout the year. Trigo and Palutikof (2001) carried out a PCA to determine the general atmospheric circulation patterns in Western Europe, and determined that the main pattern is the NAO, which explains 21%, 28% and 33% of total atmospheric circulation variability in spring, autumn and winter, respectively.

The NAO affects winter precipitation significantly in the Iberian Peninsula (Trigo *et al*., 2004; Ullbrich *et al*., 1999; Martín-Vide and Fernández, 2001). Nevertheless, other atmospheric circulation patterns can be identified during the boreal winter in Western Europe (Barnston and Livezey, 1987). These patterns have an important role in the climatology of the western Mediterranean area (Marshall *et al*., 2001; Rodríguez-Puebla *et al*., 1998; Krichak and Alpert, 2005; Dünkeloh and Jacobeit, 2003).

In this paper, we have considered the circulation indices that explain the main atmospheric circulation patterns in the North Atlantic region: the NAO, the East Atlantic (EA) Pattern, the East Atlantic/West Russian (EA/WR) Pattern and the Scandinavian (SCA) Pattern. To quantify the NAO, we used the index made by the Climate Research Unit (University of East Anglia) (http://www.cru.uea.ac.uk/cru/data/nao.htm, Jones *et al*., 1997). The other indices were obtained from the National Centers for Environmental Prediction (NCEP) of the USA (ftp://ftpprd.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/tele_index.nh), which were obtained by means of PCA according to Barnston and Livezey (1987).

2.2. Winter drought quantification

2.2.1. Database. The study was carried out in a north–south gradient in Northeast Spain, from the Mediterranean Sea to the Pyrenees (Figure 2). Differences in topography are very important within the study area. The north corresponds to the Pyrenean Mountains, where 3000 m a.s.l. are exceeded. The climate of this area is characterised by humidity (mean winter precipitation is higher than 400 mm) and cold temperatures (Cuadrat, 1999). The centre of the study area is a well-defined geographic region, the Central Ebro Valley, with an elevation range between 250 and 600 m, which is one of the most arid regions of Europe (annual precipitation does not exceed 400 mm, and winter precipitation is less than 100 mm). The aridity, along with the continental features of the climate, causes an important constraint for vegetation and human activities (Austin *et al*., 1998; Pedrocchi, 1998). The south of the study area corresponds to the north of the Valencia region, close to the Mediterranean Sea, where temperatures are milder than in the centre of the Ebro Valley (Pérez-Cueva, 1994) and precipitation is higher owing to the influence of the Mediterranean (Camarasa, 1993; Millán *et al*., 1995).

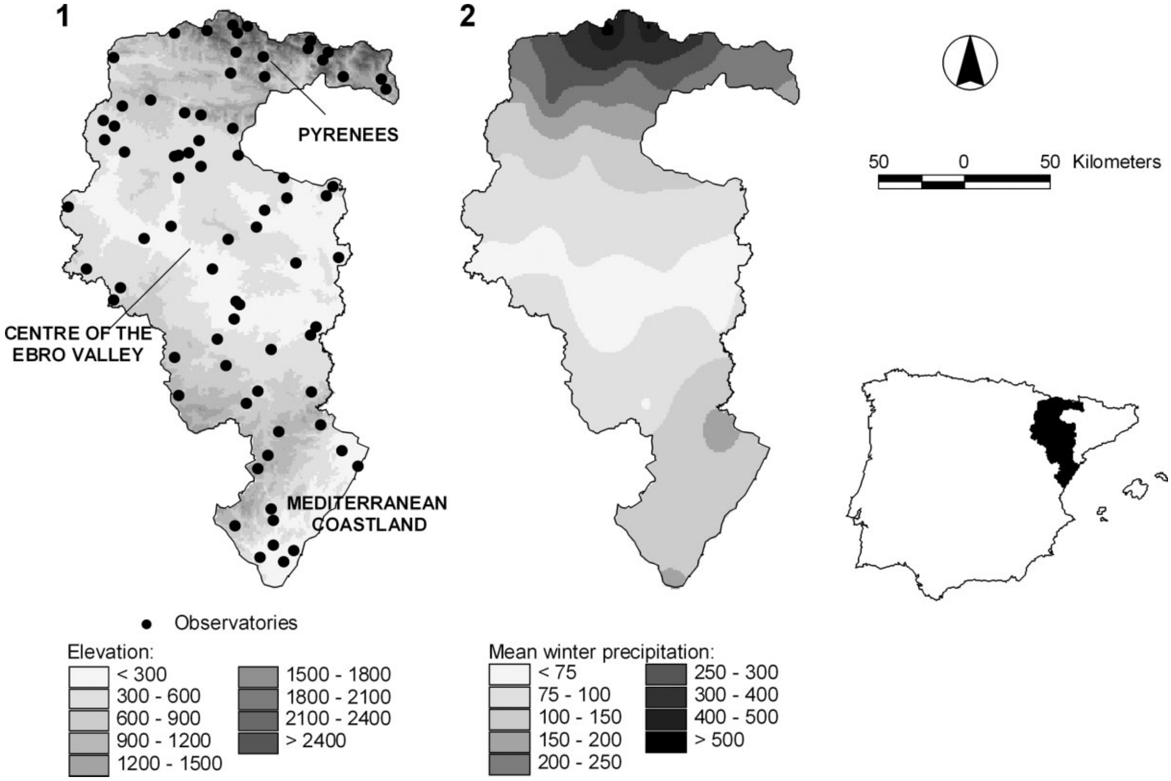

Figure 2. Spatial distribution of observatories, elevation (1) and winter mean precipitation (2) in the study area

For analysis, we used 75 monthly precipitation observatories in this region, from 1951 to 1999. These observatories were selected from a dense database of more than 400 observatories obtained from the National Institute of Meteorology (Spain). Some series had to be created by combining data from different observatories within the same locality, owing to the frequent changes of location of Spanish observatories during the twentieth century. The 75 observatories selected had less than 15% loss of data between 1951 and 1999. Eighteen of these series were created by merging different series of the same locality, which cover different periods. The data were subjected to a process of quality control that identified anomalous records using a quartile-based range statistic, in line with González-Rouco *et al.* (2001). Owing to the creation of some of the series by means of merging two or more observatories of the same locality, and to guarantee the final quality of the precipitation series, the homogeneity of each one was checked (Peterson *et al.*, 1998; Lanzante, 1996) against an independent reference series that was generated by selecting five of the series whose difference series correlated best with the difference series in question (Peterson and Easterling, 1994). The average correlation coefficient between the five most correlated series of each observatory and the objective series was 0.82. Moreover, the minimum correlation obtained for a series that was included in a reference series was 0.66. Thus, the values above 0.75 are considered dominant, which implies a high reliability of the reference series created.

To test the homogeneity of the series, the Standard Normal Homogeneity Test was used (SNHT, Alexandersson, 1986; Alexandersson and Moberg, 1997), a technique widely applied in the homogenisation of climate records in several areas (Keiser and Griffiths, 1997; Moberg and Bergstrom, 1997; González-Hidalgo *et al.*, 2002). For this purpose the ANCLIM program was used (Štìpánek, 2004). Only seven nonhomogeneous series were identified and corrected using the difference between the average of the records before and after the date of the inhomogeneity was identified, in line with Alexandersson and Moberg (1997). Finally, temporal gaps were completed after homogenisation using linear regressions with respective reference series (Štìpánek, 2004).

2.2.2. Drought index calculation. In the last decade, the most popular drought index has been the Standardised Precipitation Index (SPI), which is valued for its theoretical development, robustness and versatility in drought analysis. The SPI was developed by McKee *et al.* (1993, 1995) to identify non-normal dry and humid periods more precisely than others. The SPI only needs precipitation data for its calculation (Guttman, 1998, 1999). Keyantash and Dracup (2002) tested the robustness of 18 different drought indices by means of statistical methods, and concluded that the SPI is the best climatic index for drought identification and for quantification of the severity, duration and spatial extent of droughts. Although the development of the SPI is recent, this index has been used for drought analyses in many areas, including the USA (Hayes *et al.*, 1999), Europe (Lloyd-Hughes and Saunders, 2002b), South Africa (Rouault and Richard, 2003), Hungary (Domonkos, 2003), Italy (Bonaccorso *et al.*, 2003), East Africa (Ntale and Gan, 2003), Greece (Loukas and Vasiliades, 2004), Germany (Bordi *et al.*, 2004) and Korea (Min *et al.*, 2003).

Guttman (1999) examined the properties of the SPI in further depth and described the effects of using different stochastic models. He concluded that Pearson III distribution is better for calculating the SPI because its three parameters allow more flexibility than the two parameters of the Gamma distribution.

The probability density function of a Pearson III distributed variable is written as

$$f(x) = \frac{1}{\alpha\Gamma(\beta)}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\alpha}\right)}$$

where α, β and γ are the shape, scale and origin parameters, respectively, for precipitation values $x > 0$. $\Gamma\ (\beta)$ is the Gamma function of β. The calculation of parameters was carried out by means of the L-moment method. Hosking (1990) and Sankarasubramanian and Srinivasan (1999) have discussed the advantages of L-moments in the estimation of distribution parameters. For small samples (fewer than ten cases) the difference between using moments or L-moments is small, but when the size of the sample increases, and with highly biased distributions, the reliability of L-moments is higher (Sankarasubramanian and Srinivasan, 1999).

The Pearson III distribution is not defined for $x = 0$, which is a problem, considering that precipitation series can include months in which there is no precipitation. With this in mind, an adapted statistic $H(x)$ can be calculated using the following formula:

$$H(x) = q + (1-q)F(x)$$

where q is the probability of precipitation $= 0$ and $F(x)$ is the cumulative probability of a precipitation of magnitude x following a Pearson III distribution. Edwards and McKee (1997) suggests that q can be calculated simply as m/n, where n is the overall number of months and m is the number of months in which precipitation is 0.

Once $H(x)$ is calculated, it is normalised so that the mean is 0 and standard deviation is 1. This normalised variable is interchangeable with the SPI, and is commensurable with other SPI values over time and space. An SPI of 0 indicates precipitation corresponding to 50% of the accumulated probability according to the Pearson III distribution. The complete formulation of the SPI calculation according to the Pearson III distribution and the L-moment method can be found in Vicente-Serrano and Cuadrat (2002) and Vicente-Serrano (2006).

2.3. Analysis of drought spatial and temporal patterns

To determine the general patterns of temporal evolution in the winter-SPI series, we used a PCA, which is widely used to analyse spatial and temporal patterns of droughts in different regions (Karl and Koscielny, 1982; Eder *et al.*, 1987; Bonaccorso *et al.*, 2003; Vicente-Serrano *et al.*, 2004b; Vicente-Serrano, 2006). To summarise the general temporal patterns of droughts in the study area, we used a PCA in S-mode (Serrano *et al.*, 1999), in which observatories are the variables and years the different cases. The S-mode allows determination of regions in which the structure of evolution of winter droughts is the same. Components obtained were rotated (Varimax) to obtain more stable patterns, maintaining the orthogonal structure of components (Richman, 1986). Because the SPI is a standardised variable, the components obtained can be identified as the regional SPI of a representative region (Lana *et al.*, 2001).

Trends in the different variables were analysed by means of Spearman's rank correlation test because it is less affected by the presence of outliers and non-normality of the series (Lanzante, 1996). For temporal change detection in climatology, the moving average procedure is a conventional procedure (Sneyers, 1990). This procedure allows filtering the year-to-year variations to reveal more persistent trends (Wheeler and Martín-Vide, 1992; Salinger *et al.*, 1995; De Luis *et al.*, 2000). For this reason, prior to trend analysis, the different variables were smoothed by means of a moving average of 9 years, following De Luis *et al.* (2000). The smoothing procedure decreases the degrees of freedom of the series because it reduces the number of samples (from 49 to 41 records), but it also reduces the higher frequency variability (noise) that can hide existing trends.

Finally, to assess the role of atmospheric circulation on spatial and temporal patterns of droughts, we obtained correlation coefficients (R-Pearson) between the non-filtered time series of the components and the SPI series in each observatory as well as the time series of weather-type frequency and the teleconnection indices. In the case of observatories, we continuously mapped the R-Pearson coefficients to determine the spatial differences in the role of atmospheric circulation on droughts in the study area. For this purpose we used an algorithm of splines with tension (Mitasova and Mitas, 1993; Vicente-Serrano *et al.*, 2003).

3. RESULTS AND DISCUSSION

3.1. Winter weather types: characteristics and evolution

Figure 3 shows the average of the winter frequency in each weather type between 1952 and 1999. The highest frequency corresponds to anticyclonic days (A), with 37 days. The mean of cyclonic days (C) is 12, and the directional weather types show a lower frequency, although the N, SW, W and NW show a higher frequency than the weather types from east and south.

Figure 4 shows the evolution of the number of A and C weather types in winter and one example of the evolution of two directional weather types (NE and SW). In the most frequent weather types, such as A and C, there is an important interannual variability, mainly in the frequency of A weather types, with important variations from the maximum (54 days in 1995) to the minimum (17 days in 1996). Also, there are important interannual variations in the number of C days, with a maximum of 25 in 1996 and a minimum of 0 in 1995. Black lines indicate a moving average of 9 years, which, in the case of the A weather types, show a clear increase in the frequency of these weather types from 1952 to 1999. On the other hand, there were clear decreases in the frequency of NE and SW weather types.

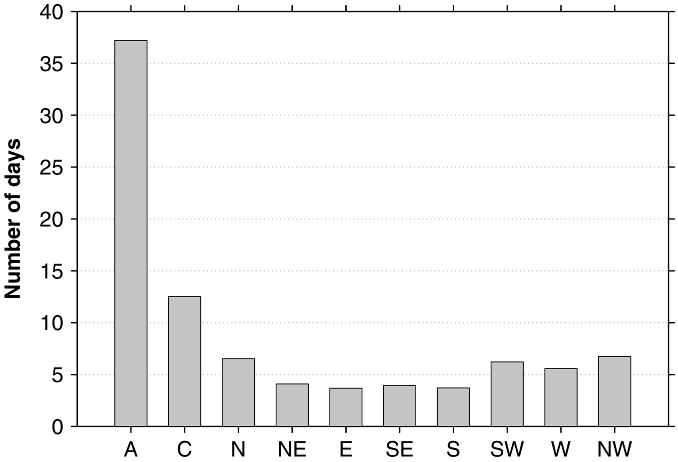

Figure 3. Average frequency of the winter weather types (1952–1999)

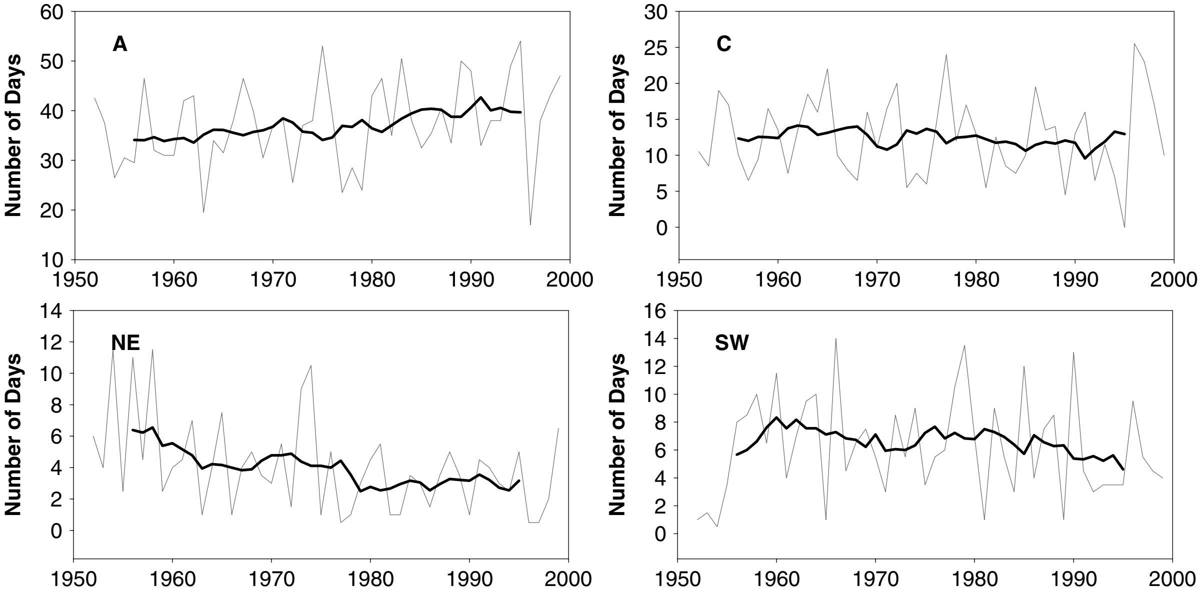

Figure 4. Evolution of the frequency of different weather types. Black line indicates a moving average of 9 years. 1952–1999

Table I. Trends in the different winter weather types in the Iberian Peninsula (1952–1999)

Weather type	Rho-Spearman	Weather type	Rho-Spearman
A	0.87[a]	SE	0.54[a]
C	−0.45[a]	S	−0.38[b]
N	−0.62[a]	SW	−0.52[a]
NE	−0.81[a]	W	−0.31
E	0.32[b]	NW	−0.26

[a] Significant trend ($\alpha < 0.01$).
[b] Significant trend ($\alpha < 0.05$).

Table I shows the trend in the frequency of each weather type, considering the moving averages of 9 years. There is a positive and statistically significant trend in the frequency of A days and a decrease, although of lower magnitude, in the frequency of C days. In relation to the evolution of the directional weather types, between 1952 and 1999 there was a decrease in the frequency of N types and an increase in the weather types of the east (E and SE). A decrease was also recorded in the frequency of the west weather types, statistically significant in the case of the SW type.

In general, there was an increase in the frequency of weather types that indicate atmospheric stability and high pressures on the Iberian Peninsula, such as the A, E and SE weather types, whereas there was a decrease in the frequency of weather types that indicate low pressures, such as the C and SW types.

Figure 5 shows the average of pressure anomalies in relation to average winter surface pressure in the days classified as A (1), C (2), SE (3) and SW (4). The A and SE weather types, whose frequency shows a positive and significant increase between 1952 and 1999, indicate the influence of high relative pressures centred on the Iberian Peninsula, while the C and SW weather types, which have a negative trend, show low relative pressures in this region. The increase in the frequency of weather types characterised by atmospheric stability is related to the increase in the atmospheric surface pressures. This has been identified in the Mediterranean

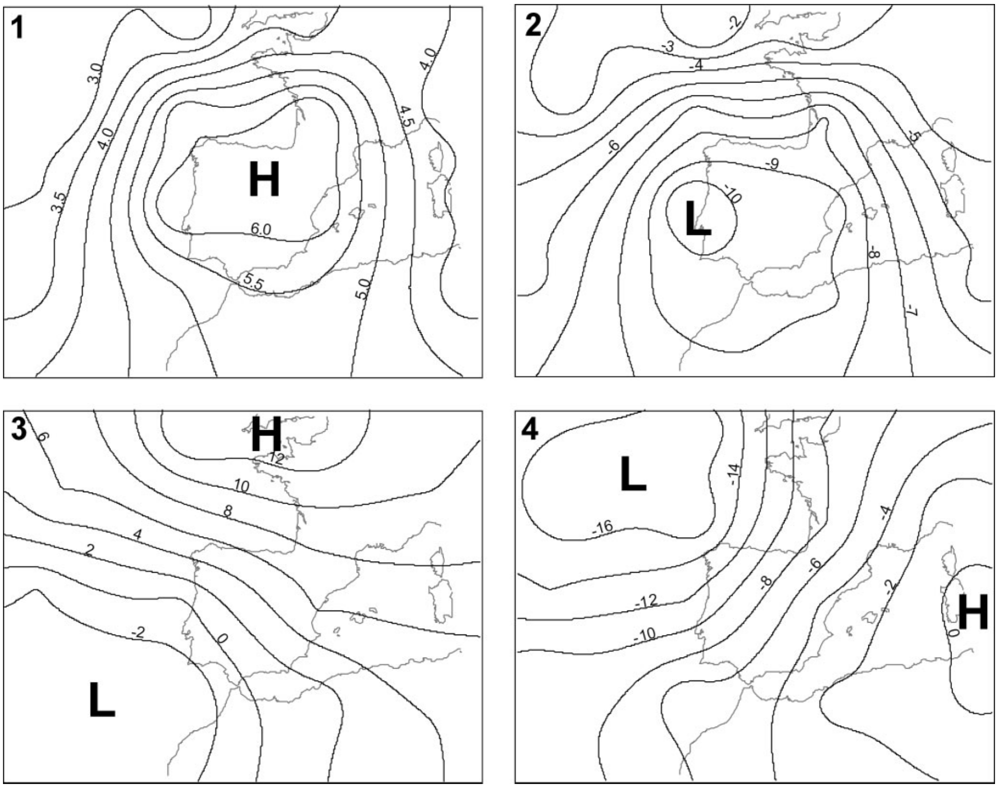

Figure 5. Average of pressure anomalies in relation to average winter surface pressure in the days classified as A (1), C (2), SE (3) and SW (4). L: Low pressures, H: High pressures

region, where there were significant increases of sea-level pressures in the last decades of the twentieth century. Crisciani *et al*. (1994) showed a significant increase in sea-level surface pressure in Italy between the 1970s and 1990s. In the centre of the Iberian Peninsula, Labajo *et al*. (1998) indicated an abrupt change in sea-level pressure in the 1970s, with a significant increase of 0.06 mmHg/year.

The evolution of the winter weather types in the Iberian Peninsula agrees with the evolution of sea-level surface pressure and also with the evolution of the weather types in the Mediterranean region, as indicated by other authors. Trigo and DaCamara (2000) showed a decrease in the frequency of cyclonic weather types in Portugal, the same as Piervitali *et al*. (1997) and Brunetti *et al*. (2000) showed in Italy. Amanatidis *et al*. (1993) indicated a general increase in the northern flows in the eastern Mediterranean region and an increase of the southern flows in the western areas. Corte-Real *et al*. (1998) indicated that the general decrease in precipitation identified in the Iberian Peninsula between 1960 and 1995 (Hisdal *et al*., 2001) coincides with the decrease in the frequency of weather types prove to generate precipitation (C, W and SW) and also with an increase of anticyclonic weather types. Wanner *et al*. (1997) showed that there has been a zonal increase in circulation in Europe in the winter season since 1965, which caused important north–south pressure gradients and an increase of the frequency of A weather types. Flohn *et al*. (1993) ascribed the winter increase of zonal flows to the increase of evaporation processes in the tropical oceans as a consequence of the increase in temperature (Jones and Moberg, 2003), which would cause a meridian transport of latent heat from tropical to Mediterranean latitudes.

3.2. Drought spatial and temporal patterns during the winter season

The PCA summarised the spatial variability of winter SPI in seven components (Table II). We selected the first four components, which accumulate 83.8% of the total variance. Figure 6 shows the spatial distribution

Table II. Results of the Principal component analysis from winter-SPI series

Component	% of the variance	% Accumulated
1	26.9	26.9
2	23.4	50.3
3	20.9	71.2
4	12.6	83.8
5	2.2	86.0
6	1.8	87.8
7	1.7	89.5

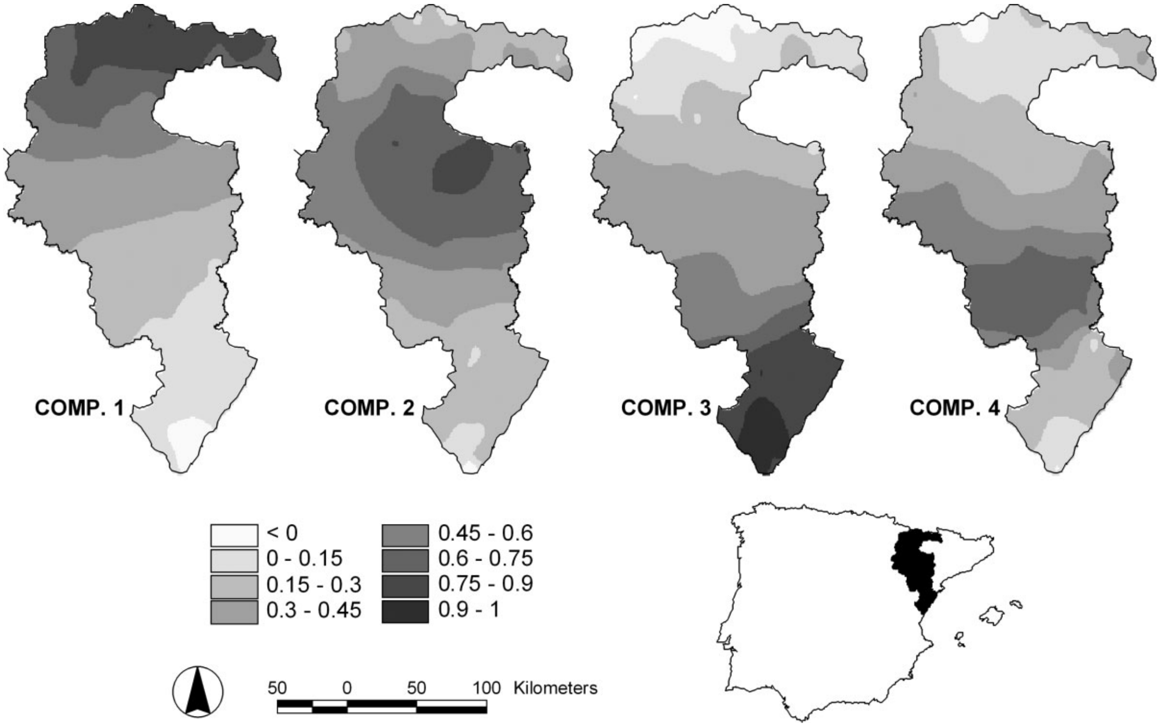

Figure 6. Spatial distribution of loadings from PCA

of the correlation between the winter-SPI series in each observatory and the components. Component 1 (26.9%) indicates the temporal evolution of the winter-SPI series in the north, corresponding to Pyrenean mountain area. The second component (23.4%) shows temporal evolution of winter droughts in the centre of the Ebro Valley. The third component (20.9%) represents the evolution in the Mediterranean coastland and the fourth component (12.6%) represents a transitional region between the centre of the Ebro Valley and the Mediterranean coastland. This pattern is less clear, with loadings no higher than 0.6, which indicates that a percentage of drought variance in this region is also explained by the evolution of components 2 and 3 (loadings >0.4 in the areas represented by component 4), which would confirm the transitional character of this area.

Figure 7 shows the evolution of the four components obtained from analysis. The first component (northern region) shows the most important winter droughts in the decades of 1980s and 1990s and a sharp decrease

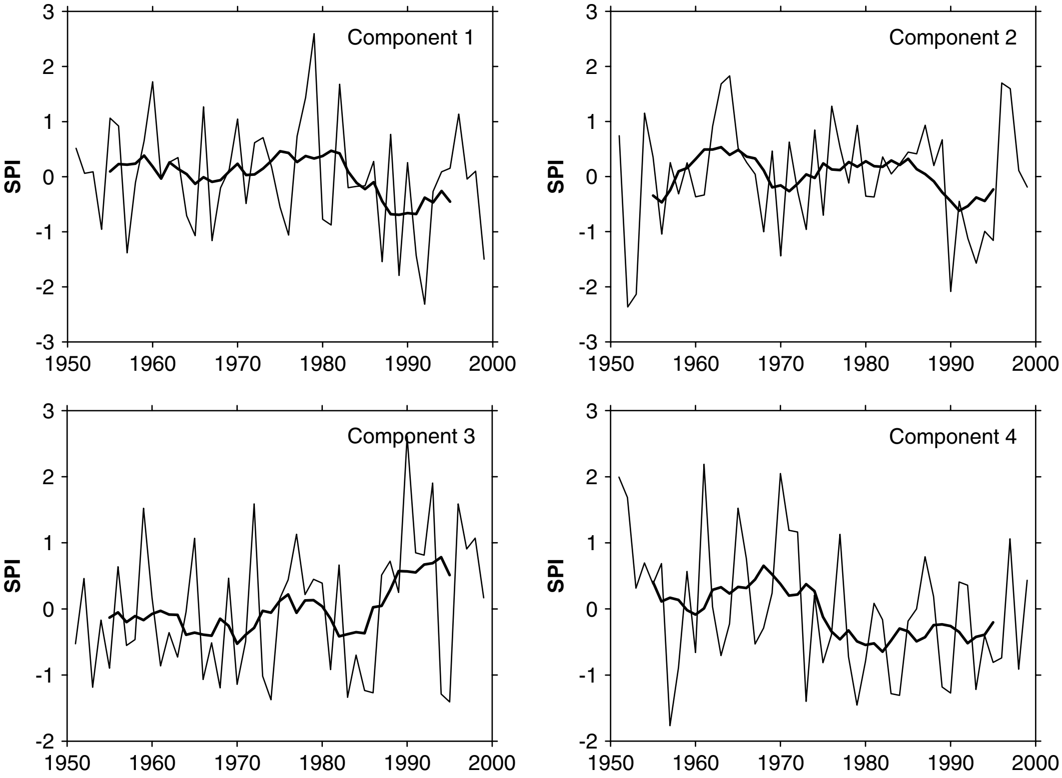

Figure 7. Evolution of four first principal components. Black lines indicate a moving average of 9 years

in winter-SPI values at the beginning of the 1980s. There is a negative and significant trend ($Rho = -0.49$, $\alpha < 0.01$) caused by this abrupt change. Component 2 also shows very dry winters between 1989 and 1995. Moreover, the winters of 1953 and 1954 were also very dry in the centre of the Ebro Valley. This series also shows a negative and significant trend ($Rho = -0.43$, $\alpha < 0.01$). Component 3, representative of the Mediterranean coastland, shows an important interannual variability, but the general trend summarised by the 9-year moving average shows the opposite of the other components, with a trend ($Rho = 0.56$, $\alpha < 0.01$) to positive values in the last decades of the century. In the 1990s, all the years showed positive SPI values, with the exception of 1994 and 1995. Component 4 shows a negative and significant trend ($Rho = -0.66$, $\alpha < 0.01$) caused by a sustained and progressive decrease in the SPI values since the decade of 1950s.

The trend in the different observatories is shown in Figure 8. There is a general predominance of observatories in which negative and significant trends have been recorded. Forty-nine observatories showed a significant negative trend at 99% and seven at 95%. Thirteen observatories had non-significant trends and only eight had a positive trend (three at 95% and five at 99%). Nevertheless, the spatial differences in trends are very clear and agree with the results from the PCA series. Observatories with negative trends are concentrated in the centre of the Ebro Valley and the eastern Pyrenean areas. The positive trends are observed close to the Mediterranean Sea, where some observatories with non-significant trends have also been identified, just as in the northwestern area. Nevertheless, although some spatial differences were identified, the general decrease in the winter-SPI values is the main characteristic in the evolution of drought in the study area between 1952 and 1999.

The spatial patterns of SPI show that the evolution between 1952 and 1999 was different among the Northern Pyrenean areas, the centre of the Ebro Valley and the Mediterranean coastland. The important spatial variability of droughts has been identified in several regions between neighbouring areas (Oladipo, 1986; Karl and Koscielny, 1982; Estrela *et al.*, 2000; Bonaccorso *et al.*, 2003). In the Iberian Peninsula, the

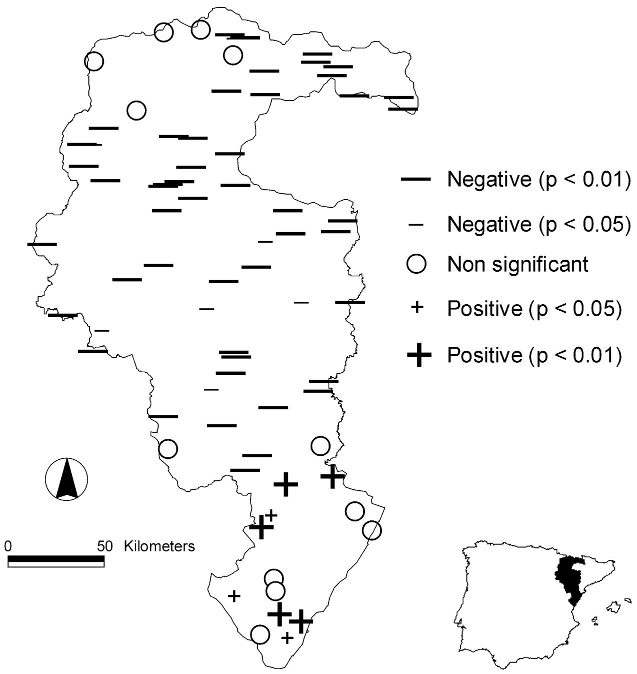

Figure 8. Spatial distribution of trends in winter-SPI values (1951–1999)

differences in temporal evolution of droughts between regions are very important (Vicente-Serrano, 2006). The region analysed here is identified by different authors as a climatic area of transition between the Mediterranean and the Atlantic regions (Fernández-Mills, 1995; Esteban-Parra *et al.*, 1998). The centre of the Ebro Valley coincides with a semi-arid area with important continental characteristics (Cuadrat, 1999). Therefore, the differences in the temporal evolution of droughts are a general characteristic within the study area, with defined patterns and differentiated regions.

Although spatial differences in drought evolution have been recorded, and positive trends have also been recognised in the Mediterranean coastland, the general increase in droughts observed agrees with precipitation trends in other Mediterranean regions. In Spain, the dry period recorded in the 1980s and 1990s has been recorded in Andalusia (Pita, 2001), Catalonia (Rodríguez *et al.*, 1999; Lana *et al.*, 2001) and, in general, in the main part of the Iberian Peninsula (Esteban-Parra *et al.*, 1998). This has also been identified in other Mediterranean regions, such as Italy (Brunetti *et al.*, 2001; Ventura *et al.*, 2002). The 1960s and the 1970s were humid in the main part of the western Mediterranean region (Maheras, 1988), as we observed in the study area.

Some studies in the Mediterranean region have shown a general negative trend in precipitation since the 1960s, which is related to the increase in the succession of dry years. Dry years were concentrated in consecutive years in the last decades of the twentieth century (Hisdal *et al.*, 2001; Szinell *et al.*, 1998). This phenomenon was also identified in the centre of the study area, where the persistence of dry winters was very clear between 1989 and 1995. In the Pyrenees, decrease in winter precipitation led to a marked downtrend of snow accumulation, with several hydrological implications (López-Moreno and García-Ruiz, 2004; López-Moreno, 2005)

3.3. *Influence of weather-type frequency on drought spatial and temporal patterns*

Table III shows the correlation between the SPI series of each component and the series of weather-type frequency. As expected, negative and positive correlations with the frequency of A and C weather types,

Table III. Correlation between the components and the frequency of the different weather types

	A	C	N	NE	E	SE	S	SW	W	NW	C + SW + NW + W	A + SE + NE + E	C + E + SE + S
Comp. 1	−0.47**	0.25	0.18	−0.24	−0.39**	−0.32**	−0.07	0.54**	0.60**	0.32*	0.67**	−0.71**	−0.1
Comp. 2	−0.40**	0.54**	−0.22	−0.09	−0.03	−0.06	0.20	0.24	0.08	0.06	0.44**	−0.41**	0.37**
Comp. 3	−0.27	0.52**	−0.39**	−0.22	0.30*	0.25	0.20	0.14	−0.05	−0.31*	0.24	−0.13	0.59**
Comp. 4	−0.20	0.30*	0.29*	0.12	−0.12	−0.06	0.06	−0.26	−0.09	0.10	0.07	−0.20	0.15

** Significant trend ($\alpha < 0.01$)
* Significant trend ($\alpha < 0.05$)

respectively, were found. Nevertheless, correlations are only significant with components 1 and 2 in the case of A weather types, and with components 2, 3 and 4 for C weather types. The frequency of east weather types shows negative correlations with component 1 (northern region), significant for the E and SE weather-type frequencies. Nevertheless, for component 3 (Mediterranean coastland), the correlation is positive and statistically significant for the east weather types. We aggregated different weather types according to their influence on components. The sum of the frequency of C and west directional weather types (SW + W + NW) shows a high positive correlation ($R = 0.67$) with component 1, and the opposite pattern is identified for the sum of A and east weather types, with a negative and significant correlation ($R = -0.71$). The sum of west and C weather types does not increase the correlation in the centre of the study area (Component 2). Nevertheless, the sum of the southeast types (E + SE + S) to C weather types increases the correlation in the case of component 3 (Mediterranean coastland).

Results are confirmed when correlations between weather-type frequency and winter-SPI series in each observatory are mapped continuously. Figure 9 shows the spatial distribution of correlations between the SPI series and the frequency of C, A and the sum of some directional weather types. Important spatial differences in the influence of the frequency of the different weather types on winter-SPI values were recorded. Negative and significant correlations were identified in most of the study area with the frequency of A weather types. Nevertheless, correlations are more intense in the centre of the study area. The opposite pattern is shown when considering the frequency of C weather types, with higher correlations ($R > 0.7$) in the centre of the Ebro Valley. The sum of A + NE + E + SE shows marked negative correlations with SPI in the north of the study area and non-significant correlations in the Mediterranean coastland. The sum of C + SW + W + NW weather types indicates positive correlations in the whole of the study area, but higher values are recorded in the northeast ($R > 0.7$). Finally, the sum of C + E + SE + S weather-type frequency also shows important spatial differences in correlation with the winter-SPI values. Correlation is higher near the Mediterranean Sea, and there is a gradient toward the north of the study area, where non-significant correlations are found.

Figure 10 shows the spatial distribution of correlations between the winter-SPI values and the frequency of the eight directional weather types. Correlations are lower than those for C, A, and the sum of these two directional weather types. Only significant correlations were identified with the SW, W and NW in the north of the study area, with values higher than 0.5.

In general, spatial patterns of droughts agree with spatial differences in the influence of different weather types in the SPI series. The spatial structure of component 1 (High correlations in the north and low correlations

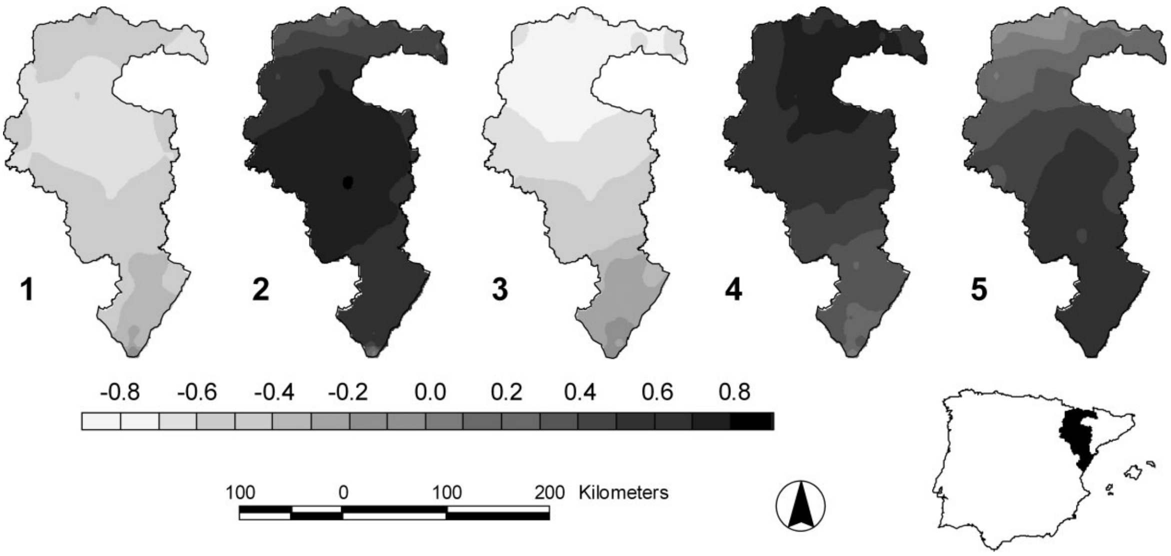

Figure 9. Correlation between the winter SPI and the series of weather-type frequency: 1, A; 2, C; 3, A + E + SE + NE; 4, C + W + SW + NW; 5, C + E + SE + S. Significant correlations correspond to R values higher than 0.29 or lower than -0.29 ($\alpha < 0.05$)

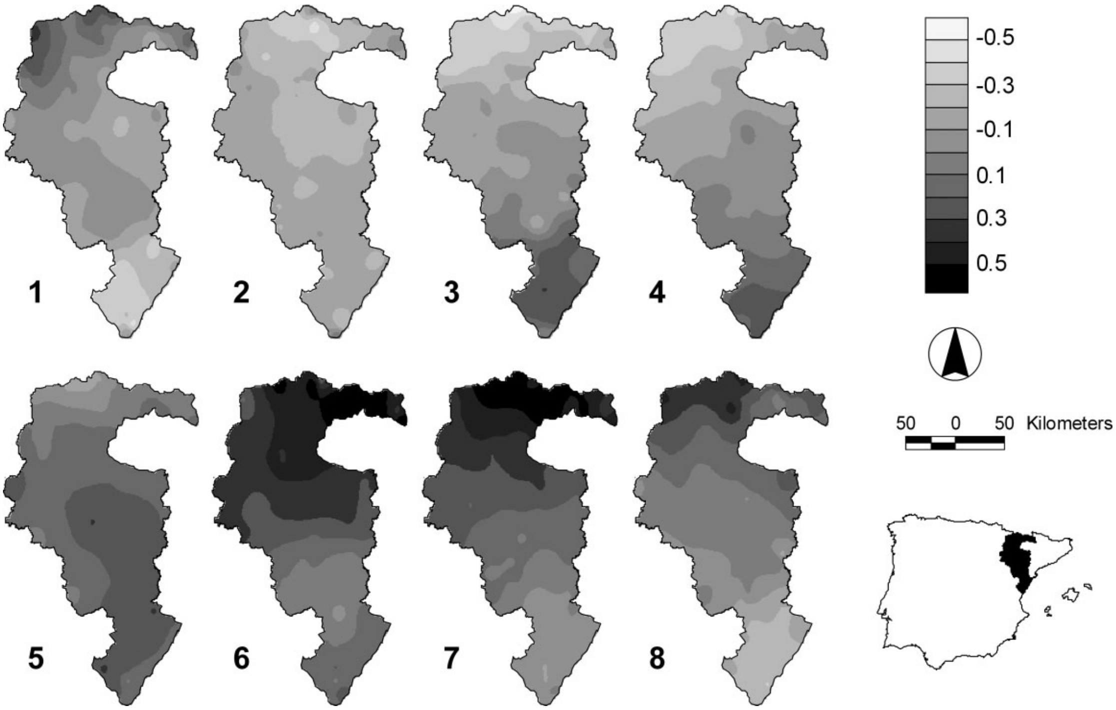

Figure 10. Correlation between the winter SPI and the series of weather-type frequency: 1, N; 2, NE; 3, E; 4, SE; 5, S; 6, SW; 7, W; 8, NW. Significant correlations correspond to R values higher than 0.29 or lower than -0.29 ($\alpha < 0.05$)

in south) agrees with spatial differences in the influence of the western weather types (NW, W and SW) and also with the sum of the frequency of these weather types and the frequency of the cyclonic weather types. The same was observed with component 2, representative of the centre of the Ebro Valley, with a spatial structure similar to spatial patterns of correlation between the frequency of the C weather type and the winter SPI. The spatial configuration of component 3 (high correlations in the Mediterranean coastland) agrees with the spatial differences of correlations between the SPI and the sum of C + E + SE + S weather types. This implies that the spatial differences in the temporal evolution of the winter SPI are related to the evolution of different weather types and their different spatial influence on winter drought conditions.

Olcina (2001) has indicated that the synoptic conditions that usually cause droughts in the Iberian Peninsula correspond to the persistency of different anticyclonic configurations. Martín-Vide (2002) also indicates that the high frequency of flows of the NW or SW causes atmospheric instability and higher precipitations in the Iberian Peninsula. Nevertheless, the complex relief that characterises the Iberian Peninsula and the maritime influence can modulate these influences spatially. In the Mediterranean coastland, different authors have shown that flows from east, and cyclonic weather types have an important role in precipitation (Romero *et al*., 1999; Goodess and Jones, 2002). Moreover, the flows from east can be reactivated because of hot conditions in the sea-surface temperature, which is frequent in autumn and early winter (Martín-Vide and Llasat, 2000; Serra *et al*., 1996; Millán *et al*., 1995). In the centre of the study area, the Ebro Valley, atmospheric influence on precipitation is greatly determined by relief (Creus and Ferraz, 1995). Because of this when the moist W and NW flows come into the valley they are progressively dryer (Creus, 1983). Hence, the W component flows only show significant correlations in the north, near the Atlantic Ocean and in areas with higher elevations. In the centre of the valley, only well-defined cyclonic configurations cause important precipitation.

We also identified significant trends in the frequency of the different weather types in the study area. Moreover, a general negative trend was identified in the winter-SPI values within the study area. The negative trends of C, SW and W, which are prone to cause precipitation in the main part of the study area, and the positive trend of A and east directional weather types, which are negatively correlated with the winter-SPI values, could be the cause of the general negative trend of the winter-SPI values. In the whole of the Iberian Peninsula, Goodess and Jones (2002) indicated that the decrease in precipitation is mainly explained by the positive trend towards the occurrence of less-intensive rain days. They indicated that this could be associated with the decrease in the influence of the Atlantic westerly and southwesterly air-masses. Likewise, Esteban-Parra *et al*. (1998) indicated that the dry periods of the 1950s and 1990s, which have been identified in large areas of the Iberian Peninsula, were related to an intensification of the Azores anticyclone and a displacement to the east.

Relationships between precipitation trends and the trends in the frequency of different weather types have been indicated in other Mediterranean regions. Corte-Real *et al*. (1998) and Trigo and DaCamara (2000) indicated that the decrease in the frequency of C, SW and SW weather types was the main cause of the decrease in precipitation observed in Portugal during the second half of the twentieth century. Maheras (1988) indicated that droughts between 1980 and 1985, identified in large areas of the western Mediterranean region, were related to a minimum of W and SW circulation modes. Brunetti *et al*. (2000) also identified a negative decrease of precipitation in Italy, which they related to the increase of sea-surface pressure and the higher frequency of anticyclones. Maheras *et al*. (2000) indicated a connection in the eastern Mediterranean area between the decrease in precipitation and the negative trends in the frequency of cyclonic weather types during the second half of the twentieth century.

Nevertheless, although the general winter-SPI explanation, by means of the evolution in weather-type frequency, agrees with the general results in the Mediterranean region, important spatial differences in winter drought trends have been identified in the study area, in addition to the influence of the different weather types on SPI. Therefore, we also analysed the different roles in the influence of weather types to explain spatial differences in winter-SPI trends.

Table IV shows the mean correlations between the frequency of the different weather types and the winter-SPI values in all the observatories located in the study area, grouped according to trends in winter-SPI observed between 1952 and 1999. Non-significant differences in R values between groups were found for C, NE and S weather types. The results indicate that negative trends in SPI coincide with negative correlations between the SPI and the frequency of A weather types and with positive correlations between the SPI and the sum of C + SW + W + NW weather types. Moreover, higher correlations were also identified more with the frequency of SW and W flows than in areas with non-significant or positive trends in winter-SPI values. The opposite behaviour is observed with the sum of C + E + SE + S weather types, because the highest correlations with the SPI series are recorded in the observatories with positive trends.

Figure 11 shows the distribution of R correlations between the frequency of some weather types and the winter SPI for the different groups of observatories according to SPI trends. Spatial differences in winter-SPI trends are highly related to the increase or decrease in influence of the different weather types.

The results indicate that areas which have experienced a negative trend of winter-SPI values show the highest negative correlations with the frequency of the weather types that experienced a positive trend between 1952 and 1999, such as the A, E and SE weather types. On the other hand, areas with positive trends show lower negative correlations with the frequency of these weather types, and even positive correlations are found. Areas with negative trends also show the highest positive correlations between the SPI and the sum of C + SW + W + NW weather types whose winter frequency has had a negative trend during the second half of the twentieth century.

3.4. General atmospheric circulation – weather-type frequency relationships during the winter season in the Iberian Peninsula

In order to assess the general connection between the winter weather-type frequency variability in the Iberian Peninsula and the general patterns of atmospheric circulation in the North Atlantic area, Table V shows correlations between the winter teleconnection indices of the North Atlantic region and the frequency of the different weather types in the Iberian Peninsula in winter. Different positive and negative correlations were found, but, in general, higher correlations are identified with the NAO index than with the other teleconnection indices. The frequency of A and C weather types is highly determined by the winter NAO

Table IV. Mean values of correlation between the weather-type frequency and the winter SPI in each observatory as a function of trends in winter-SPI values. The last row indicates if there are significant differences between groups

Groups	A	C	N	NE	E	SE	S	SW	W	NW	A + NE + E + SE	C + SW + W + NW	C + E + SE + S
1	−0.59	0.64	−0.03	−0.18	−0.19	−0.16	0.15	0.36	0.31	0.14	−0.67	0.66	0.33
2	−0.57	0.66	−0.04	−0.23	−0.16	−0.13	0.15	0.33	0.26	0.12	−0.66	0.64	0.37
3	−0.43	0.53	−0.06	−0.24	−0.05	−0.05	0.10	0.24	0.20	0.04	−0.48	0.48	0.34
4	−0.41	0.66	−0.37	−0.19	0.22	0.22	0.25	0.16	−0.03	−0.23	−0.27	0.36	0.66
5	−0.34	0.60	−0.32	−0.20	0.23	0.17	0.21	0.10	−0.02	−0.23	−0.22	0.30	0.60
p-value	0.00	0.07	0.00	0.40	0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.01

1: Negative and significant trend ($\alpha < 0.01$).

2: Negative and significant trend ($\alpha < 0.05$).

3: Non-significant trend.

4: Positive and significant trend ($\alpha < 0.05$).

5: Positive and significant trend ($\alpha < 0.01$).

index (Figure 12), but significant and negative correlations between the western weather types (SW and W) and the NAO index were also found.

The EA index shows significant negative correlations with the frequency of the east weather types (E and SE), whereas the EA/WR pattern indicates a positive correlation with the frequency of weather types from the east and a negative correlation with the west types. On the contrary, the SCA Pattern shows a positive and significant correlation with the frequency of the SW, W and NW weather types.

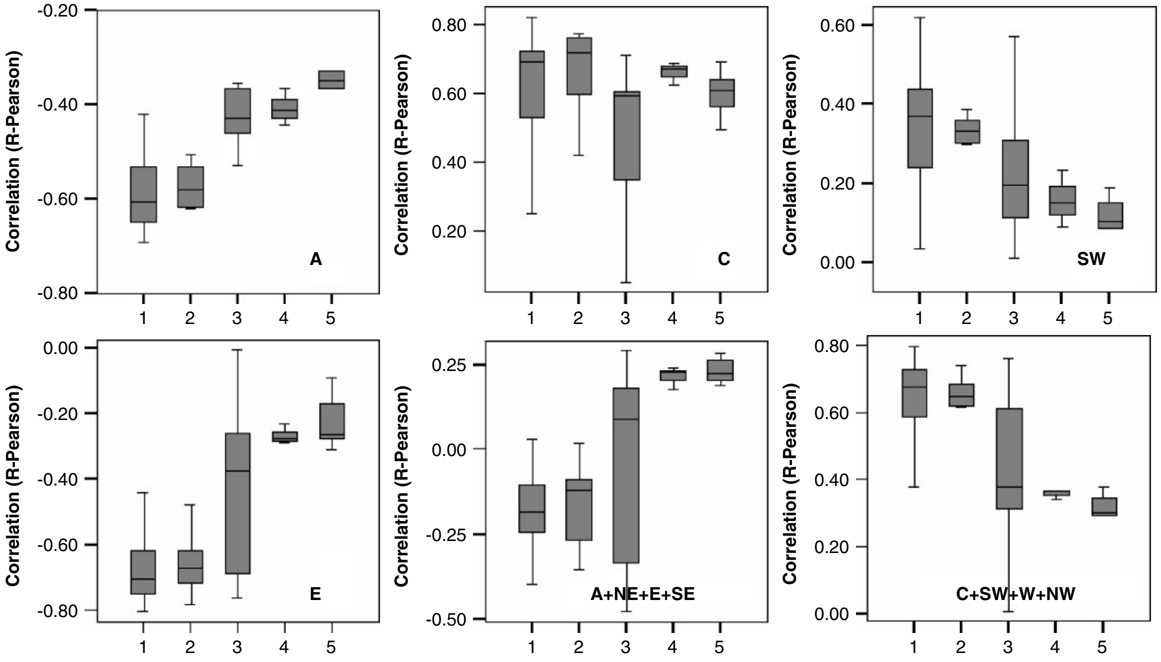

Figure 11. Box-plot of correlation values between weather-type frequency and winter SPI as a function of observatories with negative, positive and non-significant trends in winter SPI values. 1, Negative and significant trend ($\alpha < 0.01$); 2, Negative and significant trend ($\alpha < 0.05$); 3, Non-significant trend; 4, Positive and significant trend ($\alpha < 0.05$); 5, Positive and significant trend ($\alpha < 0.01$)

Table V. Correlation between the winter teleconnection indices and the frequency of the different weather types

	NAO	EA	EAWR	SCA
A	0.84[a]	0.38[a]	0.22	−0.41[a]
C	−0.76[a]	−0.25	−0.15	0.34[b]
N	−0.05	−0.25	−0.07	−0.11
NE	0.16	−0.24	−0.04	−0.18
E	0.06	−0.43[a]	0.36[a]	−0.28
SE	−0.05	−0.32[b]	0.47[a]	−0.01
S	−0.15	−0.06	0.20	0.12
SW	−0.40[a]	0.23	−0.29[b]	0.29[b]
W	−0.39[a]	0.25	−0.48[a]	0.34[b]
NW	−0.05	0.12	−0.34[b]	0.29[b]
A + NE + E + SE	0.77[a]	0.03	0.44[a]	−0.48[a]
C + SW + W + NW	−0.74[a]	0.07	−0.47[a]	0.51[a]
C + E + SE + S	−0.54[a]	−0.46[a]	0.27	0.16

[a] Significant correlation ($\alpha < 0.01$).
[b] Significant correlation ($\alpha < 0.05$).

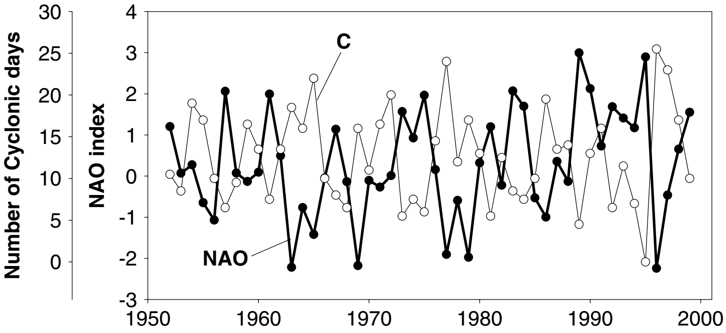

Figure 12. Evolution of the winter NAO index and the frequency of winter cyclonic (C) days (1952–1999)

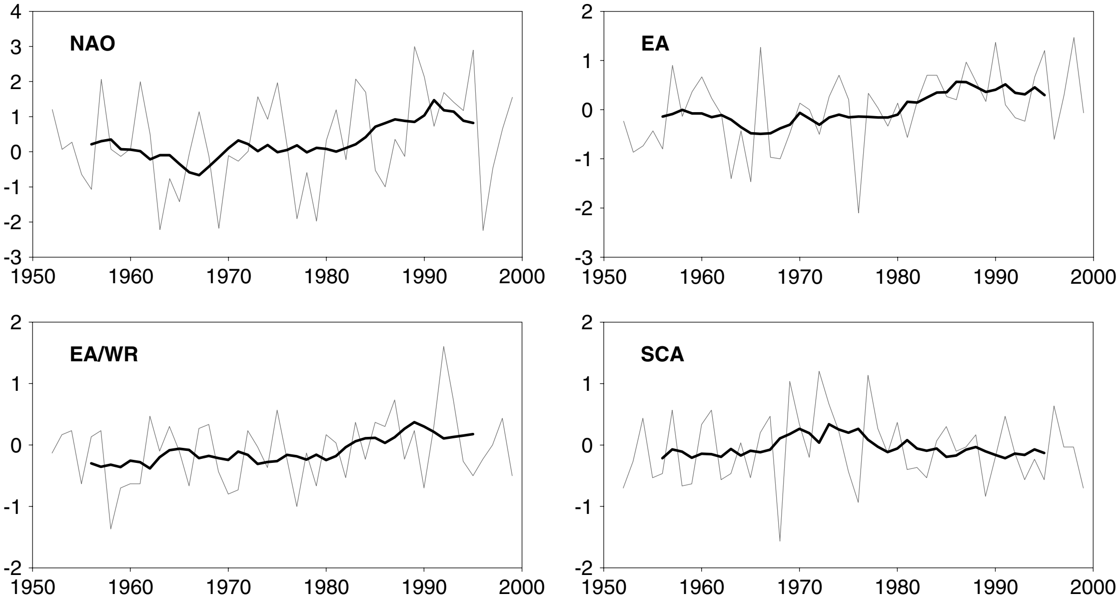

Figure 13. Evolution of the different teleconnection indices. Black line indicates the 9-year moving average. 1952–1999

The evolution of the four atmospheric circulation patterns is shown in Figure 13. The NAO index shows a positive and significant trend ($Rho = 0.67$, $\alpha < 0.01$), the same as the EA ($Rho = 0.67$, $\alpha < 0.01$), and the EA/WR pattern ($Rho = 0.82$, $\alpha < 0.01$). The SCA pattern does not show a significant trend.

Thus, the variability of the general atmospheric circulation modes in the Northern Hemisphere greatly determines the temporal variability of the different weather types, mainly the NAO. Moreover, the trends observed in the frequencies of different weather types agree with the trends observed in the Atmospheric circulation patterns. Positive trends of Anticyclonic weather types and negative trends in cyclonic types are related to the increase in the NAO index during the second half of the twentieth century. The decrease in the frequency of the SW and W weather types is also related to the NAO evolution.

The NAO shows persistent positive and negative phases of several years duration (Hurrell, 1995). A clear dominance of positive values has occurred since the 1980s. Winters with positive NAO values show an increase of zonal flows (Hurrell, 1995) and dry conditions are usually recorded in the Iberian Peninsula (Hurrell and Van Loon, 1997; Trigo *et al*., 2004), which is associated with an increase in the frequency of anticyclonic days. In the Iberian Peninsula, Corte-Real *et al*. (1998) indicated that the reduction of weather types prone to precipitation since 1960 was greatly related to changes in the NAO intensity.

Nevertheless, although NAO has the highest importance in explaining the temporal patterns in the frequency of the weather types, the increase of the east types and decrease of the west types were also related to the positive trend of the EA/WR pattern, whose positive phase shows high pressures on the British Isles and low pressures west of the Iberian Peninsula, generating dominant flows from the east.

3.5. Influence of the general atmospheric circulation patterns on winter droughts

Finally, we analysed the role of the general atmospheric circulation patterns on the spatial and temporal variability of winter droughts in the study area. Table VI shows the correlation between the teleconnection indices and the four drought components obtained from PCA. Significant correlations were found only between the series of components 1 (north) and 2 (centre of the Ebro Valley) and the NAO and between the series of component 1 and the EA/WR pattern. Component 3 does not show significant correlations with any atmospheric circulation pattern.

The spatial distribution of correlations is shown in Figure 14. There are general negative correlations between the NAO index and the SPI values in the whole of the study area, although correlations are higher in the centre of the Ebro Valley ($r < -0.6$), whereas correlations are not significant in the south. The correlations

Table VI. Correlation between the series of each component and the time series of the winter atmospheric circulation patterns

Components	NAO	EA	EA/WR	SCA
Component 1	−0.47[a]	0.14	−0.54[a]	0.17
Component 2	−0.47[a]	−0.18	−0.04	0.16
Component 3	−0.17	−0.03	0.07	0.12
Component 4	−0.26	−0.18	−0.16	0.15

[a] Significant correlation ($\alpha < 0.01$).

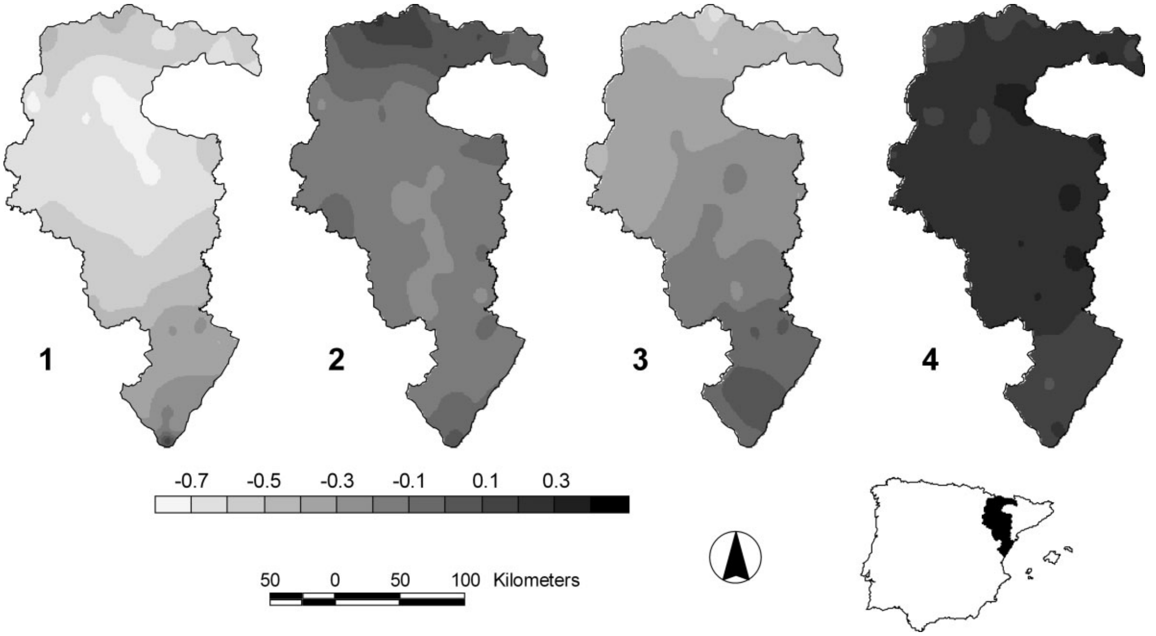

Figure 14. Spatial distribution of correlation between winter SPI and the general winter atmospheric circulation patterns. 1, NAO; 2, EA; 3, EA/WR; 4, SCA. Significant correlations correspond to R values higher than 0.29 or lower than −0.29 ($\alpha < 0.05$)

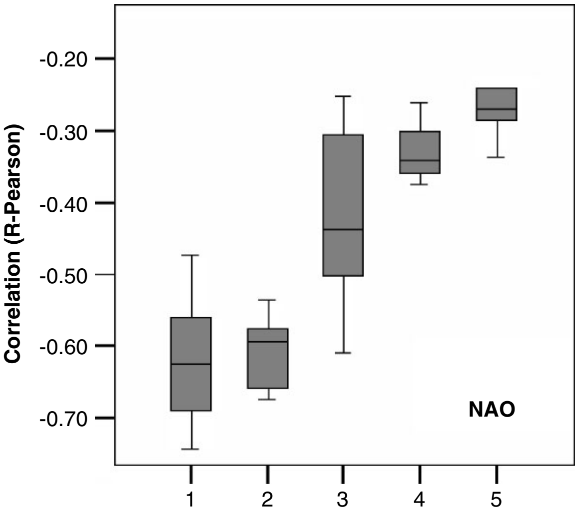

Figure 15. Box-plot of correlation values between the NAO and the winter SPI as a function of observatories with negative, positive and non-significant trends in winter-SPI values. 1, Negative and significant trend ($\alpha < 0.01$); 2, Negative and significant trend ($\alpha < 0.05$); 3, Non-significant trend; 4, Positive and significant trend ($\alpha < 0.05$); 5, Positive and significant trend ($\alpha < 0.01$)

with the EA and SCA patterns are lower, and negative and significant correlations were also obtained only in the north of the study area between the winter SPI and the EA/WR pattern.

The correlations between the teleconnection indices and the winter-SPI series are lower than the correlations obtained between SPI and the frequency of the different weather types. Moreover, only in the centre and north of the study area is the role of the general atmospheric circulation patterns on winter droughts well identified.

Differences in the correlations between the atmospheric circulation patterns and the SPI as a function of trends in SPI values were also identified for the NAO. Figure 15 shows the distribution of the R values between the winter NAO and the SPI in each observatory as a function of trends in the winter SPI. The areas with negative and significant trends show the highest average correlations between the SPI and the NAO (average $R = -0.62$), whereas the areas with positive trends do not show significant correlations with the NAO index (average $R = -0.26$).

4. CONCLUSIONS

This paper has analysed the influence of the atmospheric circulation at different spatial scales on spatial and temporal patterns of winter droughts in a semi-arid north–south gradient in Northeast Spain. We obtained a daily weather-type classification for the whole of the Iberian Peninsula during the winter season, finding a general positive trend in the frequency of the weather types prone to dry conditions (A, SE and E) and a general negative trend of cyclonic and west weather types (SW, W and NW).

We analysed the winter droughts in the study area by means of the SPI, considering a high density of observatories (75). Winter droughts show an important spatial variability, and the temporal evolution of droughts within the study area was very different between regions, differentiating three well-defined patterns corresponding to the north, the centre of the Ebro Valley, and the Mediterranean coastland. The evolution indicates a general negative trend in the SPI values, indicative of drier conditions between 1952 and 1999, and this also agrees with the evolution in the Iberian Peninsula and in other Mediterranean regions as a consequence of the persistence of dry winters during the decades of 1980 and 1990 (Hisdal *et al*., 2001; Szinell *et al*., 1998; Brunetti *et al*., 2001; Esteban-Parra *et al*., 1998). Nevertheless, the study area also recorded important spatial differences: negative trends were identified in the north and centre of the study area, whereas trends were positive in the Mediterranean coastland.

These results indicate that although some studies on droughts have been performed on a continental scale (Briffa *et al*., 1994; Lloyd-Hughes and Saunders, 2002b), in areas under Mediterranean climate conditions, model outputs are not the best approach for sub-regional management of droughts, which are highly variable in space. The spatial differences in the weather-type influence on droughts have been identified through the use of a dense net of observatories, which confirms the need for using dense databases for climatological studies in areas of high spatial precipitation variability (Houghton *et al*., 2001).

In general, very clear spatial gradients in the influence of the different weather types was shown between the north and south regions or between the centre of the Ebro Valley, the Pyrenean range, and the Mediterranean coastland. The weather-type frequency that most affects winter drought conditions differs greatly between areas.

Significant negative and positive correlation between the respective frequency of anticyclonic and cyclonic weather types and the winter-SPI series were found in the whole of the study area. Nevertheless, correlations are higher in the centre of the Ebro Valley than in the north or the Mediterranean coastland. In the Pyrenean mountains, correlations are higher considering the sum of the frequency of cyclonic and directional weather types of the west, W + SW + NW, whereas in the south the correlations are higher considering the cyclonic and the east weather types, E + SE + S. When the directional weather types are considered independently, only the west weather types (W + SW + NW) show significant correlations with the winter SPI in the northern region.

Although air temperature and atmospheric humidity, which can be determinants to better explain the role of weather types on precipitation (Goodess and Jones, 2002; Maheras *et al*., 2004), were not considered in this research, an important percentage of the interannual variability of winter SPI and its spatial differences in the study area are well explained by means of the frequency of only a few weather types.

The general negative trends in winter-SPI values agree with the decrease in the frequency of weather types prone to cause precipitation, such as the C, SW and W weather types, and the increase in the frequency of A weather types. This was observed in the areas where precipitation is most affected by the C, SW and W weather types, where an increase in droughts was the general pattern between 1952 and 1999. Nevertheless, in the Mediterranean coastland the positive trend in SPI values agrees with the increase in the frequency of weather types of the east (E, SE), which are prone to cause precipitation in this area.

The interannual variations in the frequency of the different weather types were greatly determined by different general atmospheric circulation patterns, mainly the NAO. Moreover, the NAO significantly affects the SPI spatial and temporal variability in the study area. This suggests that the use of weather-type classifications and time series of weather-type frequency to explain the winter drought variability could be substituted by a few atmospheric indices that summarise the general atmospheric circulation in Northern Europe. Nevertheless, in this paper we have shown that although the NAO strongly determines the frequency of different weather types, correlations between weather-type frequency series and the winter SPI is higher than correlations found between SPI and NAO. Moreover, spatial differences and gradients found in the influence of weather types on droughts coincide with the general spatial patterns of SPI series. This suggests that differences in the winter-SPI evolution were greatly determined by spatial differences in the weather-type influence. We must also take into account that in some areas, such as the Mediterranean coastland, the interannual variability of winter droughts are not well explained by the general atmospheric circulation patterns, while the frequency of some weather types strongly affects the drought conditions.

Thus, although the interannual variability of the NAO explains an important percentage of the interannual differences in weather-type frequency, this general atmospheric circulation index is insufficient to explain the spatial and temporal variability of droughts in the study area, since these droughts respond better to the atmospheric variability at more detailed (synoptic) spatial scales.

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