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Precipitation concentration changes in Spain 1946–2005

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Abstract. An analysis was made of the Precipitation Concentration Index using the new MOPREDAS database of monthly precipitation in Spain (Monthly Precipitation Data base of Spain). The database was compiled after exhaustive quality control of the complete digitalized Spanish Meterological Agency (AEMet) archives and contains a total set of 2670 complete and homogeneous monthly precipitation series from 1946 to 2005. Thus, MOPREDAS currently holds the densest information available for the 1946–2005 period for Spain and ensures a high resolution of results. The Precipitation Concentration Index (PCI) is a powerful indicator of the temporal distribution of precipitation, traditionally applied at annual scales; as the value increases, the more concentrated the precipitation. Furthermore PCI is a part of the well-known Fournier index, with a long tradition on natural system analyses, as for example soil erosion. In this paper, the mean values of annual, seasonal and wet and dry periods of PCI in the conterminous Spain and for two normal periods (1946–1975 and 1976–2005) were studied.

Precipitation in Spain follows a general NW-SE spatial pattern during the wet (months) period due to the Atlantic storm track, while during the dry (months) period, it follows a predominantly N-S spatial pattern. As a result, the annual values of PCI combine the two patterns and show a SW-NE PCI gradient.

The analyses of the two sub-periods show significant changes in the precipitation occurred in conterminous Spain from 1946 to 2005, and precipitation concentration increased across most of the IP. At an annual scale, PCI increases mostly due to an increase in precipitation concentration during the wet season. At a seasonal scale significant changes were detected between 1945–1975 and 1976–2005, particularly in autumn (increase of PCI values), while changes in winter, spring and summer were mostly localized and not generalized (both increase and decrease). Changes in PCI seem to be complex and appear to be related to global atmospheric features and synoptic and local factors affecting precipitation trends. We discuss the possible explanation linked to the atmospheric pattern and monthly trends and their implications.

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1 Introduction

Precipitation is one of the most important climate elements directly affecting the availability of water resources (Randall et al., 2007). Recently, it has been suggested that one of the most noticeable consequences of global atmospheric warming is water cycle modification (Allen and Ingram, 2002; Huntington, 2006), with precipitation being a key point in the process (Mariotti et al., 2002; Mauguet, 2006).

The recent IPCC-2007 report (Solomon et al., 2007) confirmed an increase in precipitation for the period 1900–2005 north of 30° latitude, due to global warming (Trenberth et al., 2007). It also confirmed a decrease in the precipitation from 1970 in tropical areas and an increase in land affected by drought in tropical and subtropical areas from the 1970s (Trenberth et al., 2007). Precipitation in the northern subtropics (20–40° N), including the Mediterranean area, did not display a clear or significant trend throughout the 20th century (New et al., 2001). The global hydrological cycle in the region of the Mediterranean basin is dominated by very high spatial and temporal variability (Lionello et al., 2006; Norrant and Douguedroit, 2006) and model predictions for the end of the 21st century show a high degree of uncertainty (Christensen et al., 2007).

The IPCC-2007 suggests that the sub-regional variability in precipitation should be analysed in depth. This requires detailed spatial datasets going as far back as possible in time (Huntington, 2006).

Recently, great importance has been placed on precipitation in Spain, not only from the point-of-view of climate, but also as a natural resource due to scarcity and high spatial and temporal variability (de Castro et al., 2005). However, until now, there have been no detailed, high resolution analyses covering the whole country (de Castro et al., 2005). The new Spanish database, MOPREDAS (Monthly Precipitation Database of Spain) constitutes a very suitable tool for this purpose, because of its temporal record and its spatial density (González-Hidalgo et al., 2011).

Recent studies using MOPREDAS databases identify large spatial and temporal variability in the behaviour of precipitation across Spain. Thus, the precipitation trends vary from coherent spatial trend patterns in particular months or seasons, to highly regionalized trend patterns in others (González-Hidalgo et al., 2011; De Luis et al., 2010a) and these changes may have a strong influence, modifying fluvial regimes, groundwater recharge and water availability (Aguado et al., 1992; Paredes et al., 2006; Lopez-Moreno et al., 2009), which might also affect hydroelectric production (Paredes et al., 2006) and erosion (Michiels et al., 1992), etc. Precipitation totals on annual, seasonal or monthly scales are key elements affecting water availability, but precipitation concentration in time also plays a decisive role.

In this respect, there are some straightforward indicators to evaluate the precipitation concentration that can be used to provide information on its variability and to analyse and understand hydrological processes (Apaydin et al., 2006). Different indices have been used for this purpose and among these the Precipitation Concentration Index (PCI) (Oliver, 1980) is recommended, as it provides information on long-term total variability in the amount of rainfall received (Michiels et al., 1992; Apaydin et al., 2006; De Luis et al., 2010b).

This paper analyses the variability in space and time of the PCI by using the dense precipitation database MOPREDAS, recently developed for the Spanish conterminous land. The PCI is calculated for annual and seasonal scales, as well as for the wet and dry seasons over a 60-year period (1946–2005), and, therefore, enables the comparison between two independent 30-year sub-periods (1946–1975 and 1976–2005).

2 Data and methods

We used the monthly precipitation database (MOPREDAS) recently presented by González-Hidalgo et al. (2011). This database was set up following an exhaustive quality control process designed to detect suspicious data and inhomogeneous series. MOPREDAS contains a total of 2.670 completed homogenous series from the total original observatories (6.821) and extends from December 1945 to November 2005 (60 years).

To facilitate spatial analysis of precipitation, stations were interpolated onto a regular grid. The grid resolution chosen was equal to the mean distance between the 2.670 selected stations (10 km, i.e., 1/10 degree longitude and latitude). The final gridded dataset consists of 5.334 cells covering the whole of Spain. Previous analyses have confirmed the internal consistency and coherence of the database. Details on the database and grid construction can be found in González-Hidalgo et al. (2011).

The Precipitation Concentration Index (PCI, Oliver, 1980), proposed as an indicator of rainfall concentration and rainfall erosivity (Michiels et al., 1992), was calculated on an annual scale for each grid point according to Eq. (1):

$$\mathrm{PCI}_{\mathrm{annual}} = \frac{\sum_{i=1}^{12} p_i^2}{(\sum_{i=1}^{12} p_i)^2} \cdot 100 \qquad (1)$$

where p_i is the monthly precipitation in month i.

The precipitation concentration index was also calculated on a seasonal scale for winter (D-J-F), spring (M-A-My) summer (Jn-Jl-A), autumn (S-O-N), and on supra-seasonal scales for wet (October to March) and dry (April to September) seasons according to Eqs. (2) and (3):

$$\mathrm{PCI}_{\mathrm{seasonal}} = \frac{\sum_{\mathrm{i=1}}^{3} p_i^2}{(\sum_{i=1}^{3} p_i)^2} \cdot 25; \qquad (2)$$

$$\mathrm{PCI}_{\mathrm{sup}\,ra\,\mathrm{seasonal}} = \frac{\sum_{\mathrm{i=1}}^{6} p_i^2}{(\sum_{i=1}^{6} p_i)^2} \cdot 50 \qquad (3)$$

According to the proposed formulae, on the annual, seasonal and supra-seasonal scale, the lowest theoretical value of PCI is 8.3, indicating the perfect uniformity in precipitation distribution (i.e., that same amount of precipitation occurs in each month). Also, on all scales, a PCI value of 16.7 will indicate that the total precipitation was concentrated in 1/2 of the period and a PCI value of 25 will indicate that the total precipitation occurred in 1/3 of the period (i.e., total annual precipitation occurred in 4 months; total supra-seasonal precipitation occurred in 2 months and total seasonal precipitation occurred in 1 month).

According to this classification, Oliver (1980) suggested that PCI values of less than 10 represent a uniform precipitation distribution (i.e., low precipitation concentration); PCI values from 11 to 15 denote a moderate precipitation concentration; values from 16 to 20 denote irregular distribution and values above 20 represent a strong irregularity (i.e., high precipitation concentration) of precipitation distribution.

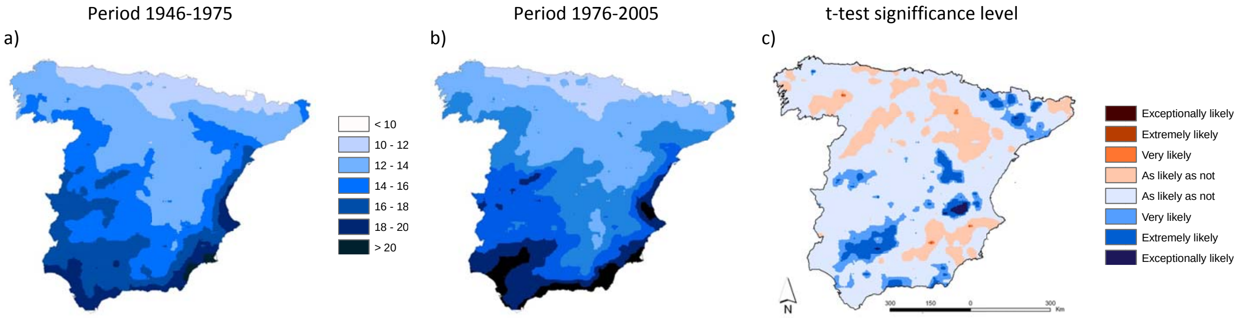

Fig. 1. Mean value of the Precipitation Concentration Index (annual scale) during the periods: **(a)** 1945–1975 and **(b)** 1976–2005. **(c)** Changes between periods according to different levels of probability categorized as follow: exceptionally likely ($p < 0.01$); extremely likely ($p < 0.05$); very likely ($p < 0.10$); as likely as not ($p > 0.10$). Blue positive, red negative changes.

In order to explore changes of PCI in time, the PCI index was calculated for two 30-year independent sub-periods (1946–1975 and 1976–2005). Statistical significance of the differences between the 30-year periods at each grid point was assessed using a t-test with different levels of probability categorized as follows: exceptionally likely ($p <0.01$); extremely likely ($p <0.05$); very likely ($p <0.10$); very low probability ($p >0.10$).

3 Results

3.1 Annual precipitation concentration index

The precipitation concentration index (PCI) calculated on an annual scale varies across the area under study from values lower than 10 in the central Pyrenees to higher than 20 in southeast (Fig. 1). In general, lower values are detected in the northern Iberian Peninsula, while higher values are found in the south and along the Mediterranean coast. Spatial patterns are similar in the two 30-year periods analysed (Fig. 1a, b). However, we detected a general increase in PCI values in the most recent period. Thus, significant increases in precipitation concentration values are found mainly in the central Pyrenees and Ebro basin to the north-east, the Iberian range to the east inland and to the south-west (Fig. 1c).

4 Seasonal precipitation concentration index

The precipitation concentration index calculated on a seasonal scale shows complex spatial patterns of precipitation across Iberian Peninsula (IP). During winter, higher PCI values are detected in the eastern IP along the Mediterranean coast, while lower values are detected in northern areas (Fig. 2a, b). Spring (Fig. 2d, e) is the season where precipitation is generally more regularly distributed within months (lower PCI values), while summer (Fig. 2g, h) is the season where higher PCI values are observed (especially in the SW). Autumn (Fig. 2j, k) shows a spatial pattern similar to summer, but with lower PCI values.

Significant changes in the PCI index between 1945–1975 and 1976–2005 occur in winter in the extreme NW of the IP where precipitation concentration significantly decreases (Fig. 2c). During spring, precipitation concentration rises in most of the IP, but areas where there are significant increases are spread throughout the territory (Fig. 2f). During summer, a general decrease in the PCI is displayed mainly in the western and southern areas, while significant increases are found in the north-east (Fig. 2i). On the other hand, there is a general increase in precipitation concentration in autumn over most of the IP, with the exception of the Mediterranean coast, where PCI values decrease (Fig. 2l).

4.1 Wet-Dry season precipitation concentration index

During the dry season, PCI values show a clear north (lower) to south gradient (higher) (Fig. 3a, b). In contrast, a clear west (lower) to east (higher) gradient is observed during the wet season (Fig. 3d, e).

Changes in precipitation concentration between the two periods analysed are mainly not significant during the dry season (Fig. 3c), while highly significant changes are observed during the wet season, where an extremely likely increase in precipitation concentration is found in the central Pyrenees, central IP and South West (Fig. 3f).

5 Discussion

Precipitation variability has caused serious problems over the last few decades in Spain and this has generated a social and political debate that has not reached a general consensus in establishing an accepted basis for water planning and future management of the most essential of natural resources (Barreira, 2003; Pulido-Calvo et al., 2003; Embid and Gurrea, 2004). At the beginning of the 1990s, a long, persistent drought period caused high stress to agricultural and forest

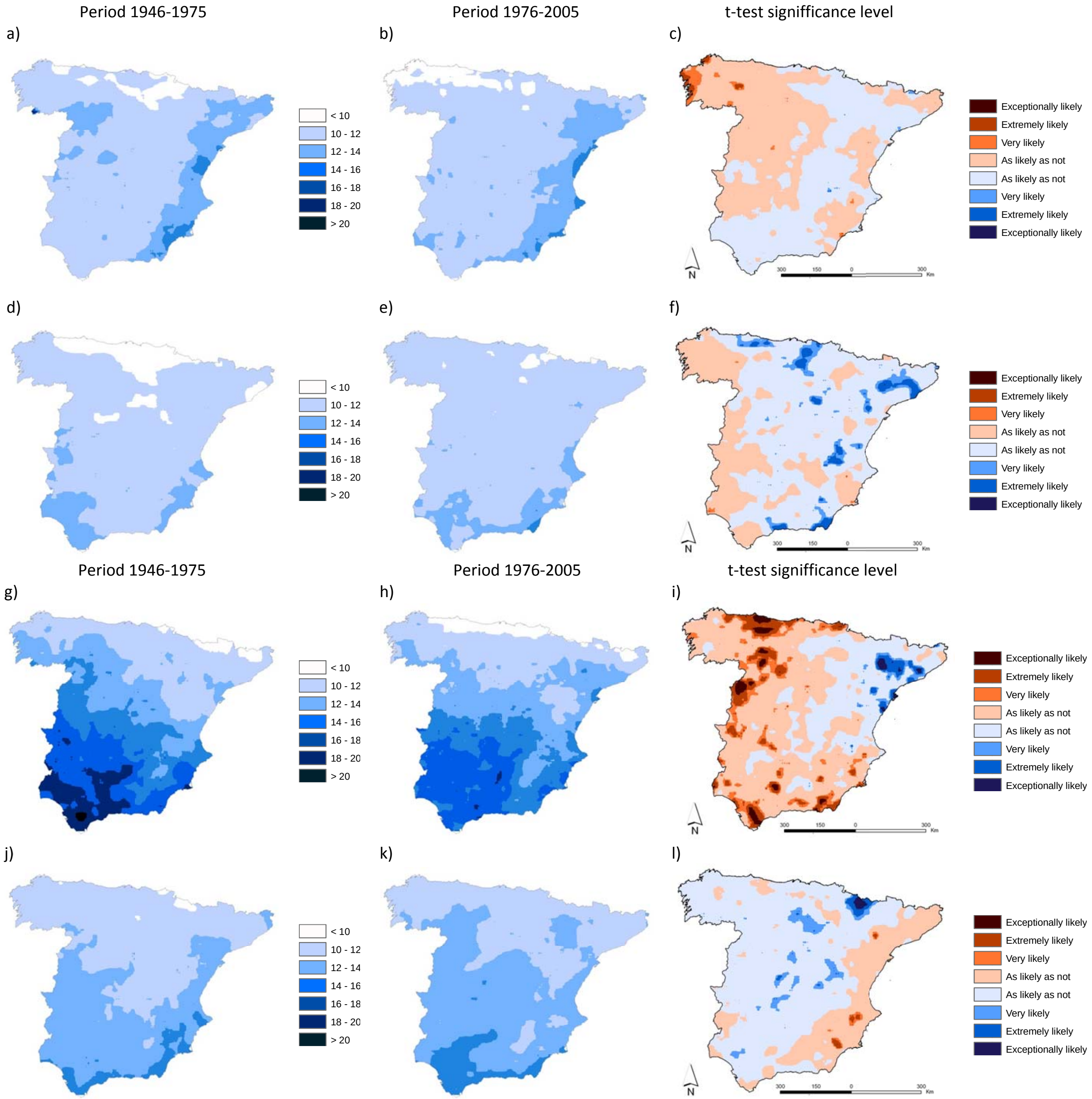

Fig. 2. Mean value of the Precipitation Concentration Index (seasonal scale) during the periods 1945–1975 and 1976–2005 and changes between periods according to different levels of probability categorized as follow: exceptionally likely ($p < 0.01$); extremely likely ($p < 0.05$); very likely ($p < 0.10$); as likely as not ($p > 0.10$). **(a)**, **(b) (c)**) Winter; **(d)**, **(e)**, **(f)**) Spring; **(g)**, **(h)**, **(i)**) summer; **(j)**, **(k)**, **(l)**) autumn. Blue positive, red negative changes.

areas (Peñuelas et al., 2001; García-Herrera et al., 2007; Vicente and Cuadrat, 2007), while at the end of the 1990s and beginning of 2000s, heavy rainfall caused floods and human and financial losses (Llasat et al., 2003; Barrera et al., 2007; Barnolas et al., 2008).

This explains why so much research has been conducted on this topic for the last decade in Spain. Studies have been made on a national scale in an attempt to identify trends in precipitation totals on different temporal scales (Rodríguez Puebla et al., 1998; González-Rouco et al., 2001; Mossmann et al., 2004; Sotillo et al., 2006; Valero et al., 2009; González-Hidalgo et al., 2011, 2010; De Luis et al., 2010a). Precipitation totals for annual, seasonal or monthly scales are key elements affecting water availability, but precipitation concentration in time also plays a decisive role.

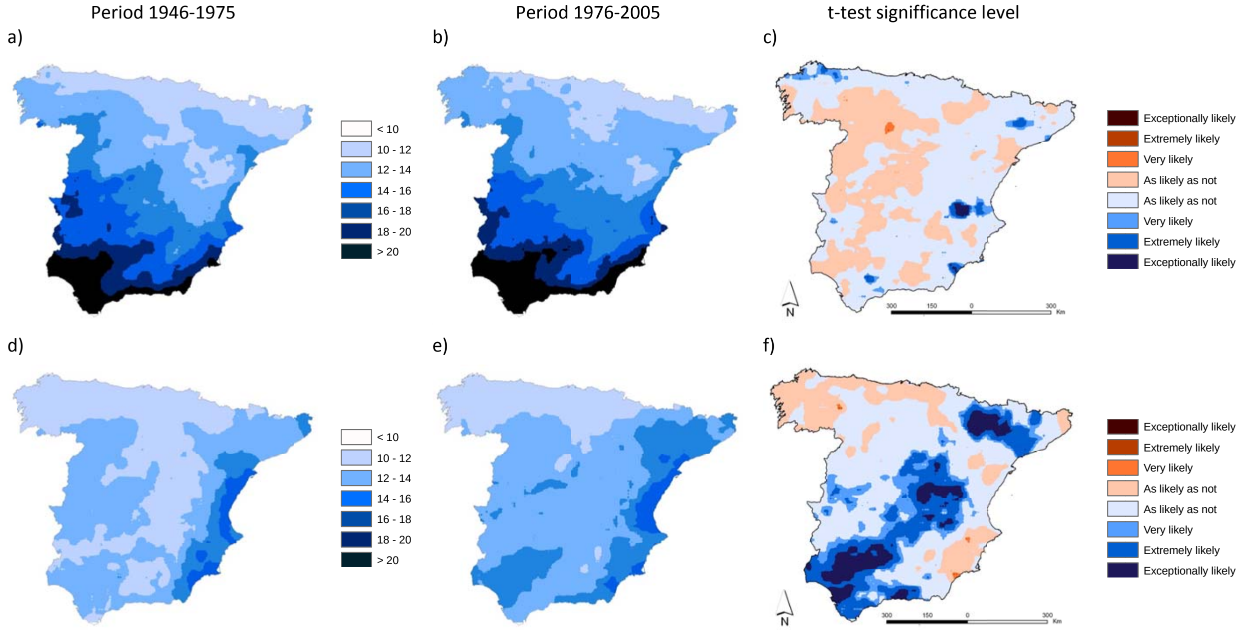

Fig. 3. Mean value of the Precipitation Concentration Index (wet-dry periods) during the periods 1945–1975 and 1976–2005 and changes between periods according to different levels of probability categorized as follow: exceptionally likely ($p < 0.01$); extremely likely ($p < 0.05$); very likely ($p < 0.10$); as likely as not ($p > 0.10$). **(a)**, **(b)**, **(c)** dry season; **(d)**, **(e)**, **(f)** wet season. Blue positive, red negative changes.

On an annual scale, precipitation concentration in the IP can be described as strongly irregular on the south and east (more influenced by the Mediterranean), irregular in the central south-west areas, moderately irregular in the central-northern part and uniform in the northern areas (more influenced by the Atlantic). Such spatial patterns result from different behaviour patterns in the precipitation trends in the IP during the wet and dry seasons. Thus, during the dry season (April to September), and especially during summer period, PCI values are distributed according to a clear N to S gradient, ranging from uniform precipitation in the north to strongly irregular concentration in the south. On the contrary, during the wet season (October to March) precipitation concentration is lower all over the IP and especially during winter, and PCI is distributed according to a clear W to E gradient (from uniform precipitation concentration in the W and central areas of IP to moderated irregular in the Mediterranean coast).

In addition to great spatial variability across the IP, PCI shows temporal changes if it is evaluated for the two 30-year periods (1946–1975 and 1976–2005). Results indicate that, in general, on an annual scale, precipitation concentration increased across most of the IP particularly from SW to NE, with this increase being caused by an increase in precipitation concentration particularly during the wet season (October to March).

Seasonal rainfall in conterminous Spain has changed dramatically between 1945–1975 and 1976–2005 (de Luis et al., 2010a), and PCI is strongly linked to these seasonal changes. During the first period (1945–1975), spring precipitation predominated in inland areas; winter precipitation predominated to the west and north; and on the Mediterranean coast, autumn rainfall contributed the highest amount of precipitation to annual totals. During the second period (1976–2005), a dramatic change was observed, with a decrease in the percentage of spring precipitation over the annual total; however, the autumn percentage increased in many central-inland areas (de Luis et al., 2010a). These changes were caused by precipitation characterised by an extensive significant negative trend in March, and a significant positive trend in October (González-Hidalgo et al., 2011); thus, due to monthly behaviour, the total precipitation during the wet season (October-March) falls within a shorter period (irrespective of global trends during the wet season), and explains the spatial changes in PCI between 1945–1975 and 1976–2005, which may underlie the significant changes occurring in inland areas.

Therefore, changes in PCI seem to be complex and appear to be related to global atmospheric features and synoptic and local factors affecting precipitation trends. In a previous paper (see de Luis et al., 2010a), we discussed such a relationship, including changes in storm tracks associated with the NAO during winter (Paredes et al., 2006), and the observed increase in cyclone frequency in the western Mediterranean region in autumn (Trigo et al., 2000; Bartholy et al., 2009). In fact, a positive trend in the sea level pressure has been observed in the Mediterranean basin recently (Brunetti et al., 2002), particularly evident in winter and spring, and linked to the more frequent and persistent anticyclones over the Mediterranean and to redistribution of precipitation among the seasons, with a reduction in rainfall in winter, spring and summer (De Luis et al., 2010a). Thus, a relevant part of spatial changes in PCI can be interpreted in terms of changes in atmospheric circulation.

Given that, in the Iberian Peninsula, global precipitation follows two spatial gradients, their juxtaposition seems to be the underlying cause for the spatial pattern of PCI observed Globally, during the wet period, precipitation follows a general NW-SE spatial pattern due to the Atlantic storm track, while precipitation during the dry period follows a predominantly N-S spatial pattern. As a result, the annual PCI spatial pattern combines the two gradients and shows a SW-NE global PCI spatial pattern (Fig. 1a and b).

Even if past precipitation trends are not indicative of future tendencies, the results presented in this paper are valuable for Water Planning Agencies and should be taken into account, since the implications of described changes might have a strong influence on natural processes such as soil erosion, modifying fluvial regimes, groundwater recharge and water availability, and may affect the production of hydroelectricity. Finally, if we consider that the PCI index is part of the well-known Fourier index on research into erosion, our results show that the precipitation factor has changed and this should be borne in mind when carrying out studies on erosion.

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