Aridity conditions in the Iberian Peninsula during the XX century

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Abstract: Aridity is one of the key elements characterizing the climate of a region, having a severe impact on water management, availability and human activities. Aiming at assessing aridity conditions in the Iberian Peninsula during the XX century, the spatial distribution of the De Martonne aridity index and Pinna Combinative index are analysed between 1901–2012 and three sub-periods: 1901–1940, 1941–1980 and 1980–2012. Gridded precipitation totals and air temperature datasets are used on a monthly basis. Results show that the southernmost of Iberia is particularly vulnerable to water stress and hence to desertification processes. In particular, both aridity indices revealed an increase and northward extension of the semi-arid regime in the Iberian Peninsula between 1901 and 2012. This increase is noteworthy for the period 1981 to 2012. More than 50% of the north and western territory have experienced humid to very humid conditions, while the other regions underwent semi-dry to dry settings. Results also reveal that climate was subjected to spatial and temporal variabilities with an overall statistically significant (at a 95% confidence level) trend towards to more severe aridity conditions in the south-easternmost and central regions with the exception of a small portion of the northwestern Iberia. The remaining territory of the Iberian Peninsula does not reveal statistically significant trends. High spatial correlations were also depicted between the De Martonne aridity index and the Pinna Combinative index.

Key-Words: Climatic indices, De Martonne Aridity Index, Pinna Combinative Index, Aridity indices, Iberian Peninsula

1 Introduction

The Earth's climate has experience changes throughout history. Most of the climate changes in the past are attributed to very small variations in Earth's orbit that results in alterations of the amount of solar energy that our planet receives. However, over the last century the climate-warming trends are likely due more to anthropogenic factors rather than to natural processes [8]. The Mediterranean region is particularly vulnerable since it is considered a climate change hotspot [11].

In a warmer climate, the recent changes in climate variables, such as air temperature and precipitation, are highly relevant to analyze how climate of a certain region respond to these climatic changes. The aridity conditions (by opposition of humidity), refers to the degree to which the climate of a region lacks effective and life promoting moisture [5]. Due to the relevant role of temperature and precipitation in describing aridity characteristics the variability of these variables over time and space contributes to evaluate changes in various climate variables, such as humidity and pressure. Moreover, regions of limited water resources and population growth, the assessment of the impacts of these recent changes in rainfed crop, water management and availability is highly relevant.

This study focuses on the spatial distribution of two climatic indices that determine the aridity conditions of the Iberian Peninsula. Towards this aim the De Martonne Aridity Index (DMI) and the Pinna Combinative Index (PCI) were computed from mean monthly air temperature and monthly precipitation totals between 1901 and 2012.

2 Data and methodology

In this study, two gridded monthly precipitation and temperature gauge-based datasets, retrieved from Climate Research Unit (CRU) TS3.21 (https://climatedataguide.ucar.edu/climatedata/cru-ts321-gridded-precipitation-and-other-meteorological-variables-1901) were used between January 1901 to December 2012. The mean temperature (T' in ˚C) and precipitation totals (P' in mm) have a 0.5˚ grid resolution [6]. Only a Euro-Atlantic sector 35.25ºN–44.75ºN, 10.25ºW–5.75ºE covering the Iberian Peninsula is analysed.

Fig. 1 Location of the Iberian Peninsula in Europe and administrative division of Spain.

These datasets have a relatively high spatial resolution thus ensuring a robust representation of the regional behaviour and variability of the climatic conditions in Iberia. No further validation against in situ data was performed.

2.1 Aridity indices

Climate indices have been widely used to characterize and classify climatic conditions. The majority of climate indices are based on meteorological or hydrological variables. For example, continentality and oceanity indices only rely on temperature, whilst some aridity indices rely on temperature and precipitation data. As aforementioned, the scope of this study is focused on analyzing the spatial distribution of two aridity indices, and their mean annual climatic evolution over the Iberian Peninsula.

The annual indices were attained from the mean monthly air temperature and precipitation totals, at selected grid points for the period comprised between 1901 and 2012. The spatial distribution of the aridity indices were also analyzed for the three following sub-periods: 1901–1940, 1941–1980 and 1981–2012. All the anomalies were computed considering the period between 1961 and 1990 as the climatological reference period.

2.1.1 De Martonne aritdity index

Due to its efficiency and relevance with respect to identifying dry and humid conditions in different climatic zones worldwide the De Martonne aridity index [5] is going to be computed and analyzed. In this study the methodology presented by De Martonne [4] is followed, as such, DMI is defined by:

$$\mathrm{DMI} = \frac{\mathrm{P}}{\mathrm{T}+10} \quad (1)$$

where P is the annual precipitation total (mm) and T is the mean annual air temperature (˚C). The climate is then characterized as indicated in Table 1.

Climate	DMI values	P values (mm)
Dry	DMI < 10	P < 200
Semi-dry	10 ≤ DMI < 20	200 ≤ P < 400
Mediterranean	20 ≤ DMI < 24	400 ≤ P <5 00
Semi-humid	24 ≤ DMI < 28	500 ≤ P < 600
Humid	28 ≤ DMI < 35	600 ≤ P < 700
Very humid	35 ≤ DMI ≤ 55	700 ≤ P < 800
Excessively humid	DMI > 55	P > 800

Table 1. De Martonne aridity index climatic classification.

2.1.2 Pinna combinative index

The Pinna combinative index was also computed following [7] formulation, as such, PCI is defined by:

$$\mathrm{PCI} = \frac{1}{2}\left(\frac{\mathrm{P}}{\mathrm{T}+10} + \frac{12\mathrm{P}_d^{'}}{\mathrm{T}_d^{'}+10}\right) \quad (2)$$

where P (mm) and T (˚C) are the annual precipitation total and the mean annual air temperature, and $\mathrm{P}_d^{'}$ and $\mathrm{T}_d^{'}$ are the precipitation total and the mean air temperature of the driest month.

Since this index takes into account the precipitation total and the mean air temperature of the driest month, PCI allows an insight of the seasons and regional impacts have on crop irrigation. The climate is then characterized as indicated in Table 2.

Climate	PCI values
Dry	PCI < 10
Semi-dry	10 ≤ PCI ≤ 20
Humid	PCI > 20

Table 2. Pinna combinative index climatic classification.

2.2 Temporal evolution of the aridity indices

Aiming at identifying long-term changes, the linear trends of the two aridity indices, for each grid point, were first computed and their corresponding statistical significance (at a 95% confidence level) was evaluated by the Spearman's rho test (non-parametric test; [3]).

The correlation coefficient, significant at a 95% confidence level, was computed at each grid point, between DMI and PCI and is presented herein.

3 Results

As abovementioned, the evaluation of the aridity conditions in the Iberian Peninsula was undertaken throughout the computation of the De Martonne aridity index and the Pinna combinative index. Both indices will be analyzed on an annual time scale, due to the definition restrictions of the DMI.

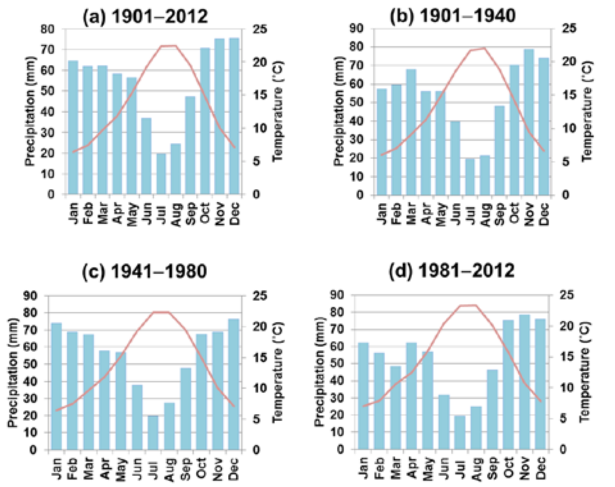

Fig.2 Seasonal cycle of mean air temperature (˚C) and precipitation totals (mm) between (a) 1901–2012, (b) 1901–1940, (c) 1941–1980 and (d) 1981–2012 for the Iberian Peninsula.

These indices allow the assessment of temperature and precipitation forcing in the study region. Results show that the wet season (see Fig. 2) is primarily observed for the summer months between 1901–2012 and also for the three sub-periods for the entire Iberia. However, a small increase in mean monthly temperature can be found for July and August between 1981–2012 in comparison with the other periods. Significant differences can be found when the Iberia is divided into different sub-regions (not shown) thus revealing considerable regional variations.

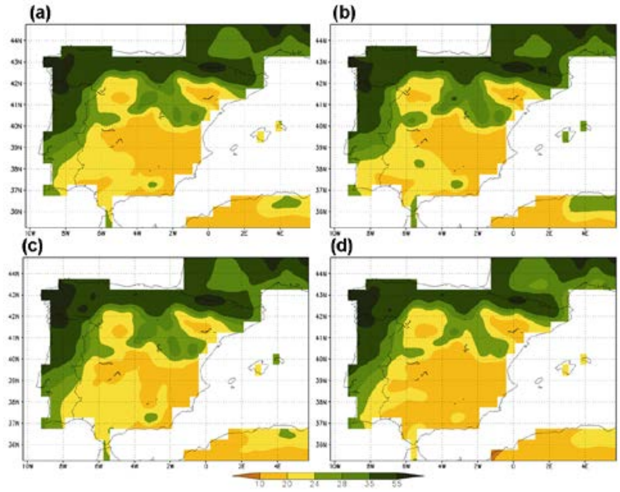

Fig.3 Mean annual DMI values for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

Results show (see Fig.3 and Fig.4) that aridity conditions in the Iberian Peninsula did not remain constant during the XX century. DMI patterns presents a Mediterranean and semi-dry in inner Iberia and towards southeast (Extremadura, Castile-La Mancha, Andalusia, Murcia, and Valencia) contrasting with the humid to excessively humid characteristics found towards north and northwest.

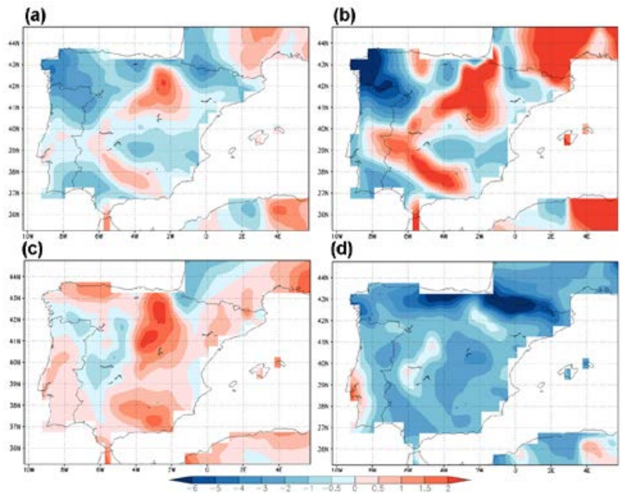

Fig.4 Mean annual DMI anomalies for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

The anomalies patterns Fig.4 display a clear difference between the three analyzed sub-periods, with a clear signal change from positive to negative, between 1941–1980 and 1981–2012, respectively.

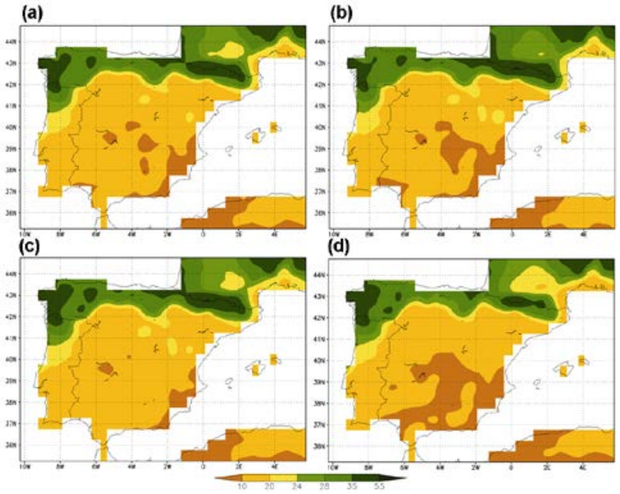

Fig.5 Mean annual PCI values for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

The latter results are complemented with those attained for PCI, Fig.5. In fact PCI presents spatial patterns very similar to the ones depicted for DMI. As before, the spatial extent of dry conditions increased in the latter period (1981–2012) in comparison with the other periods, mainly in the south-easternmost (Castilla–La Mancha, Andalusia, Murcia and Valencia) portion of Iberia, Fig.5d. Again, humid conditions are depicted in the north and northwestern regions for all periods.

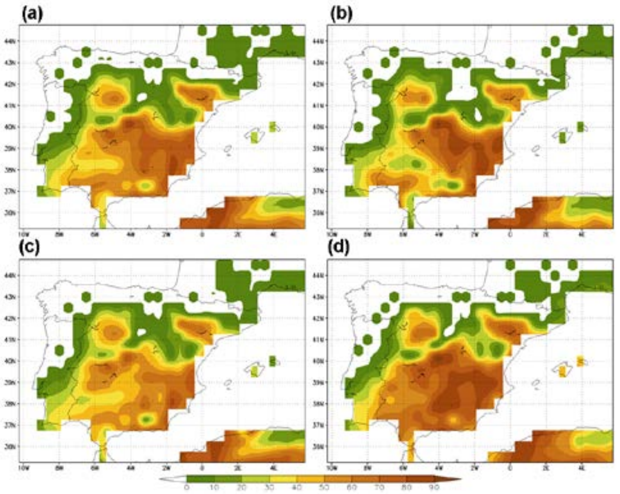

Fig.6 Percentages of years with $10 \leq DMI < 20$ (semi-dry) for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

PCI anomalies patterns (not shown) are quite similar to the ones depicted for DMI. As for DMI, the PCI anomalies revealed a shift in the anomalies signal in the most recent period, towards negative values almost in the entire Iberian Peninsula.

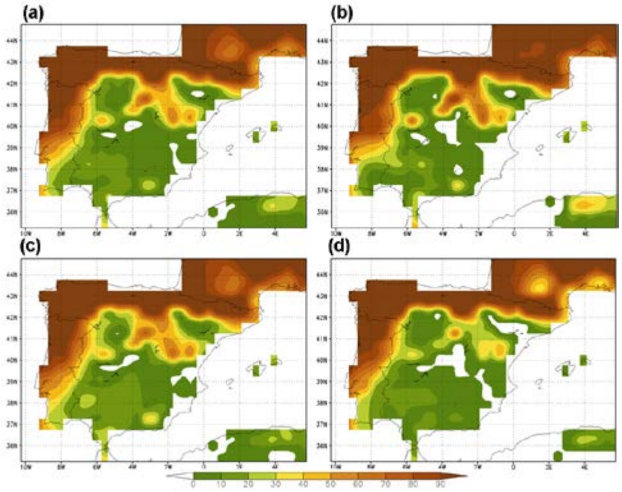

Fig.7 Percentages of years with $DMI \geq 28$ (humid, very humid and excessively humid) for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

The latter results are complemented with those attained for DMI regarding the percentage of years with semi-dry (Fig.6) and humid to excessively humid conditions (Fig.7). It is quite evident that approximately the southern (northern) half of the Iberian Peninsula experience semi-dry (humid to excessively humid) climatic conditions above 50% of the years for all periods. It is worth noting that in regions in between the ones abovementioned, a smaller percentage of the years experienced Mediterranean ($20 \leq DMI < 24$) and semi-humid ($24 \leq DMI < 28$) conditions (not shown). Also, a very small percentage of dry years were experienced in the southernmost regions of Iberia (not shown).

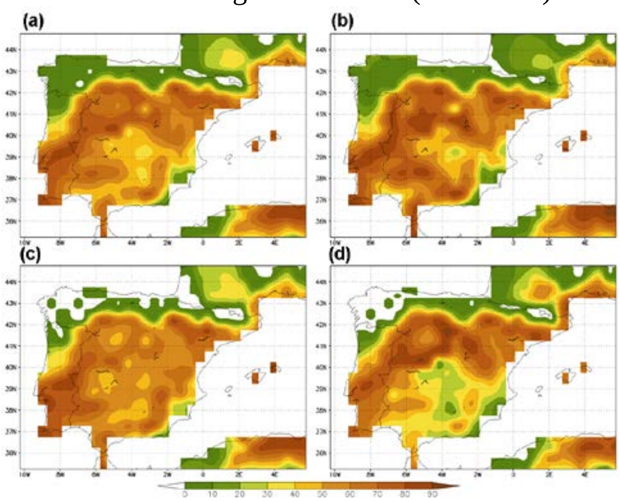

Fig.8 Percentages of years with $10 \leq PCI \leq 20$ (semi-dry) for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

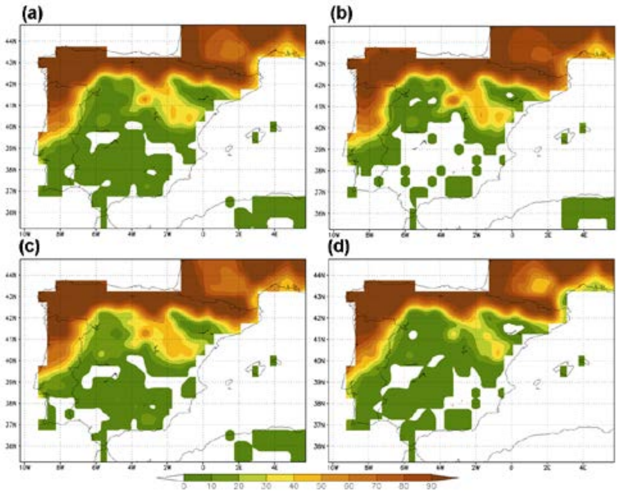

Fig.9 Percentages of years with PCI > 20 (humid) for the periods (a) 1901–2012, (b) 1901–1940 (c) 1941–1980 and (d) 1981–2012.

As for DMI, the spatial patterns of the percentage of years with PCI values classified as semi-dry (10 ≤ PCI ≤ 20) and humid (PCI > 20) is quite similar (see Fig.8 and Fig.9). Again, the southernmost (northernmost) region of Iberian experience semi-dry (humid) climatic conditions above 50% for all the periods analyzed.

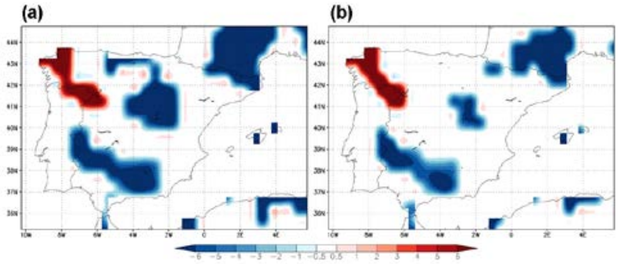

Fig.10 Statistically significant linear trends at the 95% confidence level (Spearman's rho test) of the annual mean values of (a) DMI and (b) PCI between 1901–2012. White areas denote Non-Significant (N.S.) trends.

It is still worth mentioning, the statistically significant increase in DMI and PCI dry conditions, for the period between 1901 and 2012 (see Fig.10) mainly in southern and inner Iberia and Pyrenees region. However, in the north-westernmost region (Galicia and Asturias) statistically significant positive values can be depicted. These results show that between 1901 and 2012, this region experienced an increase towards humid conditions. Let us remind that this region is characterized by strong topographic contrasts, since along the northern coast lay the Cantabrian Mountains and its 'Picos da Europa'. Therefore this increase can be due to the influence of orography and oceanic proximity, with prevailing annual western transport of moist air ascending windward the Cantabrian Mountains. The remaining territory of the Iberian Peninsula does not reveal statistically significant trends.

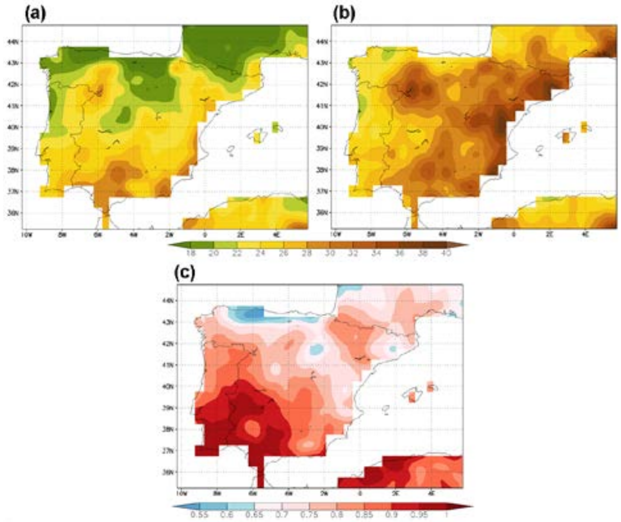

Fig.11 Variation coefficient of (a) DMI, (b) PCI and (c) correlation coefficient between DMI and PCI for 1901–2012.

Despite the differences, statistically significant spatial correlations between DMI and PCI were found (see Fig.11) at a 95% confidence level. Therefore it can be concluded that both indices are suitable for analysing the spatial characteristics of the aridity condition in the Iberian climate.

4 Conclusions

This study is focused on the spatial analysis of two aridity indices for the Iberian Peninsula during 1901 and 2012, the De Martonne Aridity index and the Pinna Combinative index. Due to the overall warming trends observed in the last decades, the temporal evolution was assessed in three sub-periods: 1901-1940, 1941-1980 and 1981-2012.

Due to its location the geographical contrasts of the Iberian Peninsula strongly influence the spatial and temporal variability of its climate. The proximity of the Atlantic Ocean and Mediterranean Sea play a relevant role in the annual precipitation totals and mean air temperature distributions. Results show the intra-annual variability (Fig.2) of both precipitation totals and air temperature for the Iberian territory.

It is quite evident the division in the aridity indices patterns into two major regions northwest/southeast. This can be due to the prevailing annual western winds that transport moist air in the northern regions, resulting in more intense and frequent rainstorms [9, 10]. Also noteworthy is the orography of this region characterized by the presence of the Cantabrian Mountains and Pyrenees that acts as a barrier. In fact, on the leeward side of these mountains, there is a clear decrease of the aridity conditions, since the annual precipitation is lower when compared with the mean annual air temperature. This can be due not only to the adiabatic sinking [1] but also to an enhancement of the continentality characteristics of the climate [2].

Results for DMI and PCI show that for the entire period of this study (1901–2012) the Iberian Peninsula experienced annual humid to very humid conditions in its northermost portion, semi-dry to dry conditions in the inner and south-eastern regions and mediterranean to humid conditions in between (see Fig.3 and Fig.5). An increase in the dry conditions in its southern half is worth emphasizing between 1981–2012. This increase is highlighted by a clear change in the signal of the anomalies in both indices during this period in comparison with the others (Fig.4). Also by the percentage of years that undergone semi-dry and humid to excessively humid climatic conditions for all periods (see Fig.6, Fig.7, Fig.8 and Fig.9).

Statistically significant linear trends for both DMI and PCI highlight the increase of dry conditions in the south, central and Pyrenees region (Fig.10), contrasting with its decrease in the north (Galicia and Asturias). Both indices are highly correlated, since statistically significant correlations at a 95% confidence level were found mainly in the southern region.

Overall, the south-easternmost region of the Iberian is clearly becoming drier (more arid). These conclusions stress the importance of assessing the changes of the spatial distribution of the climatic characteristics of a region. The observed changes in the spatial distributions of these indices in the last decades highlight the need for the implementation of better water resources management policies. It is quite evident that a decrease in precipitation and an increase in temperatures have a severe impact in water storage, both superficial and subterranean. Consequently, an increase in water demand for agriculture and human consumption leads to a decrease in water quality and amount in all reservoirs. Hence these consequences must not be overlooked in order to warrant a better sustainable future.

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