

RESEARCH ARTICLE OPEN ACCESS

Aridity on the Rise: Spatial and Temporal Shifts in Climate Aridity in Spain (1961–2020)

Santiago Beguería^{1,2}  | Víctor Trullenque-Blanco^{1,2}  | Sergio M. Vicente-Serrano^{2,3}  | J. Carlos González-Hidalgo^{2,4,5} 

¹Estación Experimental de Aula Dei (EEAD-CSIC), Zaragoza, Spain | ²Laboratorio de Climatología y Servicios Climáticos (LCSC), CSIC-University of Zaragoza, Zaragoza, Spain | ³Instituto Pirenaico de Ecología (IPE-CSIC), Zaragoza, Spain | ⁴Geography Department, University of Zaragoza, Zaragoza, Spain | ⁵Instituto Universitario de Ciencias Ambientales (IUCA-UNIZAR), Zaragoza, Spain

Correspondence: Santiago Beguería (santiago.begueria@csic.es)

Received: 11 September 2024 | **Revised:** 9 January 2025 | **Accepted:** 23 January 2025

Funding: This work has been supported by the Biodiversity Foundation of the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) of the Government of Spain, within the framework of the Recovery, Transformation and Resilience Plan (PRTR), funded by the European Union—NextGenerationEU. We also acknowledge financial support from the Ministry of Science, Innovation and Universities of the Government of Spain through research project PID2020-116860RB-C22, and from the Government of Aragón through grant E02-17R. We are also grateful to the Spanish Meteorological Agency (AEMET) for providing the observational data.

Keywords: aridity index | climate aridity | climate change | precipitation | reference evapotranspiration | Spain | Western Mediterranean Basin

ABSTRACT

Climate aridity (the long-term balance between water availability through precipitation and the atmospheric evaporative demand) has a fundamental role in determining water availability and the geographic distribution of ecosystems and agricultural regions, and plays a crucial role in shaping ecological transitions under current climate change. We computed the Aridity Index, computed as the ratio of precipitation to reference evapotranspiration, over Spain for the period 1961–2020. Here we present spatially detailed climatologies of the Aridity Index, at the annual and the monthly scales, and an assessment of changes between the normal periods 1961–1990 and 1991–2020. The results show a transition towards reduced values of the Aridity Index (i.e., towards drier conditions) at the annual scale, which was more intense in the Canary Islands (where 16.3% of the territory transitioned towards more arid climate categories) than in mainland Spain and the Balearic Islands (11.6%). At the monthly level, the most striking changes over mainland Spain occurred in June, with 39.7% of the territory transitioning towards more arid categories, while transitions towards more humid conditions have only been relevant in March (23.5%) and October (13.0%) and did not compensate for the aridification trend when the whole year is considered. In the Canary Islands, the strongest changes occurred in May (22.6%) and September (19.4%), although drying trends were found almost in all months except the summer.

1 | Introduction

Climate aridity, that is the long-term balance between water availability through precipitation and the atmospheric evaporative demand (AED), is a fundamental environmental characteristic intrinsically linked to the geographical distribution of biomes and the agricultural viability of regions (Stephenson 1990; Lian et al. 2021). Arid regions, characterised by limited and erratic rainfall, typically support sparse vegetation well adapted to water scarcity. The ecological dynamics in these

areas are characteristic, often leading to unique biodiversity that has evolved to survive under harsh climatic conditions (Maestre et al. 2012). Agricultural practices in arid zones are similarly constrained, requiring careful water management strategies to sustain crop and livestock production (D'Odorico et al. 2013). Regions such as the Sahel in Africa, central Australia, and parts of the southwestern United States exemplify the significant influence of aridity on both natural ecosystems and human activities (Mirzabaev et al. 2022). In these areas, water scarcity largely dictates water resources, land

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial](https://creativecommons.org/licenses/by-nc/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2025 The Author(s). *International Journal of Climatology* published by John Wiley & Sons Ltd on behalf of Royal Meteorological Society.

use patterns, economic activities and settlements distribution. Consequently, the socio-economic development of these regions is closely tied to their climatic conditions (Reynolds et al. 2007). The concept of climate aridity is, therefore, essential for understanding the geographical distribution of ecosystems and the agricultural capacity of regions and their temporal dynamics.

Long-term changes in climate aridity are a significant contributor to ecological change, with vast consequences for ecosystems and human societies (Vicente-Serrano et al. 2024). Climate-driven shifts towards more arid conditions can lead to alterations in vegetation composition and structure, as drought-tolerant species outcompete others for limited water resources (Feeley et al. 2020). This, in turn, can result in reduced ecosystem productivity and fertility, as well as decreased carbon sequestration capacity (Moreno-Jiménez et al. 2019; Schlesinger and Bernhardt 2020). Furthermore, aridification can lead to biodiversity loss, as sensitive or specialised species are unable to adapt to the new environmental conditions (Vicente-Serrano et al. 2012; Weiskopf et al. 2020). All these processes can eventually lead to irreversible degradation, such as desertification (Glantz 2004; Berg et al. 2016; Berdugo et al. 2020; Lenton et al. 2023; Vicente-Serrano et al. 2024).

There is a scientific debate on the factors that control climate aridity, and even on what is understood by that term (Vaughn 2004). Some authors consider that aridity should be based on the quantification of usable water resources, such as soil moisture or water resources availability (Greve et al. 2019), while others favour a broader meaning of the term considering ecological and agricultural dimensions as a consequence of climatic aridity (Allen, Breshears, and McDowell 2015; Ma et al. 2015; Macias et al. 2006). The definition of aridity is closely related to the many indices that have been proposed to measure it (e.g., the review by Stadler 2004). One of the most extended, however, is the United Nations Environmental Programme (UNEP) Aridity Index (AI), defined as the ratio of the annual precipitation to potential evapotranspiration (P/PET), averaged over a sufficiently large number of years (UNEP 1992). The index categorises regions into hyper-arid, arid, semi-arid, dry sub-humid and humid classes. The AI serves as a crucial tool for policymakers and researchers in assessing the vulnerability of regions to desertification and formulating appropriate mitigation strategies. By standardising the measurement of aridity, the UNCCD AI facilitates global comparisons, and the monitoring of temporal changes over large time periods (UNCCD 2017; Vicente-Serrano et al. 2024).

There is currently no scientific consensus on the behaviour of climatic aridity under climate change. In the case of precipitation, no substantial changes are observed at regional and global scales (Vicente-Serrano, García-Herrera, et al. 2022; Douville et al. 2021), with natural variability being the main factor controlling its dynamics in the last century (Trenberth et al. 2014). Undoubtedly, global temperature has increased significantly in recent decades (Gulev et al. 2021). This increase, together with the decrease in relative humidity over large regions of the world (Byrne and O'Gorman 2018; Vicente-Serrano et al. 2018) has caused a notable increase in the atmospheric demand globally (Vicente-Serrano et al. 2020; Douville et al. 2021). This fact has

affected climatic aridity, which would have increased over large regions globally (Dai 2011; Fu and Feng 2014; Roderick, Greve, and Farquhar 2015; Scheff and Frierson 2015; Milly and Dunne 2016; Ullah et al. 2022; Vicente-Serrano et al. 2024).

The Intergovernmental Panel on Climate Change (IPCC) highlights that arid and semi-arid regions are particularly susceptible to the adverse effects of climate change, including shifts in precipitation patterns and increased evaporation rates (IPCC 2014; IPCC 2021). This would explain that the most recent report of the UNCCD, that analysed in depth global aridity trends and future projections, shows increased aridity conditions in the last decades, particularly as a consequence of human-induced climate change (Vicente-Serrano et al. 2024). Nevertheless, adaptation and mitigation regional policies necessitate a precise understanding of aridity changes at detailed spatial scales.

In Spain, the recently approved National Strategy to Combat Desertification (MITECO 2022) identifies changes in climate conditions as one of the direct agents of land degradation and the advance of desertification, alluding specifically to aridity and drought. However, while both terms refer to the hydric balance between water availability and water needs, and are sometimes used as synonyms, there are fundamental differences between them that need to be highlighted. Thus, while aridity refers to a long-term characteristic of some location's climate, drought represents a temporary deviation from normal water availability levels, leading to water shortages. Consequently, droughts can occur in any climatic zone, including humid regions, whereas aridity is a persistent characteristic of specific geographical areas (Vicente-Serrano, Beguería, and López-Moreno 2010; Vicente-Serrano, Lasanta, and Gracia 2010; Domínguez-Castro et al. 2019). The frequency and intensity of droughts are influenced by broader climatic patterns that vary across time and space, making it crucial to distinguish between short-term climatic anomalies and changes in the inherent dryness of a region (aridity).

There is clear evidence of an increase in temperatures over Spain (Peña-Angulo et al. 2020; González-Hidalgo, Beguería, Peña-Angulo, and Sandonis 2022), while precipitation trends are not so evident nor persisting over time (González-Hidalgo, Beguería, Peña-Angulo, and Trullenque-Blanco 2022; González-Hidalgo et al. 2024). This sheds uncertainty towards the recent evolution of climatic aridity in Spain, as it is influenced by both fundamental climatic variables. The wide extension of semi-arid climate regions in Spain suggests enhanced environmental degradation risk if these areas transition towards a more arid climate (Van Leeuwen et al. 2019). Despite its relevance, in Spain there are still few studies that assess the recent evolution of climate aridity from a broad temporal perspective, and consider a detailed spatial resolution. Previous studies focused on smaller regions, or omitted the island territories (Andrade and Corte-Real 2016; Moral et al. 2016; Paniagua et al. 2019). Other studies encompassing the whole Spanish territory did not have sufficient spatial detail due to their more ample geographic scopes (e.g., Bešfáková et al. 2023; Huang et al. 2016; Ullah et al. 2022; Spinoni et al. 2015). López et al. (2017) compared the 30-year periods 1951–1980 and 1981–2010, and they detected an increase of annual and summer aridity and a general extension of Mediterranean climate characteristics. To our knowledge, no

other analyses of climate aridity and their recent changes have been done.

In this article we present a novel dataset and a monitoring system of climatic aridity in Spain, based on data from the observational network of the Spanish national atmospheric service (AEMET). The aim of this system is twofold, as it will facilitate undertaking studies that involve this important climatic variable and also monitor their long-term changes. Using this dataset, we present spatially detailed long-term climatologies (mean values and variability) of the AI at the annual and monthly levels, and we assess the changes experienced within 1961–2020.

2 | Study Area, Data and Methods

This study focuses on the entirety of the Spanish national territory, encompassing its diverse geographical components (Figure 1). This includes the mainland (peninsular) territory between 36.0° and 43.6° N; the Balearic Islands archipelago in the Mediterranean Sea, between 38° 37′–40° 6′ N, and 1° 13′–4° 17′ E; the autonomous cities of Ceuta (35° 53′ N, 6° 39′ W) and Melilla (35° 17′ N, 3° 3′ W), located on the North African coast; and the Canary Islands archipelago in the Atlantic Ocean between 27° 37′–29° 25′ N and 13° 20′–18° 10′ W. The mainland spans a considerable surface area 493,457 km², while the Balearic Islands cover approximately 5040 km² and the Canary Islands 7447 km².

This geographical diversity is reflected in the varied relief. Mainland Spain is characterised by a complex topography dominated by the Northern Plateau (*Meseta Central*), a high plateau surrounded by mountain ranges such as the Pyrenees to the

north, the Cantabrian Mountains to the northwest, the Iberian System to the east, and Sierra Morena and Sistema Bético to the south. The Balearic Islands are also hilly, albeit with lower elevations compared to the mainland. The Canary Islands, of volcanic origin, present a rugged landscape with steep slopes, deep ravines and volcanic peaks, including Teide, the highest peak in Spain.

This varied relief contributes to a range of climatic conditions. Mainland Spain experiences climates ranging from oceanic temperate (Köppen Cf*) in the north to Mediterranean climates characterised by hot, dry summers and mild, wet winters in the south and east (Köppen Cs*, BS*). In contrast, the Canary Islands, due to their subtropical latitude and oceanic influence, range between temperate and desert climates (Köppen Csb, BWh).

We constructed monthly and annual gridded data sets of the AI over Spain (Figure 1), computed as follows:

$$AI = P / ETo,$$

where the AI (mm/mm) is the ratio of precipitation, P (mm) to reference evapotranspiration, ETo (mm), accumulated over months or years, respectively.

We obtained weekly gridded time series of both input variables from the Spanish Drought Monitor (Vicente-Serrano et al. 2017; <https://monitordesequia.csic.es/historico>), and we aggregated them to monthly and annual time scales. Following the Spanish Drought Monitor, we used the FAO-56 Penman-Monteith reference evapotranspiration (Allen et al. 1998; Tomas-Burguera et al. 2017).

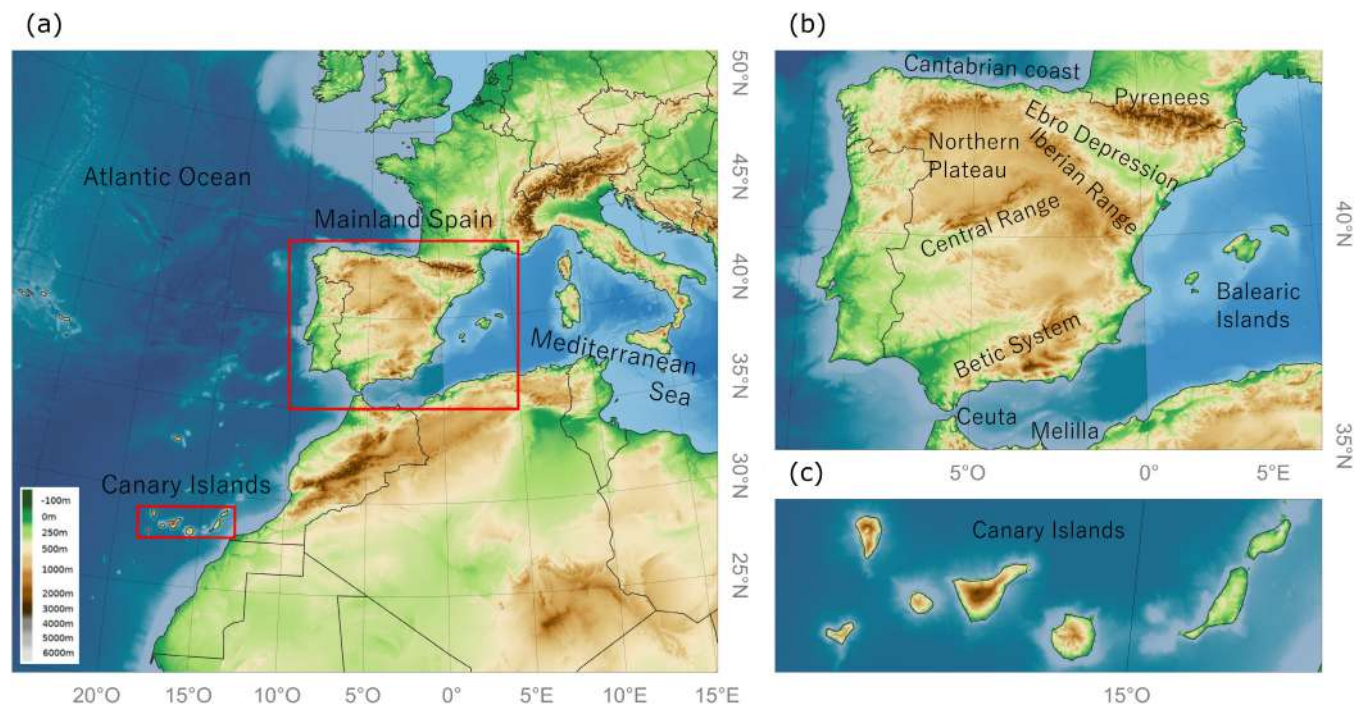


FIGURE 1 | Study area: (a) location within a regional context; (b) mainland Spain and the Balearic Islands; and (c) Canary Islands. The maps show the elevation (meters above sea level) and the main geographic features and toponyms mentioned in the article. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

Currently, the dataset covers the period between January 1961 and December 2023, and includes the mainland territory, the Balearic Islands and the Canary Islands. Following the example of the Spanish drought monitoring system (Vicente-Serrano, Domínguez-Castro, et al. 2022; Vicente-Serrano, García-Herrera, et al. 2022; Vicente-Serrano, Miralles, et al. 2022), the dataset will be updated regularly at the beginning of each year, and can be explored interactively at <https://monitordearidez.cisc.es>.

Here we considered the period 1961–2020, spanning over 60 years, to compute annual and monthly AI time series and climatologies (long-term means and coefficients of variation).

In order to assess for changes within this timeframe we used the Mann-Kendall trend test, a non-parametric test for statistical dependence based on the Kendall's tau coefficient, which we applied to annual time series of annual and monthly AI time series.

In addition to quantitative AI values, we characterised the climate aridity according to the categories defined by the UNEP (Table 1). We assessed for changes or transitions across these major classes between two 30-year (normal) periods 1961–1990 and 1991–2020 (WMO 2017). We distinguished between transitions towards more arid conditions (humid to sub-humid humid, to sub-humid dry, to semi-arid, to arid, to hyper-arid) and towards more humid conditions (reversed changes).

Although the AI is a general characteristic of the climate of a region and therefore has only relevance at the annual level, we have also analysed its monthly distribution, following the same

methodology used at the annual scale. This is somehow debatable, since at the monthly scale other factors the climatic water balance is affected by other factors than just precipitation and reference evapotranspiration, such as the water storage in the soils. However, and keeping this in consideration, the nuances of the intra-annual variability of the AI adds interesting information regarding the different regional climates, and the trend analysis at the monthly scale also allows determine when in the year the changes towards more or less arid conditions took place, which may be key to certain applications.

3 | Results

3.1 | Annual and Monthly Climatologies, 1961–2020

Figure 2 shows annual AI climatologies for the period 1961–2020. The mean value over the whole period is shown, as well as the inter-annual coefficient of variation and the classification into aridity categories. The percent area occupied by each category is provided in Table S1.

Starting with mainland Spain (continental territory and the Balearic Islands), the results evidence a large spatial variability of the mean AI values, with a striking contrast between the humid regions in the north and north-west and the rest of the peninsular territory where semi-arid conditions prevail, with the exception of the mountain ranges and the southernmost tip, with more humid climate. The inter-annual

TABLE 1 | Climate classification scheme for Aridity Index values (UNEP 1997).

Climate class	Hyper-arid	Arid	Semi-arid	Sub-humid/dry	Sub-humid/humid	Humid
Aridity Index values	< 0.03	0.03–0.2	0.2–0.5	0.5–0.65	0.65–0.75	> 0.75

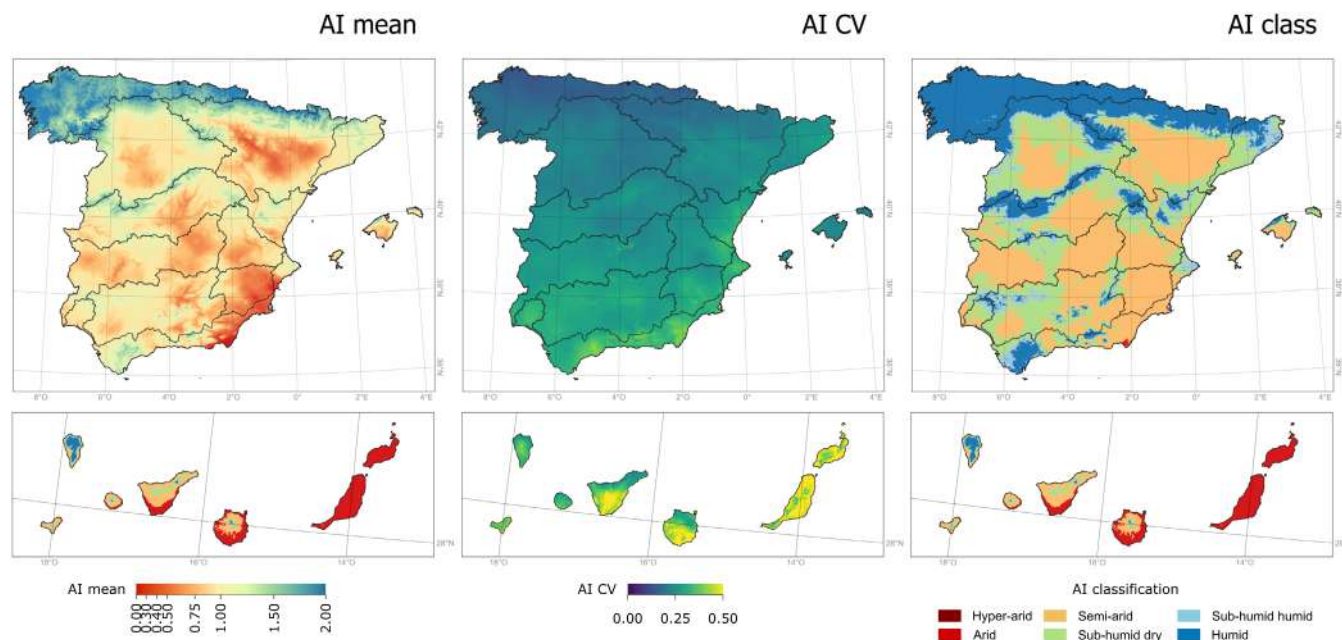


FIGURE 2 | Aridity Index over mainland Spain and the Balearic Islands (top) and the Canary Islands (bottom), computed over the period 1961–2020: (a) mean annual values; (b) coefficient of variation; and (c) Aridity Index categories. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

coefficient of variation also shows a large spatial variability, ranging between close to zero to 0.25 and exhibiting an almost inverted spatial pattern with lower values in the north and interior areas and higher values in the east and south, along the Mediterranean coast, where the mean AI values are lower. As for the categories into which the AI is divided, most of Spain (37% of the area) is classified as semi-arid for the period 1961–2020, with the next most abundant categories being dry sub-humid (28%) and humid (26%). At the opposite extreme is the arid class, with less than 1% of the territory and only appearing in the SE extreme.

In the Canary Islands these differences are even more extreme, exhibiting the largest range of mean AI values within a much smaller territory. There is a clear spatial gradient from west (more humid) to east (drier), and a strong modulation by the relief. In particular, the easternmost islands, which also have the lowest relief, have an arid climate, together with the southern (leeward) areas of the central islands. On the contrary, the westernmost island and the highest areas of the central islands, exposed to the humid oceanic winds, have sub-humid and humid characteristics. Another striking characteristic of the climatic aridity in the Canary Islands is the large inter-annual variability, which is highest in the more arid areas of the archipelago.

The strong seasonality of the Spanish climate shows in the monthly distribution of the AI (Figures 3 and 4). There is a predominance of the humid category in November, December and January (close to 100% of the territory), followed by October and February. At the opposite extreme are July and August, where in more than two thirds of Spain the AI category is arid or hyper-arid. Between these two extremes, there is a more or less gradual transition, with the exception of a somewhat abrupt change between September and October, which shows a direct passage from semi-arid to humid predominance. This fact occurs specifically in the Spanish mainland and the Balearic Islands, while in the Canary Islands there is a smoother transition between the 2 months.

Figures S1 and S2 show the mean AI and the inter-annual coefficient of variation, calculated on a monthly scale. The mean AI maps show spatial gradients that mimic quite closely those of the AI categories shown above, but the inter-annual coefficient

of variation is more interesting. Thus, between October and February, when humid conditions prevail over mainland Spain, there is higher variability along the Mediterranean coast. In June and July, on the other hand, the highest variability is found in the southern half of the Iberian Peninsula. In the Canary Islands, the leeward side of the central islands shows the lowest inter-annual variability, while the more arid eastern islands and the humid western islands exhibit the largest variability, especially between January and June.

3.2 | Recent Changes in Climate Aridity

Inspection of the time series of the annual AI averaged over the study area reveals a large inter-annual variability, with values that ranged between around 0.5 and 1 over mainland Spain and between circa 0.15 and 0.5 in the Canary Islands (Figure 5). Application of the Mann-Kendall trend test to these time series revealed a negative (towards drier) trend, with $\tau = -0.09$ and -0.183 for mainland Spain and the Canary Islands, respectively, although significance was only achieved at an $\alpha = 0.05$ confidence level in the latter case (two-sided $p = 0.311$ and 0.039 , respectively).

Comparison between the two normal periods 1961–1990 and 1991–2020 revealed a shift towards a drier AI climatology in the latter period. This is apparent by comparing the mean annual AI values of the two periods, which shifted between 0.74 and 0.71 over mainland Spain and between 0.30 and 0.25 over the Canary Islands (Figure 5a), and also by inspecting the 30-year density plots, where a shift to the right is apparent in both cases (Figure 5b).

The analysis of the monthly AI time series (Figures S3 and S4) offers further insight, and shows that 2 months, February and June, were the largest contributors to the negative trend of the AI over mainland Spain. In the case of the Canary Islands, on the other hand, May and September showed negative trends, while July had a positive trend.

These changes have not affected the territory in a homogeneous way, as evidenced by the maps of the Mann-Kendall tau statistic calculated at each grid node (Figure 6). At the annual level, most of peninsular Spain and the Balearic Islands

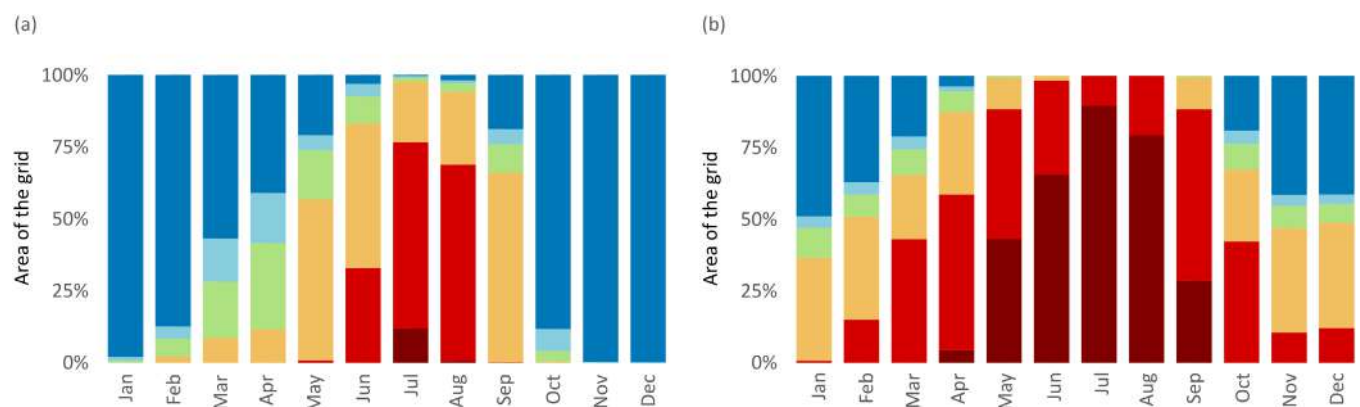


FIGURE 3 | Percent area by aridity classes over 1961–2020: (a) Spanish mainland and Balearic Islands; and (b) Canary Islands. Colours correspond to Aridity Index categories (legend as in Figure 2). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

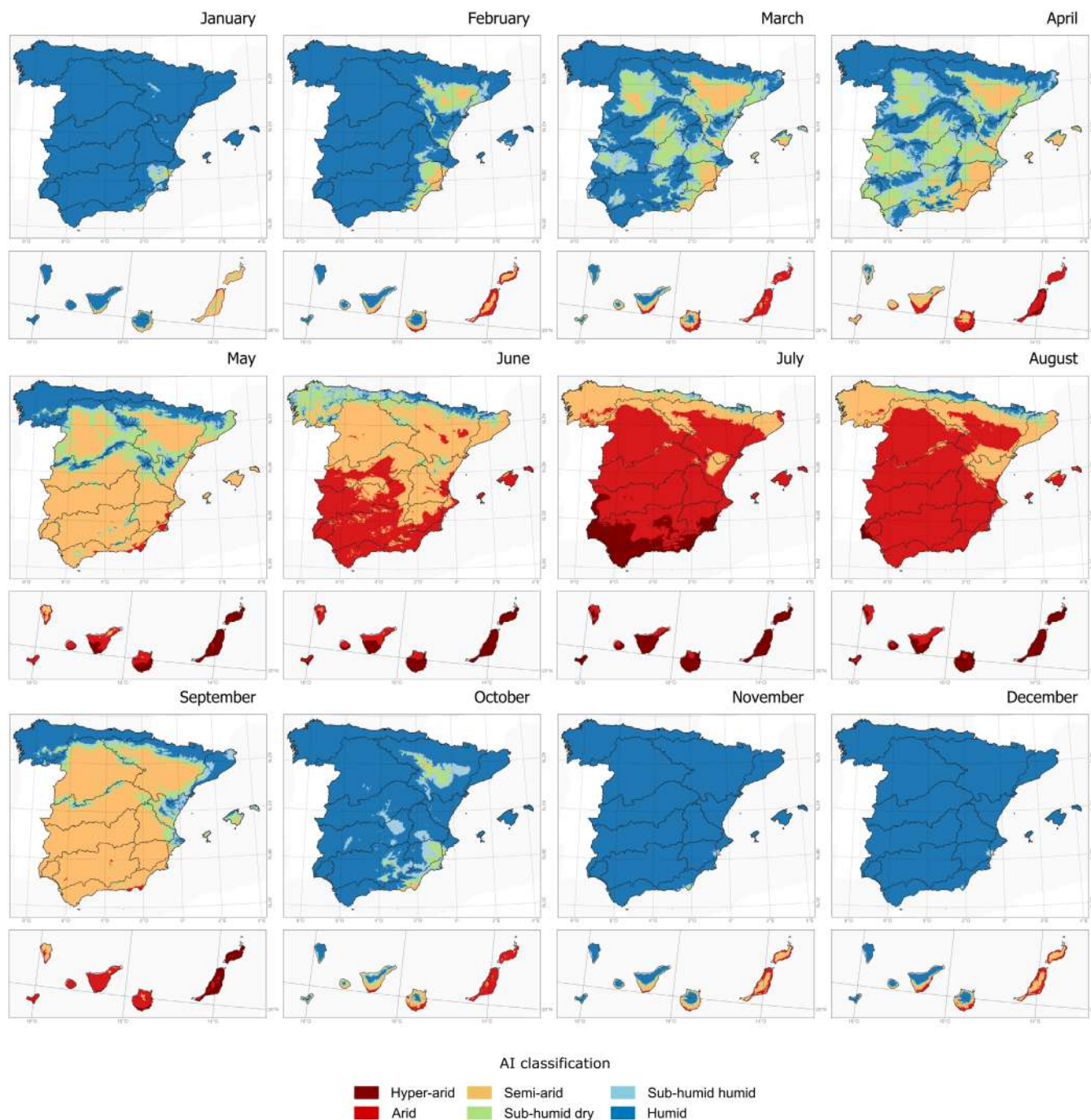


FIGURE 4 | Aridity Index categories over mainland Spain, Balearic Islands and the Canary Islands, computed over the period 1961–2020 at monthly time-scale. Legend colours as in Figure 1c. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

showed negative non-significant trends, with the exception of the south-eastern area along the Mediterranean coast, with non-significant positive trends. At the monthly level, significant negative trends found in February and June in the global time series over mainland Spain appear concentrated in the southern half of peninsular Spain and some sectors of the NE. Other months exhibit negative trends, such as the central part of the Cantabrian coast in April and August, or sectors of the south in July. There are also some areas showing positive trends at the monthly scale, the most striking being along the southern coast in September and some inner regions in July and August.

On the Canary Islands, negative trends were predominant at the annual level, with large areas achieving statistical significance. At the monthly level, the regions affected by significant negative trends were the north-western sector in April, May and September, and the piedmonts of the central islands in the latter 2 months. There were areas with positive trends in all the islands in July, and in the central and western islands in August.

Perhaps more interesting than changes in the quantitative index are the transitions in the aridity categories experienced between the two normal periods. The aridity class maps for the two periods (Figure 7a) show little differences among them upon first

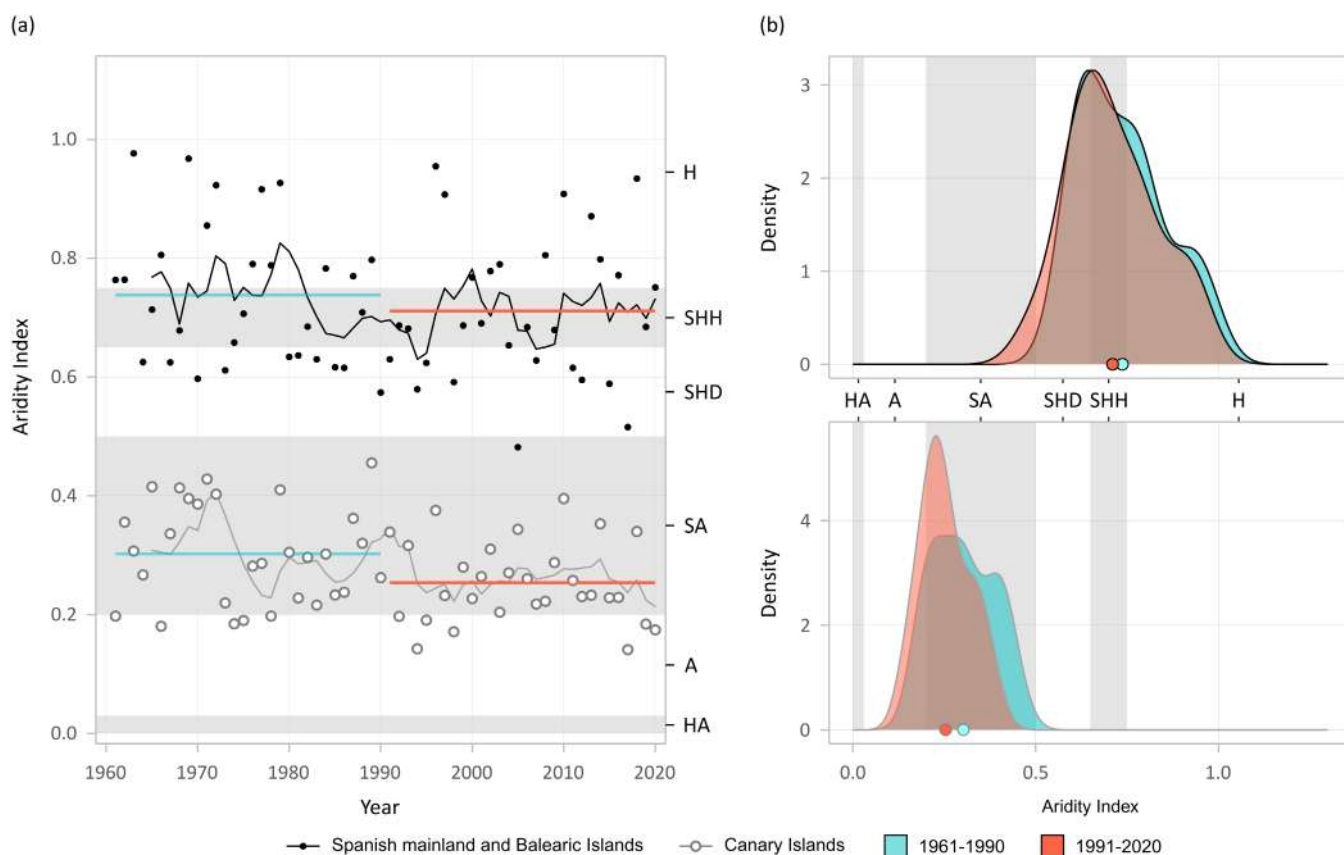


FIGURE 5 | (a) Temporal evolution of the annual Aridity Index over the Spanish mainland and the Balearic Islands (black dots and black line) and the Canary Islands (white dots and grey line), and mean AI values for the normal-periods 1961–1990 (blue horizontal lines) and 1991–2020 (red lines); and (b) density plots of AI annual values over the two spatial and temporal domains, with points representing the mean annual AI of each period. AI categories: hyper-arid (HA), arid (A), semi-arid (SA), dry sub-humid (SHD), humid sub-humid (SHH), and humid (H). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

inspection, but the transition maps and the Sankey diagrams offer a deeper insight about class changes. Thus, aridity class transitions towards more humid classes at the annual were marginal between the two periods, affecting only 0.6% of mainland Spain and 0.1% of the Canary Islands. Transitions towards more arid classes, on the other hand, affected 11.6% and 16.3% of the two spatial domains, respectively. Among these, the most relevant transitions were from dry sub-humid to semi-arid, from humid sub-humid to dry sub-humid, and from humid to humid sub-humid, accounting for 6%, 3% and 2% of the territory of mainland Spain, respectively. Only slightly more than 1% transitioned from semi-arid to arid. The spatial distribution of these changes reveals an interesting pattern, with the more arid classes expanding their domain along the interface with the less arid ones almost everywhere. Geographically, most of these changes occurred on the margins of the depressions, in the piedmonts of the main mountain areas.

On the Canary Islands, on the other hand, the most frequent transition was from dry sub-humid to semi-arid, affecting 8% of the territory, followed by transition from semi-arid to arid (3%) and humid sub-humid to dry sub-humid (3%). Most of these transitions occurred on the hillslopes of the main reliefs on the central and western islands, and especially on the leeward (N, NE) side.

Figures S5 to S7 and Table S2 provide a similar transition analysis at the monthly scale. As a summary, Figures 8 and 9

provide maps and global statistics about transitions towards more humid and more arid classes between the two periods. The most noteworthy results are the expansion of the arid and hyper-arid categories in May–June and August, respectively; and the expansion of the semi-arid and dry sub-humid classes in February, April and May. Overall, transitions towards more arid classes prevailed over transitions towards more humid. Over mainland Spain, June experienced the largest change towards more arid classes, affecting 39.7% of the territory, followed by April (22.7%), May (13.9%) and July (11.0%). On the other hand, transitions towards more humid classes were only significant in March (23.5%) and October (13%).

As for the Canary Islands, December (37.0%), November (34.3%), February (30.4%) saw the largest transitions towards more arid classes, followed by May (22.6%), September (19.4%) and April (18.6%). Transitions towards more humid classes, on the other hand, were less frequent, the most relevant being in October (13.0%), March (12.8%) and August (9.5%).

4 | Discussion

We present the first high-spatial resolution climatologies of the AI over an extended period (1961–2020), encompassing the whole of Spain. Our results not only provide detailed

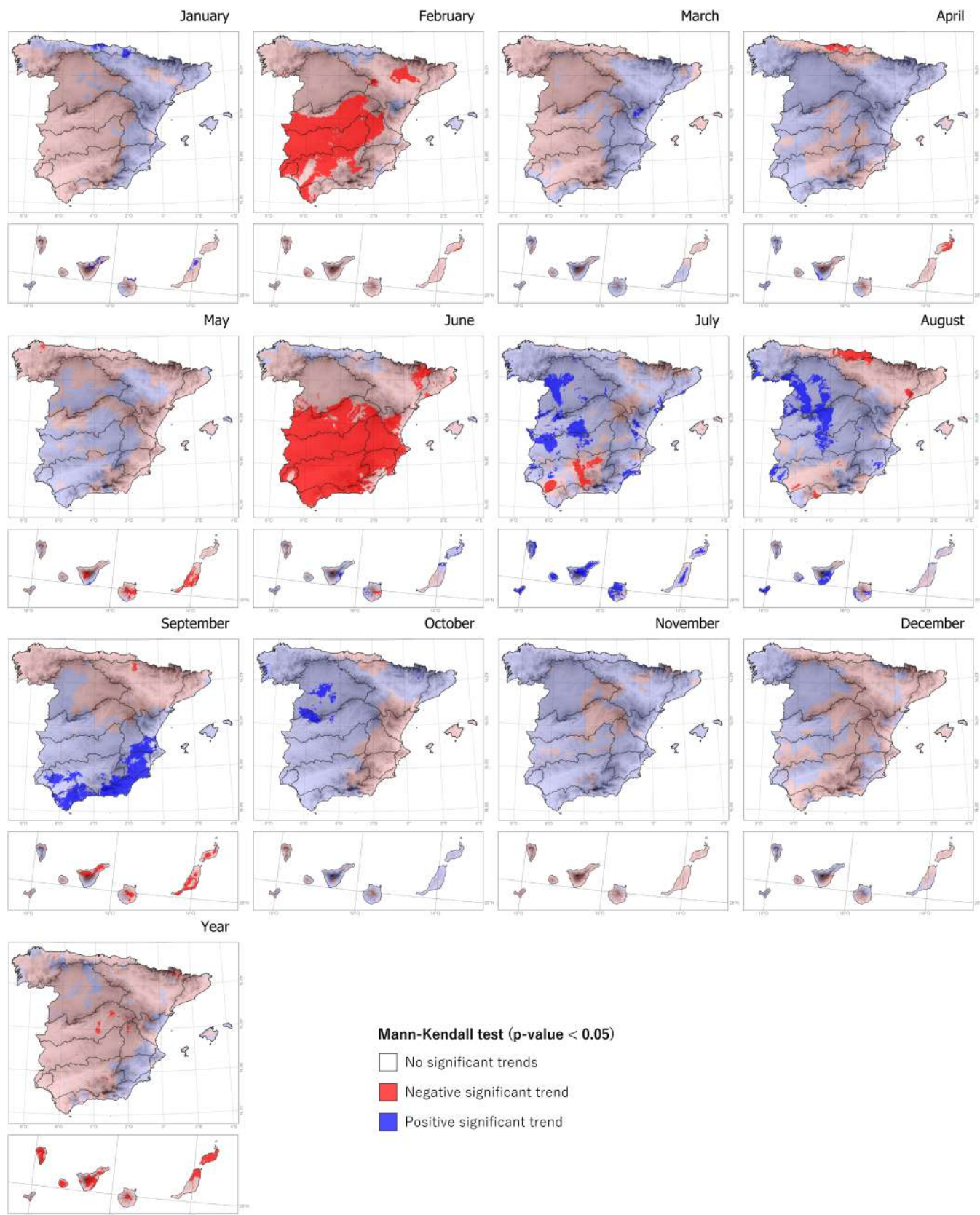


FIGURE 6 | Results of the Mann-Kendall trend test for monthly and annual Aridity Index over 1961–2020: red, significant negative trend (more arid); blue, significant positive trend (more humid). Results at the 95% confidence level. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

climatologies of annual and monthly climatic aridity, but also show that aridity increased over vast areas in Spain throughout the period 1961–2020, resulting in some areas transitioning

towards more arid climates. This is coherent with the evolution of mean annual temperature and precipitation over recent decades (Sandonis et al. 2021; González-Hidalgo et al. 2024), and

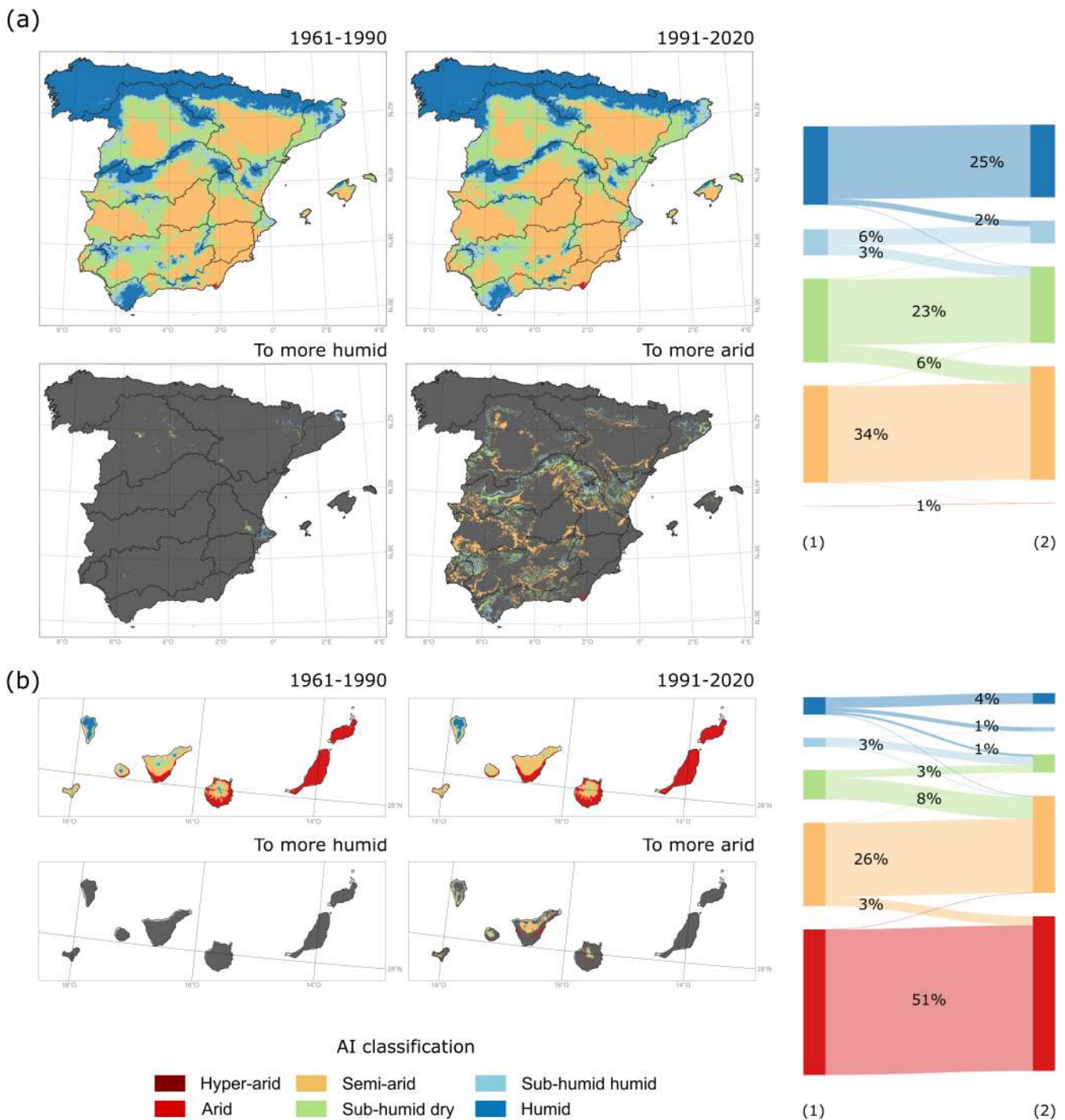


FIGURE 7 | Transitions of aridity classes between the two normal-periods, 1961–1990 and 1991–2020, at the annual scale: maps of AI classes for each period, and areas that changed towards more humid and more arid classes (no-change areas shown in grey), and Sankey diagrams showing the transitions of classes between the two periods (only those affecting more than 1% of the territory are labelled), for (a) mainland Spain and (b) the Canary Islands. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

with the results of changes in bioclimatic indices observed by López et al. (2017) between 1951 and 1980 and 1981 and 2010. Also, these results are consistent with changes in climatic aridity described in other areas of the Mediterranean basin, over a similar time frame (Gao and Giorgi 2008; Spinoni et al. 2015; Andrade and Corte-Real 2016; Huang et al. 2016; Cheval, Dumitrescu, and Birsan 2017; Paniagua et al. 2019; Myronidis and Nikolaos 2021). In their assessment of AI changes over Europe, Bestaková et al. (2023) found a general trend towards

a more arid climate over the period 1950–2019. Transitions towards drier categories in this study occurred mostly at latitudes between 45° N and 55° N, but not in the Mediterranean area, but that is due to the study focusing only on the transition between humid and dry climates, in a broad sense.

Chronologically, some authors argued that aridity increase over the Iberian Peninsula occurred especially in the late 1970s (Paniagua et al. 2019), while others maintain that it occurred

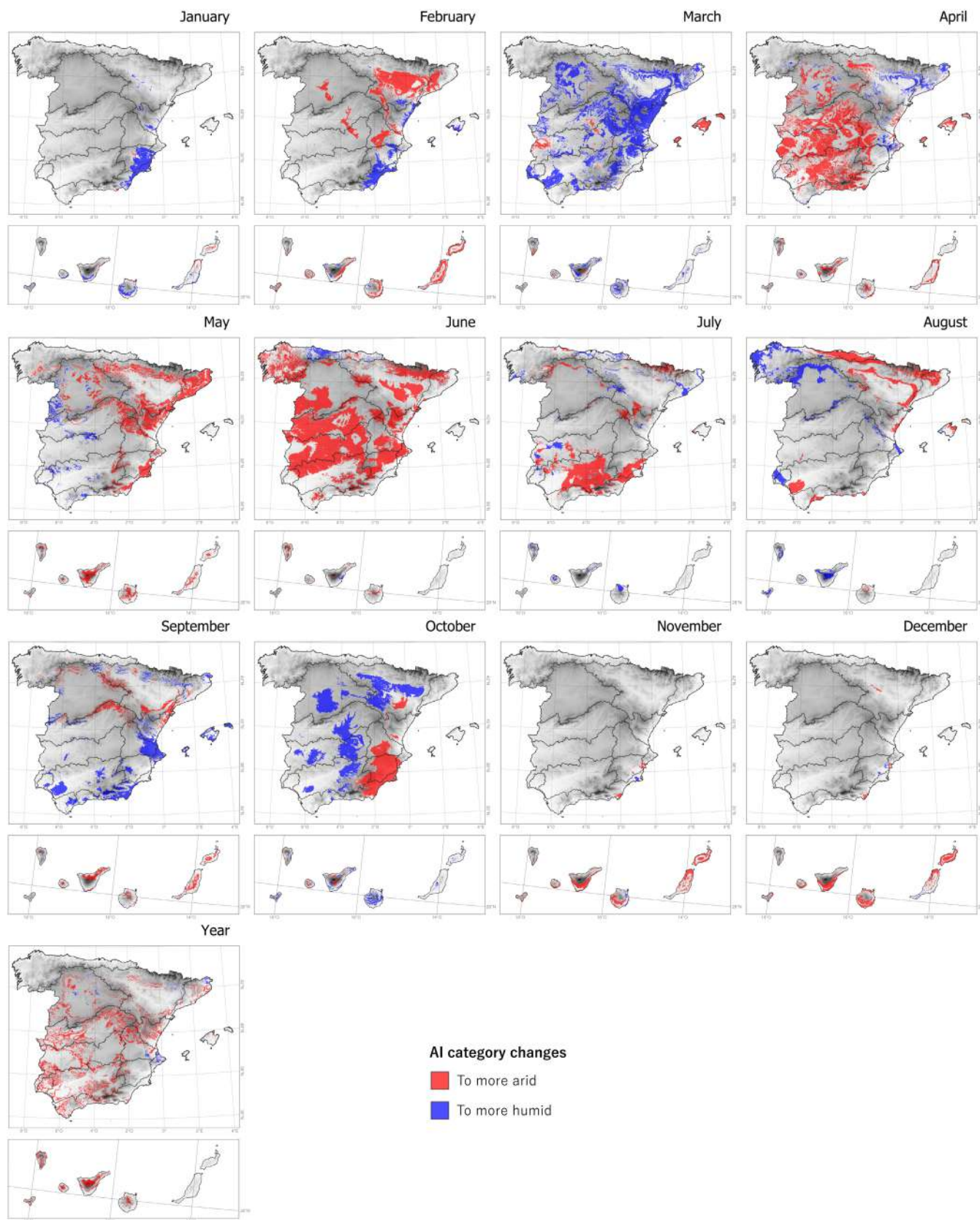


FIGURE 8 | Spatial distribution of changes in AI categories between the two normal periods at monthly and annual time-scale. Red: To arid class; blue: To more humid. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.8775)]

mostly since the 1990s (Bestaková et al. 2023). Here we focused on assessing changes between the two normal periods, 1961–1990 and 1991–2020, but inspection of the time series of annual

AI suggests that, over mainland Spain and the Balearic Islands, the main decreasing period for that index (therefore, increasing aridity) occurred around 1980 and 1995. In the Canary Islands,

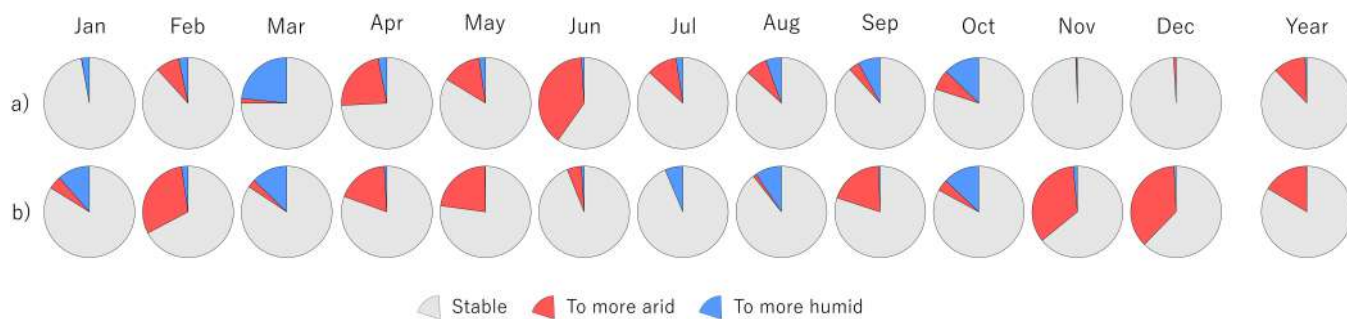


FIGURE 9 | Percent grid surface that transitioned towards a drier or wetter AI category, or that remained stable, between 1961 and 1990 and 1991 and 2020 normal periods in: (a) mainland Spain and the Balearic Islands and (b) the Canary Islands. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/joc.8775)]

on the other hand, the decrease of the annual AI happened more steadily through the analysis period. Given the climate differences by their latitudinal position, it seems that mechanisms of change could differ between both areas.

At the monthly scale, the most striking result has been the drying trends in February and June, which in the latter case caused transitions towards more arid climate classes over most of peninsular Spain. In the Canary Islands, transitions towards more arid classes took place mostly between November and February in the south and south-eastern slopes of the main reliefs (leeward side of the predominant trailing winds), and in September and April–May in the northern slopes (windward side). These intra-annual changes may have serious implications on the development of agriculture or the phenological cycles of natural vegetation, as pointed out by Tumajer et al. (2021) and by Haro-Monteagudo et al. (2023). Except for a few examples focused on small regions such as Moral et al. (2016), there are hardly any studies of aridity changes at sub-annual scales.

These results are coherent with the evolution of monthly temperature and precipitation over mainland Spain in the last decades. González-Hidalgo, Beguería, Peña-Angulo, and Sandonis (2022) and González-Hidalgo et al. (2024) studied the evolution of annual and monthly precipitation in mainland Spain considering different temporal domains. For the time window of this work (1961–2020), monthly precipitation totals exhibited negative trends over most of peninsular Spain in February and June. On the other hand, March–April, and September–October precipitation totals showed increasing trends over large parts of the Iberian Peninsula in the latter half of our study period (1991–2020 and 1981–2010, respectively). With respect to temperatures, González-Hidalgo, Beguería, Peña-Angulo, and Trullenque-Blanco (2022) and Peña-Angulo et al. (2020) showed that monthly temperature increased over most of mainland Spain in all months between 1965 and 2015, but most notably so between April and July (maximum daily temperature) and between April and November (minimum daily temperature). Maximum temperature is one of the drivers of the atmospheric evapotranspirative demand (AED), with a positive effect. Therefore, an increase in mean temperature has an effect of increasing AED, leading to more dry conditions (lower AI). In their study of potential evapotranspiration drivers and trends over Spain in the period 1961–2011, Azorin-Molina et al. (2015)

found a global increase of this variable at the annual and seasonal scales. In addition to the evolution of temperature, these authors showed that the recent evolution of relative air humidity also played a role in the evolution of AED, being therefore a main driver of climatic aridity, too.

On the Canary Islands, on the other hand, Vicente-Serrano et al. (2016) found that annual AED increased significantly over 1961–2013, with stronger trends in the summer months. Comparing the relative contributions of the radiative and aerodynamic components of potential evapotranspiration, they concluded that the latter had the largest contribution to the trend in potential evapotranspiration, with relative air humidity being the main driver of the observed changes. The digital climate atlas of the Canary Islands (Söllheim, Suarez, and Hernández 2024) provides insight into the evolution of precipitation and temperature. Considering the period 1991–2020 (thus covering only the second half of our study), temperature exhibited significant increases over most of the area at the annual level, with the trend concentrated in the summer months (July to October). Considering different time periods for the different islands (varying between 1970 and 2020 and 1991–2020), the digital atlas indicates that most precipitation trends are negative at the annual and monthly levels, although not achieving significance in most cases.

The AI, calculated as the ratio of precipitation (P) to potential evapotranspiration (PET), was selected for this study due to its ease of calculation and interpretation, widespread use, and established status as a standard metric for quantifying aridity (Vicente-Serrano et al. 2024). This widespread application facilitates direct comparison of our results with numerous other studies. While the AI has limitations, its advantages in terms of simplicity and comparability justify its use here.

A primary concern regarding the AI is its sensitivity to PET estimation. Although the UNEP's original definition employs the Hargreaves equation, we opted for the more physically based Penman-Monteith method. While different PET calculations can lead to minor variations in the spatial distribution of aridity classes, they are unlikely to substantially affect the analysis of temporal AI changes, which is the focus of this study.

Other criticisms of the AI include its neglect of spatial variations in soil water storage and precipitation concentration. While soil

water storage can influence plant water availability under similar climatic conditions, incorporating it requires a more complex water balance model, which is beyond the scope of this climatic index analysis. Similarly, while highly concentrated precipitation (common along the Mediterranean coast of Spain; Serrano-Notivol et al. 2018) can reduce effective precipitation and thus increase effective aridity, the AI's reliance on total precipitation over a longer period (typically annual) is consistent with its focus on broad-scale climatic conditions.

5 | Conclusion

Our study examined current conditions and recent change of climatic aridity over Spain, covering the period 1961–2020. The main conclusions drawn from our work are:

- We present spatially detailed climatologies of the AI (ratio of precipitation to potential evapotranspiration) over the whole Spanish territories, at the annual and the monthly scales, over the period 1961–2020.
- A slight decrease in the AI values has been detected between the two normal periods 1961–1990 and 1991–2020 on an annual scale, which was more intense in the Canary Islands than over peninsular Spain and the Balearic Islands.
- A 12% of peninsular Spain and the Balearic islands have experienced a transition towards more arid AI categories between 1961 and 1990 and 1991 and 2020, while almost no areas have undergone a transition towards more humid ones.
- In the Canary Islands, the transition towards more arid classes involved 16% of the territory.
- At the monthly level, the most striking changes occurred in June, with almost 40% of the territory transitioning towards more arid categories.
- Transitions towards more humid conditions have only been relevant in March (24%) and October (13%) of the territory, and did not counter the negative trends found in other months.

Author Contributions

Santiago Beguería: conceptualization, funding acquisition, writing – original draft, methodology, software, supervision, formal analysis. **Victor Trullenque-Blanco:** methodology, writing – original draft, visualization, formal analysis. **Sergio M. Vicente-Serrano:** writing – review and editing, conceptualization, funding acquisition, data curation. **J. Carlos González-Hidalgo:** writing – review and editing, conceptualization, funding acquisition, data curation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data repository: <https://doi.org/10.20350/digitalCSIC/16265> (Beguería and Trullenque-Blanco 2024). Interactive visualisation and monitoring system: <https://monitordearidez.csic.es>.

References

- Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. “On Underestimation of Global Vulnerability to Tree Mortality and Forest Die-Off From Hotter Drought in the Anthropocene.” *Ecosphere* 6: art129. <https://doi.org/10.1890/ES15-00203.1>.
- Allen, G. R., S. L. Pereira, D. Raes, and M. Smith. 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*, 56. Rome, Italy: Food and Agricultural Organization of the United Nations (FAO). <https://www.fao.org/4/X0490E/x0490e00.htm>.
- Andrade, C., and J. Corte-Real. 2016. “Aridity Conditions in the Iberian Peninsula During the XX Century.” *International Journal of Environmental Sciences* 1: 52–58. <https://www.ias.org/ias/loaded/ijes/2016/008-0009.pdf>.
- Azarin-Molina, C., S. M. Vicente-Serrano, A. Sanchez-Lorenzo, et al. 2015. “Atmospheric Evaporative Demand Observations, Estimates and Driving Factors in Spain (1961–2011).” *Journal of Hydrology* 523: 262–277. <https://doi.org/10.1016/j.jhydrol.2015.01.046>.
- Beguería, S., and V. Trullenque-Blanco. 2024. “Aridity Index in Spain, v1.0.0. DIGITAL.CSIC.” <https://doi.org/10.20350/digitalCSIC/16265>.
- Berdugo, M., M. Delgado-Baquerizo, S. Soliveres, et al. 2020. “Global Ecosystem Thresholds Driven by Aridity.” *Science* 367, no. 6479: 787–790. <https://doi.org/10.1126/science.aay5958>.
- Berg, A., K. Findell, B. Lintner, et al. 2016. “Land-Atmosphere Feedbacks Amplify Aridity Increase Over Land Under Global Warming.” *Nature Climate Change* 6: 869–874. <https://doi.org/10.1038/nclimate3029>.
- Bešćáková, Z., F. Strnad, M. R. Vargas, et al. 2023. “Changes of the Aridity Index in Europe from 1950 to 2019.” *Theoretical and Applied Climatology* 151, no. 1: 587–601. <https://doi.org/10.1007/s00704-022-04266-3>.
- Byrne, M. P., and P. A. O’Gorman. 2018. “Trends in Continental Temperature and Humidity Directly Linked to Ocean Warming.” *Proceedings of the National Academy of Sciences of the United States of America* 15: 4863–4868. <https://doi.org/10.1073/pnas.1722312115>.
- Cheval, S., A. Dumitrescu, and M. V. Birsan. 2017. “Variability of the Aridity in the South-Eastern Europe Over 1961–2050.” *Catena* 151: 74–86. <https://doi.org/10.1016/j.catena.2016.11.029>.
- Dai, A. 2011. “Drought Under Global Warming: A Review.” *Wiley Interdisciplinary Reviews: Climate Change* 2, no. 1: 45–65. <https://doi.org/10.1002/wcc.81>.
- D’Odorico, P., A. Bhattachan, K. F. Davis, S. Ravi, and C. W. Runyan. 2013. “Global Desertification: Drivers and Feedbacks.” *Advances in Water Resources* 51: 326–344. <https://doi.org/10.1016/j.advwatres.2012.01.013>.
- Domínguez-Castro, F., S. M. Vicente-Serrano, M. Tomás-Burguera, et al. 2019. “High Spatial Resolution Climatology of Drought Events for Spain: 1961–2014.” *International Journal of Climatology* 39, no. 13: 5046–5062. <https://doi.org/10.1002/joc.6126>.
- Douville, H., K. Raghavan, J. Renwick, et al. 2021. “Water Cycle Changes.” In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, et al., 1055–1210. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. <https://doi.org/10.1017/9781009157896.010>.
- Feeley, K. J., C. Bravo-Avila, B. Fadrique, T. M. Perez, and D. Zuleta. 2020. “Climate-Driven Changes in the Composition of New World Plant Communities.” *Nature Climate Change* 10: 965–970. <https://doi.org/10.1038/s41558-020-0873-2>.
- Fu, Q., and S. Feng. 2014. “Responses of Terrestrial Aridity to Global Warming.” *Journal of Geophysical Research: Atmospheres* 119, no. 13: 7863–7875. <https://doi.org/10.1002/2014JD021608>.
- Gao, X., and F. Giorgi. 2008. “Increased Aridity in the Mediterranean Region Under Greenhouse Gas Forcing Estimated From High

- Resolution Simulations With a Regional Climate Model.” *Global and Planetary Change* 62, no. 3–4: 195–209. <https://doi.org/10.1016/j.gloplacha.2008.02.002>.
- Glantz, M. H. 2004. “‘Desertification’ Entry.” In *Encyclopedia of World Climatology*, edited by J. E. Oliver, 318–323. Dordrecht, The Netherlands: Springer. <https://link.springer.com/referencework/10.1007/1-4020-3266-8>.
- González-Hidalgo, J. C., S. Beguería, D. Peña-Angulo, and L. Sandonis. 2022. “Variability of Maximum and Minimum Monthly Mean Air Temperatures Over Mainland Spain and Their Relationship With Low-Variability Atmospheric Patterns for Period 1916–2015.” *International Journal of Climatology* 42, no. 3: 1723–1741. <https://doi.org/10.1002/joc.7331>.
- González-Hidalgo, J. C., S. Beguería, D. Peña-Angulo, and V. Trullenque-Blanco. 2022. “MOPREDAS_century Database and Precipitation Trends in Mainland Spain, 1916–2020.” *International Journal of Climatology* 43: 3828–3840. <https://doi.org/10.1002/joc.8060>.
- González-Hidalgo, J. C., V. Trullenque-Blanco, S. Beguería, and D. Peña-Angulo. 2024. “Seasonal Precipitation Changes in the Western Mediterranean Basin: The Case of the Spanish Mainland, 1916–2015.” *International Journal of Climatology* 44, no. 5: 1277–1831. <https://doi.org/10.1002/joc.8412>.
- Greve, P., M. L. Roderick, A. M. Ukkola, and Y. Wada. 2019. “The Aridity Index Under Global Warming.” *Environmental Research Letters* 14: 124006. <https://doi.org/10.1088/1748-9326/ab5046>.
- Gulev, S. K., P. W. Thorne, J. Ahn, et al. 2021. “Changing State of the Climate System.” In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, et al., 287–422. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. <https://doi.org/10.1017/9781009157896.004>.
- Haro-Monteagudo, D., L. Palazón, C. Zoumides, and S. Beguería. 2023. “Optimal Implementation of Climate Change Adaptation Measures to Ensure Long-Term Sustainability on Large Irrigation Systems.” *Water Resources Management* 37: 2909–2924. <https://doi.org/10.1007/s11269-022-03225-x>.
- Huang, J., M. Ji, Y. Xie, S. Wang, Y. He, and J. Ran. 2016. “Global Semi-Arid Climate Change Over Last 60 Years.” *Climate Dynamics* 46, no. 3–4: 1131–1150. <https://doi.org/10.1007/s00382-015-2636-8>.
- IPCC. 2014. “Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.” In *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press. <https://www.ipcc.ch/report/ar5/wg2/>.
- IPCC. 2021. “Climate Change 2021: The Physical Science Basis.” In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1924. United Kingdom and New York, NY, USA: Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>.
- Lenton, T. M., D. I. Armstrong McKay, S. Loriani, et al. 2023. *The Global Tipping Points Report 2023*. Exeter, UK: University of Exeter.
- Lian, X., S. Piao, A. Chen, et al. 2021. “Multifaceted Characteristics of Dryland Aridity Changes in a Warming World.” *Nature Reviews Earth and Environment* 2: 232–250. <https://doi.org/10.1038/s43017-021-00144-0>.
- López, M. L., D. Peña-Angulo, R. Marco, M. S. López, and J. C. González-Hidalgo. 2017. “Variaciones espaciales y temporales de las condiciones bioclimáticas en la España peninsular (1951–2010).” *Estudios Geográficos* 78, no. 283: 553–577. <https://doi.org/10.3989/estgeogr.201719>.
- Ma, X., A. Huete, S. Moran, G. Ponce-Campos, and D. Eamus. 2015. “Abrupt Shifts in Phenology and Vegetation Productivity Under Climate Extremes.” *Journal of Geophysical Research: Biogeosciences* 120: 2036–2052. <https://doi.org/10.1002/2015JG003144>.
- Macias, M., L. Andreu, O. Bosch, J. J. Camarero, and E. Gutiérrez. 2006. “Increasing Aridity Is Enhancing Silver Fir (*Abies alba* Mill.) Water Stress in Its South-Western Distribution Limit.” *Climate Change* 79: 289–313. <https://doi.org/10.1007/s10584-006-9071-0>.
- Maestre, F. T., J. L. Quero, N. J. Gotelli, et al. 2012. “Plant Species Richness and Ecosystem Multifunctionality in Global Drylands.” *Science* 335, no. 6065: 214–218. <https://doi.org/10.1126/science.1215442>.
- Milly, P. C. D., and K. A. Dunne. 2016. “Potential Evapotranspiration and Continental Drying.” *Nature Climate Change* 6: 946–949. <https://doi.org/10.1038/nclimate3046>.
- Mirzabaev, A., L. C. Stringer, T. A. Benjaminsen, et al. 2022. “Cross-Chapter Paper 3: Deserts, Semiarid Areas and Desertification.” In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H.-O. Pörtner, D. C. Roberts, M. Tignor, et al., 2195–2231. Cambridge, UK and New York, NY, USA: Cambridge University Press. <https://doi.org/10.1017/9781009325844.020>.
- MITECO. 2022. *Estrategia Nacional de Lucha con tra la Desertificación*, 155. Madrid: Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO). https://www.miteco.gob.es/content/dam/miteco/es/biodiversidad/temas/desertificacion-restauracion/estrategia_nacional_lucha_desertificacion_web_2022_tcm30-542085.pdf.
- Moral, F. J., F. J. Rebollo, L. L. Paniagua, A. García-Martín, and F. Honorio. 2016. “Spatial distribution and comparison of aridity indices in Extremadura, southwestern Spain.” *Theoretical and Applied Climatology* 126: 801–814. <https://doi.org/10.1007/s00704-015-1615-7>.
- Moreno-Jiménez, E., C. Plaza, H. Saiz, R. Manzano, M. Flagmeier, and F. T. Maestre. 2019. “Aridity and Reduced Soil Micronutrient Availability in Global Drylands.” *Nature Sustainability* 2: 371–377. <https://doi.org/10.1038/s41893-019-0262-x>.
- Myronidis, D., and T. Nikolaos. 2021. “Changes in Climatic Patterns and Tourism and Their Concomitant Effect on Drinking Water Transfers Into the Region of South Aegean, Greece.” *Stochastic Environmental Research and Risk Assessment* 35: 1725–1739. <https://doi.org/10.1007/s00477-021-02015-y>.
- Paniagua, L., A. García-Martín, F. Moral, et al. 2019. “Aridity in the Iberian Peninsula (1960–2017): Distribution, Tendencies, and Changes.” *Theoretical and Applied Climatology* 138: 811–830. <https://doi.org/10.1007/s00704-019-02866-0>.
- Peña-Angulo, D., J. C. Gonzalez-Hidalgo, L. Sandonis, et al. 2020. “Seasonal Temperature Trends on the Spanish Mainland: A Secular Study (1916–2015).” *International Journal of Climatology* 41: 3071–3084. <https://doi.org/10.1002/joc.7006>.
- Reynolds, J. F., D. M. Stafford Smith, E. F. Lambin, et al. 2007. “Global Desertification: Building a Science for Dryland Development.” *Science* 316, no. 5826: 847–851. <https://doi.org/10.1126/science.1131634>.
- Roderick, M. L., P. Greve, and G. D. Farquhar. 2015. “On the Assessment of Aridity With Changes in Atmospheric CO₂.” *Water Resources Research* 51: 5450–5463. <https://doi.org/10.1002/2015WR017031>.
- Sandonis, L., J. C. González-Hidalgo, D. Peña-Angulo, and S. Beguería. 2021. “Mean Temperature Evolution on the Spanish Mainland 1916–2015.” *Climate Research* 82: 177–189. <https://doi.org/10.3354/cr01627>.
- Scheff, J., and D. M. W. Frierson. 2015. “Terrestrial Aridity and Its Response to Greenhouse Warming Across CMIP5 Climate Models.” *Journal of Climatology* 28: 5583–5600. <https://doi.org/10.1175/JCLI-D-14-00480.1>.
- Schlesinger, W. H., and E. S. Bernhardt. 2020. *Biogeochemistry: An Analysis of Global Change*. 4th ed, 749. London: Academic Press.

- Serrano-Notivol, R., J. Martín-Vide, M. A. Saz, et al. 2018. "Spatio-Temporal Variability of Daily Precipitation Concentration in Spain Based on a High-Resolution Gridded Data Set." *International Journal of Climatology* 38, no. S1: 518–530. <https://doi.org/10.1002/joc.5387>.
- Söllheim, Á. L. L., P. M. Suarez, and F. G. Hernández. 2024. "The Digital Climate Atlas of the Canary Islands: A Tool to Improve Knowledge of Climate and Temperature and Precipitation Trends in the Atlantic Islands." *Climate Services* 34: 100487. <https://doi.org/10.1016/j.cliser.2024.100487>.
- Spinoni, J., J. Vogt, G. Naumann, H. Carrao, and P. Barbosa. 2015. "Towards Identifying Areas at Climatological Risk of Desertification Using the Koppen-Geiger Classification and FAO Aridity Index." *International Journal of Climatology* 35, no. 9: 2210–2222. <https://doi.org/10.1002/joc.4124>.
- Stadler, S. J. 2004. "Aridity Indexes' Entry." In *Encyclopedia of World Climatology*, edited by J. E. Oliver, 64–89. Dordrecht, The Netherlands: Springer. <https://link.springer.com/referencework/10.1007/1-4020-3266-8>.
- Stephenson, N. L. 1990. "Climatic Control of Vegetation Distribution: The Role of the Water Balance." *American Naturalist* 135, no. 5: 649–670. <https://doi.org/10.1086/285067>.
- Tomas-Burguera, M., S. M. Vicente-Serrano, M. Grimalt, and S. Beguería. 2017. "Accuracy of Reference Evapotranspiration (ET₀) Estimates Under Data Scarcity Scenarios in the Iberian Peninsula." *Agricultural Water Management* 182: 103–116. <https://doi.org/10.1016/j.agwat.2016.12.013>.
- Trenberth, K. E., A. Dai, G. van der Schrier, et al. 2014. "Global Warming and Changes in Drought." *Nature Climate Change* 4: 17–22. <https://doi.org/10.1038/nclimate2067>.
- Tumajer, J., V. V. Shishov, V. A. Ilyin, and J. J. Camarero. 2021. "Intra-Annual Growth Dynamics of Mediterranean Pines and Junipers Determines Their Climatic Adaptability." *Agricultural and Forest Meteorology* 311, no. 15: 108685. <https://doi.org/10.1016/j.agrformet.2021.108685>.
- Ullah, S., Q. You, M. Sachindra, et al. 2022. "Spatiotemporal Changes in Global Aridity in Terms of Multiple Aridity Indices: An Assessment Based on the CRU Data." *Atmospheric Research* 268: 105998. <https://doi.org/10.1016/j.atmosres.2021.105998>.
- UNCCD. 2017. *The Global Land Outlook*. Bonn, Germany: United Nations, United for Land. <https://www.unccd.int/resources/global-land-outlook/overview>.
- United Nations Environmental Programme. 1992. *World Atlas of Desertification*, 034055512. Edward Arnold, London: United Nations Environment Programme. <https://wedocs.unep.org/20.500.11822/42137>.
- Van Leeuwen, C. C. E., E. L. H. Cammeraat, J. de Vente, and C. Boix-Fayos. 2019. "The Evolution of Soil Conservation Policies Targeting Land Abandonment and Soil Erosion in Spain: A Review." *Land Use Policy* 83: 174–186. <https://doi.org/10.1016/j.landusepol.2019.01.018>.
- Vaughn, D. M. 2004. 'Aridity' Entry, *Encyclopedia of World Climatology*, edited by J. E. Oliver, 85–89. Dordrecht, The Netherlands: Editorial Springer. <https://link.springer.com/referencework/10.1007/1-4020-3266-8>.
- Vicente-Serrano, S. M., A. Zouber, T. Lasanta, and Y. Pueyo. 2012. "Dryness Is Accelerating Degradation of Vulnerable Shrublands in Semiarid Mediterranean Environments." *Ecological Monographs* 82, no. 4: 407–424. <https://doi.org/10.1890/11-2164.1>.
- Vicente-Serrano, S., T. R. McVicar, D. G. Miralles, Y. Yang, and M. Tomas-Burguera. 2020. "Unraveling the Influence of Atmospheric Evaporative Demand on Drought and Its Response to Climate Change." *Wiley Interdisciplinary Reviews* 11, no. 2: e632. <https://doi.org/10.1002/wcc.632>.
- Vicente-Serrano, S. M., C. Azorin-Molina, A. Sanchez-Lorenzo, et al. 2016. "Recent Changes and Drivers of the Atmospheric Evaporative Demand in the Canary Islands." *Hydrology and Earth System Sciences* 20, no. 8: 3393–3410. <https://doi.org/10.5194/hess-20-3393-2016>.
- Vicente-Serrano, S. M., S. Beguería, and J. I. López-Moreno. 2010. "A Multi-Scalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index." *Journal of Climate* 23, no. 7: 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>.
- Vicente-Serrano, S. M., F. Domínguez-Castro, F. Reig, et al. 2022. "A Near Real-Time Drought Monitoring System for Spain Using Automatic Weather Station Network." *Atmospheric Research* 271: 106095. <https://doi.org/10.1016/j.atmosres.2022.106095>.
- Vicente-Serrano, S. M., R. García-Herrera, D. Peña-Angulo, et al. 2022. "Do CMIP Models Capture Long-Term Observed Annual Precipitation Trends?" *Climate Dynamics* 58: 2825–2842. <https://doi.org/10.1007/s00382-021-06034-x>.
- Vicente-Serrano, S. M., T. Lasanta, and C. Gracia. 2010. "Aridification Determines Changes in Forest Growth in *Pinus halepensis* Forests Under Semiarid Mediterranean Climate Conditions." *Agricultural and Forest Meteorology* 150, no. 4: 614–628. <https://doi.org/10.1016/j.agrfor.2010.02.002>.
- Vicente-Serrano, S. M., D. G. Miralles, N. McDowell, et al. 2022. "The Uncertain Role of Rising Atmospheric CO₂ on Global Plant Transpiration." *Earth-Science Reviews* 230: 104055. <https://doi.org/10.1016/j.earscirev.2022.104055>.
- Vicente-Serrano, S. M., R. Nieto, L. Gimeno, et al. 2018. "Recent Changes of Relative Humidity: Regional Connections With Land and Ocean Processes." *Earth System Dynamics* 9: 915–937. <https://doi.org/10.5194/esd-9-915-2018>.
- Vicente-Serrano, S. M., N. Pricope, A. Toreti, et al. 2024. "Provision of Science-Based Evidence on the Historical Regional and Global Aridity Trends and Future Projections." In *Science Policy Interface-United Nations Convention to Combat Desertification. SPI Report. UNCCD-SPI Technical Series*. Bonn, Germany.
- Vicente-Serrano, S. M., M. Tomás-Burguera, S. Beguería, et al. 2017. "A High Resolution Dataset of Drought Indices for Spain." *Data* 2, no. 3: 22. <https://doi.org/10.3390/data2030022>.
- Weiskopf, S. R., M. A. Rubenstein, L. G. Crozier, et al. 2020. "Climate Change Effects on Biodiversity, Ecosystems, Ecosystem Services, and Natural Resource Management in the United States." *Science of the Total Environment* 733: 137782. <https://doi.org/10.1016/j.scitotenv.2020.137782>.
- World Meteorological Organization (WMO). 2017. *WMO Guidelines on the Calculation of Climate Normals*. Vol. 1203, 29. Geneva, Switzerland: World Meteorological Organization. https://www.ncei.noaa.gov/pub/data/normals/WMO/Guidelines%20for%20the%20Calculation%20of%20Climate%20Normals.WMO%20No1203_en.pdf.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.