Received: 5 May 2023 | Revised: 6 February 2024 | Accepted: 21 February 2024

DOI: 10.1002/joc.8412

RESEARCH ARTICLE

International Journal of Climatology RMetS

Seasonal precipitation changes in the western Mediterranean Basin: The case of the Spanish mainland, 1916–2015

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Funding information
Ministerio de Ciencia e Innovación-FSE, Grant/Award Numbers: PID2020-116860RB-C22, CGL2017-83866-C3-1-R; Regional Government of Aragon, Geoenvironmental and Global Climate Change Research Group, Grant/Award Number: E02-17R

Abstract

This study examines the spatial and temporal variations in seasonal precipitation patterns across the Spanish mainland, within the western Mediterranean Basin, spanning the years 1916–2015. Utilizing the recently developed MOPREDAS_century database at a 10 × 10 km grid resolution, our analysis reveals predominantly negative trends in precipitation across the study area over the entire period, primarily driven by declines in spring precipitation, with lesser decreases in summer and winter. Notably, these trends exhibit complexity, manifesting as two distinct pulses occurring roughly at the outset and conclusion of the 20th century. However, upon employing a moving windows analysis, we find that since the mid-1970s, seasonal precipitation trends have largely been nonsignificant. Spatially, the precipitation regime across 1916–2015 delineates three primary zones: a winter-maximum zone in the north, an autumn-maximum zone along the eastern coast, and a transition from winter-maximum to spring-maximum towards the western and inland regions. Noteworthy shifts in this spatial distribution are evident over the four 25-year intervals examined. Initially, during 1916–1940, winter, autumn and spring regimes occupied 44.1%, 24.2% and 31.7% of the land, respectively. Subsequently, in the periods 1941–1965 and 1966–1990, winter dominance expanded to over 50% of the grid area, while spring varied between 34.7% and 25.5%, and autumn decreased notably to 12.4% and 13.5%. Lastly, significant alterations occurred in the final period of 1991–2015, with winter coverage decreasing to 33.7%, spring to 15.8% and autumn expanding to 50.1% of the grid area. In summary, the prevalent winter and spring regimes at the dawn of the 20th century have transitioned towards an autumn-dominated regime, particularly in much of the central and western Spanish mainland, with these shifts possibly linked to the evolving precipitation trends. These findings contribute novel insights, particularly pre-1950, and align with published results post-1950 across the Mediterranean, particularly in its western regions. Furthermore, they suggest a potential connection between changes in the spatial distribution of seasonal precipitation regimes and temporal variations in the primary moisture sources over the study area.

KEYWORDS

Mediterranean Basin, MOPREDAS_century, precipitation, seasonal regime, Spanish mainland

1 | INTRODUCTION

The Mediterranean Basin is a highly populated area with a high water demand and scarce resources, where water resources management is key to social and natural systems. This fact explains why the analysis of precipitation has been the subject of abundant research. Nevertheless, the research on precipitation in the Mediterranean Basin is far from complete. Traditionally, and following Schonwiese and Rapp (1997), a negative trend in the mean annual precipitation in the entirety of Southern Europe (i.e., the Mediterranean Basin) has been assumed. This idea has been repeated by Tanarhte et al. (2012), Caloiero et al. (2018a, 2018b), Deitch et al. (2017) and Seager et al. (2020), among others, and is mostly attributed to a decrease in winter precipitation (Hoerling et al., 2012; Quadrelli et al., 2001). However, detailed reviews by Norrant and Douguedroit (2005), Reiser and Kutiel (2010) or Gonzalez-Hidalgo et al. (2011) have shown that noticeable variations have occurred around the basin. Recent study encompassing the whole Mediterranean Basin has not found overall negative or significant trends, contrary to prior assumptions (Peña-Angulo et al., 2020).

Previous seasonal analyses in the western Mediterranean revealed a negative trend in spring and positive in autumn during the last decades of the 20th century (López-Moreno et al., 2009). Both trends were confirmed in the Spanish mainland (de Luis et al., 2010). Positive trends in autumn precipitation have also been found in the Moroccan Atlas (Diani et al., 2019) or Algeria (Achite & Ouillon, 2016; Bougara et al., 2020; Bouklikha et al., 2021). Particularly, the spring trend was associated with a general decrease in precipitation in March in the western sector (see revision in Gonzalez-Hidalgo et al., 2023), but the same trend has also been detected in the central basin in Croatia (Cindrić et al., 2016) and Italy (Boi, 2018; Caloiero et al., 2018a, 2018b, 2020), and to the east in Turkey (Güner Bacanli, 2017; Yavuz & Erdoğan, 2012). A second, less well-known pattern is a negative trend in February, which has been detected in the last decades of the 20th century in Algeria (Bouklikha et al., 2021), Turkey (Partal & Kahya, 2006; Yavuz & Erdoğan, 2012), Moldova (Mihăilă et al., 2017), Montenegro (Gocic & Trajkovic, 2014) and parts of Serbia (Milovanović et al., 2017). Meanwhile, positive trends in autumn have been associated to widespread positive trends, particularly in September and October in the western area (Gonzalez-Hidalgo et al., 2023), but also in Italy (Bartolini et al., 2018) and Serbia (Luković et al., 2015), and to the east in Israel (Ben-Gai et al., 1993), Turkey (Türkeş et al., 2009; Yaman & Ertuğrul, 2020; Yavuz & Erdoğan, 2012), Romania (Cheval et al., 2014) and Moldova (Mihăilă et al., 2017).

In brief, precipitation trends around the Mediterranean Basin during the last decades of the 20th century appear to have gone through a period of spring loss just as autumn precipitation appears to have increased, with implications for seasonal regimes and potential impacts on ecosystems and human activities such as agriculture. For example, in the Spanish mainland, López et al. (2017), by comparing phytoclimatic indices in two normal periods (1951–1980 and 1981–2010), observed a spread of hydric stress conditions from the central area towards their wetter mountain margins (see López et al., 2017, fig. 1). Nevertheless, information from before 1950 is scarce and the centennial context of precipitation evolution is hardly known.

Previous analysis has shown that seasonal rainfall regimes have changed over extended areas of the Iberian Peninsula during the second half of the 20th century, and de Luis et al. (2010) identified that the highest contribution of seasonal precipitation has shifted from winter–spring towards autumn (1946–2005). This change is highly relevant, for instance, for winter cereals that depend on spring rains, and may also cause problems for both vines and olive trees by reducing the soil water reserve during the dry summer season. Moreover, seasonal precipitation changes can affect the river regimes (Estrela et al., 2012) and water storage in the reservoir network, with impacts on irrigated crops and other water uses.

This work analyses the seasonal precipitation regime changes in western Mediterranean basin (Spanish mainland, Iberian Peninsula) during the period 1916–2015, using the new MOPREDAS_century database (Beguería et al., 2023). The study includes the analysis of seasonal trends over the whole period, and also over subperiods using a moving-window approach, as well as the analysis of spatial changes in precipitation regimes in four 25-year periods. The main objective is to establish a centennial background of the changes in seasonal precipitation regimes and up to date previous research.

2 | STUDY AREA

The Iberian Peninsula (IP, mostly Spanish mainland; Figure 1) is located between two contrasted water masses (Atlantic Ocean and Mediterranean Sea) in the subtropical transition latitudinal band, and is characterized by relief systems (mountain ranges and main valleys and plateaus) that are distributed in a west-to-east direction. In this area the seasonal precipitation regimes distribution is autumn-maximum along the East Mediterranean coastland, winter-maximum in the north and west of the IP, and finally maximum-spring time is common in the inland areas. This spatial distribution of seasonal rainfall regimes is mostly accounted for by the concurrence of spatial distribution of mountain chains and an oceanic component from the Atlantic (more evident to the north and west) and the Mediterranean component (to the eastern coastland) (from general description by Gonzalez-Hidalgo et al., 2011; de Luis et al., 2010).

3 | DATA AND METHODS

The study uses the recently presented monthly precipitation grid MOPREDAS_century, encompassing the period 1916–2020 (Beguería et al., 2023; Gonzalez-Hidalgo et al., 2023). Following description in Gonzalez-Hidalgo-et al. (2023) and Beguería et al. (2023), the new MOPREDAS_century database has been created by combining digital data stored at the National Climate Database of the Spanish Meteorological Agency (AEMET) with new data digitized from the Annual Climate Summaries published by the former National Meteorological Service of Spain (1916–1950); the combined sources resulted in a high-resolution grid (10 × 10 km), which was analysed in the 1916–2015 version in this study. Raw data were quality controlled and local universal kriging were used to create monthly precipitation grids following a two-stage process: first, interpolation of the probability of zero precipitation, and second estimation of the precipitation magnitude using as independent variables different geographical characteristics and the monthly mean climatology (1961–2000). To maximize the original information (because of different amount of data among years) and with the aim of achieving the highest possible spatial density, instead of reconstructing individual series (i.e., data points), we adopted a monthly field reconstruction along the 1916–2015 period.

The analysis of precipitation regimes was carried out by calculating seasonal totals for each pixel of the grid

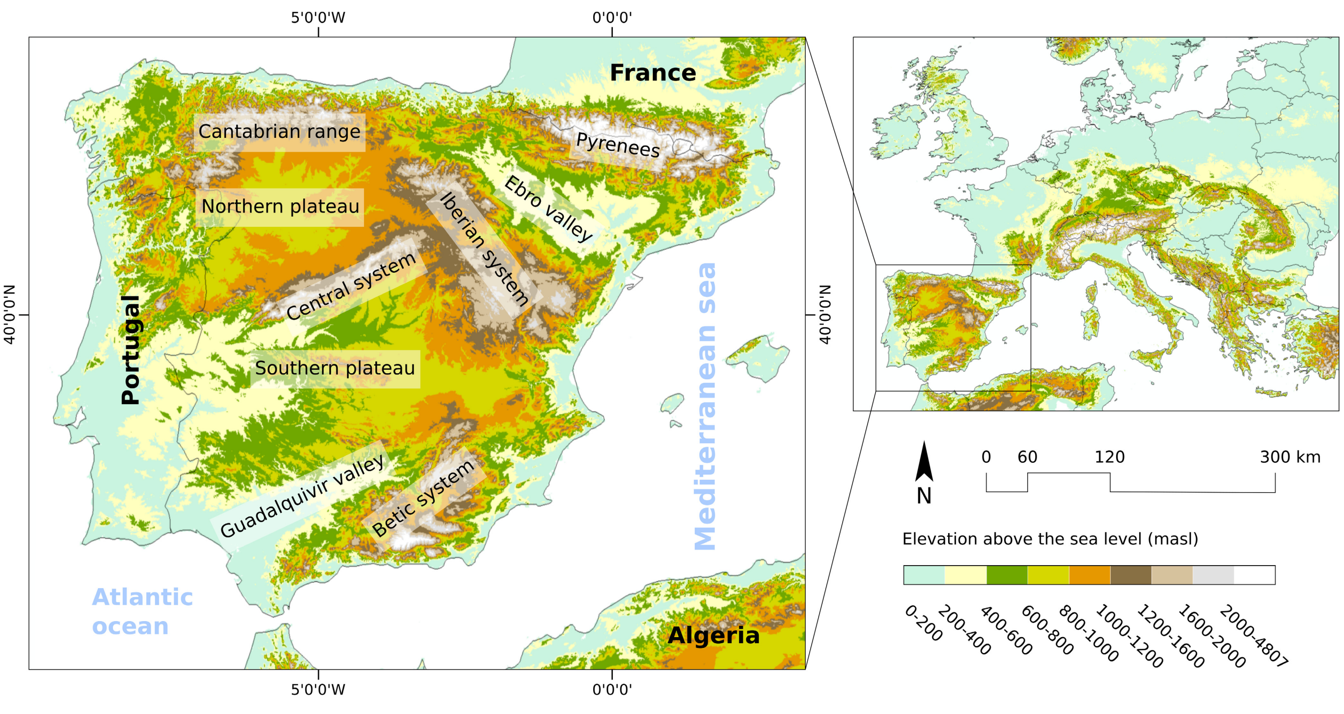

FIGURE 1 Study area. Location of Iberian Peninsula in Mediterranean basin (right) and main features of the relief (left). Partially from Gonzalez-Hidalgo et al. (2023).

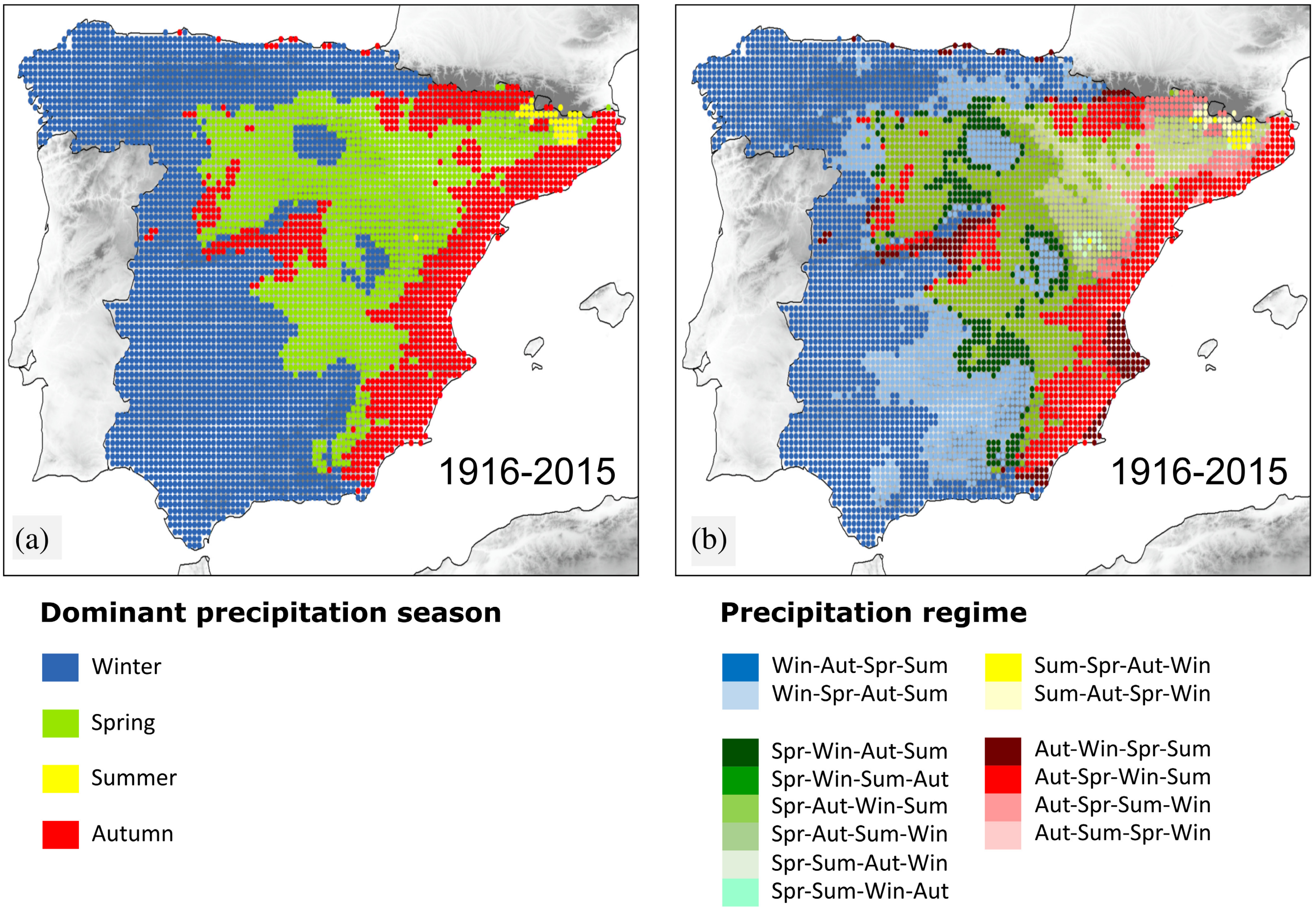

FIGURE 2 Precipitation regimes over the Spanish mainland (1916–2015): (a) dominant precipitation regimes (season with the highest contribution to the annual total); and (b) subregimes (order of seasonal contributions). Win, winter; Spr, spring; Sum, summer; Aut, autumn.

and year, using the traditional approach: winter (December–January–February), spring (March–April–May), summer (June–July–August) and autumn (September–October–November). Then, the percent contribution of each season's precipitation to the annual total was computed, and the main contributing season was recorded to classify precipitation regimes into four classes: winter, spring, summer and autumn dominant precipitation. Additionally, the order of the four seasons in their contribution to the total was also recorded.

The temporal stability of the precipitation regimes was assessed by repeating the analysis for four non-overlapping 25-year periods: 1916–1940, 1941–1965, 1966–1990 and 1991–2015. The spatial analysis was completed by computing change matrices between the periods represented by Sankey's flow chart.

Seasonal precipitation trends were also computed at each grid cell, considering the entire study period and also, to complete the analysis, we also included information on the ongoing temporal windows with 30 and 60 years in length, and also decreasing length from 1916–2015 to 1996–2015, to evaluate the last decades' context. The sign (positive/negative) and significance of the trend were estimated using the Mann–Kendall test on the pre-whitened series for correcting possible auto-correlation effects, at a significance level $\alpha = 0.10$ for compatibility with previous studies. The trends in the grid cells were classified into four groups according to the sign and significance of the trend (negative significant, negative non-significant, positive nonsignificant and positive significant), and the percent area (as the proportion of cells in the total grid) of each group was recorded.

4 | RESULTS

4.1 | Rainfall regimes in the Spanish mainland

The spatial distribution of the dominant precipitation regime (1916–2015) over the Spanish mainland can be roughly divided into three areas (Figure 2, left). On the

TABLE 1 Average seasonal and annual precipitation for the whole 1916–2015 period and subperiods (in mm) and change (in percentage) with respect to the first period (1916–1940).

	Precipitation (mm)					Change (%)				
	Win	Spr	Sum	Aut	Year	Win	Spr	Sum	Aut	Year
1916–2015	212.6	191.4	83.0	198.6	685.6					
1916–1940	208.0	200.7	84.2	204.2	697.1					
1941–1965	222.1	199.2	85.0	194.3	700.6	+6.8	−0.8	+1.0	−4.9	+0.5
1966–1990	224.7	187.8	88.5	187.0	688.0	+8.0	−6.4	+5.1	−8.4	−1.3
1991–2015	195.7	178.1	74.3	208.7	656.8	−5.9	−11.3	−11.7	+2.2	−5.8

Note: Season abbreviations as in Figure 2.

northern front, winter-maximum regimes and their variants predominate. Along the Mediterranean coast, to the east, the predominant regime is autumn-maximum.

Over an extense area in the interior of the Iberian Peninsula the winter-maximum regime predominates from north to south, changing to spring towards the east, with some smaller areas with autumn-maximum. Finally, there is small sector with summer maxima in the Eastern Pyrenees related to local factors and convective activity. Generally speaking, spring offers the highest variants regime (Figure 2, right).

4.2 | Temporal changes in seasonal precipitation

Table 1 shows annual and seasonal precipitation averages for the whole period 1916–2015 and for the four 25-year subperiods, as well as the intraseasonal percent change respect to 1916–1940 period.

In general, the contributions (in percentage) of winter, spring and autumn to the annual totals more or less remain unchanged, with global seasonal averages of about 200 mm except summer, and global seasonal percentage contribution of 31% in winter, 27.9% in spring, 12.1% in summer and 29% in autumn. Nevertheless, there are changes over the study period. Total annual precipitation remained stable at around 700 mm during the first two subperiods, but experienced a reduction in the third (688 mm) and fourth periods (656.8 mm) that represent a loss of 40.4 mm (−5.9%). Per seasons, spring experienced a reduction from around 200 mm in the first two periods to 188 and 178 mm in the 3rd and 4th periods, thus the final mean losses are 22.6 mm (−11.3%) with respect the first period. In contrast, winter gained precipitation by around 8% in the second and third periods, but decreased in the latter, with a final loss of −2.3 mm (−6%). Autumn precipitation experienced a reduction of about 17.2 mm (−8.4%) in the first three periods, but recovered in the last one with a global increase of 2.2%. Finally, summer precipitation is lower than 100 mm and experienced a slight decrease in the last period of around 10 mm (−11.7%). Therefore, the observed change in annual precipitation between the first and last subperiod of about 40.4 mm seems to be mostly due to the decrease in the spring, winter and summer (50%, 25% and 25% of total loss, respectively), while autumn precipitation practically does not change or slightly increase. Consequently, the percent seasonal contribution seems to remain more or less in the same values along the century.

4.3 | Precipitation trends over the whole study period

Figure 3 shows the spatial distribution of annual and seasonal precipitation trends for the period 1916–2015. Significant negative trends for annual precipitation are found in the mountain areas in the north (Cantabrian Range, Pyrenees; see Figure 1), centre (Central System and Iberian System) and the south (Betic System). Most of the study area shows negative trends, although not achieving significance. Positive trends, on the contrary, are only found in narrow areas in the north and the east, and are mostly not significant.

Table 2 summarizes the results of the trend analysis, indicating the percent of grid under each trend class. On an annual basis, significant negative trends account for about 22.5% of the grid, while the opposite positive signal hardly exceeds 1%. Per seasons, spring had the largest fraction of area with significant negative trends amounting to more than 40%. These are located predominantly in the western half of the study area and in the Pyrenees Range in the NE, while positive trends are only significant along the Mediterranean coast (Figure 3).

Summer precipitation shows the second largest area with negative significant trends, amounting to 20% of the

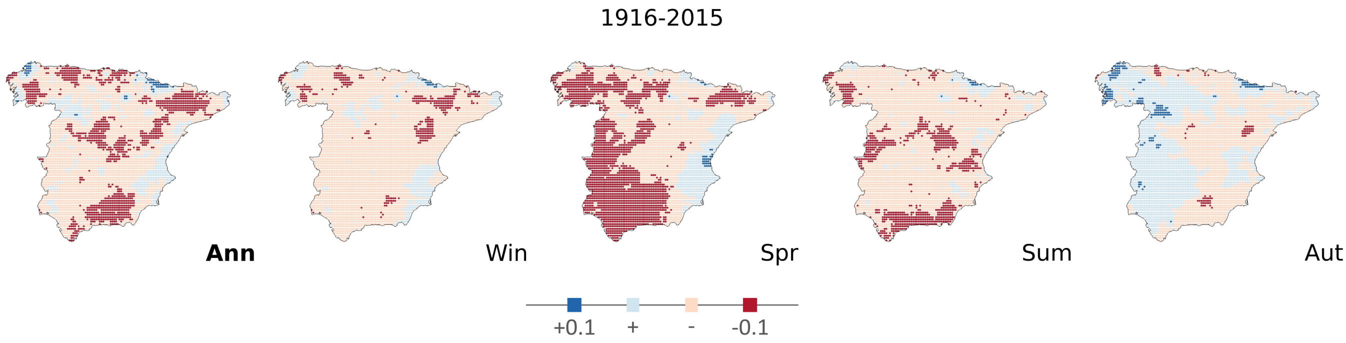

FIGURE 3 Annual and seasonal precipitation trend analysis over 1916–2015. Four-class classification: positive significant (dark blue), positive not significant (light blue), negative not significant (light red) and negative significant (dark red). Mann–Kendall test, significance level $\alpha = 0.10$. Season abbreviations as in Figure 2.

TABLE 2 Percent area under each trend class over the 1916–2015 period, according to the Mann–Kendall at the $\alpha = 0.10$ confidence level.

	Positive trend		Negative trend	
	Signif.	Not signif.	Not signif.	Signif.
Annual	1.2	14.9	61.4	22.5
Winter	0.6	11.5	80.9	7.0
Spring	0.8	12.6	46.0	40.6
Summer	0.4	9.0	70.6	20.0
Autumn	3.9	47.7	46.5	1.8

territory mainly in the centre and the southern parts, while winter shows also predominantly negative trends, although with lower significant areas and a less clear spatial pattern (Figure 3).

In contrast, autumn shows positive trends in the western half of the study area while the eastern half has mostly negative trends, although the percentage of significant trends are restricted to almost 4% (positive) and 2% (negative) (Figure 3).

In summary, annual precipitation trends over the period 1916–2015 were mostly negative, and mainly related to the decrease in spring, which has not been fully compensated by an increase in autumn.

4.4 | Changes in annual and seasonal precipitation trends

The moving windows analysis complements the results over the whole period described in the previous section, and reveals the temporal patterns of change. Figure 4 (left) shows annual and seasonal precipitation trends using a 60-year moving window approach ranging from 1916–1975 to 1965–2015. The figure shows the percent area classified by their trend sign and significance. The map sequence showing the spatial distribution of the trends for each time window can be found in Figure S1, Supporting Information.

In general, the percent area with negative trends increases towards the present at the annual scale, and also in winter, spring and summer. At the end of the study period, almost 50% of the area experienced significant negative trends over the last 60 years in winter and summer. Spatially, the trends are more concentrated towards the southwest, while in winter they show a more heterogeneous distribution (see Figure S1). On the other hand, positive trends predominate at the beginning of the study period, especially in winter and, to a lesser extent, in summer. Negative trends also predominate in spring, although the largest fraction of the territory affected by negative trends peaks towards the middle of the study period, while it shows a decreasing trend in later decades.

Autumn trends are positive and significant in about 10% of the study area around the middle of the century, while spring negative significant trend affects an area of about 25% since the middle of the century.

Figure 4 (right) shows the trend spatial fluctuations in 30-year moving windows (corresponding to the length of the normal periods) from 1916–1945 to 1986–2015. Over such a period, the development of seasonal precipitation trends appears to evolve in four phases (see Figure S2 for detailed spatial evolution). In the first half of the century a clear and strong decrease is observed only in autumn, affecting the eastern half of the Iberian Peninsula. Between around 1940 and the mid-1980s there is a marked increase in precipitation in autumn and later in winter and summer, especially in the western and southwestern areas, while precipitation decreases in spring, especially in the west. The third period begins in the 1960s and is characterized by negative and significant trends in winter, summer and spring over extense

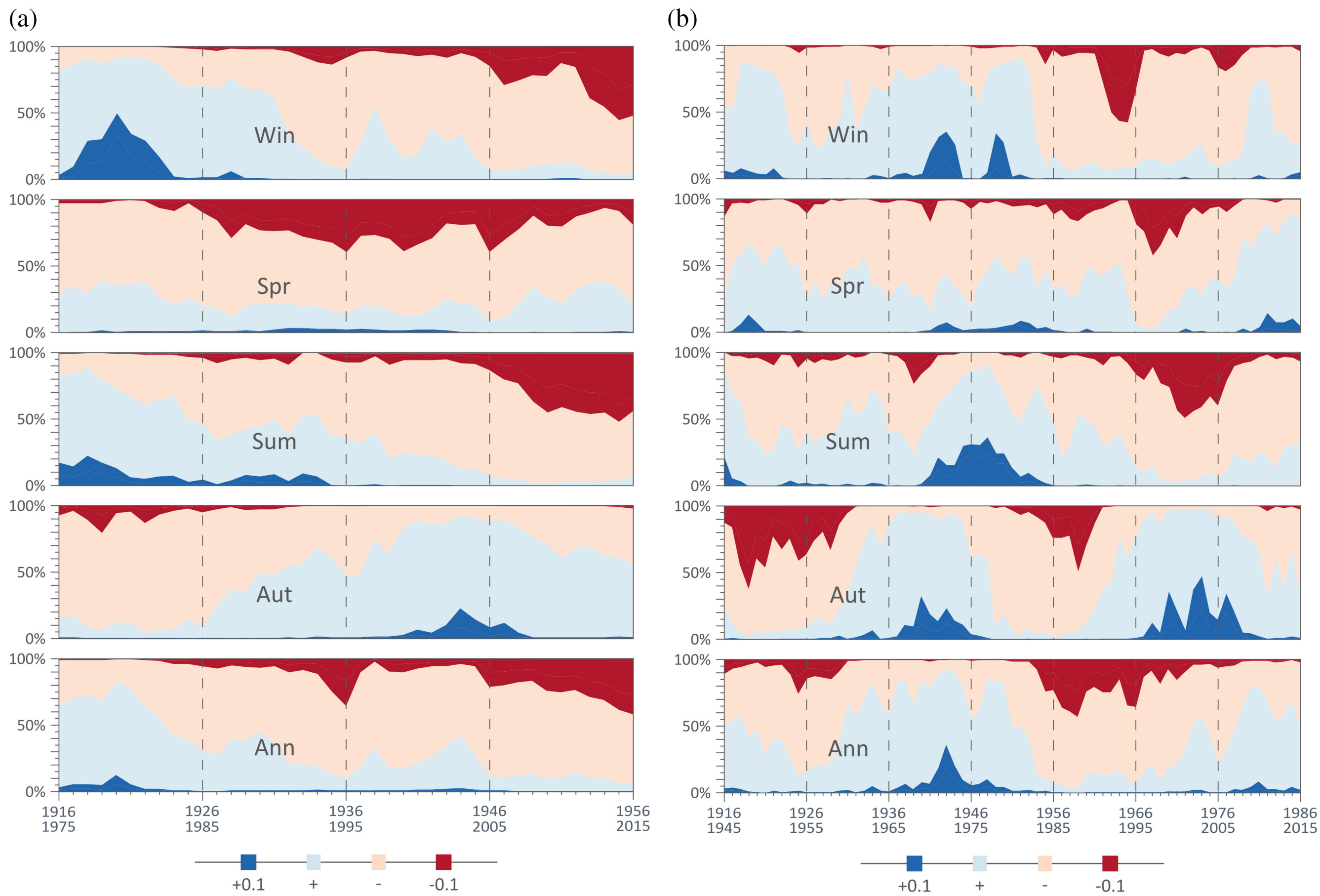

FIGURE 4 Annual and seasonal percentage of the grid by signal and significance (year by year) of rainfall trend at 60-year (left) and 30-year (right) moving windows. Season abbreviations as in Figure 2, trend classification as in Figure 3.

areas, and a positive trend in autumn, more discrete, in the north. Finally, in recent decades (starting around 1975) the areas occupied by significant trends whatever the sign is very small, which makes it appear that during this period the amount of precipitation falling in each season has remained more or less stable (see Figure S2).

At the annual scale, the temporal evolution of the trends shows two negative significant periods (early 20th and around the 1970s), and positive ones in windows around the 1950s. The most remarkable result, however, is that the trends in total annual precipitation in recent decades are not significant. In fact, since the 30-year windows 1975–2004 to 1986–2015 the trends with statistical significance do not exceed 10% of the grid area in any of the 30-year windows.

Finally, Figure 5 shows the decreasing temporal windows analysis, with windows ranging from 1916–2015 to 1986–2015. The figure provides information about the present context of seasonal precipitation and resembles the effects of the year in which the stations of the precipitation measurement network were put into operation (see Figure S3).

The evolution of the area affected by positive/negative and significant/nonsignificant trends shows that during more than the last four decades, no significant trend could be detected both at annual and seasonal levels, and a slight positive trend could also be detected in spring and winter in different recent windows. In summary, the study of variations in seasonal precipitation trends suggests that changes in the precipitation regime may have occurred between 1916 and 2015.

4.5 | Changes in the seasonal rainfall regimes

Table 3 shows the spatial percent of the grid occupied by each dominant and co-dominant regime (2nd, 3rth, 4rth season) in 25-year period. The figures illustrate the high variability of seasonal rainfall in the Spanish mainland. From 24 possible combinations we recognized, respectively, 10, 12, 13 and 12 regimes from 1916–1940 to 1991–2015 periods, and a total of 14 in the overall period (see Figure 2, right). It is noted that the co-dominant season

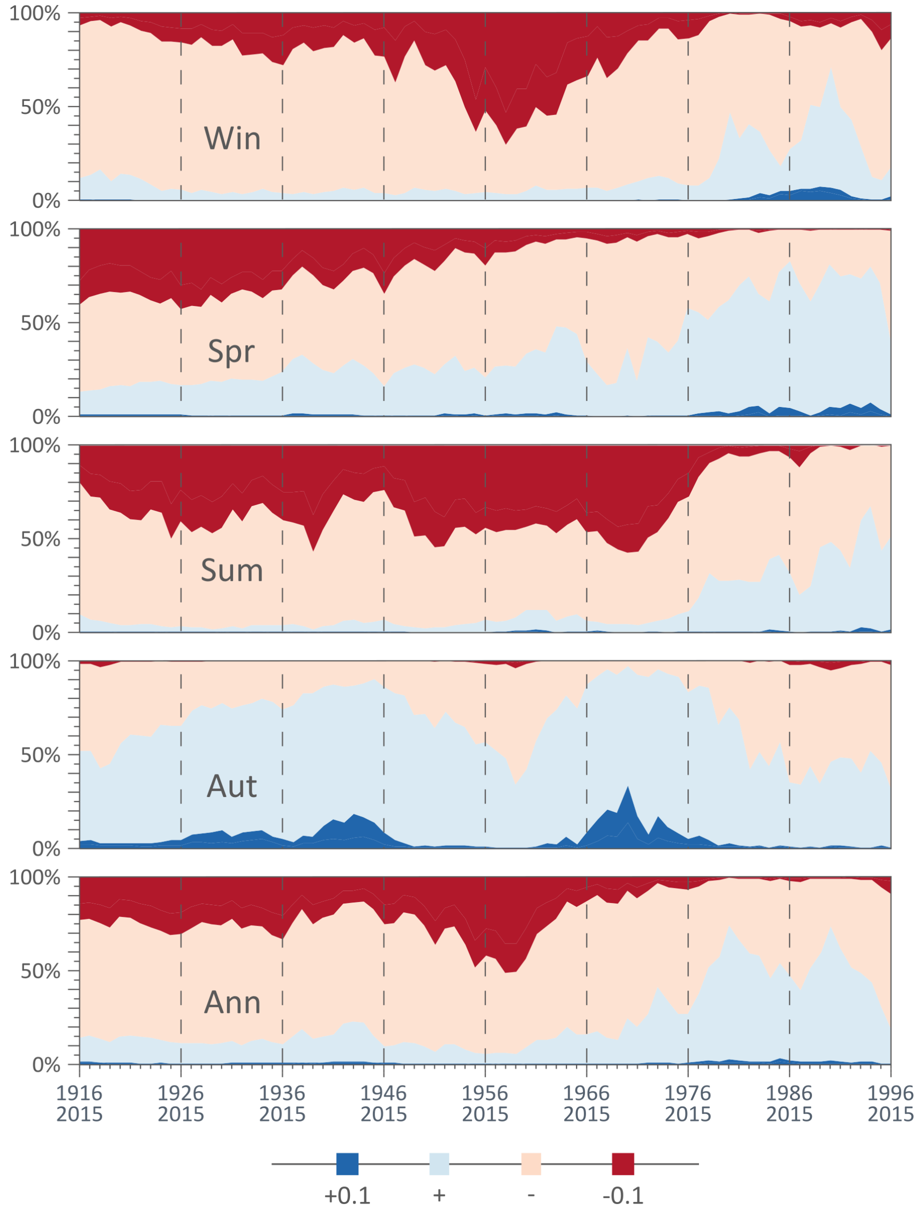

FIGURE 5 Annual and seasonal percentage of the grid classified by the sign and significance of the trend under decreasing temporal windows (1916–2015 to 1996–2015). Season abbreviations as in Figure 2, trend classification as in Figure 3.

(2nd, also 3rth season) may eventually have the same amount of precipitation that the dominant one. Generally, the annual precipitation usually depends on two seasons whatever the case, with the most frequent combination being winter + spring, winter + autumn, autumn + spring or autumn + winter (the order can be changed).

During the first half of the 20th century, and even up to the 1990s, the most extended dominant regime was winter, occupying more than 40% in different combinations. Furthermore, from 1916 to 1990 (along the first three periods) we found an increase of 50% in the area with winter regime, reaching almost 60% of the grid in the period 1966–1990. The spring dominant area increased between 1916–1940 (24.2%) and 1941–1965 (34.7%), but then decreased to 25.5% in 1966–1990 and to a meagre 15.8% of the area in the last period. The autumn regime experienced the most intense changes, as it undergoes a change from circa 32% of the area in 1916–1940, to 12.4% and 13.5% in 1941–1965 and 1966–190, respectively, to finally recover during the most recent period extending over slightly more than 50% of the grid. The area gain of autumn in the last period is achieved at the expense of both winter and spring. It is also interesting to note that autumn is the second (co-dominant) most important season in the most recent period time (45.6% of the grid), while spring has lost percentage also as second season (31.1% in the fourth period) while winter has gained slightly (22.3%).

The results show that the combined contributions of winter + spring to the annual precipitation, which amounted to 21.8%, 36.9% and 28.6% during the first three periods, respectively, do not reach 3% in the latest period. The alternative, spring + winter, varied from 5.6%

TABLE 3 Percent of the grid according to dominant and co-dominant seasonal precipitation regimes.

	1916–1940	1941–1965	1966–1990	1991–2015
Win-Aut-Spr-Sum-	22.2	14.6	31.2	31.0
Win-Spr-Aut-Sum-	21.8	36.9	28.6	2.7
Winter dominant	44.1	51.5	59.8	33.7
Spr-Aut-Sum-Win-	4.4	4.8	7.2	4.1
Spr-Aut-Win-Sum-	14.2	16.3	5.3	10.2
Spr-Sum-Aut-Win-	0.0	1.4	1.6	0.6
Spr-Sum-Win-Aut-	0.0	0.0	0.2	0.0
Spr-Win-Aut-Sum-	5.6	12.2	11.2	0.9
Spr-Win-Sum-Aut-	0.0	0.0	0.1	0.0
Spring dominant	24.2	34.7	25.5	15.8
Sum-Aut-Spr-Win-	0.0	0.1	0.0	0.3
Sum-Spr-Aut-Win-	0.0	1.3	1.2	0.0
Summer dominant	0.0	1.4	1.2	0.3
Aut-Sum-Spr-Win-	0.1	0.1	0.1	0.5
Aut-Spr-Sum-Win-	6.7	2.3	2.2	5.3
Aut-Spr-Win-Sum-	19.2	7.1	9.9	23.1
Aut-Win-Spr-Sum-	5.7	2.9	1.3	21.3
Autumn dominant	31.7	12.4	13.5	50.1

to 12.2%, 11.2% and collapsed to 0.9% in the last period. On the contrary, autumn emerges as the key season to understand the behaviour of precipitation in the recent decades. Its contribution in the autumn + spring combination changed from around 26% to circa 9% and 11% in the 2nd and 3rth periods, and more than 28% in the latest period. Autumn + winter raised from lower than 6% to 21.3% in the last period and winter + autumn varied between 22.2% to more than 31% (Tables 3 and S1).

The results suggest that the seasonal regime has varied over time, and agrees with the results of the trend analysis shown before. Figure 6 shows the spatial distribution of seasonal rainfall regimes for four subperiods. A detailed analysis of change (transition matrix) can be found in Table S1. As the four maps evidence, precipitation seasonality has undergone very noticeable changes during the study period, especially in the latest period (1991–2015). Figure 7 summarizes the transitions experienced between each pair of subperiods.

The analysis of both figures evidences that rainfall regime changes mostly affected the inland areas, that is the transition area between an area dominated by winter precipitation to the west and the area dominated by autumn along the Mediterranean to the east. Between 1916–1940 and 1941–1965, 14.8% of the area under autumn regime changed to spring in the Ebro basin (see Figure 1 for location and names), and to a lesser extent to winter (3.8%), mostly in the southern basins of Tajo and Guadiana. As minor changes, 4.8% of the spring area shifted to a winter regime. The most notable changes between 1941–1965 and 1966–1990 were the percentage of spring lost in favour of winter (9.7%) in the northern Duero basin and autumn (4.1%). Finally, the transitions between 1966–1990 and 1991–2015 show a remarkable increase of the percent area under autumn regime, and this is achieved especially at the expense of spring (11.1%) to the north-east (Ebro basin), but above all the recession of winter (26.7%) to the western inland areas (Duero, Tajo and Guadiana basins). As a result, autumn was the dominant season for precipitation in the last period, in spite of winter.

To summarize, the most notable change in the seasonal precipitation regimes in the Spanish mainland over 1916–2015 is a transition from a winter predominance, complemented with spring, towards a situation dominated by autumn and winter in second place, affecting extended areas mainly in the inland of the study area.

5 | DISCUSSION AND CONCLUSIONS

5.1 | Seasonal rainfall changes between 1916 and 2015

The evolution of seasonal precipitation regimes in the Spanish mainland from 1916 to 2015 reveals a gradual shift from winter and spring precipitation to favouring

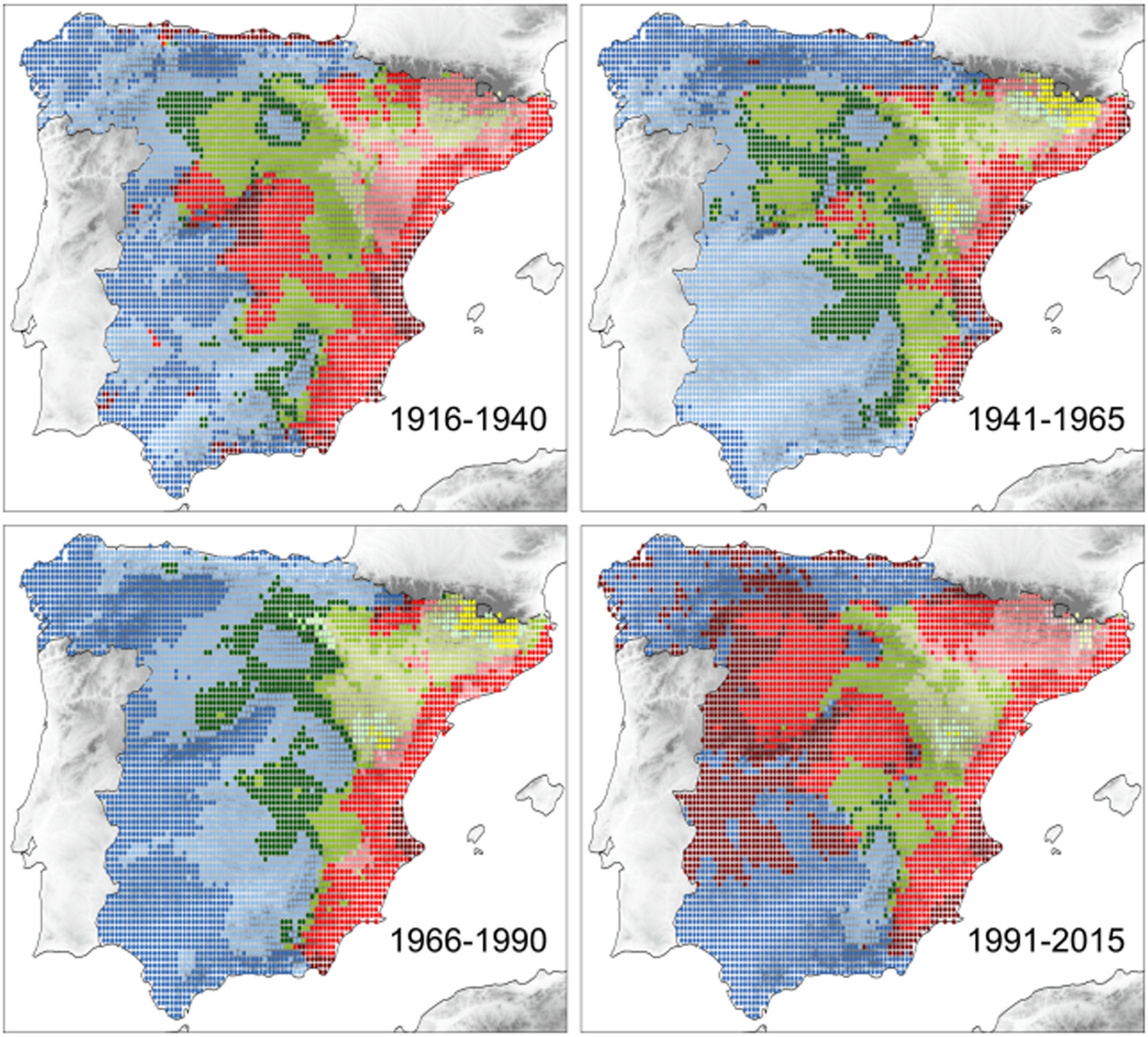

FIGURE 6 Precipitation regimes over the Spanish mainland during four 25-year periods. Colour legend as in Figure 2 (II, right).

autumn. This transition occurred in the context of a slight annual decrease of approximately 0.4 mm per year, which was not evenly distributed across the study area (Table 1 and Figure 3). Moreover, the decreases were mostly insignificant in recent decades (Figure 5). These findings suggest that the most noteworthy changes related to 20th- and 21st-century precipitation in Spain are the alterations in seasonal patterns rather than total precipitation amounts.

The origins of these seasonal shifts can be traced back to trends in specific months and periods. Drawing from previous research (as reviewed in the introduction), it can be inferred that the decline in spring precipitation is primarily attributed to a generalized reduction in March, occasionally coupled with late-winter decreases in February. However, in recent decades, positive trends in precipitation during both of these months have been observed in various regions, including the central Mediterranean basin (Kalimeris & Kolios, 2019), Algeria (Achite & Ouillon, 2016), the Sea of Marmara (Karaburun, 2011), Italy (Caloiero et al., 2020), several Serbian areas (Milovanović et al., 2017), and notably in March in the Moroccan Atlas (Diani et al., 2019) and Turkey (Güner Bacanli, 2017; Yavuz & Erdoğan, 2012). These recent findings align with the results for Spain presented in a prior study by Gonzalez-Hidalgo et al. (2023).

Conversely, the increase in autumn precipitation is predominantly linked to significant upticks in October, with a lesser influence from September. Comparing these trends with other Mediterranean basin regions, positive

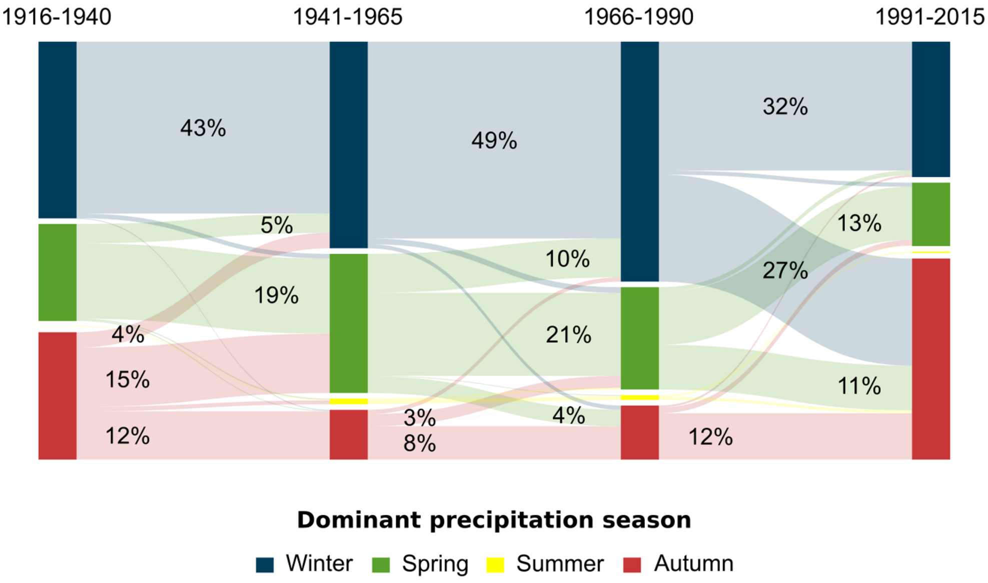

FIGURE 7 Sankey diagram of the intensity and direction of changes between dominant precipitation regimes between the four 25-year subperiods.

trends were identified in September in the Marmara Sea (Karaburun, 2011), while negative trends for the same month were observed in Turkey (Partal & Kahya, 2006), Montenegro (Gocic & Trajkovic, 2014) and Serbia (Luković et al., 2015). Additionally, some studies report positive trends in September and negative trends in October in Greece (Markonis et al., 2017), Italy (Gentilucci et al., 2018) and Tunisia (Snoussi et al., 2018).

The changes in precipitation regimes observed from 1916 to 2015 underscore the already well-documented high variability noted since 1950 (de Luis et al., 2010). In the four analysed periods, regardless of the affected spatial regions, the seasonal rainfall patterns exhibited a range of 10–13 variants out of a total of 24 possible combinations. This means that within the relatively small area of the Iberian Peninsula, we can find 50% of all possible combinations. The ultimate factors contributing to this variability are linked to the advection of air masses, influenced by the geographical alignment of the primary mountain chains (Figure 1).

Following the insights of Cortesi et al. (2014), precipitation on the northwestern facade and within large inland areas is reliant on a limited set of synoptic conditions, or weather types, consistently associated with the advection of Atlantic air masses. In the northern regions, winter precipitation is tied to northerly and westerly circulation patterns, as well as the inflow of Atlantic air masses. These atmospheric conditions bring substantial moisture and, when combined with the orographic arrangement of mountains parallel to the coast (Cantabrian range; see Figure 1), promote convective forcing and the generation of frontal-orographic precipitation. Along the eastern Mediterranean coast, precipitation is influenced by various weather types associated with eastern flows from the Mediterranean. Here, the orographic sheltering effects, in relation to the prevailing westerly circulation, explain that precipitation is primarily linked to the warming of the Mediterranean Sea during the summer and autumn seasons. Within this region, the cutoff of cold air at higher altitudes can establish subregional circulation patterns with a dominant east–west direction. Consequently, warm and humid air masses from the Mediterranean are forced to ascend orographically due to the relief parallel to the coast (Iberian and Betic systems; see Figure 1).

Finally, relief topography plays a significant role in the extensive inland areas primarily subject to a winter precipitation regime. The east–west alignment of the major mountain ranges in these areas (from north to south Cantabrian range, Central systems, Betic system; see Figure 1) does not pose a significant barrier to the advance of Atlantic air masses from the west coast. As a result, frontal precipitation tends to dominate these inland plateaus, even at considerable distances from the coast.

5.2 | Towards an explanation

The preceding results raise the problem of the sources of moisture in the study area. Shaman and Tziperman (2011) and Winschall et al. (2014) suggested that the main source of moisture in winter and autumn in the western part of the Mediterranean basin is the Atlantic Ocean, while in summer local evaporation predominates. Dayan et al. (2015), on the other hand, suggested that in the case of convective processes in late summer and autumn not only the moisture from the

Mediterranean but also that provided by advection at altitude from distant areas and specific synoptic configurations should be considered. An interesting study by Blanchet et al. (2018) analysed the atmospheric patterns associated with daily maxima in the southeastern Alps in the period 1958–2017, identifying two main influences: the Atlantic extended southward in winter and spring, and the dominant Mediterranean in autumn. This is in agreement with Lemus-Canovas et al. (2021), who found that the moisture sources of the autumn torrential events in the eastern Mediterranean Iberian façade came mostly from the Mediterranean Sea.

The meteorological processes that generate the observed precipitation patterns in the Mediterranean basin are intricate. Precipitation in the region exhibits a characteristic winter-maximum and a dry, warm season. The determinants of rainfall in the Mediterranean are the result of a complex interplay between large-scale circulation patterns and thermodynamic factors (Tuel & Eltahir, 2020; Zappa et al., 2015). In the case of large-scale patterns during the cold season (typically October–March), several atmospheric circulation patterns have been identified as significant contributors to precipitation variability across the entire basin. These include the North Atlantic Oscillation (NAO), the Mediterranean Oscillation (MO) and the Atlantic Multidecadal Oscillation (AMO) (Beranová & Kyselý, 2016; Kelley et al., 2012; Kotsias et al., 2020; Mariotti & Dell'Aquila, 2012; Suárez-Moreno et al., 2022; Xoplaki et al., 2004, among others). Additionally, some patterns, such as the Western Mediterranean Oscillation in western areas (Martin-Vide & Lopez-Bustins, 2006) and the Eastern Mediterranean Pattern in eastern regions (Kotsias et al., 2020), exert more localized influences.

Conversely, the dynamics of summer precipitation are primarily driven by thermodynamic processes, often linked to Mediterranean Sea temperatures (Brogli et al., 2019; Tuel & Eltahir, 2021). However, it is worth noting that summer precipitation has also been associated with the NAO (Mühlbauer et al., 2016).

Most of the cited works primarily focus on the period after 1950 (Kelley et al., 2012; Kotsias et al., 2020; Quadrelli et al., 2001), with limited information available for earlier decades. The scarcity of data for these earlier periods hinders the ability to undertake spatially detailed analyses (Martin-Vide & Lopez-Bustins, 2006; Vicente & López-Moreno, 2008). However, Merino et al. (2015), utilizing the Global Precipitation Data Base grid with a resolution of 0.25° (approximately 250 km^2), offered insights into the relationship between the North Atlantic Oscillation (NAO) and precipitation anomalies. They observed a 5–6-year periodicity between the NAO and precipitation anomalies in western areas during the initial years of the 1901–2010 period, which reduced to a 2–3-year periodicity in the later years.

In the Iberian Peninsula, prior research has confirmed the robust connections between winter, spring and autumn precipitation patterns and the NAO and WEMO during the latter half of the 20th century (see Gonzalez-Hidalgo et al., 2011, for a comprehensive review). Furthermore, the effects of other atmospheric patterns have also been identified (del Rio et al., 2011; Martinez-Artigas et al., 2021). It is interesting to observe that the NAO and WEMO exert distinct influences on different regions of the Iberian Peninsula. The central and western areas are primarily under the influence of the NAO, whereas the Cantabrian coast to the north and the Mediterranean coast to the east are predominantly influenced by the WEMO. Moreover, the main mountain chains within the region (see Figure 1) act as spatial boundaries that correspond to the effects observed by Tuel and Eltahir (2020).

While we have not conducted a formal analysis of the relationship between atmospheric patterns and seasonal precipitation in this paper, there is evidence indicating changes in these patterns over the years. Figure 8 displays the slope coefficients of linear regressions using 30-year running windows, illustrating the evolving relationship between precipitation and NAO and WEMO seasonal indices over the period from 1916 to 2015. It is evident from the figure that this relationship has undergone substantial changes throughout this century.

There are discernible relationships between the findings presented in Figure 8 and the trends observed in seasonal precipitation. For example, we noted a positive association between spring and autumn precipitation and the North Atlantic Oscillation (NAO) until around the 1941–1970 period, while the relationship with winter precipitation was negative. This aligns with the observed increase in the winter rainfall regime during the initial two periods analysed in our research, particularly in the central-western areas. Following this period, the relationship between winter precipitation and the NAO turned positive, whereas spring precipitation exhibited a negative association until the 1964–1993 timeframe, coinciding with a positive relationship observed for autumn precipitation. These findings correspond to the increase in the spring rainfall regime during the same period. Lastly, autumn precipitation displayed a negative relationship with the NAO from the 1960s until the end of our study period, whereas spring and winter precipitation showed a positive relationship. These relationships help elucidate the expansion of the spatial extent of the autumn rainfall regime in recent decades.

The relationship with the WEMO is more intricate due to its variable spatial influence, characterized by a

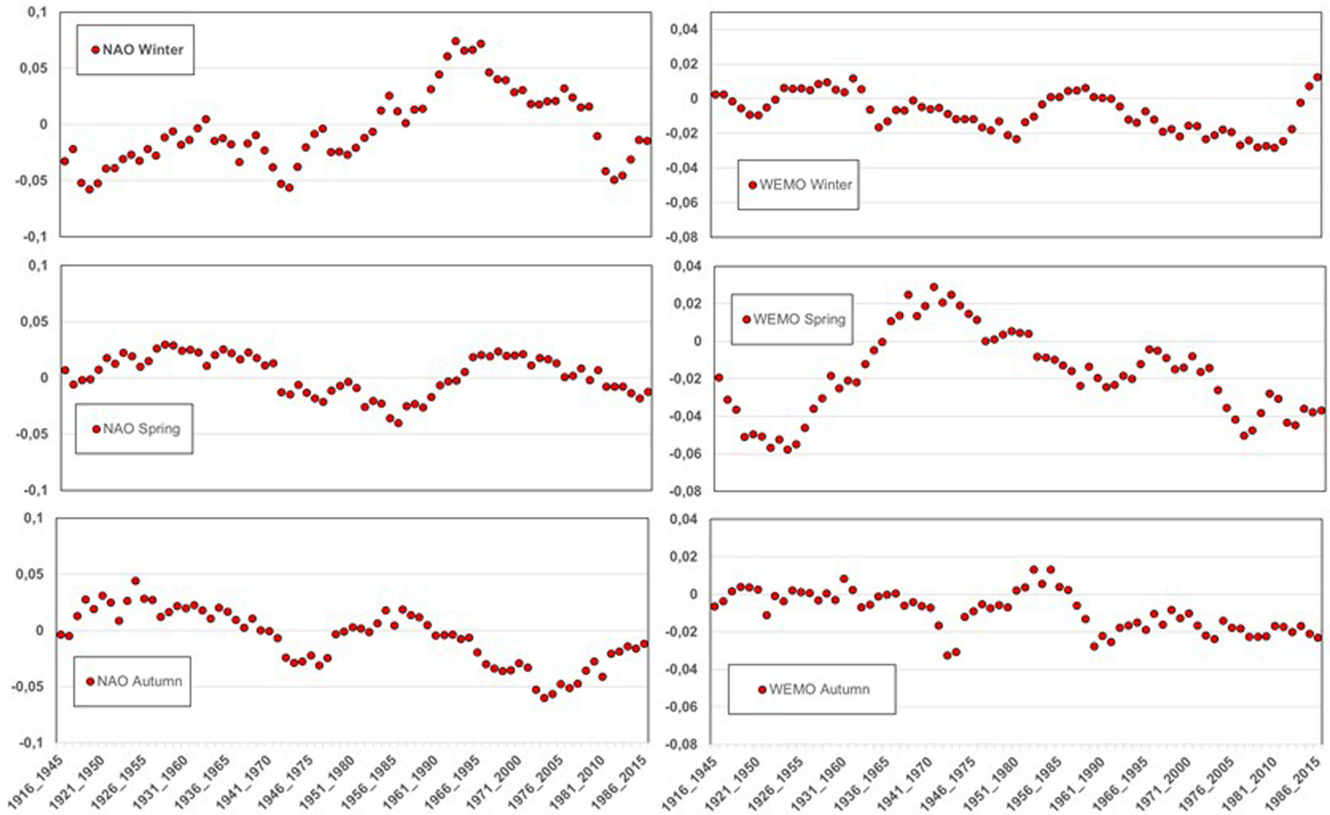

FIGURE 8 Magnitude of the linear regression of precipitation against seasonal NAO and WEMO indices using 30-year running windows (1916–1945 to 1986–2015).

positive impact in the north and a negative influence towards the east. Nonetheless, a general negative relationship has become evident since the mid-20th century in winter, spring, and autumn.

These initial findings, coupled with well-established connections between these atmospheric patterns and precipitation, offer valuable insights into the seasonal precipitation changes observed throughout the 20th and 21st centuries, including the pre-1950 period. However, it is important to note that further research is necessary to thoroughly understand the spatial variability of these relationships. As we have observed, there are spatial differences in the roles of these large-scale atmospheric patterns in relation to precipitation within our study area.

6 | CONCLUSIONS

The analysis of seasonal precipitation in the Spanish mainland in the period 1916–2015 reveals an increase in the area under autumn rainfall and decrease those areas under winter and spring regime. This result is mostly due to decreasing precipitation in spring and, to a lesser extent, winter and then negative trends prevail at the annual scale when considering the whole study period. The temporal evolution of these trends is complex, too, as negative trends are concentrated in two main pulses corresponding, approximately, to the first and last thirds of the 20th century. The latest three decades, on the other hand, show almost no significant changes in any season. This results are consistent with previous analysis on the Iberian Peninsula and the Spanish mainland with a shorter time span (covering mostly the final decades of the 20th century), which tended to agree on decreasing March and (to a lesser extent) February precipitation, and increasing October and (to a lesser extent) September for spring and autumn changes.

As a consequence of changes in seasonal precipitation, rainfall regimes have been modified with preference to the inland of the study area. Temporal changes between precipitation regimes has not been monotonic during the study period, since the autumn contribution diminished over a large part of the 20th century (1916–1990) at the benefit of winter, while this trend was notably reversed in the last decades (1991–2015). The northern regions along the Atlantic coast and the south-west retain their winter regime, and also the Mediterranean coast maintains its autumn regime, nevertheless extended inland areas under spring rainfall regime have changed to autumn-maximum. These changes seem to be well related to changes in NAO and WEMO atmospheric patterns as research in progress suggest.

AUTHOR CONTRIBUTIONS

José Carlos Gonzalez-Hidalgo: Conceptualization; formal analysis; funding acquisition; investigation; project administration; supervision; writing – review and editing; writing – original draft. **Víctor Trullenque-Blanco:** Data curation; visualization; investigation; software; writing – review and editing. **Santiago Beguería:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; software; writing – review and editing; supervision. **Dhais Peña-Angulo:** Data curation; formal analysis; investigation; methodology; software; writing – review and editing.

ACKNOWLEDGEMENTS

We acknowledge with thanks to Spanish Meteorological agency (AEMET) for providing data 1951–2020 and to the repository of scanned documents (ARCIMIS). Financial support was provided by Regional Government of Aragon, Geoenvironmental and Global Climate Change Research Group, Grant/Award Number: E02-17R; Spanish Government, Ministerio de Ciencia e Innovación-FSE, Projects: PID2020-116860RB-C22 (AEI/10.13039/501100011033), CGL2017-83866-C3-1-R. NAO and WEMO indices from Climate Research Unit, University East Anglia, and University of Barcelona.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in https://digital.csic.es/handle/10261/341441?mode=full at http://hdl.handle.net/10261/341441.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Gonzalez-Hidalgo, J. C., Trullenque-Blanco, V., Beguería, S., & Peña-Angulo, D. (2024). Seasonal precipitation changes in the western Mediterranean Basin: The case of the Spanish mainland, 1916–2015. *International Journal of Climatology*, *44*(5), 1800–1815. https://doi.org/10.1002/joc.8412