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Non-Stationary Dry-Spell Hazard Probabilities for Spain

S. M. Vicente-Serrano[1,2] | S. Beguería[2,3] | A. Royo[1,2] | A. El Kenawy[1,2] | M. Franquesa[1,2] | A. Halifa-Marin[1,2] | M. Adell-Michavila[1,2] | A. Crespillo[1,2] | D. Pérez-Pajuelo[1,2] | F. Domínguez-Castro[1,2] | C. Azorin-Molina[4] | L. Gimeno[5,6,7] | R. Nieto[5,6,7] | L. Gimeno-Sotelo[8,9]

[1]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Zaragoza, Spain | [2]Laboratorio de Climatologia y Servicios Climaticos (LCSC), CSIC–Universidad de Zaragoza, Zaragoza, Spain | [3]Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC), Zaragoza, Spain | [4]Centro de Investigaciones Sobre Desertificación, Consejo Superior de Investigaciones Científicas (CIDE, CSIC-UV-Generalitat Valenciana), Climate, Atmosphere and Ocean Laboratory (Climatoc-Lab), Moncada, Spain | [5]Centro de Investigación Mariña, Environmental Physics Laboratory (EPhysLab), Universidade de Vigo, Ourense, Spain | [6]Unidad Asociada CSIC-Universidad de Vigo: Grupo de Física de la Atmosfera y del Océano, Pontevedra, Spain | [7]Climate System Research Unit, UVigo-CESGA, Santiago de Compostela, Spain | [8]Departamento de Ciências Matemáticas, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal | [9]CEAUL – Centro de Estatística e Aplicações, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal

Correspondence: S. M. Vicente-Serrano (svicen@ipe.csic.es)

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ABSTRACT

This study provides a comprehensive assessment of long-term changes in dry-spell dynamics across Spain for the period 1961–2024, using both classical non-parametric methods and a novel non-stationary probabilistic framework applied to exceedance series of dry-spell durations. Using daily precipitation data from a dense network of quality-controlled stations, dry-spells were identified based on four thresholds (0.1, 1, 5, and 10 mm) to characterize their duration statistics, and generalized Pareto distributions (GPDs) were fitted under both stationary and non-stationary specifications. A systematic percentile-based evaluation was performed to determine optimal exceedance thresholds, and a bootstrap-based significance test was applied to compare stationary and non-stationary return levels. Complementary analyses examined trends in annual frequency, mean duration, and maximum dry-spell length. Results consistently reveal that dry-spell behaviour across Spain is dominantly stationary. Only a very small fraction of stations show significant non-stationary effects in the GPD location parameter, whereas non-stationary scale, shape, or full-parameter models provide no robust improvement and introduce substantial uncertainty. Traditional trend analyses corroborate this finding: most stations (> 70%–85%, depending on threshold) exhibit no statistically significant changes in dry-spell frequency, mean duration, or maximum duration. Spatial patterns of change are weak, and return levels associated with long recurrence periods (e.g., 50 years) remain highly stable throughout 1961–2024. Overall, these results support long-term stationarity in the probability of extreme dry-spells across Spain.

1 | Introduction

The assessment of drought hazard probability is a complex task. Drought is defined as an anomalous period during which the availability of water resources falls below normal average conditions (Vicente-Serrano 2016; IPCC 2023). Because these normal average conditions can differ markedly between regions and across seasons, drought metrics are commonly transformed into non-dimensional variables (e.g., based on standardized values) to quantify drought severity (Slette et al. 2020; Vicente-Serrano, Dominguez-Castro, et al. 2025). This transformation ensures that low index values—indicative of drought severity—have the same frequency everywhere. Consequently, these indices cannot be used to determine potential spatial differences in drought quantiles.

There are two possibilities for determining the drought hazard probability, which allow for the generation of maps of expected

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drought quantiles or return periods useful for agricultural, hydrological and ecological management, both of them based on the run theory (Yevjevich 1967). The first one identifies drought events based on thresholds applied to time series of standardized drought indices (Agnew 2000; Buttafuoco et al. 2015; Baronetti et al. 2020). This allows for the quantification of the characteristics of drought events (e.g., their duration and total magnitude) and the generation of event series that are analysed by means of extreme values theory to estimate high-event duration or magnitude quantiles (Domínguez-Castro et al. 2019a).

The second approach focuses on consecutive periods during which recorded precipitation falls below a given threshold, commonly referred to as dry-spells (Martin-Vide and Gomez 1999; Lana, Martínez, Burgueño, Serra, Martin-Vide, and Gómez 2008; Tramblay and Hertig 2018; Rivoire et al. 2019). Dry-spell hazard probability can then be estimated using different methods, including censored statistical distributions such as the negative binomial and Markov chains for short-duration dry-spells (Davy 1975; Nobilis 1986; Douguedroit 1987; Lana, Martínez, Burgueño, Serra, Martin-Vide, and Gómez 2008), as well as extreme value distributions like the Gumbel or the Generalized Pareto for assessing the probability of long-duration dry-spells (Vicente-Serrano and Beguería-Portugués 2003; She et al. 2013; Cindrić Kalin and Pasarić 2022). Following this approach, it is possible to generate dry-spell hazard probability maps (Perzyna 1994; Vicente-Serrano and Beguería-Portugués 2003), under the assumption that regions with higher quantile values are characterized by stronger drought hazard probability. This approach to identifying higher drought risk based on dry-spell hazard probability is supported by numerous studies that have documented the negative impacts of long-duration dry-spells on crops and natural ecosystems (Lana, Martínez, Burgueño, and Serra 2008; Cindrić Kalin and Pasarić 2022).

Most applications of extreme value theory to assess hazard relied on the assumption of stationarity (Serinaldi and Kilsby 2015). However, under the current climate change scenario, several studies have highlighted the need to consider techniques that allow for a non-stationary analysis of such events (Cheng and AghaKouchak 2014; Sarhadi et al. 2016; Šraj et al. 2016). Most of non-stationary hydroclimatic analysis has focused on extreme precipitation events (Tramblay et al. 2012; Gao et al. 2016; Yilmaz et al. 2017; Beguería et al. 2025), although some studies have also analysed droughts, particularly through standardized drought indices under a non-stationary framework (Salvi and Ghosh 2016; Shiau 2020; Stagge and Sung 2022). Nevertheless, to our knowledge, such non-stationary approaches have not been applied to dry-spell series obtained from daily precipitation records to assess potential non-stationary behaviour over time.

The study of potential changes in dry-spell duration associated with climate change has traditionally relied on indices that summarize dry-spell characteristics over a given period, for example, the mean annual frequency of dry-spells or the maximum duration observed within a year. These annual series are then analysed using non-parametric statistical methods to detect potential changes in drought conditions. Numerous regional studies have explored changes in dry-spell occurrence using these approaches (Douguedroit 1987; Anagnostopoulou et al. 2003; Piccarreta et al. 2013; Song et al. 2015; Zhang et al. 2017; Bichet and Diedhiou 2018; Caloiero and Coscarelli 2020). However, these methods have limitations, as actual extreme events may be masked or smoothed, preventing a robust assessment of changes in dry-spell hazard—understood as the probability that an extreme event of a given magnitude (in this case, spell duration) varies over time.

Spain is a country strongly affected by droughts (Trullenque-Blanco et al. 2024), with precipitation showing high interannual and seasonal variability. Different studies analysing drought dynamics from various perspectives suggest an increase in drought severity (Vicente-Serrano et al. 2014; Domínguez-Castro et al. 2019b), mainly driven by rising atmospheric evaporative demand (Azorin-Molina et al. 2015; Tomas-Burguera et al. 2021), while precipitation dynamics have remained largely stationary (Vicente-Serrano, Tramblay, et al. 2025). However, these studies primarily focus on drought dynamics driven by precipitation amount. There are comparatively few studies analysing the dynamics of dry-spells defined as days without or low precipitation (Martin-Vide and Gomez 1999; Lana et al. 2006; Lana, Martínez, Burgueño, Serra, Martin-Vide, and Gómez 2008), and none covers the whole of Spain with a long-term dataset using a high-density meteorological network. In this study, we address this gap by analysing dry-spell dynamics using two methodological approaches: (i) a non-stationary probabilistic framework, applied for the first time to dry-spell series, and (ii) a classical non-parametric analysis of annual series of dry-spell frequency, mean duration, and maximum duration.

2 | Data

Our study used daily precipitation observations from 904 gauging locations for 1961–2024. The data source for these stations was the comprehensive repository of daily precipitation measurements provided by the Spanish Meteorological Agency (AEMET), which contains unprocessed data for approximately 11,000 locations. This collection underwent stringent scrutiny for quality (Vicente-Serrano et al. 2010). To address missing values, any series retaining over 75% of its original observations was infilled. This infilling employed a quantile matching technique based on data from surrounding stations (Beguería et al. 2019). The criteria for using a neighbouring station were a minimum 15-year shared observation period and proximity within a 50 km radius of the target location (for further details, see Beguería et al. 2025).

3 | Methods

The methodological approach includes different steps: (i) to identify dry-spells from daily precipitation using thresholds, (ii) to extract dry-spell durations using a high quantile threshold, (iii) to model these extremes using a Peaks-Over-Threshold (POT) framework with the generalized Pareto distribution (GPD), including non-stationary specifications, and (iv) to estimate return levels and return periods with bootstrap-based confidence intervals.

Considering a daily precipitation series $\{P_t\}$, the first approach is to define the dry days and to develop the segmentation into spells. A dry day is defined for a precipitation threshold μ_P. Here, we have followed four different thresholds: 0.1, 1, 5, and 10 mm as the threshold strongly determines the statistical characteristics of the dry-spells (Paton 2022):

$$\boldsymbol{I_t} = \{\boldsymbol{P_t} < \boldsymbol{\mu_P}\}$$

A dry-spell i is a maximal block of consecutive days with $I_t = 1$. For each spell we derive: (i) starting date: $s_i = \min\{t : I_t = 1 \text{ and } t \text{ belongs to the spell } i\}$, (ii) ending date: $e_i = \max\{t : I_t = 1 \text{ and } t \text{ belogns to the spell } i\}$, (iii) duration: $d_i = e_i - s_i + 1$ (in days) and (iv) starting year: $y_i = Y_{s_i}$. From the obtained dry-spell series, we developed a Peak-of-threshold selection of extreme durations (Leadbetter 1991; Beguería 2005). From all durations $\{d_i\}$, a quantile τ (usually a high quantile, e.g., 0.90) is fixed. The duration threshold is: $\mu = \hat{Q}_\tau(d)$, where $\hat{Q}_\tau$ is the empirical τ-quantile. We select the excesses:

$$d = \{X_j = Dd_j - \mu : Dd_j > \mu\}, j = 1, \dots, n,$$

Associated with years y_j. The average annual rate of all spells is:

$\lambda = \frac{N}{|y|}$, being N = total number of spells in y and $|y|$ is the number years.

To determine appropriate thresholds for defining the sample of dry-spell duration exceedances *(d)*, we applied a systematic percentile-based approach (Vicente-Serrano and Beguería-Portugués 2003). Candidate thresholds were defined using percentiles ranging from the 50th to the 99th (p = 0.50, 0.51, ..., 0.99). For the dry-spells obtained from each precipitation series considering the four thresholds, we extracted the exceedances corresponding to each percentile value. The sample of values above a certain (usually high) threshold is assumed to follow the GPD (Pickands III 1975), with parameters of location (origin) μ_j, which corresponds to the threshold defined by the corresponding percentile, scale σ_j and shape ξ_j. Let d_j be the duration of the dry-spell exceedances; the cumulative distribution function (CDF) for the duration d is given by:

$$F_D(d, \mu_j, \sigma_j, \xi_j) = \begin{cases} 1 - \left(1 + \dfrac{\xi_j (d - \mu_j)}{\sigma_j}\right)^{-1/\xi_j}, & \xi_j \neq 0, \\ 1 - \exp\left(-\dfrac{d - \mu_j}{\sigma_j}\right), & \xi_j = 0, \end{cases} \quad d \geq \mu_j, \quad 1 + \xi_j (d - \mu_j)/\sigma_j > 0.$$

Parameters were estimated by means of the maximum likelihood approach. For observed durations $d_j \geq \mu_j$, the log-likelihood contribution (for $\xi_j \neq 0$) is:

$$\begin{aligned} \ell(\theta) &= \sum_{j=1}^{n_e} \log f_D(d_j; \mu_j, \sigma_j, \xi_j) \\ &= -\sum_{j=1}^{n_e} \left[\log \sigma_j + \left(1 + \frac{1}{\xi_j}\right) \log\left(1 + \frac{\xi_j (d_j - \mu_j)}{\sigma_j}\right)\right] \end{aligned}$$

In the limit $\xi_j \to 0$ (exponential), the log-likelihood simplifies to

$$\ell(\theta) = -\sum_{j=1}^{n_e} \left[\log \sigma_j + \left(\frac{d_j - \mu_j}{\sigma_j}\right)\right],$$

which is the log-likelihood optimized by fitting GPD exceedances with μ_j set to the threshold (time varying or not).

The goodness-of-fit of the dry-spell exceedance series obtained above the different candidate thresholds was evaluated by means of the comparison between the theoretical CDF according to the GPD and the empirical CDF through the Kolmogorov–Smirnov (KS) and anderson-darling (AD) tests. In addition, we considered the Sample size (N)–number of cases available for model fitting to guarantee a sufficient sample for fitting purposes. These statistics were used to identify optimal threshold percentiles ensuring both statistical robustness and adequate sample sizes.

Figure 1 shows the results of the KS test, which assesses the fit of the exceedance series to the GPD using different percentiles as thresholds, based on dry-spell series derived from the four precipitation thresholds. The bar plot indicates that when low precipitation thresholds (0.1 and 1 mm) and low percentiles are used to define the exceedance series, most series do not fit a GPD. However, when higher percentiles are considered, the majority of exceedance series show a good fit to the GPD. Similar results are found for the AD test (Figure S1). In this study, we selected the 94th percentile for the 0.1 mm dry-spells, as more than 85% of the series fit a GPD at this threshold. For the higher precipitation thresholds (1, 5, and 10 mm), we selected the 92nd, 80th, and 50th percentiles, respectively, to define the exceedance series. These choices also provide a suitable balance between model fit and sample size, ensuring that the exceedance series remains large enough for robust analysis in the vast majority of meteorological stations (Figure S2). As the precipitation threshold increases, the percentile required for the exceedance series to follow a GPD decreases, indicating that exceedance series defined at lower quantiles still show an adequate fit to the GPD.

Once the thresholds were defined, we used the GPD considering a non-stationary approach to calculate dry-spell quantiles and return periods. This approach uses a parametric non-stationarity modelling of the distribution parameters (Coles 2001). For models with a time-dependent threshold, the conditional quantile τ of duration given year y is estimated by quantile regression:

$$Q_{D|Y}(\tau | y) = \beta_0 + \beta_{1y},$$

where coefficients minimize the check loss:

$$(\hat{\beta}_0, \hat{\beta}_1) = \arg\min_{\beta_0, \beta_1} \sum_i \rho_\tau(d_i - \beta_0 - \beta_1 y_i), \quad \rho_\tau(r) = r(\tau - 1\{r < 0\})$$

The local threshold is $u(y) = \hat{\beta}_0 + \hat{\beta}_1 y$. For covariates in non-stationary models, years are standardized:

$z_j = \frac{y_j - \bar{y}}{s_y}$, where $\bar{y}$ is the mean and s_y is the standard deviation.

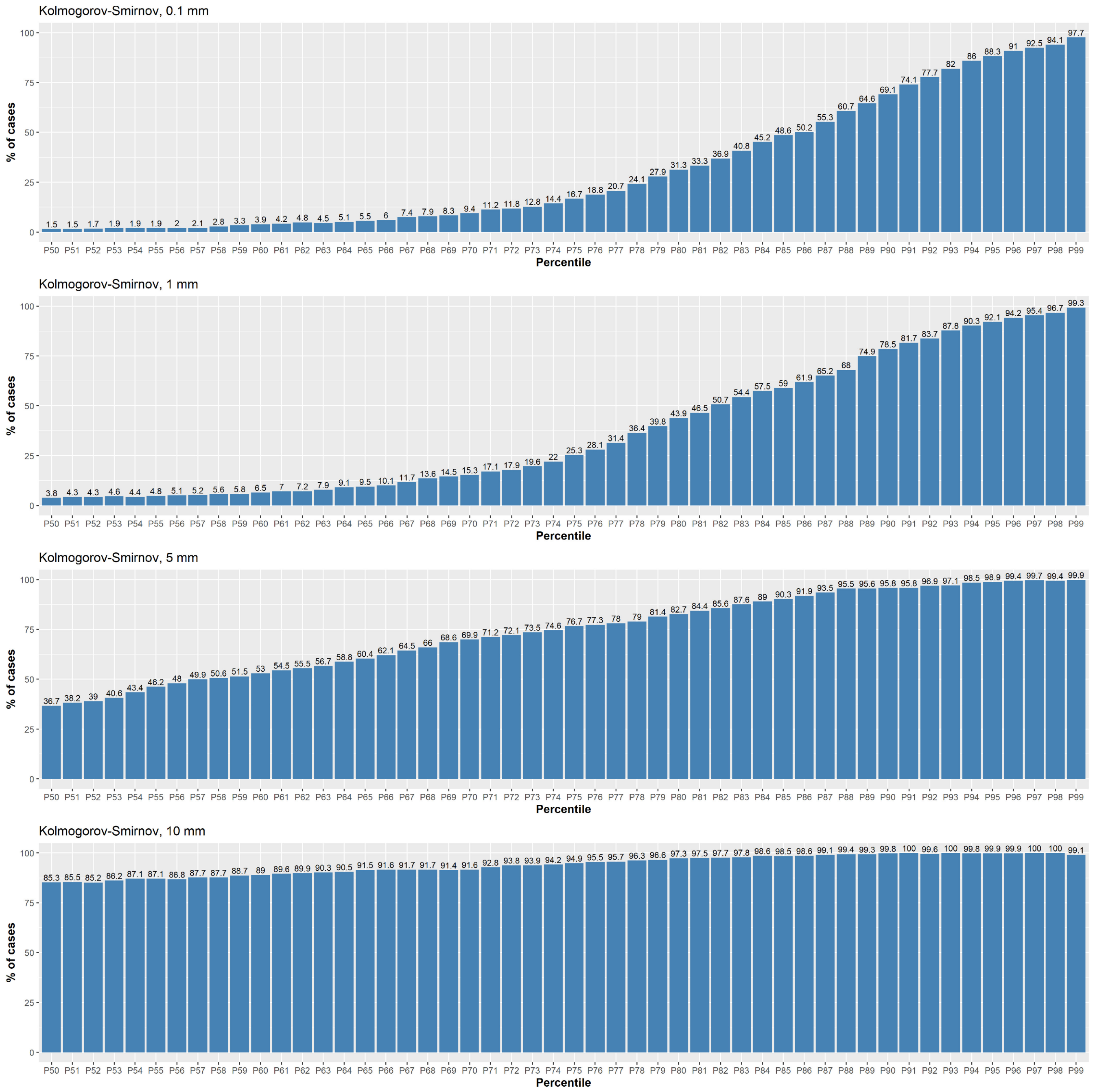

FIGURE 1 | Percentage of the dry-spell series obtained on the four thresholds showing a fit to the Generalized Pareto distribution according to the Kolmogorov–Smirnov test. [Colour figure can be viewed at wileyonlinelibrary.com]

Five specifications are considered to obtain the PDF associated to the dry-spell exceedances: (i) stationary: $u_j = \mu, \sigma_j = \sigma, \xi_j = \xi$, (ii) location varies with time: $u_j = \mu(y_j), \sigma_j = \sigma, \xi_j = \xi$, (iii) scale varies with time: $u_j = \mu, \log \sigma_j = \alpha_0 + \alpha_1 z_j, \xi_j = \xi$, (iv) shape varies with time: $u_j = \mu, \sigma_j = \sigma, \xi_j = \gamma_0 + \gamma_1 z_j$ and (v) full parameters vary with time: $u_j = \mu(y_j)$, $\log \sigma_j = \alpha_0 + \alpha_1 z_j, \xi_j = \gamma_0 + \gamma_1 z_j$. Here z_j is the standardized year covariate. The constraint $1 + \xi_j (d - \mu_j) / \sigma_j > 0$ must hold for all observed d.

When the GPD parametrized for the original durations D with location $\mu(y)$, scale $\sigma(y)$, and shape $\xi(y)$, and events arrive with annual rate λ, the N-year return level at year y is:

$$q_N(y) = \begin{cases} \mu(y) + \dfrac{\sigma(y)}{\xi(y)} \left[(\lambda N)^{\xi(y)} - 1 \right], & \xi(y) \neq 0, \\ \mu(y) + \sigma(y) \log(\lambda N), & \xi(y) = 0 \end{cases}$$

The return period of a target duration $d \geq \mu(y)$ is

$$T_d(y)=\begin{cases}\dfrac{1}{\lambda}\left(1+\dfrac{\sigma\xi(y)[d-\mu(y)]}{\sigma(y)}\right)^{1/\xi(y)}, & \xi(y)\neq 0,\\ \dfrac{1}{\lambda}exp\left(\dfrac{d-\mu(y)}{\sigma(y)}\right), & \xi(y)=0\end{cases}$$

To determine if the non-stationary approaches provide a significant contribution to the assessment of high precipitation quantiles and what is the best non-stationary approach, we applied a nonparametric bootstrap for comparing return levels. According to this approach, the null hypothesis H_0 shows that the return level from the non-stationary model equals that of the stationary model, where the observed difference is:

$$\Delta_{\text{obs}}=q_N^{(NS)}-q_N^{(S)}$$

where $q_N^{(NS)}$ and $q_N^{(S)}$ are the return levels from the non-stationary and stationary models, respectively. A nonparametric bootstrap was applied to assess the uncertainty in Δ_{obs}.

For $b=1,\ldots,B=1000$, this approach resamples entire dry-spells with replacement to preserve the temporal structure and the covariate-threshold relation, then the threshold $\mu^{(b)}$ is recomputed by means of quantile regression and the stationary and the non-stationary GPD models are fitted to the bootstrap sample, estimating $\alpha^{(b)}$ and $\xi^{(b)}$. The next step is to compute the corresponding return levels $q_N^{(NS)}$ and $q_N^{(S)}$ and record $d^{(b)}=q_N^{(b,NS)}-q_N^{(b,S)}$. From the valid replicates $\left\{d^{(b)}\right\}$ the test computes the 95% percentile confidence interval (CI):

$$\widehat{CI}_{95\%}=\left[Q_{0.025}\left(d^{(b)}\right),Q_{0.975}\left(d^{(b)}\right)\right]$$

And the two-sided empirical p-value is obtained according to:

$$\widehat{p}_{\text{emp},2}=2\ \min\left\{\frac{1}{B^*}\sum_b 1\left\{d^{(b)}\geq\Delta_{\text{obs}}\right\},\frac{1}{B^*}\sum_b 1\left\{d^{(b)}\leq\Delta_{\text{obs}}\right\}\right\}$$

where B^* is the number of valid replicates. Differences were considered significant when the CI did not include zero and $p_{\text{emp}}<0.05$.

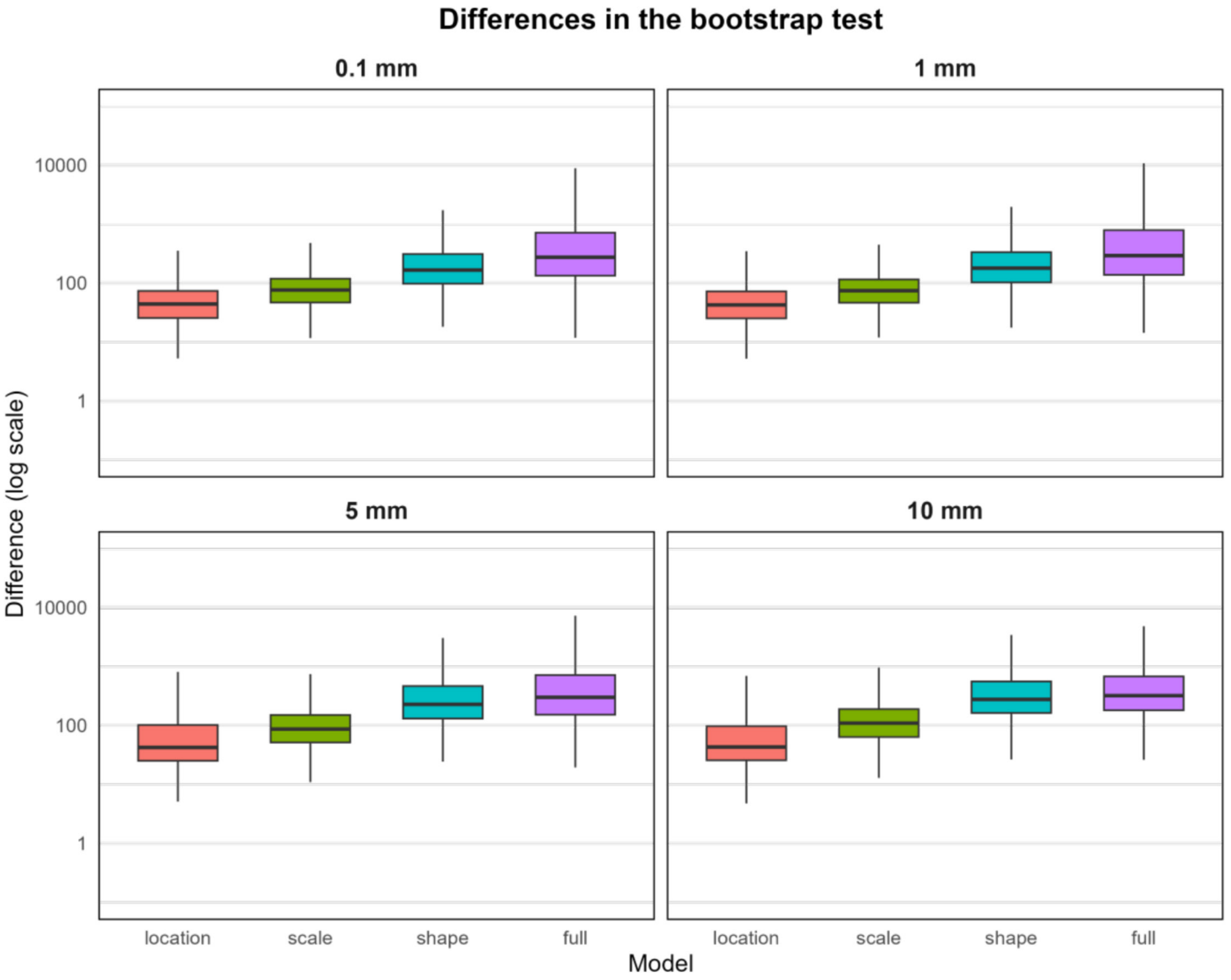

FIGURE 2 | Differences between the lower and upper confidence intervals derived from the bootstrap test, associated to uncertainties in the estimation of Δ for the different non-stationary models obtained from the dry-spell series at 0.1, 1, 5, and 10 mm. [Colour figure can be viewed at wileyonlinelibrary.com]

This nonparametric bootstrap resamples full dry-spells rather than only exceedances, ensuring consistency with threshold models that depend on time (e.g., quantile-regression thresholds in the non-stationary origin model) and it preserves the dependence between threshold and covariates while remaining model-free regarding residuals.

Figure 2 presents boxplots showing the differences between the lower and upper confidence intervals derived from the bootstrap test for models in which different parameters were allowed to vary with time. Table 1 additionally reports the percentage of stations for which the various non-stationary models provide more robust information compared with the stationary model. The width of the confidence intervals offers a good measure of model performance, as large values indicate high uncertainty in the estimates.

TABLE 1 | Percentage of the stations in which the different non-stationary models show significant differences with the stationary model according to the bootstrap test.

	Location	Scale	Shape	Full
0.1 mm	5.53	0.00	0.00	0.11
1 mm	1.66	0.00	0.11	0.11
5 mm	1.99	0.00	0.00	0.00
10 mm	3.87	0.00	0.00	0.00

Overall, the results show that, in most cases, fitting a non-stationary model does not provide more robust information. Only the model with a non-stationary location parameter adds meaningful information, and even then only for a very limited number of stations. The models with non-stationary shape, scale, or all parameters do not contribute relevant improvements for any of the four precipitation thresholds used to define dry-spells. Moreover, the differences between the lower and upper confidence intervals reveal highly uncertain estimates for the non-stationary scale, shape, and full-parameter models. In models where all parameters depend on time, uncertainty completely dominates the results.

These issues are illustrated in Figure 3, which shows the estimated dry-spell quantiles associated with different return periods for the year 2024 in three meteorological stations. In these examples, the estimates from the stationary model and the non-stationary location model are similar. However, the quantile estimates produced by the other three non-stationary models deviate substantially from the stationary model. For these reasons,

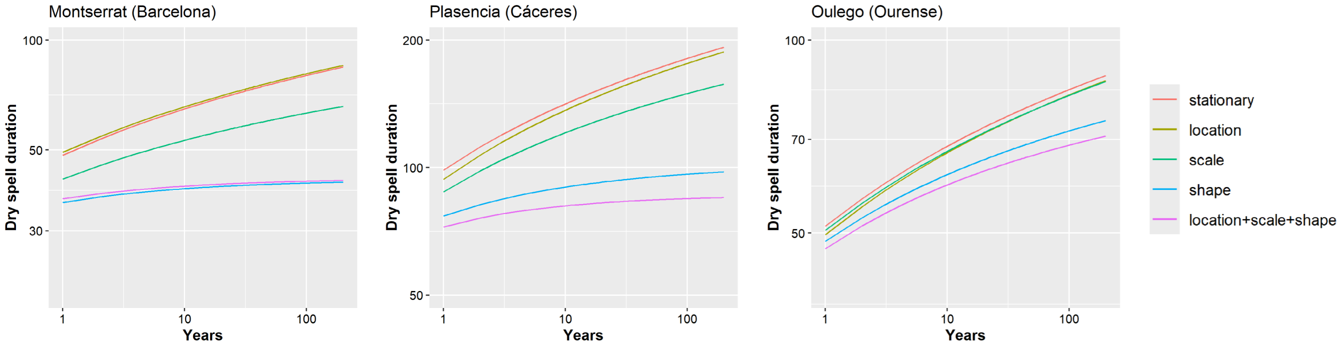

FIGURE 3 | Examples of the quantile dry-spells obtained for different return periods considering the stationary and the different non-stationary models corresponding to the year 2024. [Colour figure can be viewed at wileyonlinelibrary.com]

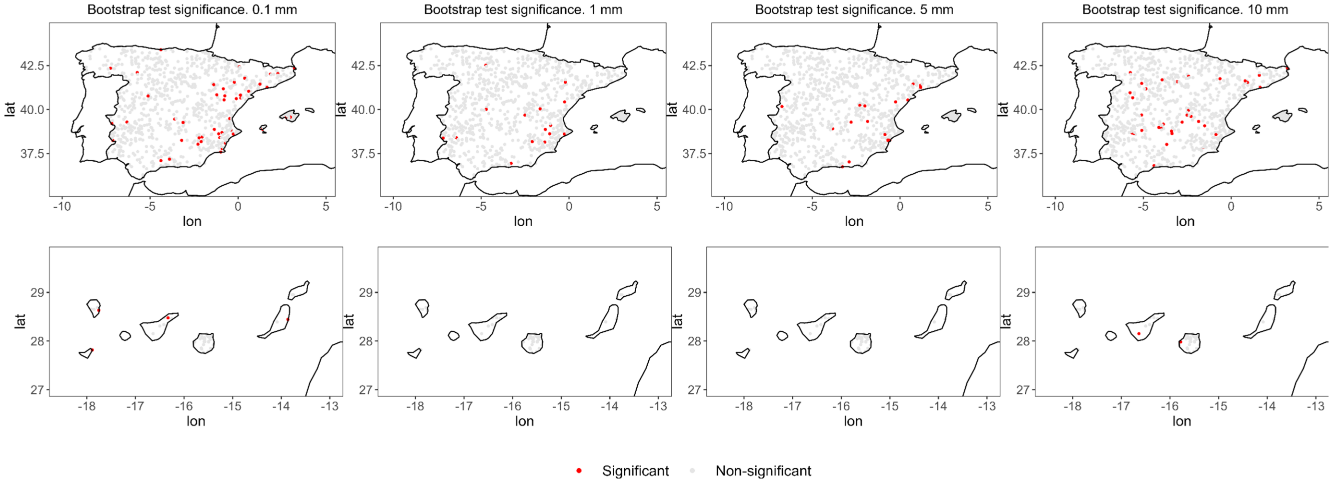

FIGURE 4 | Spatial distribution of the results of the Bootstrap test significance to determine the statistical significance of the non-stationary behaviour of the high quantile dry-spell durations. [Colour figure can be viewed at wileyonlinelibrary.com]

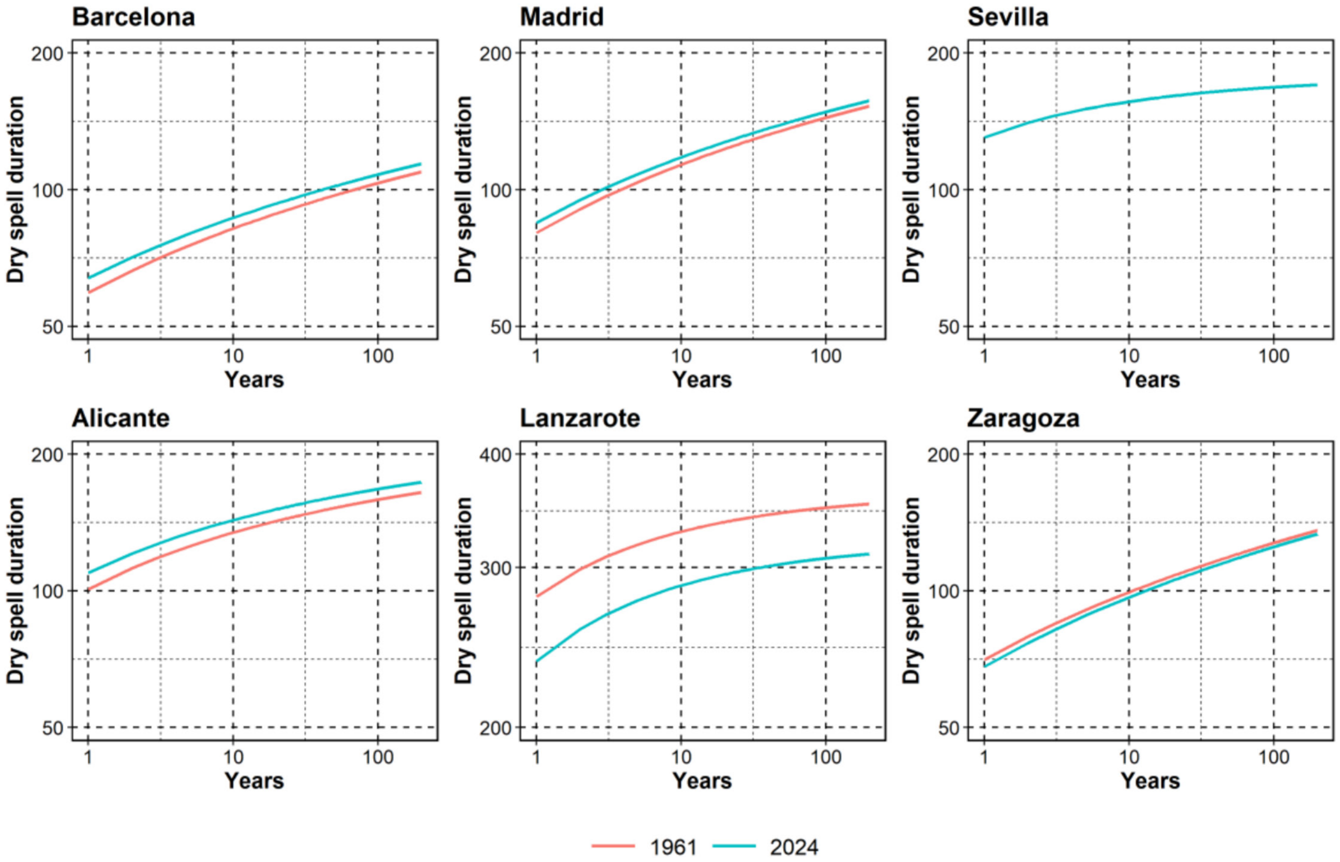

FIGURE 5 | Examples of duration-frequency curves that relate the dry-spell duration with its return period for the years 1961 and 2024 in six meteorological stations. Dry-spells were defined with a threshold of 1 mm. [Colour figure can be viewed at wileyonlinelibrary.com]

in this study we focus on the location model to assess potential non-stationary behaviour of dry-spells in Spain.

Finally, an annual summary is also generated to analyse the dynamic by means of classical non-parametric statistics. For this purpose, for each year the number of spells Ny and the mean duration $\overline{Dy}$ were obtained for each series and the four thresholds. Trend calculated in these parameters was calculated by means of the nonparametric Mann–Kendall statistic that measures the degree to which a trend is consistently increasing or decreasing. Autocorrelation was considered in the trend analysis applied to the annual series, performing the modified Mann–Kendall trend test, returning the corrected *p*-values after accounting for temporal pseudoreplication (Hamed and Rao 1998; Yue and Wang 2004). To assess the magnitude of change, we used the Sen's slope estimator as it is insensitive to outliers and it can be used even when residuals are not normally distributed.

4 | Results

Table 1 shows that the non-stationary model based on a time-varying location parameter was characterized by a small percentage of stations in which the return level provided by this model offered significant information compared with the stationary model, regardless of the threshold used to generate the dry-spells. The spatial distribution of stations with significant and non-significant non-stationary behaviour reveals very few stations with significant changes, and these are scattered irregularly across Spain (Figure 4).

This suggests that the occurrence of high dry-spell quantiles has remained mostly stationary in Spain for 1961–2024. The duration–frequency curves for selected stations confirm this pattern, showing only small differences between the curves for 1961 and 2024, with few exceptions (Figures 5 and S3–S5). In certain locations, notably Seville and Zaragoza, the curves corresponding to the two periods coincide, reflecting the absence of significant differences in their estimated quantiles. In general, these figures are representative of most stations across the country, indicating a broadly stationary behavior in dry-spell duration for all thresholds considered.

Figure 6 shows the relationship between the maximum dry-spell duration expected for a return period of 50 years in 1961 and 2024 for thresholds of 0.1, 1, 5, and 10 mm. There is very limited dispersion, meaning that the 50-year dry-spell durations are very similar at the beginning and end of the study period, except for a few stations. This indicates that long dry-spells have remained highly stable through time, reinforcing the stationary pattern. Accordingly, the spatial distribution of these 50-year dry-spells also shows minimal differences between 1961 and 2024 (Figures 7 and S6–S8). For the 0.1 mm threshold, a slight decline in the 50-year dry-spell duration is observed at a few stations in southeast Spain and the Canary Islands, but elsewhere

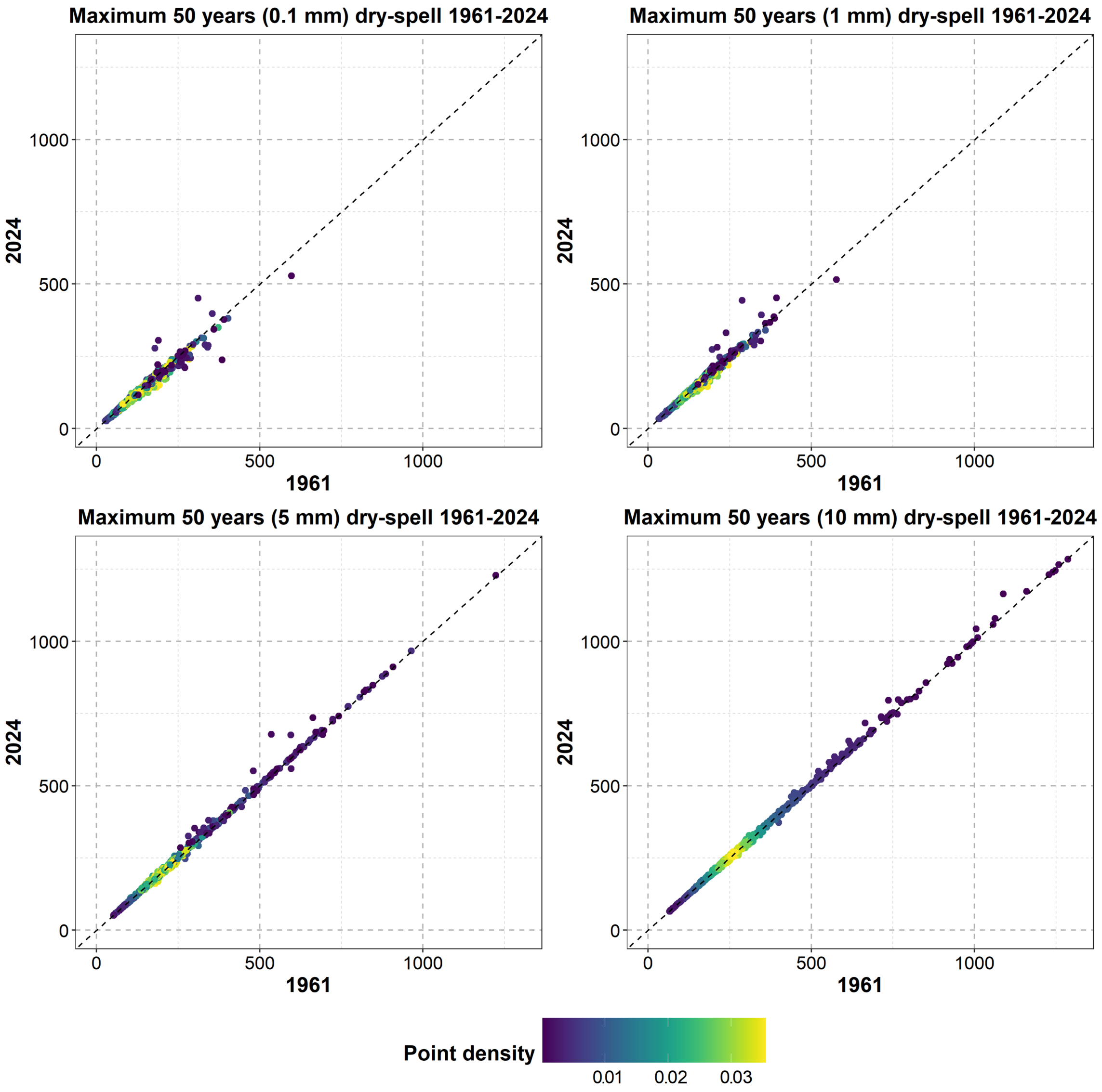

FIGURE 6 | Relationship between the 50-years dry-spell duration (in days) calculated from thresholds of 0.1, 1, 5, and 10 mm for the years 1961 and 2024. Each point represents each of the 904 meteorological stations used in this study. Colours represent the density of points. [Colour figure can be viewed at wileyonlinelibrary.com]

differences are close to zero. The same behaviour is found for the 1 mm threshold. For the 5 and 10 mm thresholds, no significant changes are detected, with a clear dominance of near-zero differences between the 2 years.

The strongly dominant stationary behaviour in the occurrence of high-duration dry-spells is confirmed when the data are analysed using more traditional methods based on time series analysis and non-parametric techniques. Analysis of the annual frequency, average duration, and maximum duration of dry-spells obtained with different thresholds reveals predominantly non-significant trends. Table 2 presents the percentage of stations showing positive and negative trends and their statistical significance. The most notable changes appear in the average duration and frequency of dry-spells, particularly for the 5 and 10 mm thresholds. The frequency of dry-spells shows a higher percentage of statistically significant negative trends than positive ones, whereas the average duration tends to exhibit more positive than negative trends. In any case, most stations (> 70%) for the 5 and 10 mm thresholds do not exhibit statistically significant trends in either the annual frequency or average dry-spell duration. Furthermore, although trends in the annual maximum duration also tend to be more positive than negative, more than 85% of stations show no statistically significant change over the study period. Spatially, neither the absolute values nor their statistical distribution suggests substantial changes in dry-spell characteristics across the different thresholds, and the spatial distribution of trends provides no indication of coherent regional patterns. Figures 8 and S9–S11 show the spatial distribution of the magnitude of change (in per cent) in annual frequency, average duration, and maximum duration of dry-spells for the different thresholds. The maps show no consistent spatial structure in either the magnitude or significance of trends. Statistically significant changes appear scattered randomly across the domain, and most stations show no significant trends.

These results are consistent with the stationary behaviour inferred from the non-stationary probabilistic analysis. Figure 9

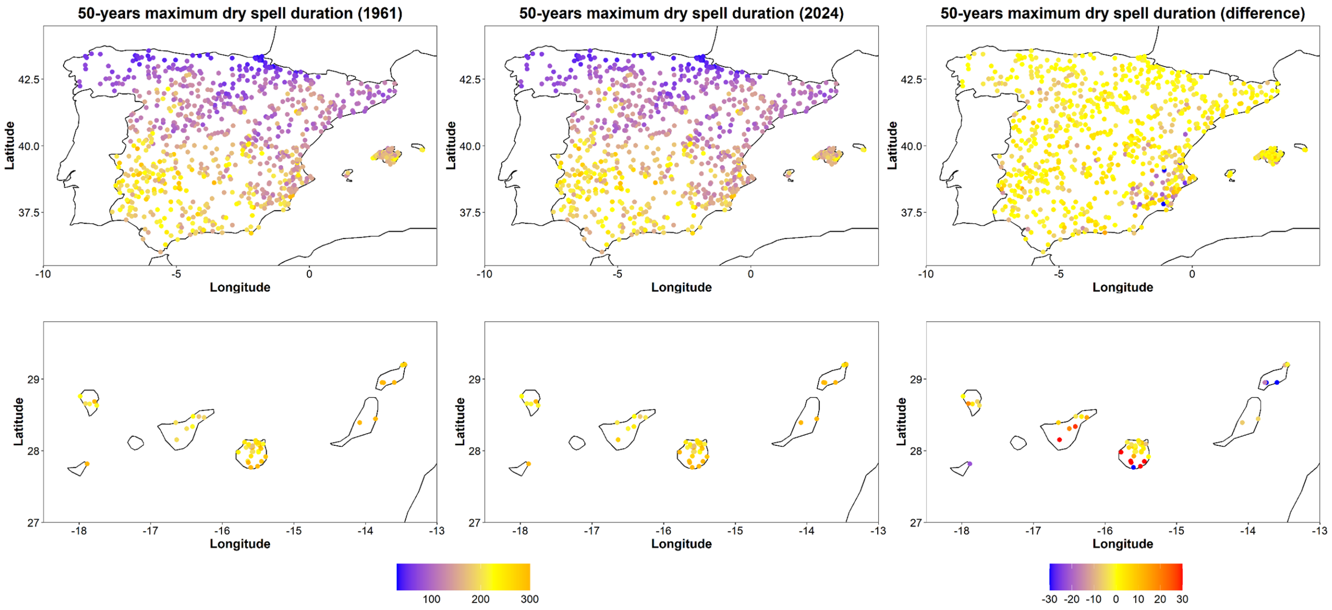

FIGURE 7 | Spatial distribution of the 50-year return level for dry-spell duration obtained from the threshold of 1 mm for the years 1961 and 2024, using a non-stationary model for the location parameter. The third column represents the difference between the 2 years. The legends represent lengths in the number of days. [Colour figure can be viewed at wileyonlinelibrary.com]

displays density plots showing the distribution of percentage change in the annual frequency, annual average duration, and annual maximum duration of dry-spells derived from the four thresholds. Dry-spells defined using the 0.1 and 1 mm thresholds exhibit no significant changes, although the average and maximum duration series for the 0.1 mm threshold tend to show a slight decrease. Conversely, for dry-spells defined using the 5 and 10 mm thresholds, both variables tend to show an increase. In all cases, however, these changes are not statistically significant at the vast majority of stations, and there is no clear shift relative to the zero-change line.

5 | Discussion

This study shows that dry-spell dynamics in Spain exhibited a dominantly stationary behaviour for 1961–2024. This main conclusion is derived from two complementary approaches: (i) a classical non-parametric analysis of dry-spell characteristics commonly used in climate change studies based on climate indices (Easterling et al. 2003; Donat et al. 2013), and (ii) a novel non-stationary probabilistic analysis applied for the first time to dry-spells obtained from daily precipitation series. In the proposed non-stationary analysis, the comparison of 1961 and 2014 does not imply that the selection of particular years biases the results obtained. As explained in the methodological section, the non-stationary generalized Pareto distribution considers a non-fixed location parameter, modelled as a linear function, so potential decadal oscillations do not affect the estimation of dry spell quantiles for specific periods. In other words, the non-stationary approach does not aim to capture decadal variations in quantiles associated with particularly dry or wet years, but rather to detect long-term changes in these quantiles. For this reason, the years 1961 and 2024 were selected to illustrate the differences in dry spell quantiles, as they represent the first and last years of the study period. Given the linear nature of the change in the location parameter, comparing these two endpoints better captures the potential changes in dry spell quantiles than selecting intermediate years.

Methodologically, our study demonstrates that exceedance series derived from dry-spells defined using four thresholds fit a GPD, in agreement with previous research (She et al. 2013; Cindrić Kalin and Pasarić 2022). However, the percentile used to define the exceedance series—at which most stations follow a GPD—varies considerably as a function of the precipitation threshold. For dry-spells defined at 0.1 or 1 mm, the series fit a GPD only when high percentiles are used. In contrast, we show that dry-spells defined using the 5 and 10 mm thresholds follow a GPD at lower percentiles, meaning that the common assumption of using very high percentiles to define exceedance series may need reconsideration, as lower percentiles can be used while increasing sample size. Previous studies have highlighted the distinct spatial and temporal behaviour of dry-spells defined using different thresholds (Lana, Martínez, Burgueño, Serra, Martin-Vide, and Gómez 2008; Serra et al. 2014; Paton 2022), and here we demonstrate that their statistical properties also differ markedly. The more extreme nature—in terms of duration—of dry-spells defined using high thresholds (5 and 10 mm) likely explains the better model fit obtained with lower percentiles.

In this study, we adopted a non-stationary approach to assess changes in dry-spell quantiles, testing different models in which the GPD parameters varied with time. Tramblay and Hertig (2018) applied a similar concept using the Generalized Extreme Value distribution to model dry-spells with non-stationary location and scale parameters driven by atmospheric circulation indices, finding that models with a time-varying location parameter performed best. Our results, based on the

TABLE 2 | Percentage of stations showing positive, negative and statistically significant trends in the annual frequency, average and maximum dry-spell duration considering dry-spell series obtained with thresholds of 0.1, 1, 5, and 10 mm.

	Average duration (0.1 mm.)	Annual frequency (0.1 mm)	Annual maximum (0.1 mm)	Average duration (1 mm)	Annual frequency (1 mm)	Annual maximum (1 mm)	Average duration (5 mm)	Annual frequency (5 mm)	Annual maximum (5 mm)	Average duration (10 mm)	Annual frequency (10 mm)	Annual maximum (10 mm)
Negative ($p < 0.01$)	19.7	3.8	15.2	6.2	5.0	4.6	0.6	13.4	1.9	0.4	16.2	0.8
Negative ($p < 0.05$)	9.5	3.3	8.3	5.4	5.8	6.1	1.5	13.2	1.5	1.2	13.1	1.2
Negative ($p > 0.05$)	36.2	41.3	49.3	36.1	54.1	49.7	19.5	60.6	35.0	21.9	63.5	32.0
Positive ($p > 0.05$)	26.2	26.8	22.9	40.8	23.7	34.1	52.4	10.0	52.0	49.8	5.9	55.4
Positive ($p < 0.05$)	3.4	9.1	2.3	6.6	5.0	2.8	13.1	1.5	5.6	11.5	0.8	6.5
Positive ($p < 0.01$)	5.0	15.8	2.0	4.9	6.5	2.8	12.9	1.3	4.0	15.2	0.7	4.1

GPD, closely agree: the non-stationary location model yields the best performance due to its lower uncertainties and greater consistency with the stationary model for a fixed reference year.

To our knowledge, this is the first application of a non-stationary probabilistic approach to dry-spell series derived from daily precipitation records. Previous studies applied non-stationary methods to extreme precipitation analyses to detect changes in return periods associated with high precipitation amounts (Tramblay et al. 2012; Gao et al. 2016; Yilmaz et al. 2017). Other research proposed non-stationary methods for the calculation of standardized drought indices under scenarios of increasing drought severity (Salvi and Ghosh 2016; Stagge and Sung 2022). With the exception of Tramblay and Hertig (2018), who modeled annual maximum dry-spells using non-stationary GEV parameters linked to atmospheric circulation indices, no previous studies have applied non-stationary modeling to dry-spells. Moreover, that study did not analyze temporal changes directly and used an annual-maximum-based distribution, which is suboptimal relative to exceedance-based approaches for estimating dry-spell return periods (Vicente-Serrano and Beguería-Portugués 2003). Therefore, our work constitutes a methodological advance, as the non-stationary approach allows assessment of changes in the probability of high dry-spell quantiles and associated return periods—metrics directly linked to ecological, agricultural, and water-resource risk—beyond the capabilities of classical non-parametric trend analysis.

Regarding observed changes in dry spells, our study shows that dry spell dynamics in Spain have been predominantly stationary over the long term. This is clearly demonstrated by the application of the new non-stationary GP fitting, which allows significant changes in the occurrence of high quantiles to be detected. In other words, the probability of occurrence of high-duration dry spells, quantified across different thresholds, has not changed in Spain between 1961 and 2024. Some previous studies analysing the temporal dynamics of dry spells in parts of Spain had suggested an increase in dry spell duration (e.g., Miró et al. 2018). Nevertheless, the results obtained from the probabilistic non-stationary analysis are also consistent with the conventional trend analysis based on annual dry spell metrics, which reveals no significant trends in annual frequency, duration, or maximum duration across most meteorological stations. Although significant increases in dry spell duration were found at some stations for thresholds of 0.1, 5, and 10 mm, these represented less than 30% of the total, while the remaining more than 70% showed no statistically significant trends. Similar findings have been reported in other Mediterranean regions, including France (Raymond and Ullmann 2021), Greece (Nastos and Zerefos 2009), and Italy (Caloiero et al. 2015; Pavan et al. 2019), as well as across Spain as a whole for the periods 1903–2003 (Gallego et al. 2011) and 1950–2000 (Lana, Martínez, Burgueño, Serra, Martin-Vide, and Gómez 2008), where changes in dry spell length have consistently proved difficult to detect. Furthermore, our results show that not only have the annual characteristics of dry spells remained predominantly stationary in Spain, but more importantly, the probability of high dry spell quantiles has also remained essentially unchanged between 1961 and 2024.

In the western Mediterranean, some studies have suggested a decline in precipitation (Hoerling et al. 2012; Seager et al. 2019),

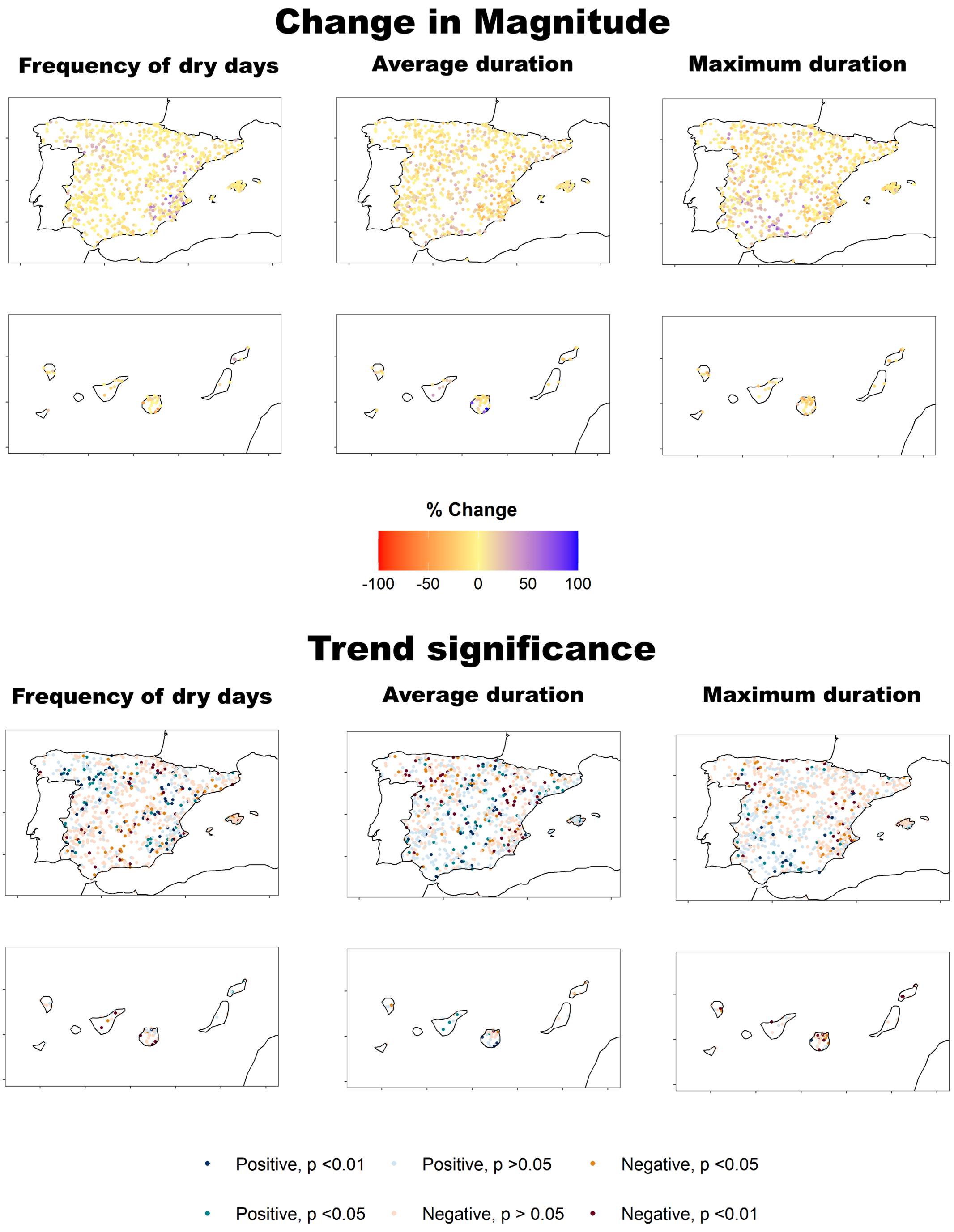

FIGURE 8 | Spatial distribution of the % of change and statistical significance of the trend of the annual frequency, average and maximum dry-spell duration considering the dry-spells calculated with a threshold of 1 mm. [Colour figure can be viewed at wileyonlinelibrary.com]

which would be compatible with longer dry-spells. However, a recent study provides evidence against a persistent regional decline (Vicente-Serrano, Tramblay, et al. 2025), indicating that precipitation exhibits high temporal variability driven primarily by atmospheric dynamical variability (Kelley et al. 2012). Indeed, between the 1960s and 2000s, western Europe experienced a decline in precipitation due to atmospheric circulation patterns that produced high rainfall in the early 1960s and low rainfall in the 1990s (Kelley et al. 2012; Vicente-Serrano, Tramblay, et al. 2025). In our dry-spell analysis, we show that even when the observational period begins in the 1960s, no dominant significant changes are detected in dry-spell characteristics, even for high thresholds such as 5 and 10 mm and particularly the probability of high dry-spell quantiles remains dominantly stationary. This reveals that total precipitation in Spain has not only remained stable, but that its characteristics have also remained unchanged, including the duration of dry-spells and, as shown in recent research, the nature of extreme daily precipitation events (Beguería et al. 2025). Altogether, these results reinforce the dominant stationary behaviour of precipitation in Spain, not only in terms of total amounts but also in the properties of daily precipitation, even for a period starting in the decade of

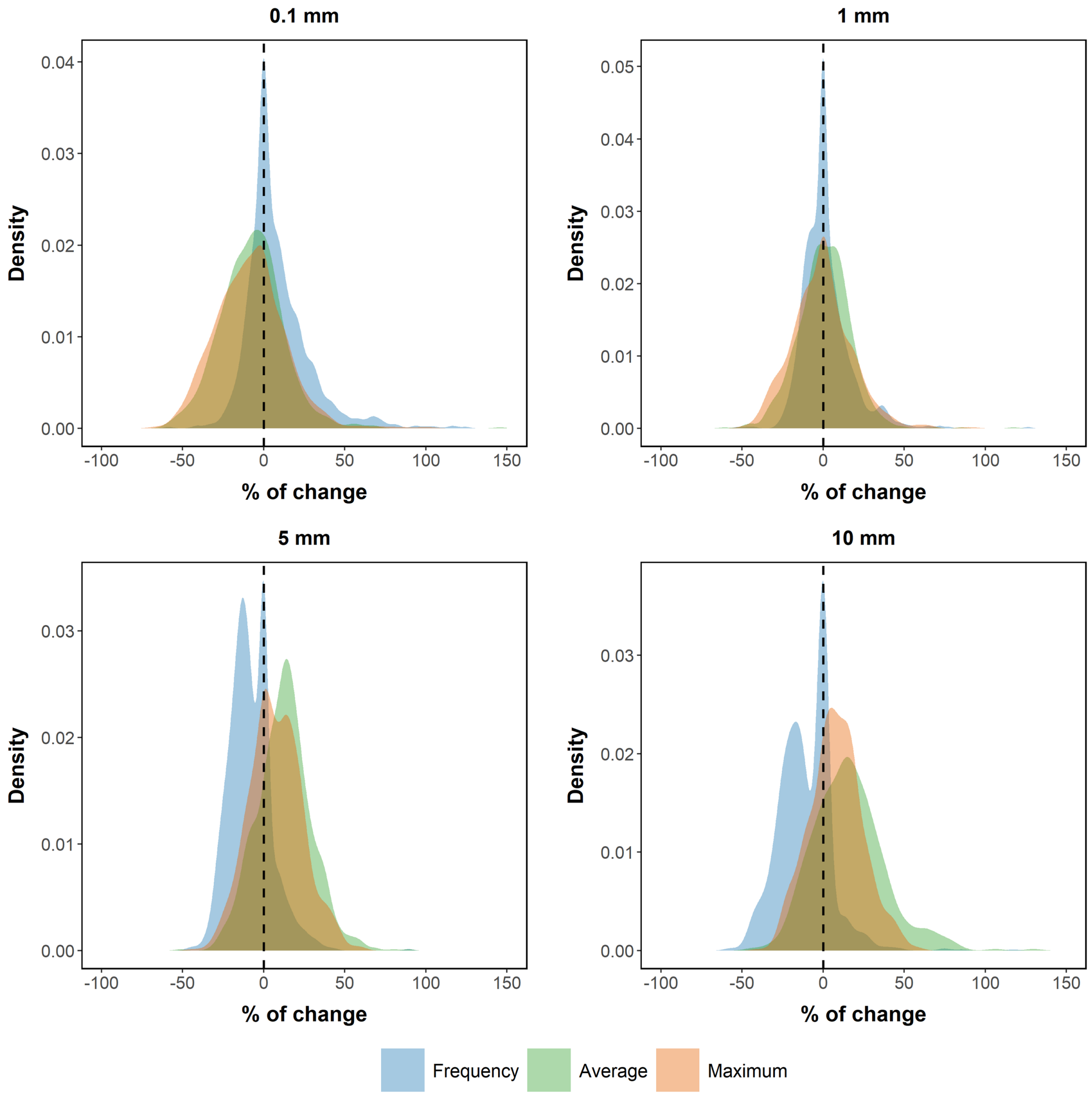

FIGURE 9 | Density plots showing the distribution of the percentage of change in the annual frequency of dry-spells, the annual average duration of the dry-spells, and the annual maximum duration of dry-spells. The analyses are based on dry-spell series obtained with thresholds of 0.1, 1, 5, and 10 mm. [Colour figure can be viewed at wileyonlinelibrary.com]

1960, which was particularly humid in the region. The persistent control of precipitation by atmospheric dynamics—evident at both monthly (Vicente-Serrano, Tramblay, et al. 2025) and daily (Vicente-Serrano, Garrido-Perez, et al. 2025) time scales—helps explain the long-term stability. Several atmospheric circulation mechanisms, from large-scale teleconnection patterns to regional processes such as blocking events, ridges, and storm-track variability, appear to have remained stationary throughout the study period, thereby supporting the observed long-term precipitation and dry-spell stationarity.

6 | Conclusions

The analysis of dry-spell dynamics in Spain, based on both classical trend techniques and a novel non-stationary probabilistic framework provides a coherent picture of long-term stability. Non-stationary models involving scale, shape, or full parameter variation introduce substantial uncertainty. Moreover, only a very small fraction of stations exhibit significant non-stationary effects in the GPD location parameter, and these are spatially random.

Overall, the statistical behaviour of dry-spells—particularly their extreme durations—has remained remarkably stationary for 1961–2024, with no evidence of long-term intensification in either duration or frequency. Thus, return levels associated with extreme dry-spells (e.g., 50-year durations) are nearly identical when comparing 1961 and 2024 and spatial maps confirm that differences in long-return-period quantiles are minimal, with values clustered near zero. Moreover, annual indicators (frequency, average duration, maximum duration) show no statistically significant trends for 70%–85% of stations. These results indicate that for risk assessment and climate services, stationary models remain appropriate and reliable for estimating dry-spell hazard in Spain. Even though drought severity has increased due to rising atmospheric evaporative demand, dry-spell duration has not intensified, confirming the independence of both processes.

Author Contributions

S. Beguería: data curation, conceptualization, methodology, funding acquisition. **R. Nieto:** conceptualization, writing – review and editing. **D. Pérez-Pajuelo:** writing – review and editing. **F. Domínguez-Castro:** writing – review and editing. **L. Gimeno:** conceptualization, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The daily precipitation data used in this study were obtained from the Spanish Meteorological Agency (AEMET) and are subject to access restrictions. Processed datasets and derived dry-spell series supporting the findings of this study are available from the corresponding author upon reasonable request, subject to AEMET data-sharing policies.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Percentage of the dry spell series obtained on the four thresholds showing a fit to the Generalized Pareto distribution according to the Anderson-Darling test. **Figure S2:** Density distribution of the number of dry spell cases for each precipitation threshold (0.1, 1, 5, and 10 mm). The dashed vertical line indicates the mean number of cases for each threshold, with the corresponding value shown alongside. Distributions are based on 904 observations. **Figure S3:** Examples of duration-frequency curves that relate the dry spell duration with its return period for the years 1961 and 2024 in six meteorological stations. Dry spells were defined with a threshold of 0.1 mm. **Figure S4:** Examples of duration-frequency curves that relate the dry spell duration with its return period for the years 1961 and 2024 in six meteorological stations. Dry spells were defined with a threshold of 5 mm. **Figure S5:** Examples of duration-frequency curves that relate the dry spell duration with its return period for the years 1961 and 2024 in six meteorological stations. Dry spells were defined with a threshold of 10 mm. **Figure S6:** Spatial distribution of the 50-year dry spell obtained from the threshold of 0.1 mm for the years 1961 and 2024. The third column represents the difference between the 2 years. The legends represent lengths in the number of days. **Figure S7:** Spatial distribution of the 50-year dry spell obtained from the threshold of 5 mm for the years 1961 and 2024. The third column represents the difference between the 2 years. The legends represent lengths in the number of days. **Figure S8:** Spatial distribution of the 50-year dry spell obtained from the threshold of 10 mm for the years 1961 and 2024. The third column represents the difference between the 2 years. The legends represent lengths in the number of days. **Figure S9:** Spatial distribution of the % of change and statistical significance of the trend of the annual frequency, average and maximum dry spell duration considering the dry spells calculated with a threshold of 0.1 mm. **Figure S10:** Spatial distribution of the % of change and statistical significance of the trend of the annual frequency, average and maximum dry spell duration considering the dry spells calculated with a threshold of 5 mm. **Figure S11:** Spatial distribution of the % of change and statistical significance of the trend of the annual frequency, average and maximum dry spell duration considering the dry spells calculated with a threshold of 10 mm.