Characterisation of the intra-annual rainfall and its evolution (1837–2010) in the southwest of the Iberian Peninsula

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Abstract:

Variability in precipitation affects annual total records and causes instability in rainfall distribution throughout the year. Our aim in this study was to develop a procedure, based on pluviometric centralisation and dispersion parameters, that is able to characterise rainfall distribution throughout a year of precipitation in a unique, condensed and precise manner. This enabled the evolution of intra-annual precipitation from 1837 to 2010 in the southwest of the Iberian Peninsula to be determined. The obtained results showed irregular oscillations of the parameters during the selected period. Specifically, patterns of precipitation in recent decades revealed the following differentiating features: the displacement of the most intense rainy periods to the autumn with a consequent decrease in precipitation in the spring; and more erratic distribution throughout the year with an increase of the frequency of intra-annual dispersion peaks.

Keywords Intra-annual rainfall; centralisation index; dispersion index; Mediterranean ecosystems; Iberian Peninsula

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1 INTRODUCTION

Irregular rainfall is a feature of areas with a Mediterranean climate, including most of the Iberian Peninsula (Lionello et al. 2006; García-Ruiz et al. 2011). Inter-annual irregularity is evident in the successive occurrence of years with rainfall values well below the average and others with very high values. Due to the natural and social effects this has, several studies have been undertaken on the inter-annual variability and, in particular, the recurring periods of drought in the Iberian area (Pita 1995; Vicente-Serrano 2006; Vicente-Serrano and Cuadrat-Prats 2007; Sousa PM et al. 2011). So, there is a great number of studies aimed at determining the temporal variation in the rainfall patterns (González-Hidalgo et al. 2003; Muñoz-Díaz and Rodrigo 2003; Martín-Vide 2004; Santos et al. 2005; Norrant and Douguédroit 2006; Aguilar 2007; Cuadrat et al. 2007; Rodrigo and Trigo 2007; González-Hidalgo et al. 2009; De Luis et al. 2010; López-Moreno et al. 2010; Reiser and Kutiel 2010), the occurrence of extreme precipitation (Rodrigo 2002; García et al. 2006; Costa et al. 2008; Queralt et al. 2009; Durão et al. 2010; Machado et al. 2011) and the impact of high daily concentrations and torrential rainfall (Martín-Vide et al. 2008; Llasat et al. 2010; Pastor et al. 2010; Ribera et al. 2011).

We believe that, in addition to the total annual rainfall, the intensity and location of the rainy season throughout the year are also relevant factors in the characterisation of rainfall in a particular geographic area. Rainfall distribution directly affects the behaviour of many environmental processes. Together with other bioclimatic and edaphic factors, it plays a key role in the diversity of natural ecosystems and has a significant economic impact on rain-fed agriculture. Knowledge of annual rainfall distribution and its variability is therefore useful in establishing classification criteria and also links with other natural science fields (Lázaro et al. 2001; Nippert et al. 2006; Fay et al. 2008; Taguas et al. 2010; Perez-Camacho et al. 2012).

In this sense, changes in seasonal precipitation trends, as identified by García-Barrón (2002) for spring and for March by Aguilar (2007) can have direct environmental consequences, even though there is no change in the total annual precipitation. Thus, at least since the late nineteenth century in the southwest of the Iberian Peninsula, a lower distribution of rainfall in spring, an increase in autumn and an increase in the frequency of dry years, prevent the recharging of aquifers, which then results in the development of hygrophytic vegetation rain and recharge processes of the wetlands in the study area (Sousa and García-Murillo 2003; Sousa et al. 2006). In addition, with the increase of rainfall during the autumn (when vegetation is less developed in European Mediterranean ecosystems), rainfall erosivity can also increase. This has consequences for increasing the risk of the flooding and silting of small streams, as occurs in the southwest of the Iberian Peninsula (Sousa et al. 2010). Therefore, changes in the pattern of the intra-annual distribution of precipitation influence wetland systems and the availability of water resources, livestock and agricultural sectors, management of pastureland and forest (including fire prevention), and erosivity, tourism, etc. It is also interesting to note other consequences, such as the effects on the phenological phases (flowering, foliation and fruit ripening) of herbaceous and tree species (García-Mozo et al. 2010), especially those having a social impact for their allergenic character or agricultural interest.

However, few authors (López-Díaz 2002; López-Moreno et al. 2009) have proposed the use and development of indices to analyse intra-annual changes in precipitation trends in the southwest of Europe. Therefore, the aim of this paper was to determine the intra-annual rainfall distribution pattern in the southwest of the Iberian Peninsula and its evolution (period 1837–2010) by means of a time series the variables of which are new indicators. To achieve this objective, the development of parameters to determine the annual rainfall, in a summary and directly interpretable form, was required. It was then possible, using these variables, to establish if the distribution throughout the year remains relatively stable or, in contrast, if there are multi-year sub-periods with trends or temporary displacements that present internal changes in the rainfall distribution. In such a case, we were then able to discuss to what extent such changes in the pattern of intra-annual precipitation distribution may result in environmental alterations.

To achieve these objectives it was necessary to define and develop previously two indicators that describe the central point of precipitation in the year (n), that is, its annual centralisation (C_n), and an index that describes the dispersion or distribution of precipitation around the central value (D_n). With these two new indices, together with the total annual precipitation (P_n), we set out to describe and characterise the intra-annual rainfall distribution pattern of each observatory.

Although all the sections in the text are obviously linked, the results described in each are separately consistent in order to characterise the distribution of intra-annual precipitation. For this reason, the results obtained are described and discussed for each section.

Section 2 describes the study area and the meteorological station from which the data have been registered. In Section 3, the authors propose the basis for the methodology to synthetically characterise the intra-annual precipitation by means of a set of the three aforementioned parameters [P_n, C_n, D_n]. This section shows and defines in detail the properties of the parameters C_n and D_n (Sections 3.1 and 3.2), which are used later. Finally, Section 3.3 shows how these three parameters provide, for every year, summary information about complementary aspects. In Section 4, the time series, integrated by the successive annual parameter values P_n, C_n and D_n for the period 1837–2010, is analysed. Finally, the evolution of the indicators linked to the intra-annual precipitation and the potential environmental consequences are briefly discussed. Moreover, its relationship with the North Atlantic Oscillation (NAO) index is introduced.

2 STUDY AREA AND DATA

2.1 Study Area

The study area is located in the southwest quadrant of the Iberian Peninsula. From a climatic point of view, this area is particularly interesting as it occupies a transition position between middle latitudes and the subtropical climate (Martín-Vide and Olcina 2001). The southwest quadrant of the Iberian Peninsula (Fig. 1) has opposite vertices in Lisbon and San Fernando, the weather stations of which have recorded a complete series of precipitation since the first half of the nineteenth century. Since the precipitation series of these aforementioned stations cover more than 173 years, they will be considered as a source for the historical study of the evolution of the intra-annual precipitation.

Fig. 1 around here

The NAO index is derived from the difference in the standardized values of the pressure between the Atlantic subpolar latitude (Icelandic low) and the subtropical latitude (Azores high), the values of which are often measured at continental weather stations. The observatories of Lisbon or Gibraltar/San Fernando have been used as the continental southernmost area in highlighting the effects of the NAO (Jones et al. 1997; Muñoz-Diaz and Rodrigo 2003; Trigo et al. 2004). The North Atlantic Oscillation generates a pressure gradient the fluctuations of which determine the climate in Europe (Qian et al. 2000; Trigo 2011). In particular, in the southwest of the Iberian Peninsula the negative NAO phase, attenuated by the Azores anticyclone, allows a wet and warm airflow from the west, bringing rainfall (Muñoz-Diaz and Rodrigo 2004; Gallego et al. 2005). In contrast, the positive phase intensifies the subtropical anticyclone, turning aside Atlantic storms and resulting in dry conditions in the study area. However, the movement of storms towards the north provokes rainfall and mild temperatures in Western Europe (Trigo et al. 2002). For these reasons, we proposed linking the intra-annual rainfall distribution in the southwest of the Iberian Peninsula with the NAO index. Using San Fernando and Lisbon as the main reference stations in our study implies that the results obtained can subsequently be useful as a basis for carrying out European projections.

To verify if the stations of Lisbon and San Fernando sufficiently characterise the geographical area of the study, we also used the rainfall series from other observatories distributed throughout the area. The period selected was the three decades between 1961 and 1990, as recommended by the World Meteorological Organisation (WMO). For this period, we generated the SW_R series as the regional average of data from the Spanish representative stations (Cordova, Jerez, Rio Tinto, Seville-Airport, Talavera la Real), from Portugal (Beja and Tavira) and from Gibraltar. All the administrative districts that comprise the study region are represented by these stations and are located in different geographic areas: the Atlantic Coast (Tavira), South Atlantic Basin (Jerez), Guadalquivir Valley (Seville and Cordova), Guadiana Basin (Talavera and Beja), Sierra Morena (Rio Tinto) and Strait of Gibraltar. Furthermore, the average SW_{LS} series of the monthly precipitation in Lisbon and San Fernando for the same period were generated. If as a result of the preliminary analysis (see Section 4.1) the correspondence between SW_{LS} and SW_R was found to high, we would conclude that the San Fernando-Lisbon series is sufficiently representative of the evolution of the temporal behaviour of the intra-annual precipitation throughout the southwest quadrant of the Iberian Peninsula during the whole period. To do that, we used an adjustment factor that generates a new San Fernando–Lisbon secular series based on the eight aforementioned observatories.

2.2 Quality control and homogeneity

The series from complementary observatories have no missing data for the period 1961–1990. A quality control was performed on monthly data using neighbouring stations before producing the annual series. The series was also analysed graphically to verify the coherence of rainfall values for the selected meteorological stations.

The Cumulative Deviations test, T-test (Buishand 1982) and Standard Normalised Homogeneity test (SNHT) for single series (Alexandersson 1986) were applied. A relative homogeneity test (García-Barrón and Pita 2001) was also applied, creating a reference series with neighbouring stations. Following this process, the observatories were shown to have no homogeneity problems. These results were consistent with a previous homogeneity analysis performed on the same series (Almarza et al. 1996).

The missing data for 1852 in the Lisbon observatory were replaced by the mean monthly values of the decade as there were no neighbouring stations at that date. The series from San Fernando Observatory is complete until 1996, but there are a few gaps in the last decade (1.6%) which were filled using data from the neighbouring station of Cadiz, with a Pearson’s correlation coefficient of 0.9. Inhomogeneities have been reported in the series of San Fernando records prior to 1882 (Almarza et al. 1996). The comparative analysis with the Gibraltar observatory indicates an excess of total annual rainfall in San Fernando, especially between 1863 and 1878. Rodrigo (2002) makes a substitution for these data from the neighbouring station "Hermanos Urrutia" (Urrutia Brothers) of Cadiz, thus overriding the identified inhomogeneities. However, the average correlation coefficient for monthly rainfall during the years of simultaneous observations (1837–1878) between San Fernando and Urrutia Brothers is 0.94.

Therefore, regarding the effect of intra-annual distribution studies, the errors in the precipitation measurements in San Fernando were compensated because the monthly proportionality is constant; so, in this work we used the original records. Furthermore, the use of averages between observatories diminishes the effect of non-simultaneous local extreme deviations, reflecting more sharply the regional climatic behaviour.

3 METHODS

The pluviometric characterisation presented was based on the development, in two consecutive phases, of the temporal parameters of centralisation and dispersion. The assignment of a time coordinate implies the choice of a common origin of the reference system for all observatories, which is justified later (Subsection 3.3) as August 1st. Therefore, the term "date" also indicates the daily order from August 1st.

The information contained in the time precipitation series is expressed by the monthly totals, as the daily records of long-term series are not preserved. The direct use of daily precipitation, rather than using interpolation mechanisms, allowed precise calculations, although we did not detect relevant differences in the overall results in previous research. In order to assign the interpolation date we considered that the monthly distribution is approximately a linear function; its position within each month was calculated by the proportional values for precipitation in the preceding and posterior months. For calculation purposes, we assumed that rainfall is concentrated in a single day of the month.

To unify the information from different observatories we used the monthly relative precipitation obtained from the ratio of monthly precipitation and the annual total.

3.1 Intra-annual centralisation parameter

In every year of observation, the centralisation parameter C_n indicates the position (date) in which first-order moments distributed throughout the year are equivalent to those that would be generated if the whole annual rainfall had occurred on that date; it is therefore a measure of days, in our case taking August 1st of each year as the time origin.

For each year we calculated the centralisation parameter for first-order moments, C_n:

$$\Sigma(x_i\, p_i) = C_n\, \Sigma(\, p_i) \;; \quad (i = 1, 2, \ldots.12) \tag{1}$$

$$C_n = \Sigma(x_i\, p_i) \,/\, \Sigma(\, p_i) \tag{2}$$

where p_i represents the precipitation for the month of the year i, and x_i the order of the day respecting the origin chosen, which is assigned to the total monthly rainfall ($1< x_1 <31; 32< x_2< 62; .... ; 334 < x_{12}< 365$). The parameter C_n corresponds to the ordinal of the date that meets the condition.

We noted that, in general, the total precipitation in the intervals before and after the date of centralisation were not coincident, since the parameter C_n is also determined by the temporal order of occurrence of precipitation. The property of centralisation, as discussed later, shows that the vertical segment indicating the position of C_n divides the surface that delimits the intra-annual distribution with the abscissa axis into two equal parts.

The intra-annual distribution for the set of years analysed was obtained by means of the monthly average of the relative rainfall of the whole series. In a similar way, the C_N value which represented the "central time" for each observatory during the period studied was calculated.

3.2 Intra-annual dispersion parameter

The intra-annual dispersion parameter D_n measures the intensity of the precipitation linked to the proximity towards the middle of the year *n*. It indicates the interval for which the second-order temporal moment of the total annual rainfall coincides with the real time of rainfall distribution throughout the year, in both cases taking the value C_n as the common origin of such moments.

Every year, d_i is the interval between the date x_i assigned to the rainfall in each month and the date C_n at the centre of the calculated annual rainfall.

$$d_i = \left| x_i - C_n \right| \tag{3}$$

We defined the rainfall dispersion as the square root of the sum of the second order moments of time divided by the total annual rainfall.

$$\Sigma(d_i^2 \, p_i) = D_n^{\,2} \, \Sigma(\, p_i) \;\; ; \quad D_n = [\Sigma(d_i^2 \, p_i) \, / \, \Sigma(\, p_i)]^{1/2} \tag{4}$$

The parameter D_n indicates information additional to the centralisation and allows the dispersion to be evaluated in respect of this central position. If the precipitation is concentrated in the months close to (before or after) the date C_n, we obtain low values of D_n. Consequently, high values of D_n are obtained if the rainfall is distributed throughout the year, and particularly in the initial and final months of the annual cycle. In subsequent sections, we present different examples of the intra-annual distribution.

For this proposal, D_N was considered to be the value of the dispersion of the annual precipitation average for the entire analysed series.

One characteristic of the central date C_n is that, for any given rainfall intra-annual distribution, the second temporal moment M_C has a minimum value with regard to C_n. F represents any reference date prior or subsequent to C_n and which is separated from it by an interval Δx.

$$F_n = C_n + \Delta x \;\; (\Delta x \text{ positive or negative}) \tag{5}$$

The date x_i is expressed as: $\quad x_i = f_i + F_n = d_i + C_n \qquad (6)$

Thus, $\qquad f_i = d_i + \Delta x \qquad (7)$

The second temporal moment with regard to F is:

$$M_F = \Sigma(p_i\, f_i^{\,2}) = \Sigma(p_i\, (d_i + \Delta x)^2) = \Sigma(p_i\, d_i^{\,2}) + \Sigma(p_i\, \Delta x^2) + 2\, \Delta x\, \Sigma(p_i\, d_i) \qquad (8)$$

The first augend is the second temporal moment for which C_n is referred to as M_C. The second augend is necessarily positive, regardless of sign Δx, as it is a square. The third augend is nought, as the total first moment with C_n is zero $\Sigma(p_i d_i) = 0$, given that the moments prior and subsequent to C cancel themselves.

Therefore: $$M_F = M_C + \Sigma(p_i\, \Delta x^2) \qquad (9)$$

So, whenever $$F \neq C_n : \quad M_F > M_C \qquad (10)$$

Therefore, the dispersion parameter D_n for any given annual rainfall distribution acquires a minimum value if the squared moments are calculated with respect to the central date C_n.

3.3 Characterisation of the intra-annual precipitation distribution

The method proposed in this paper was applied to all years to obtain results for the parameters C_n and D_n. The choice of the beginning of the year was not an arbitrary decision and did not introduce subjectivity. We elaborated the intra-annual distribution representing the entire period of observations (1837–2010) from the monthly averages of the entire series of observations, and applied the symmetry criterion to the resulting profile. This was based on the property of the calculation method by which the obtained centralisation parameter maximises the concentration for the entire period covering the years of observation. This origin, objectively determined, was common for all the years of the study. In this study we considered the year from August to July, i.e. the year 1900 starts on August 1st and finishes on July 31st, 1901. Furthermore, from the perspective of natural ecosystems in the areas with a Mediterranean climate in Europe, choosing each year to start in August coincides with the minimum of vegetative activity after the drought period, when new annual cycle begins. Thus, the total period of observation starts on August 1^{st}, 1837 and finishes on July 31^{st}, 2010.

Lopez-Diaz (2002) calculates intra-annual dispersion rates, based on a mobile subseries of twelve consecutive months as the annual precipitation cycle is not strictly periodic. According to this procedure, the relative minimum values of the index are related to the highest rainfall month in its temporary environment. However, the choice of a single origin, as we propose in this article, permitted the direct comparison of parameter values generated every year. This allowed the multi-annual centralisation series C_n and D_n, to be obtained by operating on temporary, similar and comparable elements.

Therefore, these two new parameters yield objective information about the evolution of rainfall distribution over large multiannual periods. Thus, the evolution of the C_n and D_n parameters reflects the actual behaviour of precipitation throughout the years. Each n year the method provides results of the centralisation C_n and dispersion D_n from the rainfall records. Therefore, it is characterised by the set of three values [P_n, C_n, D_n]. Hence, the proposed methodology allows the evolution of the intra-annual distribution of precipitation to be analysed.

Although the information provided by the set [P_n, C_n, D_n] is sufficient for the interpretation, the graphs of the intra-annual distribution of precipitation are shown afterwards. Each of these graphs, superimposed on the relative monthly distribution profile and polynomially smoothed, represents the set [P, C, D] and their values. When assigning the monthly precipitation to a determined moment, the graphical representation of the profile shows successive segments joined by the vertices. The polynomial adjustment restores the continuity, thus fitting to the actual behaviour of rainfall throughout the year. The vertical line indicates the position of the date of centralisation *C*; the length of the horizontal line, centred on *C*, indicates the dispersion degree *D*. The smaller the segment length, the higher the proportion of rainfall in the months close to the central date.

4 RESULTS AND DISCUSSION

4.1 Reference series representativeness (Lisbon–San Fernando)

To characterise the evolution of intra-annual precipitation in the southwestern quadrant of the Iberian Peninsula from the series of Lisbon and San Fernando, it was necessary to verify that these observatories are sufficiently representative of the whole study area. That is why it was necessary to perform a comparison of the data that justifies the extrapolation of the average series from Lisbon–San Fernando with other observatories in the area of study (see Table 1). If this comparison shows a similar monthly behaviour, then we can generate an adjustment factor to correct the original Lisbon–San Fernando series. Thus, we can obtain a new series based on the previous series, but which is significantly adjusted to be representative of the behaviour of the complementary regional series. Therefore, this series is capable of representing the average behaviour in the southwest of the Iberian Peninsula.

Table 1 around here

Table 2 shows the relative monthly rainfall distribution (1961–1990) of the regional average of the complementary observatories (SW_R), in contrast to that corresponding to the Lisbon–San Fernando observatories (SW_{LS}). The adjustment factor used during this period, shown in Table 2, is the quotient between the intra-annual distribution of the monthly value of the set of complementary observatories and that from Lisbon–San Fernando.

Table 2 around here

As can be seen in Table 2, in studying the simultaneous recordings during a period between 1961 and 1990, the intra-annual behaviour of the series from the original observatories (SW_{LS}) was found to be similar to that from the complementary regional observatories (SW_R). However, during the summer months, when July and August rainfalls are frequently less than 1% of the total annual, the adjustment factor calculated was greater than one.

Table 2 also shows that regional rainfall yields a small positive difference in precipitation from April to June, mainly due to the inland observatories (Cordova, Beja and Talavera). Although the intra-annual distributions between these groups of stations are sufficiently approximate (Pearson's correlation coefficient of the monthly series in the period 1961–1990 is 0.9 during the rainy semester), we obtained a better adjustment by applying the non-dimensional calculated factor, which in its turn corrects each record from the Lisbon–San Fernando series. Thus, the corrected distribution tended to coincide with the regional distribution. We assume that the series generated in this way would coincide theoretically with a series calculated from the regional stations if we had records from 1837. This allowed us to extrapolate the study more reliably to the origin of the records in the nineteenth century.

As a consequence of this analysis, we consider that the Lisbon–San Fernando corrected series is sufficiently representative of the evolution of the rainfall in the southwestern peninsular area during the whole period 1837–2010. Therefore, we have applied the term *SW* to the rainfall series from Lisbon to San Fernando and make the assumption that it characterises the whole region.

4.2 Intra-annual centralisation parameter

The centralisation parameter C_n for each year n from 1837–1838 to 2009–2010 was calculated from the monthly rainfall data based on that from Lisbon–San Fernando, thus generating a new centralisation series with 173 consecutive terms. Furthermore, the value C_N was obtained from the relative rainfall monthly average during the whole period, which corresponds to the "central date" representative of that period. The deviation for this date was taken as a reference to determine the advance or delay of each annual parameter of centralisation C_n. Figure 2 shows the intra-annual rainfall distribution in the southwestern area of the Iberian Peninsula during the period 1837–2010. It also includes a representation of the parameters C_N and D_N. This average profile is also the most common in this area, characterised by its triangular shape, slightly asymmetrical, with a single peak and a gradually ascending phase in autumn (September to November), descending in spring (March to May), and irrelevant values during the summer. The graph serves as a comparison with other results that will be presented later.

Fig. 2 around here

The annual rainfall average P_N was 664.2 mm during the period of the study. To establish the intra-annual rainfall evolution of the parameter of centralisation, δ_C deviations were calculated for each annual parameter C_n in respect of the general parameter for the whole period of the study; C_N = 167.5 days. This value of C_N gives rise to the annual series of deviations of the observed 173 years for each observatory, as demonstrated in Figure 3. We term as a sAw year (summer-autumn-winter) those years in which the centre C_n was shifted to the temporary origin (with a negative deviation), and as a wSs year (winter-spring-summer) those in which C_n was delayed with respect to C_N (positive deviation). Alternatively, we also refer to sAw years as the autumn domain and wSs years as the spring domain.

Fig. 3 around here

Figure 3 shows a sawtooth pattern with no easily discernible trends. To highlight more clearly the evolution of the centralisation parameter we used the accumulated deviations from 1837 to 2010 (Fig. 4) as the algebraic sum of the deviations of every preceding year compared to the reference point. The ascending segments indicate positive deviations, while the descending ones indicate negative deviations. Long sequences with the same sign, although showing sawtooth peaks, allowed us to detect periods in which there was a predominance of years with the same trend. We were able to conclude that the intra-annual rainfall distribution does not follow a random pattern throughout the 173 years of records.

Fig. 4 around here

The existence of two ascending subperiods from 1879 to 1894 and from 1966 to 1975, with a marked shift to spring rains, can be observed. In addition, there is a long sequence from 1894 to 1928 (with two discontinuities) with years dominated by autumn rains, and an intense final sequence from 1985 with a rainfall displacement to autumn. These negative values for deviation of the centralisation parameter, obtained during the last decades, coincided with the results obtained by García-Barrón (2002) and Aguilar (2007), using different procedures to measure other variables in the same area of study.

In the study area, the first quarter of the twentieth century was characterised by the total annual rainfall being slightly below average and with low inter-annual variability, with slightly dry or wet years (García-Barrón et al. 2011). Figure 4 shows that this period corresponds to intra-annual displacements towards autumn (descendant phase in the graph). For that reason, it is interesting to analyse whether the intra-annual location of the most intense rainy influences the total annual precipitation. Figure 5 demonstrates the dispersion between the centralisation parameter C_n and the corresponding total annual rainfall P_n. We can observe from this a markedly random spatial occupation, which corresponds to Pearson's correlation coefficient of -0.07, and has no linear organisation. The points located in the upper/lower half indicate years with the displacement wSs/sAw of the precipitation; while those points located in the left/right indicate relatively dry/wet years. Therefore, we were not able to detect any correlation between the total annual rainfall and its distribution throughout the year. Thus, from a probabilistic point of view, we cannot affirm whether or not the autumn or spring displacements generate a greater frequency of dry years.

Fig. 5 around here

Another different and interesting aspect is the generic features of the years that present a particularly marked displacement of the centralisation parameter in either direction. We selected the years in which the deviation of C_n with respect to C_N is, in absolute terms, higher than twenty-five days, $|\delta_C| > 25$ days, i.e. years with a centralisation parameter very laterally displaced. The corresponding intra-annual rainfall profiles (Fig. 6) show polynomial adjustment lines. In these profiles, we can observe approximately symmetrical behaviours in opposite directions, with maximum values in October and in March, respectively. Regarding the characteristic year distribution (see Fig. 2), the contribution to the sAw displacement in the most intense years is mainly due to the relative increase of more than 8% of rainfall in September and in October. The most intense wSs displacement is due to the increase of rainfalls in March (+ 6%) and April (+7%) but also to the significant decline in October (−6%) and November (−7%). Since the year centralisation occurs on a date around the middle of January, the impact of the three rainy months is less relevant.

Fig. 6 around here

4.3 Intra-annual dispersion parameter

The dispersion parameter D_n was calculated for every year of the period, thus generating a new time series. We also calculated the value $D_N = 66.8$ from the monthly rainfall average during the whole period. Figure 7 shows the evolution of the annual values of the dispersion degree. Low values of D_n correspond to years with rainfall concentrated in the months near the date of centralisation. High values of D_n indicate that the proportion of the rainfall in early autumn or late spring is greater than that corresponding to the intra-annual distribution that features the whole series.

Fig. 7 around here

Figure 7 shows a no-uniform oscillation around the central value. Prior to 1940 the positive or negative deviations δ_D are generally small ($|\delta_D| < 10$), and thus the probability of values being in the range $56.8 < D_n < 76.8$ is high (82%). After 1940 the frequency of extreme deviations ($|\delta_D| > 10$) increases to 48%, that is, years of widely scattered rainfall ($D_n > 76.8$) alternating with years with a very concentrated rainfall ($D_n < 56.8$).

In order to improve the analysis of this temporary increase in variance, we used the coefficient of variation for mobile periods of eleven years:

$$V_{D\,n} = \sigma_{(n\,,n\text{-}10)} \,/\mu_{(n\,,\,n\text{-}10)} \qquad (11)$$

where the numerator is the standard deviation of the partial series composed of the dispersion parameter of year n and the previous ten years, and the denominator is the corresponding average.

Figure 8 shows the rainfall dispersion variability during the years of the study period. We assigned the value of the coefficient V_{Dn} to the final year n of the corresponding interval; so, the value assigned to 1850 is the coefficient calculated for the interval 1839–1850. Therefore, the represented series decreases in ten elements. The selection of the 11-year period to derive the running variation coefficient series was based on the solar activity period. Although meteorological variability is globally determined by climatic system interactions, fluctuations of incoming energy due to solar activity is an objective relevant factor (Dima et al. 2005; Rodrigo and Trigo 2007; García-Barrón et al. 2011). Furthermore, when analysing long-term rainfall series, the eleven-year period smoothes the annual extreme values, allowing the detection of time patterns.

Fig. 8 around here

It was noted that, throughout the ninetieth and first half of the 20th century, the coefficient of variation of D_n remains stable at around 0.11. Since 1950, there has been an increase to higher values of 0.2 and, after a decline to 0.15 in the 1970s, it has over the last three decades remained at around 0.22. Therefore, we should highlight the significant change in the irregularity of the rainfall dispersion D_n in the last half of the twentieth century as a feature of the evolution of rainfall in the southwest of the Iberian Peninsula.

In order to illustrate the usefulness of the dispersion parameter, complementary to the centralisation parameter C, we selected the group of years "*m*" having a lower rainfall dispersion (1954, 1978, 1995; D_m = 44 days), together with the years "*M*" which present a major dispersion (1848, 1991, 1999; D_M = 91 days). Figure 9 shows the difference in the behaviour of both groups of years, which however have a very similar centralisation index.

Figure 9 reveals that the distribution of the years "*m*", with a lower dispersion, is very concentrated around the central date: it is unimodal with a winter maximum. The rainfall in December, January and February exceeds 65% of the total annual rainfall. In the second case, the dispersion is higher and the profile is bimodal with a winter decrease and relative peaks in October and April. The rainfall in January, December and February does not reach 20% of the total annual rainfall. However, when calculating the respective centralisation parameters, we determined that they are almost coincident (171.2 and 172.9). We observed that all the cases presented correspond approximately to a symmetrical profile in respect of the centralisation parameter, although with a different monthly rainfall distribution. Therefore, the different length of the horizontal arrow corresponding to the values D_M and D_m clearly stands out on the same vertical segment, indicating the position of the centralisation parameter.

Fig. 9 around here

4.4. Intra-annual characterisation

We have already noted that the goals of this article are the exposition and application of a methodology for characterising intra-annual precipitation. Considering the results obtained in the previous sections, the procedure for the synthetic characterisation of the intra-annual precipitation was obtained by means of three parameters: [P_n, C_n, D_n]. The characteristic values of the whole series (1837–2010) of the southwest Iberian Peninsula were: P_N = 664.2 mm, C_N = 167.5 days (corresponding with Jan 13th) and D_N = 66.8 days. This set of values for each year can be expressed by the deviations, positive or negative, of these values in relation to the representative values of the whole series. This form is convenient in comparing different years of the same observatory, or the same years from different observatories.

As an example, we selected four years, expressing the numerical values of the set [P_n, C_n, D_n] and the corresponding deviations δP_n, δC_n, δD_n respecting the values [P_N, C_N, D_N] calculated for the whole series (see Table 3). This facilitated a direct interpretation of the behaviour of each year compared to the common distribution. Relative comments from the numeric data are included.

Table 3 around here

Observation of the corresponding deviations facilitates characterisation of the selected years. So, in Table 3 we can see that 1844 was a very wet year in which the annual centralisation parameter coincides with the characteristic date and presents a similar dispersion degree to that of the whole series (see Fig. 2). However, 1848 was a very dry year with displacement of rainfall towards spring, although with a great dispersion respecting the central date (bimodal distribution with main peak in May and a secondary peak in October). 1920 was a dry year with an asymmetric distribution due to a rainfall displacement towards the autumn (peak in November–December). Meanwhile, 1978 was a wet year, for which the centralisation annual parameter is close to the characteristic date (January) and presents a high concentration of rainfall during the months near this central date.

We should highlight that the centred unimodal distribution with a peak in winter, as shown in Figure 2, is characteristic of the Atlantic zone of the Iberian Peninsula. The almost symmetrical bimodal distribution with a relative minimum in winter is a feature of the Meseta Central. The Mediterranean coast presents an asymmetric bimodal distribution, with prevalence in autumn; meanwhile in the Ebro river valley the prevalence is during the spring (García-Barrón et al. 2010). In this respect, we can ask whether the trend of the displacement of rainfall towards autumn during the later decades, together with a diminution of the value C_n, is a sign that ecosystems are evolving to feature a more Mediterranean character. These results are in line with predictions made by the "Preliminary General Assessment of the Impacts in Spain due to the Effects of Climate Change" (Fernández-González et al. 2005), which consider aridification of the Mediterranean ecosystems of southern Spain as likely to occur.

In any case, the rainfall displacement towards autumn means an accentuation of the Mediterranean climate in the southwest of the Iberian Peninsula, following the decline of Atlantic influence. In relation to this, as stated by Aguilar (2007), the effect of the rainfall decrease in March is not only due to the decline in these contributions, but mainly to the fact that it is the last month with a surplus balance. Furthermore, the concentration of rainfall before the main period of vegetative growth (autumn–winter) may stimulate erosion processes, similar to those that have been affecting coastal lagoons (Sousa et al. 2009) and the small coastal streams in the study area during recent centuries (Sousa et al. 2010). The consequences of such changes in the distribution of rainfall patterns over ecosystems may be relevant. In fact, Sousa and García-Murillo (2003) have found that anthropogenic impacts mask those associated with changes in the precipitation patterns on the hygrophytic vegetation of wetlands in the southwest of the Iberian Peninsula, mainly in the frequency of wet/dry years during the nineteenth and twentieth centuries. More recently, these same effects—where changes in climate trends are superimposed on intense anthropogenic impacts—have shown the retreat of permanent wetlands in favour of those that are more temporary, or to less-water-demanding plant communities (Sousa et al. 2011; 2013).

4.5. Influence of the North Atlantic Oscillation on the intra-annual distribution

Generally, the bibliography relates the NOA index directly to monthly, seasonal or annual precipitation (Muñoz-Díaz and Rodrigo 2004; Trigo et al. 2004). The high correspondence between the NAO index and winter precipitation stands out in the southwest of the Iberian Peninsula (Queralt et al. 2009; Rodríguez-Puebla and Nieto 2010; Castro et al. 2011). In this article, we have related the obtained dispersion parameter values to the NAO index. For this, we used the monthly values of the NAO provided by the NOAA (National Oceanic and Atmospheric Administration, US). We calculated the Pearson's correlation coefficient between the monthly NAO index and the intra-annual dispersion parameter from 1950 to 2010. Values above 0.2 were significant for $\alpha = 0.05$ (Table 4).

Table 4 around here

From these results, we can infer that positive high NAO values in the winter months—December, January and February—correspond, in the southwestern peninsular, with high dispersion parameter values in respective years. In this case, due to a deficit of wintry rain, the characteristic unimodal profile (Fig. 2) is softened, even to a valley-shape, with a consequent increase in the dispersion. However, the negative correspondence with October indicates that in a negative NAO phase this becomes a rainy month, thus shifting the profile to autumn and, consequently, the dispersion is increased.

5 CONCLUSIONS

The article comprises two main parts. To begin with, we described the methodology for characterising intra-annual precipitation. The second part is devoted to its application in the area of study. In our opinion, our paper contains innovative theoretical contributions to the procedure of studying intra-annual rainfall and in its application to its evolution in the southwest of the Iberian Peninsula during almost two centuries of records. We consider that the calculation procedure has two features that make it especially appropriate: the conceptual basis of the climate knowledge gained from the parameters of centralisation and dispersion and, simultaneously, the ability to synthesise the information. Both parameters give information about the intensity and location of the rainy season throughout the year. Each year is uniquely determined by the set of values [P_n, C_n, D_n]. The choice of these parameters allows us to determine, in a quantified way, the properties of the intra-annual precipitation. Even when information from the set of values is sufficient for characterisation, graphs of the intra-annual distribution are included to facilitate the visual interpretation. In our opinion, this approach is different from that used by other authors in the analysis of rainfall throughout the year.

From the point of view of intra-annual precipitation patterns in the southwest of the Iberian Peninsula, there is a representative asymmetrical triangular profile with an upward phase from August to November and a smoother downward phase from

December to July. For the whole period of observations, the centralisation parameter was C_n = 167.5, corresponding to January 13th, and the dispersion parameter D_n = 66.8 days. Every year presents deviations from these values that enables its classification and helps to establish the evolution of the historical series.

The evolution shows irregular oscillations of the parameters throughout the nineteenth and twentieth centuries. However, we have established the existence of multi-year periods with a greater probability of internal displacement of the rainfall periods to autumn or spring. Additionally, during the first century of observations, the range of fluctuation in the dispersion parameter remains approximately constant ($|\delta_D|>10$). This leads us to highlight two relevant aspects in recent decades that have revealed a change in the intra-annual rainfall distribution in the southwest of the Iberian Peninsula:

- The negative deviation of the centralisation parameter, which means the displacement of the most intense rainy season to the autumn with a consequent decrease during spring.

- The increase in the variability of the dispersion parameter. This indicates a greater frequency dispersion of rainfall and, in contrast, a higher frequency of years with rainfall accumulating around the central dates; that is, there is a trend to extremes of dispersion and intra-annual concentration. In this sense, García-Barrón et al. (2011) have shown that, during the last third of the twentieth century, the irregularity and disparity have increased in the southwest of the Iberian Peninsula (which is not the case in the north of the Iberian Peninsula).

Complementary to this, the relationship between the winter positive NAO index and the increase in the intra-annual dispersion parameter have been also revealed.

Although we have emphasised that the behaviour of the past few decades presents these differentiating features in respect of the nineteenth and twentieth centuries, we were not able to determine whether or not they are manifestations of climate change. To do this it would be necessary to formulate a hypothesis to test whether the detected trends will be maintained in the near future. Also, subsequent studies would be required to demonstrate that the changes described are generalizable to the entire Iberian Peninsula and the Mediterranean Basin. In this case, it would necessary to undertake interdisciplinary analysis of the possible effects of these changes on ecosystems.

ACKNOWLEDGEMENTS

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Figure legends

Fig. 1 Map showing locations of the meteorological stations used in the study area

Fig. 2 Intra-annual rainfall distribution indicating the characteristic parameters for the period 1837–2010

Fig. 3 Temporal evolution of annual deviations in the centralisation parameter C_n and the line marking the average value during the study period

Fig. 4 Evolution of the accumulated annual deviations in the centralisation parameter C_n

Fig. 5 Dispersion of pairs of annual values of the parameter C_n and rainfall P_n and regression line

Fig. 6 Intra-annual distribution of years when the centralisation deviation is outside the ranges (−25, 0) [sAw] and (0, +25) [wSs]

Fig. 7 Evolution of the rainfall dispersion parameter D_n

Fig. 8 Evolution of the dispersion degree using the coefficient of variation for mobile periods of 11 years

Fig. 9 Intra-annual distribution of years with high concentration/dispersion of rainfall

Table legends

Table 1 Features of the two main observatories (Lisbon and San Fernando) and the eight additional stations

Table 2 Comparison of the average monthly rainfall in regional stations (R) and the Lisbon–San Fernando observatories (LS), R-Pearson and adjustment factor

Table 3 Characterisation of the selected years by the set of values [P_n, C_n, D_n] indicating the corresponding deviations

Table 4 Correlation coefficient between the monthly NAO index and the intra-annual dispersion parameter

Table 1

Station	Time period	Province	Longitude	Latitude	Institution	Percentage of missing values
Main observatories (SW_{LS})						
Lisbon	1837–2010	Lisbon	9º 09´ W	38º 44´ N	Portuguese Institute of Meteorology	< 0.1
San Fernando	1837–2010	Cadiz	6º 12´ W	36º 28´ N	Spanish Navy	< 0.2
Complementary observatories (SW_R)						
Beja	1961–1990	Alentejo	7º 55´ W	38º 04´ N	Portuguese Institute of Meteorology	< 0.1
Cordova	1961–1990	Cordova	4º 51´ W	37º 51´ N	Spanish National Agency of Meteorology	< 0.1
Gibraltar	1961–1990	-	5º 16´ W	36º 03´ N	Met Office	< 0.1
Jerez	1961–1990	Cadiz	6º 03´ W	36º 45´ N	Spanish National Agency of Meteorology	< 0.1
Riotinto	1961–1990	Huelva	6º 36´ W	37º 42´ N	Riotinto Mining Company	< 0.1
Seville	1961–1990	Seville	5º 53´ W	37º 25´ N	Spanish National Agency of Meteorology	< 0.1
Talavera la Real	1961–1990	Badajoz	6º 49´´ W	38º 53´ N	Spanish National Agency of Meteorology	< 0.1
Tavira	1961–1990	Algarve	7º 39´ W	37º 07´ N	Portuguese Institute of Meteorology	< 0.1

Table 2

Month	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
SW_R	0.007	0.03	0.10	0.16	0.16	0.15	0.13	0.09	0.09	0.05	0.03	0.005
SW_{LS}	0.006	0.03	0.10	0.17	0.15	0.15	0.14	0.09	0.08	0.05	0.03	0.004
R-Pearson	0.44	0.76	0.91	0.88	0.90	0.92	0.90	0.91	0.72	0.78	0.60	0.08
Adjustment Factor	1.16	1.02	0.97	0.95	1.04	1.00	0.94	0.99	1.09	1.02	1.09	1.17

Table 3

Year	$P_{N} + \delta_{Pn}$ (mm)	$C_{N} + \delta_{Cn}$ (days)	$D_{N} + \delta_{Dn}$ (days)
1844	664.2 + 201.4	167.5- 0.3	66.8 + 0.1
1848	664.2 – 169.7	167.5 + 20.7	66.8 + 24.4
1920	664.2 – 109.9	167.5 - 15.0	66.8 -7.9
1978	664.2 + 152.1	167.5 + 3.6	66.8 - 23.0

Table 4

Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
0.02	-0.01	-0.25	0.15	0.39	0.35	0.34	0.10	0.09	0.06	0.08	0.05

Figure 1 (colour)

Figure 2 (colour)

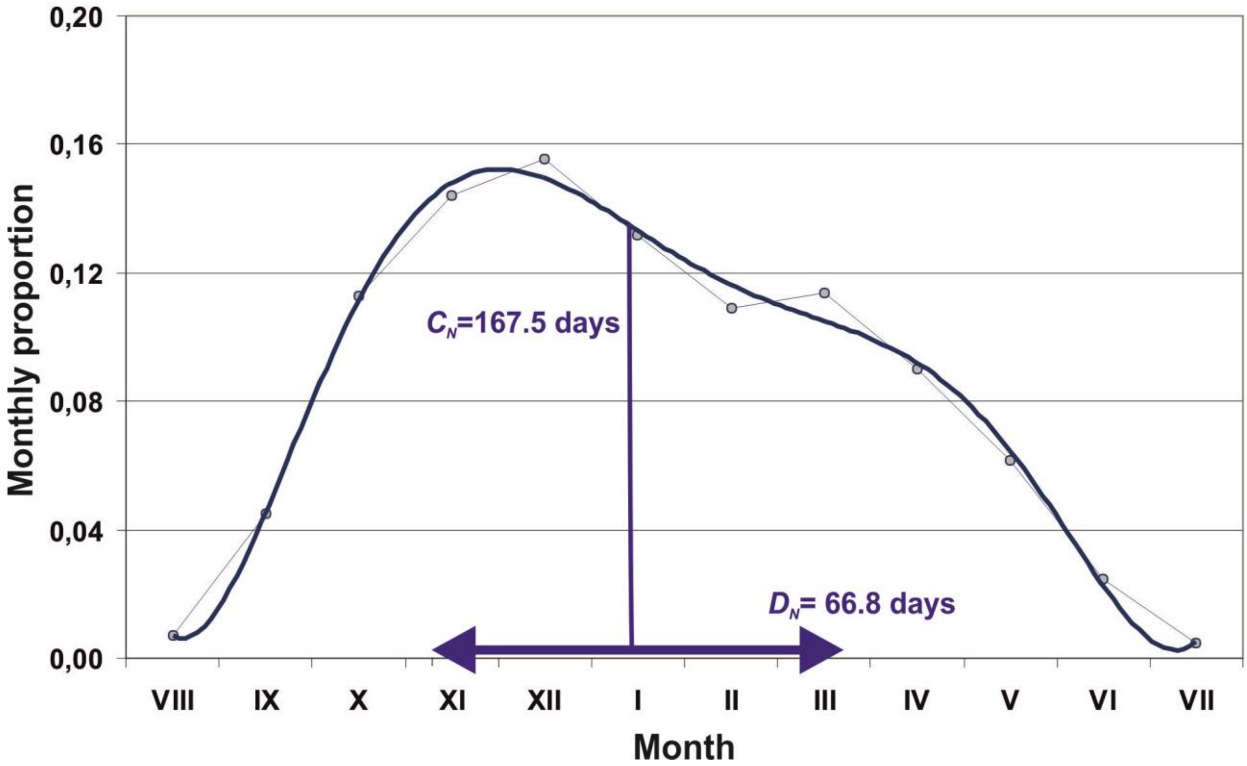


Figure 3 (colour)

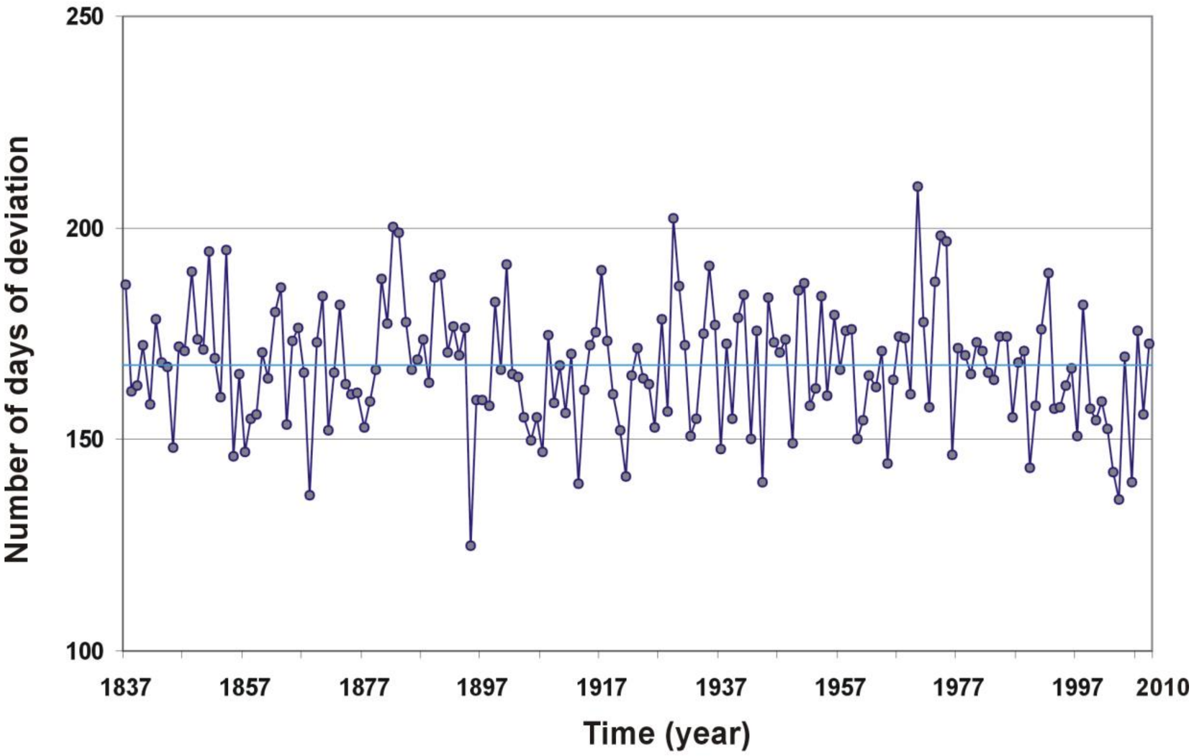
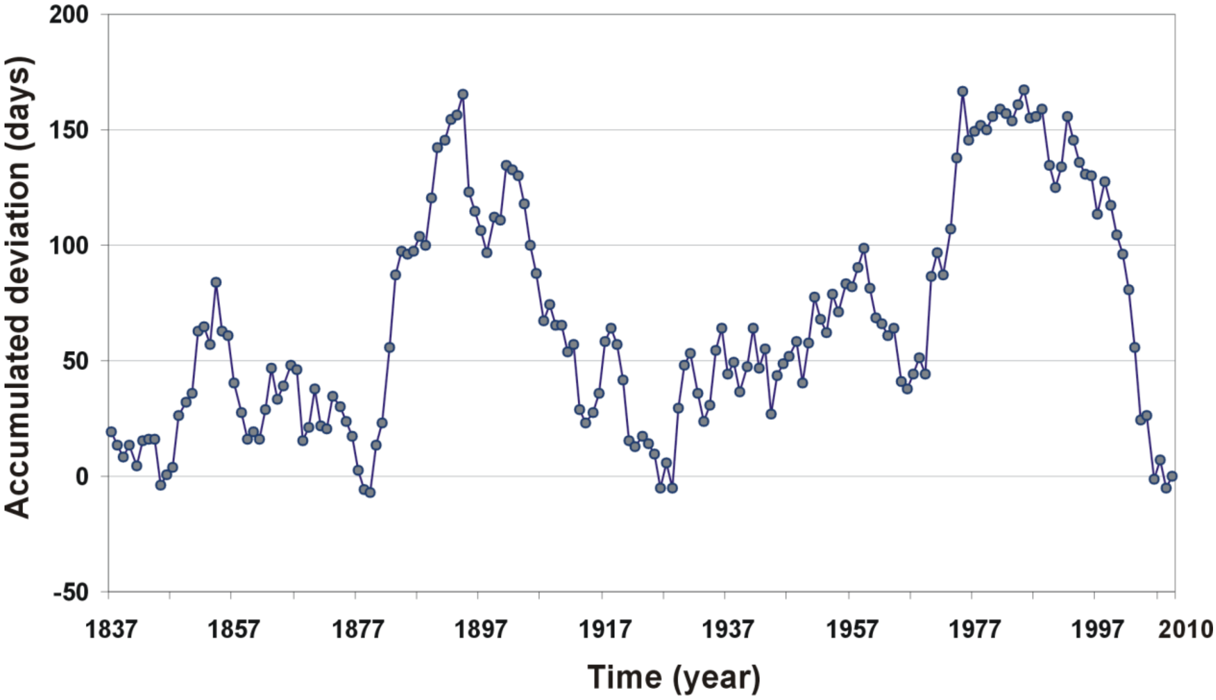


Figure 4 (colour)



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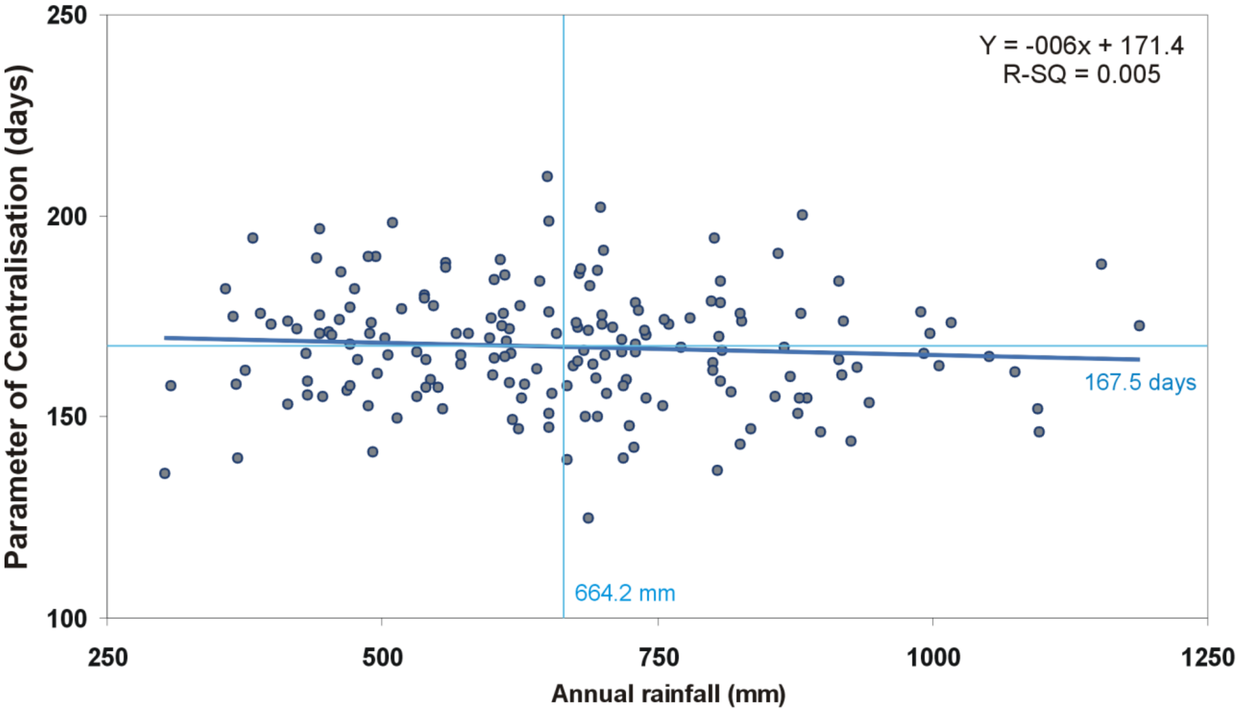

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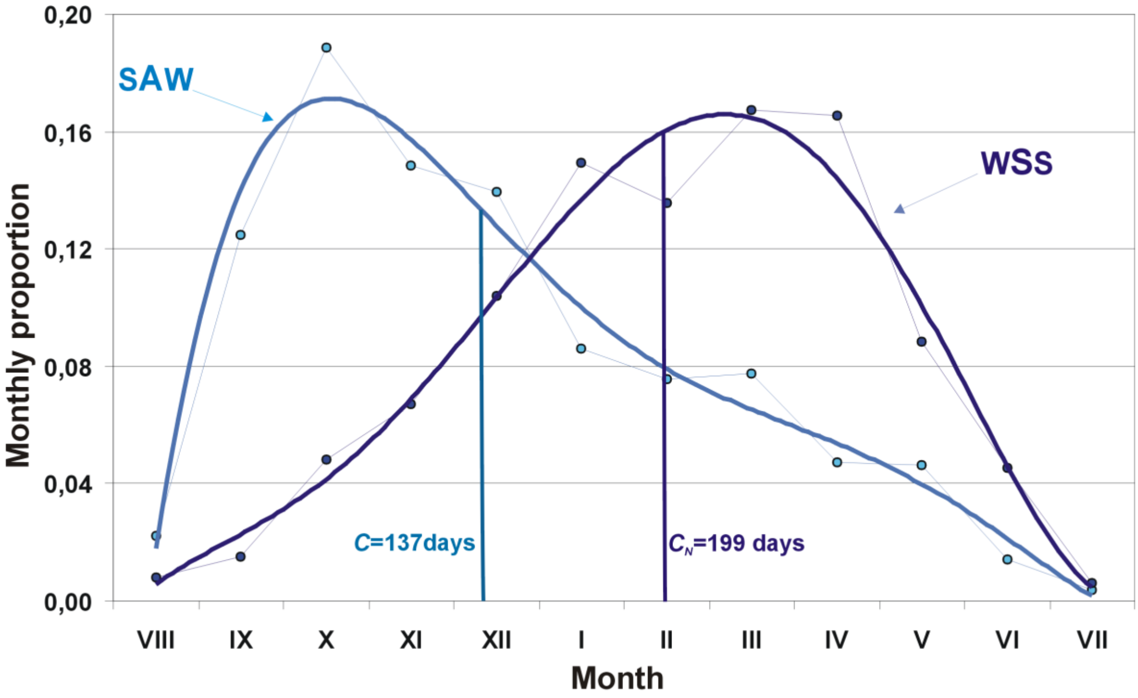

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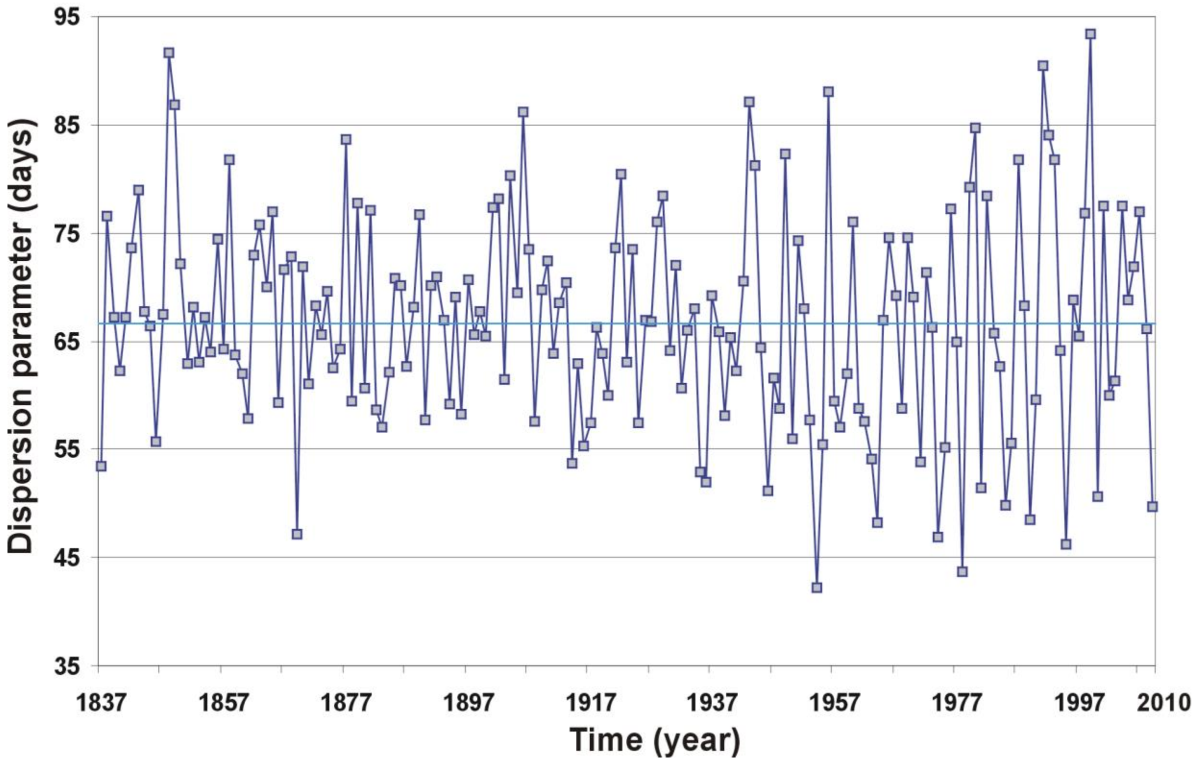

Figure 8 (colour)

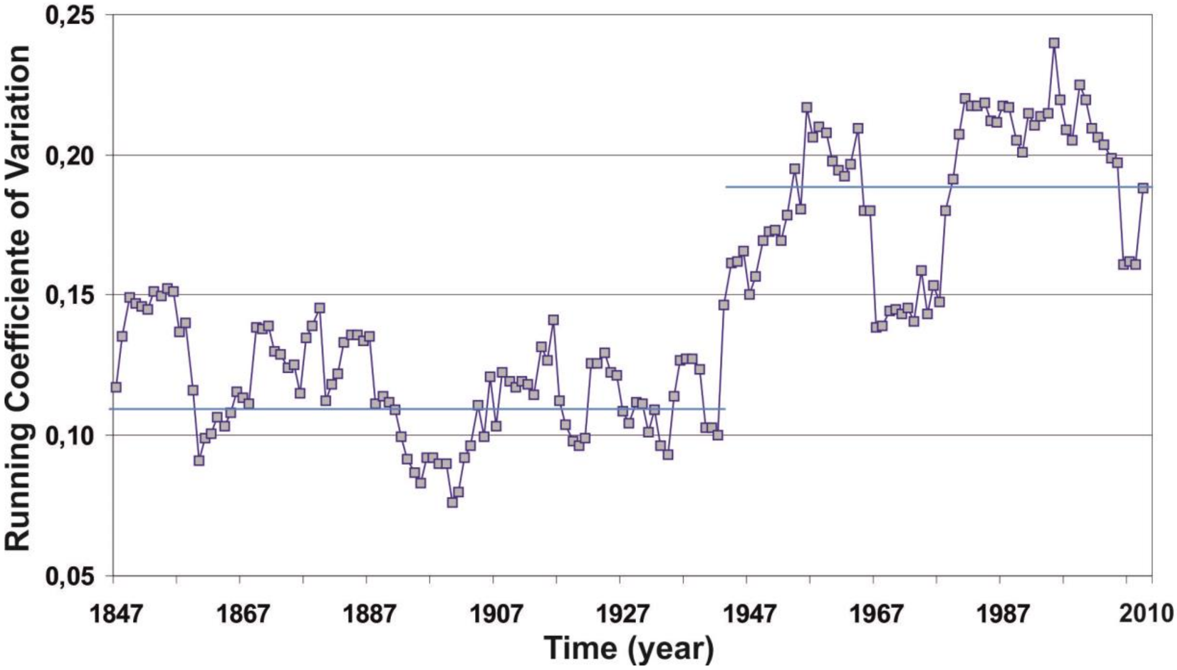

Figure 9 (colour)