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Changes in the Intensity and Variability of Precipitation in the Central Region of Argentina between 1960 and 2012

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Abstract: This study analyzes the temporal variation of different rainfall features in the central region of Argentina between 1960 and 2012, and evaluates the dynamics of temporal trends by using the Mann–Kendall–Sneyers (MKS) and Tomé–Miranda (TM) procedures. Under different criteria and levels of significance, rainfall time series show homogeneous behavior in more than 80% of cases. Only 18 of the 42 annual cases analyzed reached a significant long-term trend ($p < 0.10$). Total annual rainfall (AR) showed a significant increase only in Laboulaye Aero (LB) and Villa Dolores Aero (VD), but this does not currently persist. A decrease in the annual frequency of rainy days (DPF) is more widespread in the region. Thus, the increase in mean annual rainfall intensity (INT) seems to be particularly associated with the decrease in annual frequency of events (DPF) in the central region of Argentina. However, the increase in INT currently persists only at the Córdoba Observatorio (BO), as INT stopped growing for LB, Río Cuarto Aero (RC), and VD in the mid-1990s. The variation coefficients of total annual rainfall (ARCV) and DPF (DPFCV) have increased in the region, but with the former restricted locally to the Pilar Observatorio (PI), RC, and VM, and the latter to BO and RC. Long-term changes of the pluvial regime in the central region of Argentina appear to be not only local and restricted to some properties of rainfall during the period, but also reveal a particular dynamic where the long-term trends of the evaluated properties have now changed sign or maintain a certain constancy at present.

Keywords: intensity; rainy days; variability; climate change; trend; breaking point

1. Introduction

There was a general increase in air temperature worldwide during the twentieth century, albeit with some differences between the hemispheres, corresponding to global warming. However, the evolution of atmospheric variables linked to the hydrological cycle, in particular, precipitation, runoff, and soil moisture, is more particular to each place and the period considered [1]. The analysis of different global rainfall databases (GHCN, PREC/L, GPCP) shows a change in an anomaly that was positive between 1950 and 1980 and became negative later [2]. This contrasts with rainfall behavior in central Argentina, where the annual regime shows increasing rates from approximately the 1940s until the end of the century [3–5].

Beyond the uncertainty arising from differences between the linear trend values (increasing or decreasing) found in the different data bases globally, and from the fact that some of these values are non-significant, these discrepancies indicate the intrinsic difficulty of evaluating rainfall information given its great temporal and spatial variability [2], which adds to any instrumental errors [6]. Considering only a few examples in different regions of the world, long-term rainfall series in Italy showed a widespread decrease during the first half of the twentieth century, but in the second half, while the trend continued to be negative in the south of Italy (Palermo), it increased in the north (Genoa, Milan, and Bologna) [7]. Similarly, precipitation in the north of California (USA) showed a sustained increase in the period 1925–2007, but the south is currently drier [8]. Finally, the annual rainfall recorded between 1950 and 2009 in a network of 249 rain gauges in North Carolina (USA) showed an increase in half of them and a decrease in the other half, and an absence of significant change in the region as a whole [9,10]. The strongly local nature of rainfall, and the possible modification of atmospheric circulation and an intensification of the hydrological cycle under global warming [1], mean that the evaluation of changes in a rainfall regime must consider both the specific region of origin of the information and the period under analysis.

Changes in the intensity and variability in a regional rainfall regime are important for their consequences both in the environment and in agricultural production [11–14]. Due to alterations in the climate system from global warming, changes are more likely to occur in the intensity, frequency, and duration of events than in the total amount of rainfall [1,8,15]. These attributes are less frequently assessed and they are also more complex to incorporate into climate prediction models [16].

In the central region of Argentina it is virtually impossible to assess these more specific features of the rainfall regime, particularly the instantaneous intensity value, due to the lack of specific information from a consistent pluviographic network. In addition, assessing the influence of climate change on rainfall intensity or any other environmental variable requires a long enough time series, which is a general limitation for any region. To overcome these drawbacks, indicators have been developed using the conventional rainfall network records, evaluating intensity from daily data of the number and frequency of events [7,8,11,17].

To assess the long-term trend of extreme rainfall in the Philippines, Villafuerte et al. (2014) [14] use specific indicators and establish an absence of change in this region, as well as a certain spatial incoherence, with mixed positive and negative trends even between neighboring stations. Porto de Carvalho et al. (2014) [13] use the annual maximum daily rainfall value to assess the change in rainfall intensity in southern Brazil, and observe that values greater than 140 mm currently occur with return periods of only 1–2 years. This increase in the periodicity of return means that production losses can occur successively, adversely affecting the regional economy. Analyzing secular daily records of rainfall in California (USA), Killam et al. (2014) [8] conclude that both mean intensity and number of rainy days per year show no evidence of change over time. In Córdoba city, Argentina, [3] consider that the increase in the annual amount of rain is explained by the increase in the number of events. However, de la Casa and Nasello (2012) [18] find this behavior is not general for the entire central region of Argentina, and that while the annual rainfall increase at some sites is associated with an increase in rainy days, in others it is because of the average intensity.

The variability of the rainfall series shows short-, medium-, and long-term components attributed to the interannual, decadal, and trend dynamics of the climate system, respectively [19]. Among the different techniques applied to assess the time series variability of atmospheric properties, Tomé and Miranda (2004) [20] used a non-linear analysis method that, in addition to establishing a succession of partial slopes, determines the breakpoint of the series, i.e., the year when the slope changes sign. With this procedure, the medium-term behavior of the rainfall series and other hydrological indicators in Córdoba, Argentina, showed a periodic fluctuation of approximately 10–20 years [18,21]. On the other hand, Sneyers (1997) [22] developed the sequential or progressive version of the non-parametric Mann–Kendall trend test, used by [7,12] to determine trend changes in rainfall series from Italy and China, respectively. Sayemuzzaman and Jha (2014) [9] used this technique to determine the occurrence of a significant break in rainfall amounts during the 1960s–1970s in most of North Carolina State (USA). Also, Zhao et al. (2015) [23] used the sequential Mann–Kendall test to assess abrupt changes in hydro-climatic variables and identify the main driving factors for these changes in the Wei River Basin (China).

Assessing the long-term behavior of rains (trend or climate change) in a territory in order to make timely forecasts requires permanent and systematic monitoring of a possible change of trend [24]. The detection of a breakpoint or climatic jump is important, not only to increase knowledge about rainfall variability, but also to develop strategies and implement more adequate water management policies at regional and local scales [13]. Moreover, it is essential for the planning of sustainable agricultural practices, which contribute to both environmental protection and the profitability of agriculture [1].

Although meteorological variability is a natural expression of atmospheric dynamics, the presence of temporary discontinuities in the data is also possible, produced by non-climatic factors such as changes in the observation routine, the recalibration or degradation of a sensor, a change of the weather station location, or the modification of its environment, which may render the records unrepresentative of actual climate variability [25]. Detecting a lack of homogeneity in climatic series, it is important to identify spurious variability and thus establish a standard on the quality of the information being analyzed [11]. Based on different homogeneity test results, Costa and Soares (2009) [11] in Portugal proposed a procedure to select only those rainfall time-series suitable for studying their temporal trend.

The objective of the present work was to evaluate the long-term changes in the intensity, frequency, and variability of rainfall in the central region of Argentina between 1960 and 2012, based only on daily precipitation records aggregated at yearly and seasonal levels. In more specific terms, the quality of the rainfall series is first analyzed in terms of its homogeneity to assess the reliability of the meteorological information used. Secondly, the existence of a trend in the indicators of the intensity and variability of rainfall is evaluated during a period showing a generalized increase in atmospheric temperature. Third, the occurrence of a breakpoint that expresses a long-term trend change in the annual rainfall series in the region is assessed. Finally, in relation to the influence of global warming on rainfall in the central region of Argentina, an integral analysis is made of all the evidence collected to explain the rainfall behavior on a local and regional scale.

2. Material and Methods

2.1. Region of Study, Rainfall Data, and Indicators

The study region is the province of Córdoba in central Argentina, as shown in Figure 1, which also shows the location of the meteorological stations for which rainfall data are analyzed. The data used correspond to daily rainfall series recorded by the network of surface meteorological stations that the Servicio Meteorológico Nacional (SMN) of Argentina operates in the Province of Córdoba, which ensures the uniformity of the information in terms of its registration and processing. Rains in this region are markedly seasonal [26], with a higher frequency of more intense events during the warm season [27]. The rainfall series between 1960 and 2012 were totalized for each season in terms of quantity (annual rainfall, AR) and number of events (annual frequency of rainy days, DPF), computing annual values (from January to December) and those for both the warm (WS, from October to March) and the cold seasons (CS, from April to September).

Due to the lack of temporally and spatially extended measurements of rainfall intensity, its value was estimated using, firstly, the quotient between the AR and DPF to obtain a mean intensity value (INT), and secondly, the maximum daily value (AMDR) of the series. From the annual or seasonal ratio between AR and DPF, INT gives a mean representation of the phenomenon. The AMDR gives a direct expression of the intensity but in a 24-h interval. The variation coefficient of both AR (ARCV) and DPF (DPFCV) each year was assessed from the coefficient of variability (decimal), i.e., the quotient between the standard deviation and the mean.

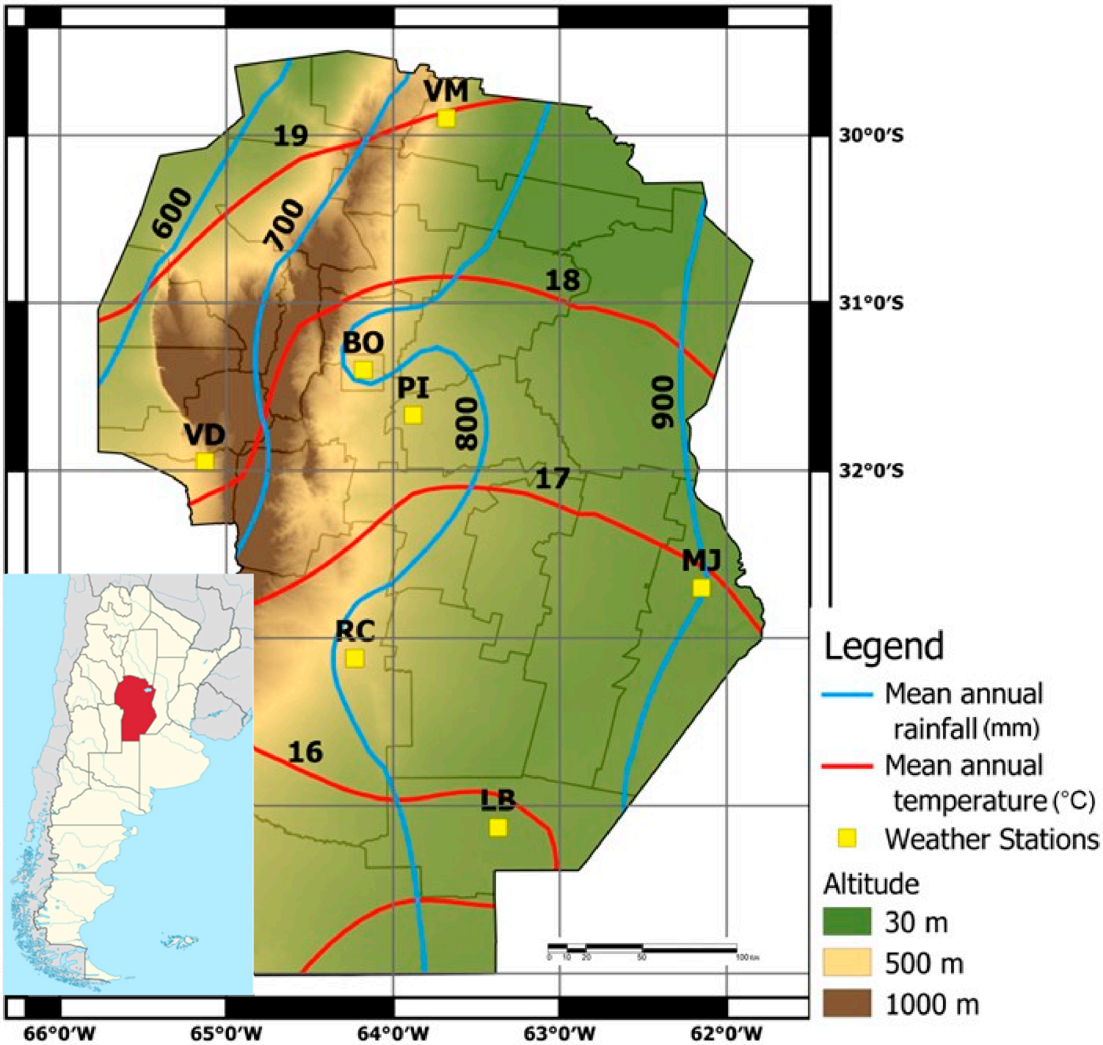


Figure 1. Geographical location of the weather stations in Córdoba Province, Argentina, used in the study: Córdoba Observatorio (BO), Laboulaye Aero (LB), Marcos Juárez Aero (MJ), Pilar Observatorio (PI), Río Cuarto Aero (RC), Villa Dolores Aero (VD), and Villa María de Río Seco (VM).

2.2. Homogeneity Tests

Different methods have been introduced to test the homogeneity of hydroclimatic variables [11,25,28]. In this study, two methods were applied.

2.2.1. Run Test

The "run test" was previously applied by [28,29] to assess the homogeneity of rain time series. This test considers time series of length n and mean value x_{med}. A binary code is assigned to data, with "1" for any value $x_j > x_{med}$ and a code "0" for any value $x_j < x_{med}$. Each uninterrupted series of "0" and "1" codes is called a "run", and n_0 and n_1 is the number of 0 and 1 cases, respectively. If the series is homogeneous, the distribution of the number of runs (R) approximates a normal distribution with the following average (E) and variance (Var):

$$E(R) = 1 + \frac{2 \times n_0 \times n_1}{n} \tag{1}$$

$$Var(R) = \frac{2 \times n_0 \times n_1 \times (2 \times n_0 \times n_1 - n)}{n^2 \times (n-1)} \tag{2}$$

Then, the Z statistic is defined as:

$$Z = \frac{R - E(R)}{\sqrt{Var(R)}} \tag{3}$$

For a significance level of α = 0.01 and α = 0.05, the null hypothesis of homogeneity is verified if $|Z| \leq 2.58$ and $|Z| \leq 1.96$, respectively.

2.2.2. Buishand Tests

Buishand (1982) [30] used cumulative deviations from the mean for the analysis of homogeneity. Tests for homogeneity can be based on the adjusted partial sums or cumulative deviations from the mean:

$$S_0^* = 0$$

$$S_k^* = \sum_{i=1}^{k} \left(Y_i - \overline{Y}\right) \qquad k = 1, \ldots\ldots, n \tag{4}$$

$$S_0^* = 0$$

Note that $S_0^* = 0$. For a homogeneous record, one may expect that the S_k^* values fluctuate around zero, since there is no systematic pattern in the deviations of the Y_i values from their average value $\bar{Y}$. Rescaled adjusted partial sums are obtained by dividing the S_k^* values by the sample standard deviation (D_Y):

$$S_k^{**} = \frac{S_k^*}{D_Y} \qquad k = 0, \ldots, n \tag{5}$$

$$D_Y^2 = \frac{\sum_{i=1}^{n} \left(Y_i - \overline{Y}\right)^2}{n} \tag{6}$$

A statistic which is sensitive to departures from homogeneity is:

$$Q = \max_{0 \leq k \leq n} |S_k^{**}| \tag{7}$$

High values of Q are an indication for a change in level. Another statistic which can be used for testing homogeneity is the range (*Range*):

$$Range = \max_{0 \leq k \leq n} |S_k^{**}| - \min_{0 \leq k \leq n} |S_k^{**}| \tag{8}$$

2.3. *Trend Detection*

Mann–Kendall (MK) Test

This procedure has been used in hydrology and climatology to test randomness against trend of time series. As it is a rank-based procedure, it is robust to the influence of extremes and a good test for skewed data. For any sample of n variables, $x_1, \ldots, x_n$, the null hypothesis states that the sample is independent and identically distributed. The alternative hypothesis of a two-sided test is that the distributions of x_i and x_j are not identical for all $k, j \leq n$ with $i \neq j$.

The MK test is based on the test statistic S defined as follows:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign\left(x_2 - x_j\right) \tag{9}$$

where x_i and x_j are the annual values in years i and j, $j > i$, respectively, and sign $(x_i - x_j)$ is -1 for $(x_i - x_j) < 0$; 0 for $(x_i - x_j) = 0$, and 1 for $(x_i - x_j) > 0$.

The mean $E[S]$ and variance $V[S]$ of the statistic S may be given as:

$$E[S] = 0 \tag{10}$$

$$V[S]\frac{n(n-1)(2n+5)-\sum_{p=1}^{q}t_p\left(t_p-1\right)\left(2t_p+5\right)}{18} \quad (11)$$

where t_p is the number of ties for the pth value and q is the number of tied values. The second term represents an adjustment for tied or censored data. The standardized test statistic (Z_{MK}) is computed by:

$$Z_{MK} = \left\{ \begin{array}{cc} \frac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{array} \right\} \quad (12)$$

A positive Z_{MK} indicates an increasing trend, and a negative Z_{MK} indicates a decreasing trend. To test for either increasing or decreasing monotonic trends at p significance level, the null hypothesis is rejected if the absolute value of Z is greater than $Z_{1-p/2}$, where $Z_{1-p/2}$ is obtained from the standard normal cumulative distribution tables. In this work, different significance levels of p (0.1; 0.05 and 0.01) were applied, considering the first of them as the significant threshold.

2.4. Tests to Detect a Change of Trend over Time

2.4.1. Mann–Kendall–Sneyers Procedure (Sequential)

This methodology has been applied in different regions of the world to assess a trend change during the study period. Nasri and Modarres (2009) [28] analyzed the trend change of dry periods in Iran, and [31] determined changes in the long-term precipitation records of a weather station also in this country. Lázaro et al. (2001) [29] analyzed rainfall behavior in the semi-arid region of Spain and its influence on vegetation. In addition, Zhao et al. (2015) [23] evaluated the temporal and spatial evolution of the trend of hydro-climatic variables in the Wei River Basin (China).

The sequential or progressive version of the Mann–Kendall test [32] was used to test assumptions about the start of a trend within the sample $x_1, \ldots, x_n$ from set of random variables x based on a rank series of progressive and retrograde rows of the sample. For each variable, the Mann–Kendall test and its progressive or sequential form were performed, as described by [32] and briefly reported by [7,12].

Let us consider a sample of random variable Y, $\{y_i, {}_j = 1, 2, \ldots, m\}$ with length m. Let us denote p_i as the number of elements of the sample with $j < i$ and $y_j < y_i$, and τ as the test statistic given by

$$\tau = \sum_{i=1}^{m} p_i \quad (13)$$

One can show that τ is asymptotically normally distributed with the mean

$$\mu(\tau) = \frac{m(m-1)}{4} \quad (14)$$

and the standard deviation

$$\sigma(\tau) = \sqrt{\frac{m(m-1)(2m+5)}{72}} \quad (15)$$

The normalized variable u(τ) = ($\tau - \mu(\tau)/\sigma(\tau)$) has a standard normal distribution, so it is easy to build the associated confidence interval. The Mann–Kendall test checks the assumption of stationarity of the study series $\{y_i\}$ by verifying that the normalized variable u(τ) is included within the confidence interval, given a significance level α.

In the progressive form of the Mann–Kendall test, the variables τ and u(τ) are calculated for each element of the sample $\tau_j = \sum_{i=1}^{j} p_i$, using u($\tau_j$) with j = 1, 2,..., m, thus obtaining m values of these variables which are compared with the $100(1-\alpha)$ confidence interval. It can be noted that the last value of the progressive Mann–Kendall test is equal to the value obtained by the traditional

Mann–Kendall test. The same procedure is also applied to the backward series; in this case, p'_i denotes the number of elements of the series $\{y_i\}$ with $j > i$ and $y_j > y_i$; from p'_I, τ'_j and $u(\tau'_j)$ are calculated. In the absence of a trend, the plots of $u(\tau_j)$ and $u(\tau'_j)$ with j exhibit several overlaps, while in the case of a significant trend, the intersection of these curves enables the start of the phenomenon to be located approximately.

2.4.2. The Tomé–Miranda (TM) Method

The TM procedure uses a least-squares approach to compute the best continuous set of straight lines that fit a given time series, subject to a number of constraints on the minimum distance between breakpoints and on the minimum trend change at each breakpoint [20]. The procedure obtains the square difference between the observed values of the time series and the values evaluated from a set of partial trends. These partial trends are obtained subject to the condition that the interval between breakpoints must exceed a certain value, called MINIX, and imposing restrictions on the difference between two successive trends. Then, the algorithm determines the best combination of continuous segments that minimizes the square error. In the present work, the MINIX values adopted were equal to 20, seeking to split the series into only two sections. When this procedure did not converge, the MINIX value was reduced to reach this condition [5].

3. Results and Discussion

3.1. Rainfall Intensity in the Central Region of Argentina

Recognizing the importance of rainfall intensity in both productive and environmental terms [14], and given the lack of specific data that can be applied to evaluate it directly and establish its long-term variability, two indicators are used as substitutes: INT and AMDR. The variability of INT and AMDR annual values at meteorological stations in the central territory of Argentina is shown in Figure 2 for the period between 1960 and 2012. As the trend of INT depends on the variation of the two parameters that constitute it (AR and DPF), both these variables must be assessed to explain the trend. Due to its nature, AMDR intrinsically has a greater capacity to represent the behavior of rainfall intensity directly.

Two aspects are noteworthy in the behavior of these rainfall indicators in the region. The first is their marked interannual variability. Using the coefficient of variation to perform a comparative analysis of the variability, Table 1 shows that the variability of AMDR (between 31 and 39%) roughly doubles that of INT (14 and 19%) at each of the weather stations, with Pilar Observatorio (PI) being the only one with a slightly lower ratio (1.67). The other aspect to be highlighted is the positive correlation between both indices (with a rank of 0.39–0.57 between stations) which, although it expresses a significant linear relationship, also suggests that each variable retains some particular behavior.

Table 1. Position (mean) and dispersion statistics (DE: standard deviation; CV: coefficient of variation (DE/mean)) of the annual maximum precipitation in 24 h (AMDR) and the mean annual intensity (INT) for different weather stations of Córdoba, Argentina, over the period 1960–2012, with the coefficient of correlation (r) between them.

	Weather Stations													
	BO		**LB**		**MJ**		**PI**		**RC**		**VD**		**VM**	
	AMDR	**INT**	**AMDR**	**INT**	**AMDR**	**INT**	**AMDR**	**INT**	**AMDR**	**INT**	**AMDR**	**INT**	**AMDR**	**INT**
Mean (mm d^{-1})	78.6	9.1	78.5	10.2	82.6	11.9	76.7	9.7	77.3	11.0	56.1	11.0	75.2	10.9
DE (mm d^{-1})	30.5	1.7	28.5	1.8	29.3	2.3	24.0	1.8	23.7	1.6	18.0	1.6	24.6	1.7
CV (%)	38.7	19.0	36.3	17.7	35.5	19.2	31.3	18.7	30.7	14.3	32.1	14.3	32.7	15.7
r	0.487 *		0.524 *		0.569 *		0.479 *		0.442 *		0.518 *		0.394 *	

References: Córdoba Observatorio (BO), Laboulaye Aero (LB), Marcos Juárez Aero (MJ), Pilar Observatorio (PI), Rio Cuarto Aero (RC), Villa Dolores Aero (VD), and Villa María de Río Seco (VM); * significant at the 0.01 level.

The uniformity of values presented in Table 1 for different sectors in central Argentina can be explained by the fact that the weather stations belong to the same rainfall region, in terms of both the precipitable water source and the main rainfall mechanisms [26]. In addition, the geographical proximity of the stations in a relatively flat territory must be expressed with some spatial coherence in the manifestation of rainfall [33]. A visual inspection of these series highlights the great temporal variability that is characteristic of the rainfall. Considering that part of this variability may be spurious, and that the occurrence of a breakpoint in a climate or hydrological time series is also due to a lack of homogeneity in the records, it is necessary to analyze the homogeneity of the data by taking account of the incidence of both climatic and non-climatic factors. The following is a formal analysis of rainfall series homogeneity, intended to provide information on the quality and reliability of the information.

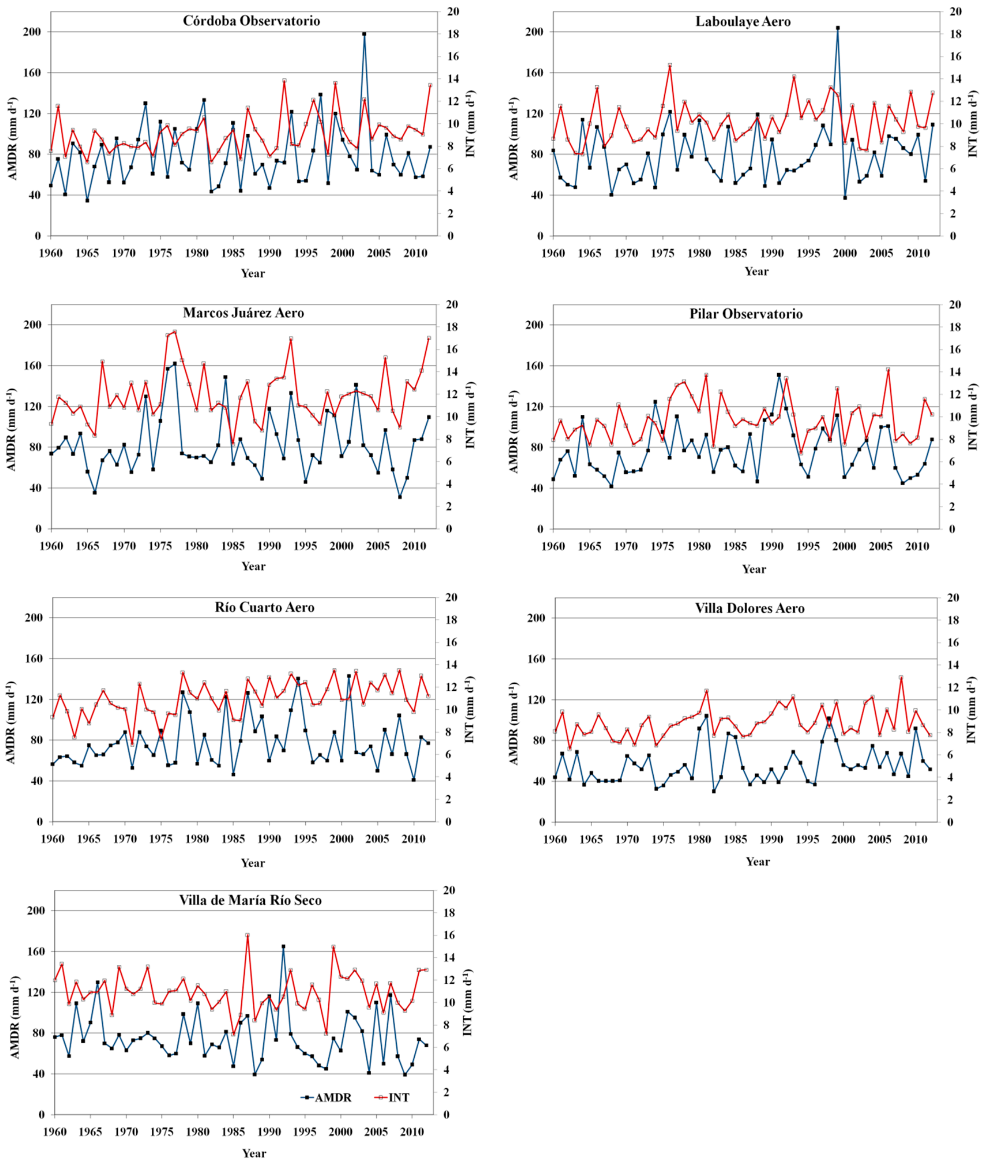


Figure 2. Annual variation of the mean intensity (INT) and the maximum daily value (AMDR) of rainfall at different weather stations of the central region of Argentina between 1960 and 2012.

3.2. *Assessment of Rainfall Time Series Homogeneity*

Homogeneity assessment in climate time series is performed using the results of different statistical tests and procedures that, when the evidence converges, validate this condition.

Wijngaard et al. (2003) [25] used a set of four tests to evaluate homogeneity in daily temperature and precipitation series, while [11] developed an integral procedure to classify the homogeneity of extreme rainfall indicators, which includes both absolute and relative procedures (i.e., with respect to another station in the network).

The results produced by the two tests and three criteria used to evaluate the homogeneity of annual rainfall series are presented in Table 2. The general condition for the complete set of indicators and stations analyzed shows that homogeneity prevails in the series as, in 79% of cases, at least two of the three criteria do not enable the condition of homogeneity to be rejected with α = 0.10 and, in 86% of cases, at least two of the three criteria do not enable homogeneity to be rejected with α = 0.05. By increasing the significance level to α = 0.01, the decision to reject homogeneity is reduced to only 7% of the cases, and only in Río Cuarto is the annual DPF rejected by the three criteria simultaneously.

Table 2. Homogeneity assessment of annual rainfall series (total amount (AR), number of rainy days (DPF), mean intensity (INT), maximum daily value (AMDR), variation coefficient of AR (ARCV) and variation coefficient of DPF (DPFCV)) with Buishand procedures (Q and R) and the run test for different weather stations of Córdoba, Argentina, and different levels of probability (α) in the period between 1960 and 2012.

	Buishand Test								*Run Test*										
Weather Station	Q	α			R	α			**Run**	n_0	n_1	n	$E(R)$	DE(R)	Z	p	α		
		0.1	**0.05**	**0.01**		**0.1**	**0.05**	**0.01**									**0.1**	**0.05**	**0.01**
AR																			
BO	6.1	no	no	no	10.2	no	no	no	26	31	22	53	26.7	3.5	0.21	0.83	no	no	no
LB	7.9	no	no	no	10.3	no	no	no	24	27	26	53	27.5	3.6	0.97	0.33	no	no	no
MJ	7.4	no	no	no	9.3	no	no	no	24	30	23	53	27.0	3.5	0.86	0.39	no	no	no
PI	8.3	no	no	no	13.0	yes	yes	yes	25	32	21	53	26.4	3.4	0.39	0.69	no	no	no
RC	5.6	no	no	no	7.9	no	no	no	28	28	25	53	27.4	3.6	0.16	0.87	no	no	no
VD	10.0	yes	yes	no	11.8	yes	yes	no	20	26	27	53	27.5	3.6	2.08	0.04	yes	yes	no
VM	8.1	no	no	no	11.4	yes	yes	no	18	24	29	53	27.3	3.6	2.59	0.01	yes	yes	yes
DPF																			
BO	10.9	yes	yes	no	13.7	yes	yes	yes	20	26	27	53	27.5	3.6	2.08	0.04	yes	yes	no
LB	4.9	no	no	no	9.4	no	no	no	18	28	25	53	27.4	3.6	2.62	0.01	yes	yes	yes
MJ	6.4	no	no	no	11.8	yes	yes	no	22	28	25	53	27.4	3.6	1.51	0.13	no	no	no
PI	5.9	no	no	no	10.5	yes	no	no	28	25	28	53	27.4	3.6	0.16	0.87	no	no	no
RC	12.9	yes	yes	yes	13.4	yes	yes	yes	17	26	27	53	27.5	3.6	2.91	0.00	yes	yes	yes
VD	5.7	no	no	no	10.3	no	no	no	22	28	25	53	27.4	3.6	1.51	0.13	no	no	no
VM	11.2	yes	yes	yes	17.0	yes	yes	yes	22	26	27	53	27.5	3.6	1.52	0.13	no	no	no
INT																			
BO	10.4	yes	yes	no	11.0	yes	no	no	28	29	24	53	27.3	3.6	0.21	0.84	no	no	no
LB	7.3	no	no	no	7.9	no	no	no	30	29	24	53	27.3	3.6	0.77	0.44	no	no	no
MJ	5.7	no	no	no	7.3	no	no	no	24	30	23	53	27.0	3.5	0.86	0.39	no	no	no
PI	8.2	no	no	no	10.9	yes	no	no	26	28	25	53	27.4	3.6	0.39	0.69	no	no	no
RC	14.1	yes	yes	yes	14.1	yes	yes	yes	24	27	26	53	27.5	3.6	0.97	0.33	no	no	no
VD	10.0	yes	yes	no	11.0	yes	no	no	25	31	22	53	26.7	3.5	0.50	0.62	no	no	no
VM	4.8	no	no	no	8.5	no	no	no	29	28	25	53	27.4	3.6	0.44	0.66	no	no	no
AMDR																			
BO	4.8	no	no	no	7.1	no	no	no	32	32	21	53	26.4	3.4	1.64	0.10	no	no	no
LB	5.6	no	no	no	6.2	no	no	no	29	29	24	53	27.3	3.6	0.49	0.63	no	no	no
MJ	5.4	no	no	no	8.7	no	no	no	24	33	20	53	25.9	3.4	0.56	0.57	no	no	no
PI	7.5	no	no	no	11.7	yes	yes	no	22	28	25	53	27.4	3.6	1.51	0.13	no	no	no
RC	6.9	no	no	no	9.7	no	no	no	29	32	21	53	26.4	3.4	0.77	0.44	no	no	no
VD	7.9	no	no	no	8.1	no	no	no	27	33	20	53	25.9	3.4	0.32	0.75	no	no	no
VM	5.4	no	no	no	6.0	no	no	no	28	33	20	53	25.9	3.4	0.62	0.54	no	no	no
ARCV																			
BO	4.6	no	no	no	6.3	no	no	no	29	28	25	53	27.4	3.6	0.44	0.66	no	no	no
LB	5.5	no	no	no	7.6	no	no	no	30	28	25	53	27.4	3.6	0.72	0.47	no	no	no
MJ	5.2	no	no	no	6.6	no	no	no	21	30	23	53	27.0	3.5	1.71	0.09	yes	no	no
PI	6.4	no	no	no	6.5	no	no	no	24	30	23	53	27.0	3.5	0.86	0.39	no	no	no
RC	7.1	no	no	no	7.5	no	no	no	30	28	25	53	27.4	3.6	0.72	0.47	no	no	no
VD	3.3	no	no	no	5.5	no	no	no	23	28	25	53	27.4	3.6	1.23	0.22	no	no	no
VM	10.2	yes	yes	no	10.3	no	no	no	24	30	23	53	27.0	3.5	0.86	0.39	no	no	no
DPFCV																			
BO	8.5	yes	no	no	8.8	no	no	no	28	25	28	53	27.4	3.6	0.16	0.87	no	no	no
LB	6.8	no	no	no	10.8	yes	no	no	20	30	23	53	27.0	3.5	1.99	0.05	yes	yes	no
MJ	5.5	no	no	no	9.1	no	no	no	26	27	26	53	27.5	3.6	0.41	0.68	no	no	no
PI	5.7	no	no	no	6.7	no	no	no	24	27	26	53	27.5	3.6	0.97	0.33	no	no	no
RC	9.9	yes	yes	no	10.0	no	no	no	27	26	27	53	27.5	3.6	0.14	0.89	no	no	no
VD	4.3	no	no	no	7.5	no	no	no	28	26	27	53	27.5	3.6	0.14	0.89	no	no	no
VM	7.5	no	no	no	11.1	yes	no	no	28	26	27	53	27.5	3.6	0.14	0.89	no	no	no

On the other hand, there is also some divergence about the homogeneity qualification depending on the test applied to identify it, with some instances where each procedure yields particular results, similar to the information presented by [30] when analyzing the homogeneity of rainfall series from five different statistical tests. Thus, on the one hand, the run test establishes the annual INT in Río Cuarto Aero (RC) as homogeneous, while, on the other hand, both criteria (Q and R) of the Buishand procedure [30] give the opposite for all levels of significance assessed; as a result this INT time series was considered nonhomogeneous. This discrepancy also occurs in Villa de María de Río Seco (VM) in the homogeneity of DPF. In contrast, for DPFCV in Laboulaye, the run test with α = 0.05 establishes the rejection of homogeneity, while the series appears as homogeneous for this level of probability from the Q and R values of the Buishand test.

3.3. Long-Term Trend Analysis

Even though annual AR is still increasing in the region, as [4] determined for the period between 1930 and 2000, the positive trend remains significant only in Laboulaye Aero (LB) and Villa Dolores Aero (VD) for the period between 1960 and 2012, while in VM it is negative even in this more recent period (Table 3). A seasonal analysis at this northern site reveals that the decrease is associated with a significant reduction of rainfall in the cold season, whereas during the warm season, with more than 80% of the annual total of rain in this region, only VD still shows a significant increase of AR over the 53 years. Considering that there was a generalized increase in rainfall in central Argentina from the mid to late twentieth century [4,34], discarding the first drier years (between 1930 and 1960) and adding a recent less rainy period to the time series would explain why the trend of annual rainfall is no longer positive in significant terms for most of the region [35–37].

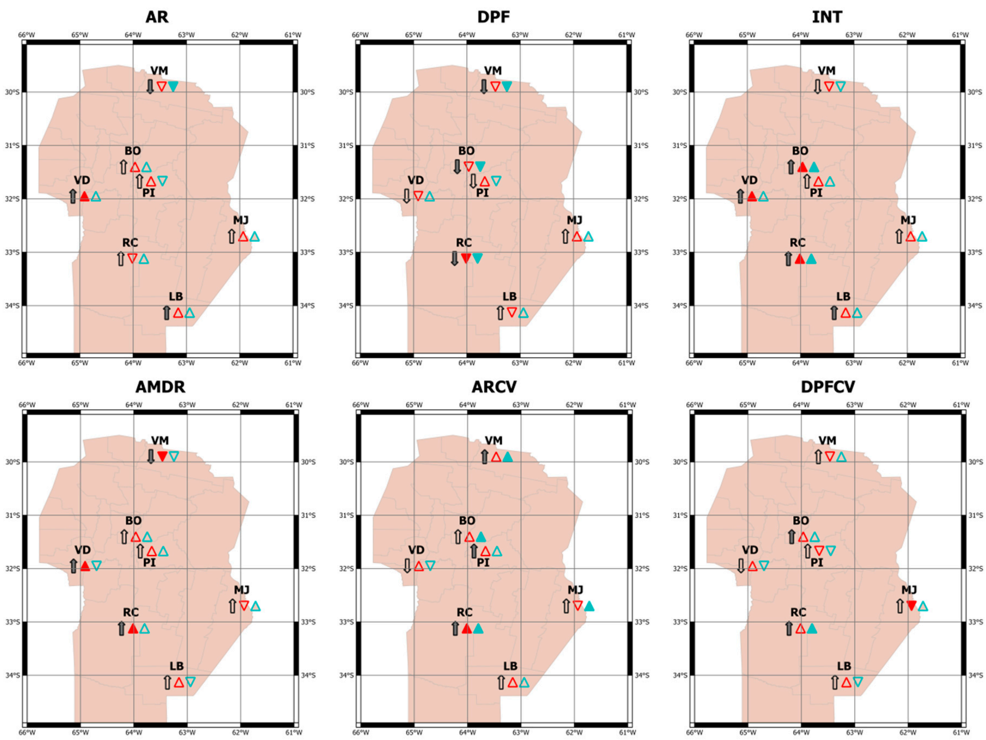


Figure 3. Mann–Kendall (MK) test (Z) to detect trend for annual (arrow), warm season (WS) (red triangle) and cold season (CS) (green triangle) rainfall time series of total annual rainfall (AR), annual frequency of rainy days (DPF), mean intensity (INT), maximum daily value (AMDR), and the coefficients of variation of AR (ARCV) and DPF (DPFCV), at different weather stations at Córdoba, Argentina. When symbols are upward (down), this indicates a positive (negative) trend, while filled symbols indicate statistical significance ($p < 0.10$).

Table 3. Classification of rainfall series with significant trend (Z values and their probability ($p < 0.10$) and slope estimated by ordinary least squares (S_{OLS})) according to the homogeneity condition assessed under different criteria (yes: rejects).

Index	Weather Station	Trend			Homogeneity Tests									Condition
					Q			*R*			Run Test			
		Z	*p*	S_{OLS}	0.1	0.05	0.01	0.1	0.05	0.01	0.1	0.05	0.01	
AR	LB	1.841	***0.0328***	2.76	no	no	no	no	no	no	no	no	no	H
AR	VD	1.312	***0.0948***	1.76	yes	yes	no	yes	yes	no	yes	yes	no	NH
AR	VM	−1.373	***0.0849***	−2.35	no	no	no	yes	yes	no	yes	yes	yes	NH
DPF	BO	−2.182	***0.0146***	−0.21	yes	yes	no	yes	yes	yes	yes	yes	no	NH
DPF	RC	−3.226	***0.0006***	−0.31	yes	yes	yes	yes	yes	yes	yes	yes	yes	NH
DPF	VM	−1.781	***0.0375***	−0.19	yes	yes	yes	yes	yes	yes	no	no	no	NH
INT	BO	2.723	***0.0032***	0.039	yes	yes	no	yes	no	no	no	no	no	H
INT	LB	1.895	***0.0291***	0.026	no	no	no	no	no	no	no	no	no	H
INT	RC	3.521	***0.0002***	0.051	yes	yes	yes	yes	yes	yes	no	no	no	NH
INT	VD	1.987	***0.0235***	0.028	yes	yes	no	yes	no	no	no	no	no	H
AMDR	RC	1.358	***0.0872***	0.216	no	no	no	no	no	no	no	no	no	H
AMDR	VD	1.988	***0.0234***	0.275	yes	no	no	no	no	no	no	no	no	H
AMDR	VM	−1.481	***0.0694***	−0.213	no	no	no	no	no	no	no	no	no	H
ARCV	PI	1.634	***0.0511***	0.18	no	no	no	no	no	no	no	no	no	H
ARCV	RC	1.404	***0.0802***	0.21	no	no	no	no	no	no	no	no	no	H
ARCV	VM	1.895	***0.0291***	0.33	yes	yes	no	no	no	no	no	no	no	H
DPFCV	BO	2.293	***0.0109***	0.22	yes	no	no	no	no	no	no	no	no	H
DPFCV	RC	2.508	***0.0061***	0.27	yes	yes	no	no	no	no	no	no	no	H

References: Weather stations as Figure 1 and rainfall index as Figure 3. S_{OLS} units: mm year^{-1} for AR, INT, and AMDR; day year^{-1} for DPF; % year^{-1} for ARCV and DPFCV.

The change in DPF is widespread in the region, but with a decreasing significant trend at Córdoba Observatorio (BO), RC, and VM, where it is associated with a significant decrease of events during the cold season (CS). At RC, also, there is a significant reduction of DPF also in the warm season (WS). Thus, the decrease of DPF seems to be causing the increase of INT, which is effectively expressed at BO and RC, as at VD. At LB, on the other hand, the increase in average rainfall intensity is accounted for by the significant increase in AR. At both, BO and RC, the increase of annual INT agreed with significant INT increase in warm and cold seasons. At VD, the INT annual increase only matches with INT increase in the warm season.

The change in AMDR shows a significant trend in RC, VD, and VM at the annual and WS scales, with increases in the first two sites and a decrease in the last one. Comparing INT with AMDR in order to consider another source of more direct evidence of rainfall intensity shows that, at VD and RC, the possibility of increased precipitation intensity becomes more consistent because both indicators (INT and AMDR) at these sites present a positive trend in annual and WS time series.

Regarding changes in rainfall variability, the annual ARCV shows an increase over time at PI, RC, and VM. While in RC this increase agrees in WS and CS, in VM only CS shows this behavior, and in BO a significant increase of ARCV also appears during the CS. On the other hand, at BO and RC there is a significant increase in variability of the annual frequency of events (DPFCV), and this behavior keeps on RC in the CS. During the WS a decrease of DPFCV only appears at MJ.

These changes detected by the MK test in the rainfall regime in the region are not generalized spatially, nor do they have the same nature in all cases. In fact, there is less evidence supporting the hypothesis of a rainfall regime change in its different expressions than to the contrary. Similarly, Villafuerte et al. (2014) [14] find that extreme rains in the Philippines exhibit spatially incoherent behavior, with mixed positive and negative trends even among neighboring weather stations. Also, assessing temporal variability of rainfall in the Upper Tennessee Valley, Jones et al. (2015) [38] concluded that only 11% of the 78 sub-basins experienced statistically significant increasing or decreasing precipitation over a 50-year period. This reveals changes in the rainfall regime are not widespread in a region nor has the same sign necessarily, as was observed in central Argentina. In eight South Australian natural resource management regions, Chowdhury et al. (2015) [39] established that increasing annual rainfall trends were observed for three of them (Arid Lands, Alinytjara Wilinara, and the Adelaide and Mount Lofty Ranges), whereas decreasing trends were found in other three regions (Murray Darling Basin, Eyre Peninsula, and the South East). Hence, this seems to be more an atmospheric water redistribution phenomenon rather than generalized trend behavior.

3.4. Trend Change Analysis

This complementary evaluation of the trend of the precipitation series over time is made by two methods independently, the Mann–Kendall–Sneyers (MKS) test [32] and the Tomé–Miranda (TM) procedure [20], to make the evaluation more complete.

Considering that the results of the homogeneity tests are not absolute, and that the systematic increase or decrease of a time series can also produce non-homogeneous data behavior, it is clear that discerning a real trend in climatic series is not easy, as the series can undergo variations that are atmospheric (natural or anthropic), and also variations produced by the monitoring system itself. Costa and Soares (20009) [11] confirmed that using absolute approaches without metadata or complementary information makes it difficult to determine if changes in a station's time series result from inhomogeneities or simply from abrupt changes in the regional climate.

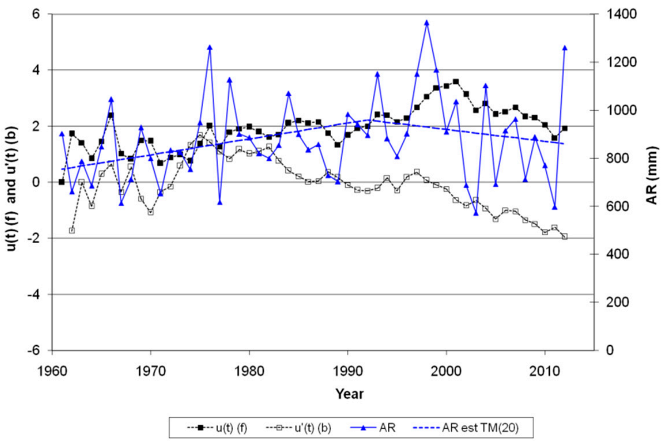
Considering the results of Table 2 and Figure 3 as a whole, the rainfall variables with a significant trend (α = 0.1) can be classified according to their homogeneity or quasi-homogeneity (i.e., when all three homogeneity tests are considered at the three levels of significance, the acceptance of H_0 predominates by majority). Following this criterion, the AR at VD and VM, DPF at BO, RC, and VM, as well as INT at RC have an actual trend but simultaneously under a non-homogeneous condition. The AR at LB, INT at BO, LB and VD, AMDR at RC, VD, and VM, ARCV at PI, RC and VM, and DPFCV at BO and RC are all cases with a long-term significant trend, also under a homogeneity condition. As the absence of homogeneity cannot be validated or corrected in this instance because of the lack of complementary information about the weather stations' performance, the MKS sequential test and the TM procedure are applied to the rainfall series to identify a possible breakpoint or climatic jump [12], with the proviso that, when the series is not homogeneous, the determining cause of discontinuity may also be extra-climatic.

3.4.1. Variation of Annual Rainfall at Laboulaye (LB), Villa Dolores (VD), and Villa de María de Río Seco (VM)

While the annual series of AR for LB is entirely homogeneous, non-homogeneous conditions predominate in the VD and VM records. For the whole period, the trend of AR is increasing at LB and VD, while the long-term trend for VM is to decrease, mainly due to the decrease of rainfall in the cold season (Figure 3). The MKS procedure, however, reveals that, during the period between 1960 and 2012, there is a change of trend at all three sites. As shown in Figure 4a–c for LB, VD, and VM, respectively, the curves of the forward and backward MKS sequential test cross and diverge approximately in the 1970s and 1980s, a little before or a little later depending on the place, indicating an increase in rainfall in the first years of the period and then a decrease.

This behavior of AR, increasing at first and currently decreasing, is fully validated from the TM results, although the breakpoint obtained from this procedure does not exactly coincide with that determined by MKS. Thus, although at LB and VD the increasing long-term trend is still significant, both procedures used to analyze the change in trend establish that AR has already reached its maximum and is now decreasing. On the other hand, a progressive decrease of rainfall at VM during the period seems to have led to a decreasing trend, although with a slightly lower significance (p < 0.10), but also showing the same change from positive to negative as at LB and VD.

Using the Hubert's method of segmentation of hydrometeorological time series, [40] show that Argentina's Pampa Region was subject to sudden shifts in average rainfall but, for the Central Pampa sub region of Argentina, annual precipitation augmented in three successive steps, the first from 1941 to 1965, then from 1966 to 1996, and finally, from 1997 to 2002. In the more recent years the rainfall trend returns back to the initial period values. This depiction for AR, first growing and now decreasing, is not far from the results shown here using other analytical procedures. In any case, as the segmentation produced depends on the method used, it is convenient to analyze it from different approaches.



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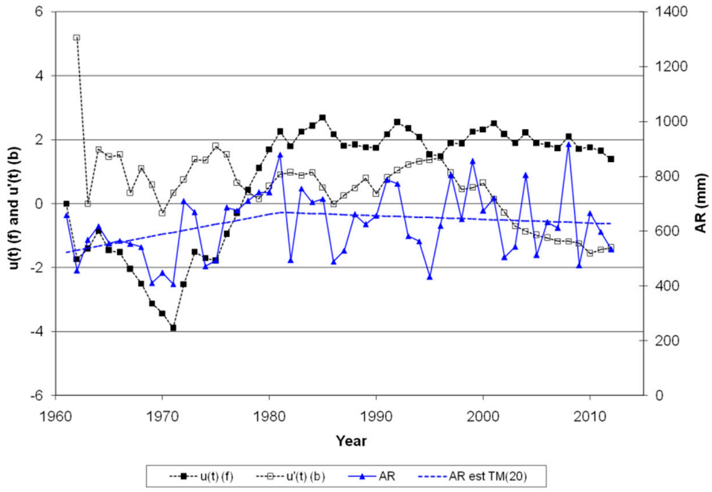

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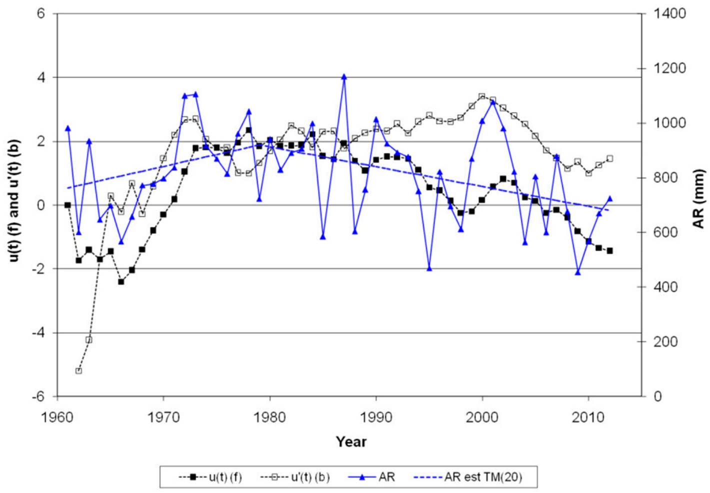


(**c**)

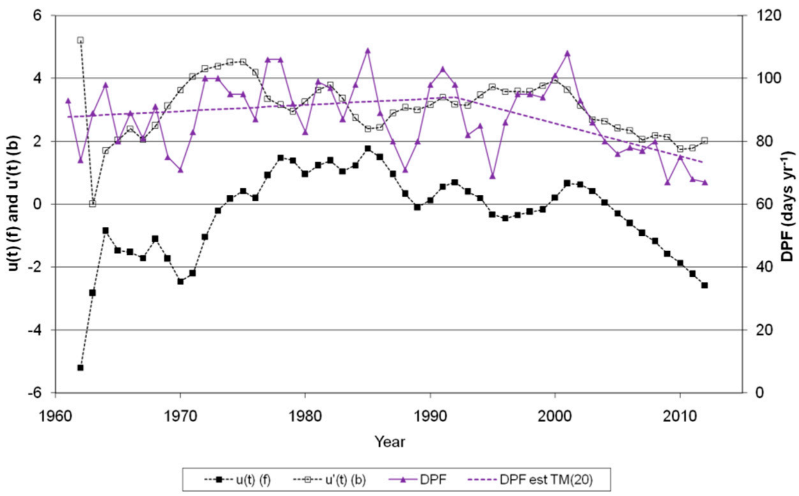
Figure 4. Annual variation of total rainfall (AR) in Laboulaye (**a**), Villa Dolores Aero (**b**), and Villa de María de Río Seco (**c**), between 1960 and 2012, and the breakpoint determination from Mann–Kendall–Sneyers, where u (t) and u′(t) are the forward (f) and backward (b) sequential test values, respectively, and from Tomé–Miranda (TM) for MINIX = 20.

Perez et al. (2015) [40] also showed the existence of teleconnections between climate fluctuation modes (Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and Southern Oscillation Index (SOI)) and precipitation in the Central, Flooding, and Southern Pampa sub-regions of Argentina. The AMO and PDO are ocean oscillations, with cycles of about 40 to 80 years that can be associated with low frequency changes in rainfall [40]. On the other hand, the SOI is an atmospheric index with an annual oscillation period and is therefore associated with high frequency variations in rainfall.

3.4.2. Variation of Rainy Days in Córdoba City (BO), Río Cuarto (RC), and Villa de María de Río Seco (VM)

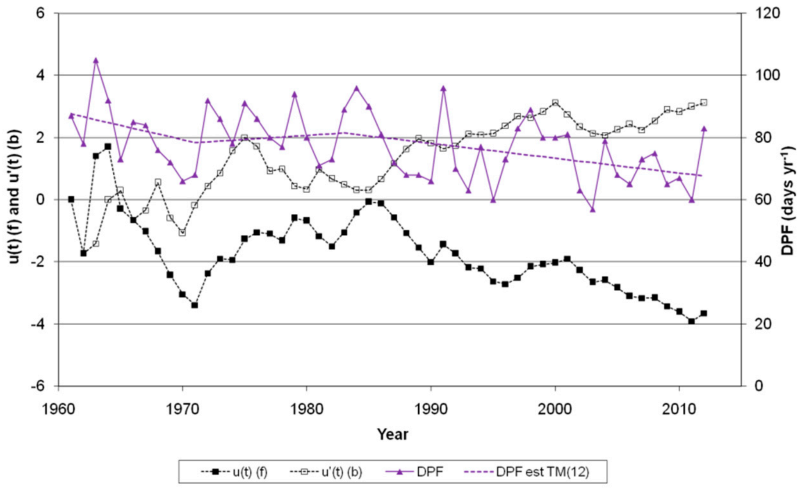
The annual DPF values between 1960 and 2012 at BO, RC, and VM, with the parameters of the sequential MKS test and the TM results, are presented in Figure 5. All three sites exhibit a significant long-term decreasing trend, as indicated in Figure 3. However, the MKS and TM procedures (Figure 5) show that this negative trend of DPF is clear only in the last years of the series. While for BO and VM there is a change from positive to negative around the 1980s, at RC the crossover of the MKS parameters occurs at the beginning of the series, and they have been diverging since then. This variation, however, is not monotonic in any of the cases, but shows shorter-scale fluctuations.

The TM procedure similarly displays the dynamics of the DPF trend, but with some differences between the three stations. At BO and VM a more conspicuous change occurs, first increasing and currently decreasing, with the breakpoints displaced from each other, being a little later at BO. At RC, the TM procedure with MINIX = 12 produces a fragmentation of three sections, with DPF decreasing until the beginning of the 1970s, slightly increasing until the beginning of the 1980s, and decreasing at the end of the period. Although the non-homogeneous character of the DPF time series predominates at the three places, this relatively similar trend change at all of them could be considered as evidence that lack of homogeneity is an expression of natural climate variation rather than of a monitoring problem.



(**a**)

Figure 5. *Cont.*



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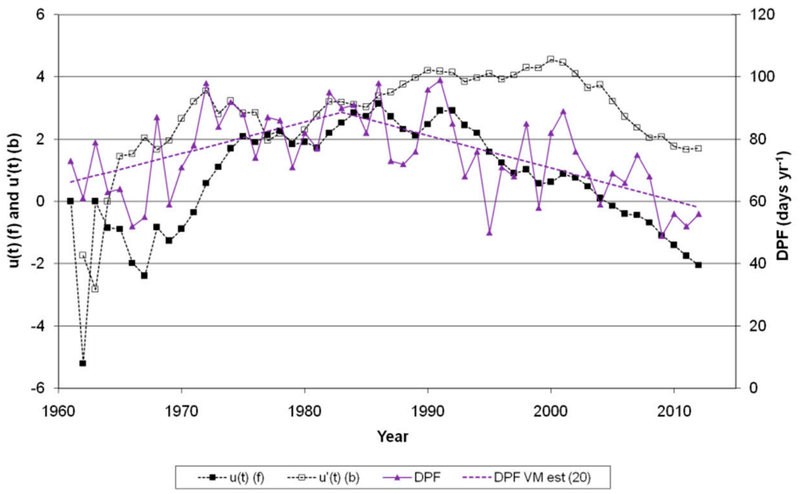


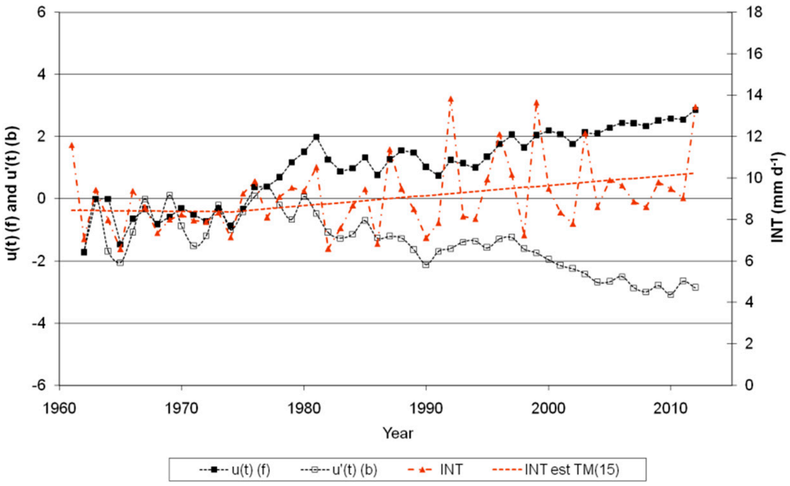
(**c**)

Figure 5. Annual variation of rainy days per year (DPF) at BO (**a**), RC (**b**), and VM (**c**) between 1960 and 2012, and determination of the breakpoint from Mann–Kendall–Sneyers, where u(t) and u′(t) are the test values forward (f) and backward (b), respectively, and from Tomé–Miranda (TM), where MINIX = 20 for (**a**,**c**) and 12 for (**b**).

3.4.3. Variation of Mean Rainfall Intensity in Córdoba city (BO), Laboulaye (LB), Río Cuarto (RC) and Villa Dolores (VD)

As shown in Figure 6, the annual INT time series show a positive trend (as indicated in Figure 3) at BO, LB, RC and VD, which, according to the intercept of the MKS curves, occurs from the 1970s. While the divergence of these curves at BO and RC is sharp thereafter, the value of breakpoint forward with the MKS test (u(t) (f)) at VD and LB has remained constant approximately since the mid-1990s. The TM method provides additional information in this case. While at BO it confirms that the increase of INT since the 1970s has been maintained to date, for RC, VD, and LB, in contrast, the rate of variation increased only until the mid-1990s and since then presented a very slight decrease. While the series of BO, VD, and LB reach a homogeneity standard, only the run test shows homogeneity at RC (Table 3).

Mean intensity (INT) is the attribute of rainfall that has apparently changed more generally in central Argentina, with an increase that seems to be associated with the decrease of DPF. However, this increase in rainfall intensity is corroborated by an increase in AMDR only at VD and RC. On the other hand, the trend of INT at present may be increasing only at BO, as the TM results show in Figure 6a.



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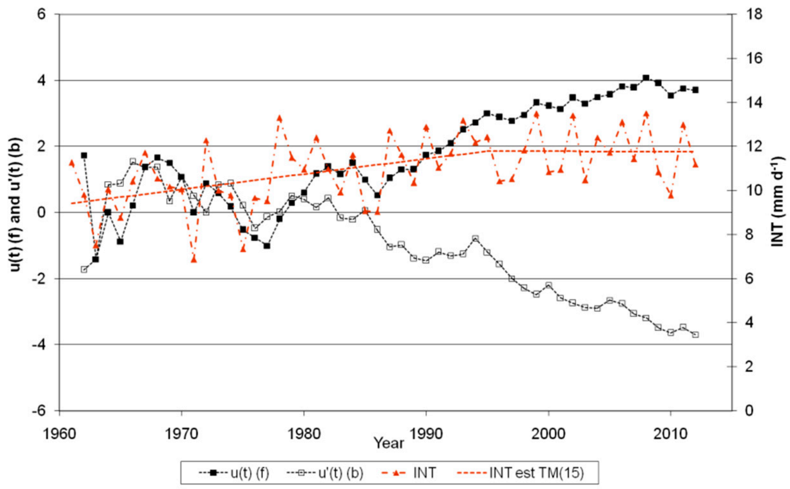

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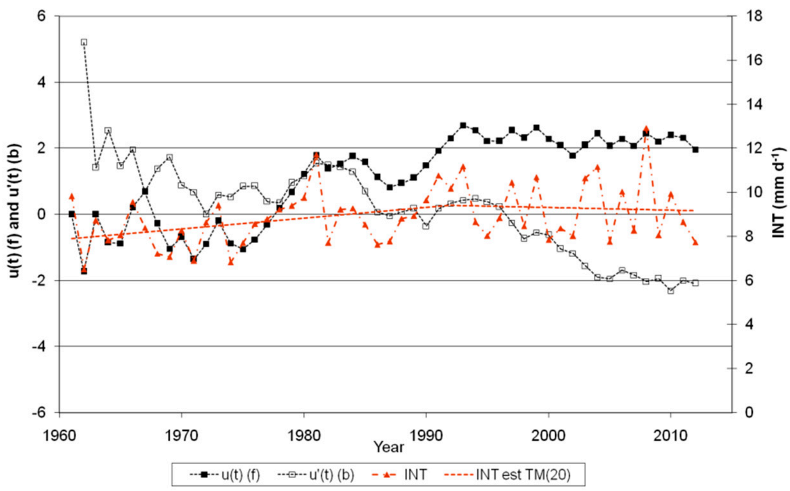

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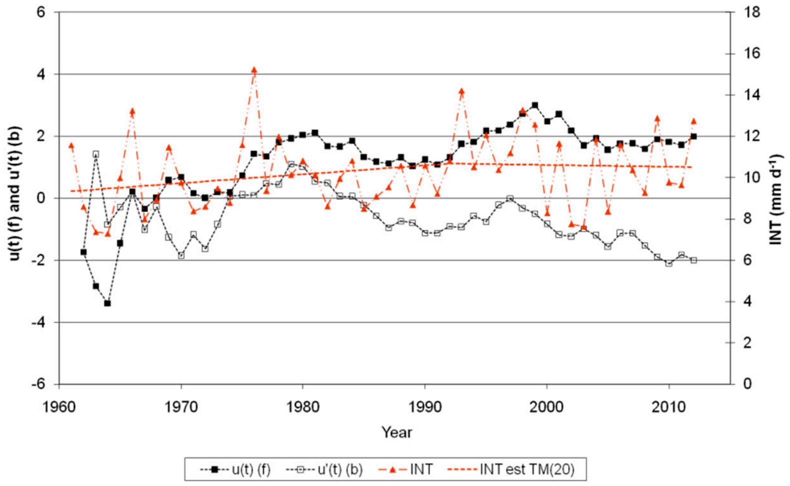
Figure 6. *Cont.*



(**d**)

Figure 6. Annual variation of mean rainfall intensity (INT) at BO (**a**), RC (**b**), VD (**c**), and LB (**d**) between 1960 and 2012, and determination of the breakpoint from Mann–Kendall–Sneyers, where u(t) and u′(t) are the test values forward (f) and backward (b), respectively, and from Tomé–Miranda (TM) where MINIX = 15 for (**a**) and (**b**), and 20 for (**c**) and (**d**).

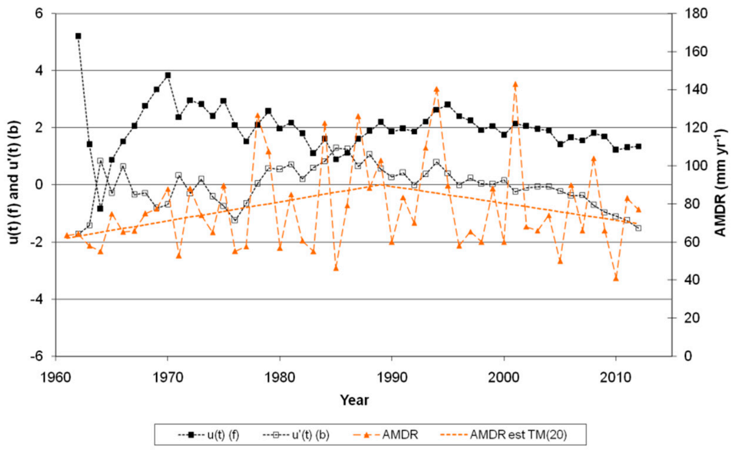
3.4.4. Variation of Maximum Daily Value of Annual Rainfall in Río Cuarto (RC), Villa Dolores (VD), and Villa de María de Río Seco (VM)

In the long term, RC shows a positive trend of AMDR, although with less statistical significance ($p < 0.10$). While this change is more noticeable at the beginning of the period, Figure 7a shows a decrease in the value of u(t) (f) in the mid-1980s. To the west of the region, as Figure 7b shows, VD also presents a positive AMDR trend that starts towards the end of the 1970s according to MKS. VM has shown a decreasing trend of AMDR since approximately 1970, according to MKS. The TM analysis, consistent with the MKS results, shows that the increase of AMDR is currently maintained only at VD.

Similarly to the pluviometric indicator trend change observed in the province of Córdoba, there is also an abrupt change of trend in rainfall in southern Australia [39] and in South Carolina (USA) [9] in the 1960s and 1970s, which may correspond to a more generalized atmospheric phenomenon linked to the multidecadal dynamics of the North Atlantic Oscillation (NAO) and the South Oscillation Index (SOI).

Another important feature of the long-term changes is that they are not monotonic but rather fluctuate on a shorter temporal scale, similar to the temporal variation that [10] observed in North Carolina (USA) and [38] in the Upper Tennessee Valley (USA). Likewise, [12] showed this medium-term variation of the precipitation series in China and determined, from sequential MKS procedures and the moving average difference (mobile t-test), the occurrence of up to three jumps or breakpoints between 1960 and 2008. de la Casa and Nasello (2010) [5] observed a fluctuation of between 10 and 20 years in rainfall time series of Cordoba, Argentina, analyzed from the nonlinear method of partial slopes [20]. Also, Yuan and Yonekura (2011) [41] point out a quasi-decadal variability in the climate system of high southern latitudes, particularly in the Southern Annular Mode (SAM) and in subpolar to mid-latitude sea surface temperatures (SST).

While there is a long-term increase in AMDR at VD and RC, the trend at VM is decreasing. The rainfall behavior at VD and RC to some extent supports the hypothesis of [15,16], who consider it more likely that climate change associated with global warming produces changes in the intensity and frequency of rainfall rather than altered total amounts. However, when the time series is broken down by MKS or TM, the long-term changes are reversed or, at least, appear to no longer be happening at present. On the other hand, the hypothesis of [16], postulating an increase in rainfall frequency as a result of atmospheric warming and the consequent increase of the capacity of air to contain moisture, is not supported by the DPF decrease in the central region of Argentina. These results for central Argentina are in accordance with those of [38] who claim that, although the IPCC's analysis of global climate change trends is relevant, regional weather patterns should be considered critical to local climates in the future.



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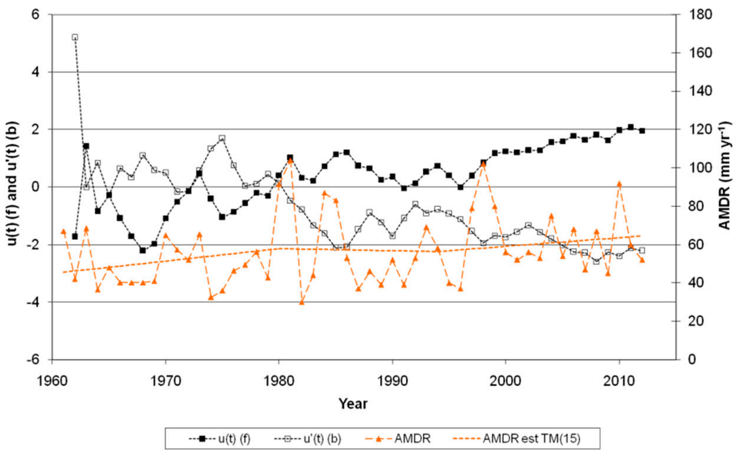

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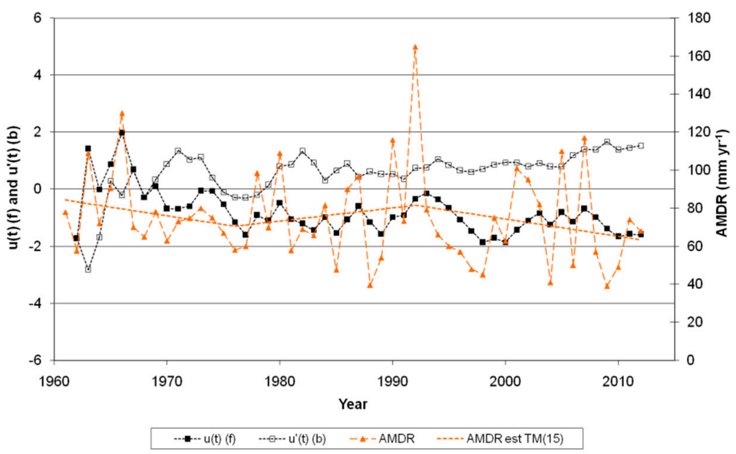
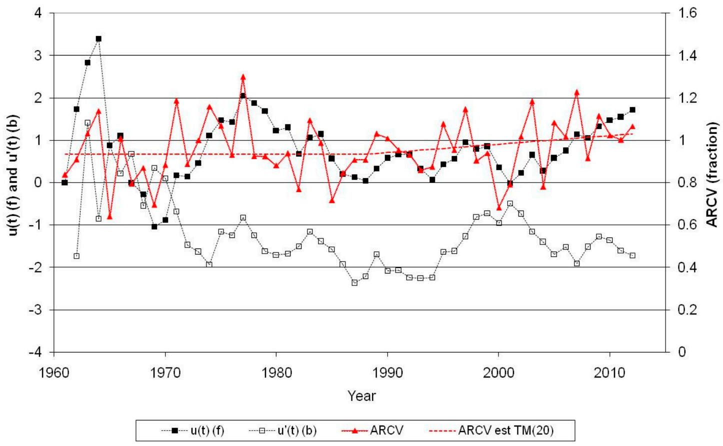


(**c**)

Figure 7. Variation of the annual maximum value of daily rainfall (AMDR) at RC (**a**), VD (**b**), and VM (**c**) between 1960 and 2012, and determination of the breakpoint from Mann–Kendall–Sneyers, where u(t) and u′(t) are the forward (f) and backward (b) test values, respectively, and from Tomé–Miranda (TM), where MINIX = 20 for (**a**) and 15 for (**b**,**c**).

3.4.5. Variation of Annual Rainfall Variability in Pilar (PI), Río Cuarto (RC), and Villa de María de Río Seco (VM)

The long-term change of annual ARCV is seen in a significant positive trend at PI, RC, and VM ($p < 0.10$). The MKS sequential test, as shown in Figure 8, indicates that this increase began from the 1970s at all three sites.



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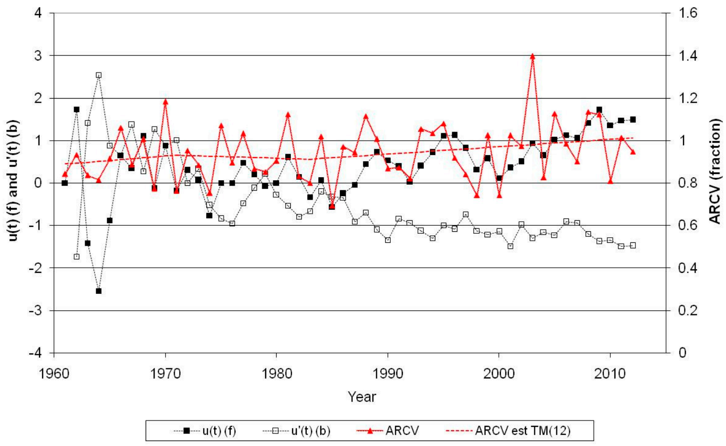

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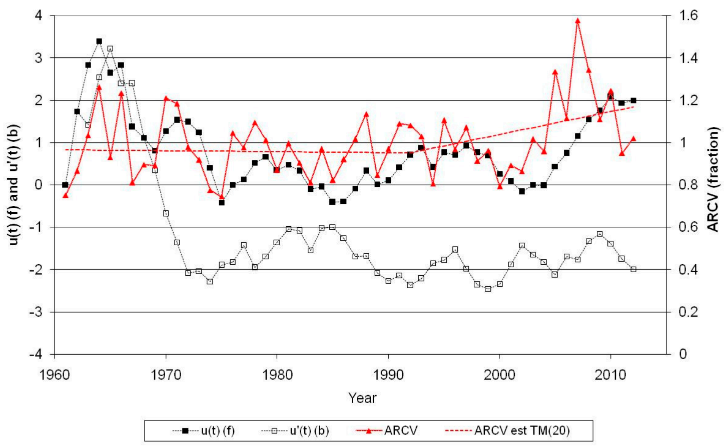


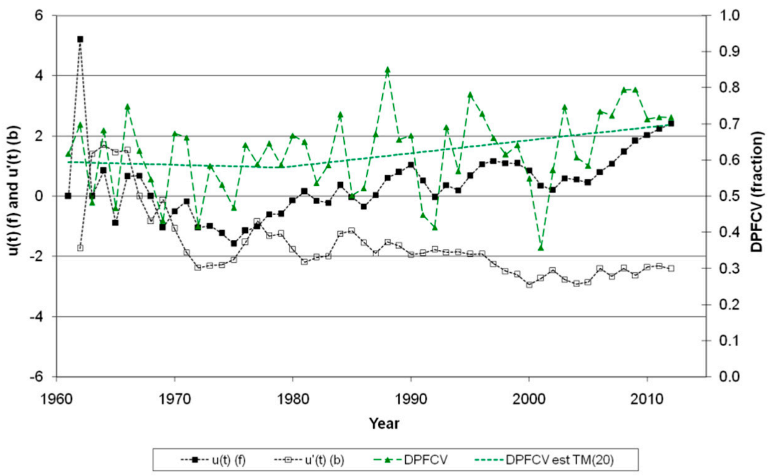
(**c**)

Figure 8. Variation coefficient of total annual rainfall (ARCV) at PI (**a**), RC (**b**) and VM (**c**) between 1960 and 2012, and determination of the breakpoint from Mann–Kendall–Sneyers, where u(t) and u′(t) are forward (f) and backward (b) test values, respectively, and from Tomé–Miranda (TM), where MINIX = 20 for (**a**,**c**) and 12 for (**b**).

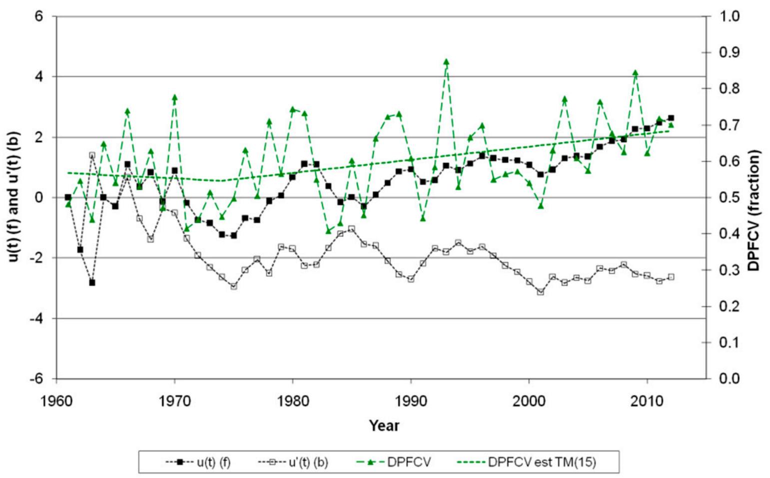
Using the TM procedure with MINIX = 20 to force a division of the time series into two sections, ARCV at VM shows no notable change until approximately the 1990s; since then the trend has grown. At PI, this break occurs a little earlier, while the procedure in RC determines three sections when MINIX is reduced to 12, although the results in general are very similar and confirm a progressive increase of rain variability in recent years. However, Figure 8 shows a certain periodicity in rain variability, with breakpoints or slope changes every 10–20 years, similar to the fluctuation of the annual total rainfall previously noted by [18]. This decadal fluctuation is equally noticeable at all three sites and partially masks the long-term increase.

3.4.6. Variation of Annual Rainy Day Variability in Córdoba City (BO) and Río Cuarto (RC)

The interannual DPFCV at BO and RC is shown in Figure 9. It is similar at both sites, with an increasing trend that begins around the 1970s and persists in recent years, although with fluctuations as seen in other rainfall indices. The TM method fully corroborates the results of the MKS, with a slight decrease in the variability of annual rainy days until the 1970s and a subsequent sustained increase, which is very similar at both sites. The breakpoint for RC occurs a little earlier, as the TM method indicates with MINIX = 15.



(**a**)



(**b**)

Figure 9. Variation coefficient of annual rainy days (DPFCV) at BO (**a**) and RC (**b**) between 1960 and 2012, and determination of the breakpoint with Mann-Kendall–Sneyers, where u(t) and u′(t) are the forward (f) and backward (b) test values, respectively, and from Tomé–Miranda (TM), where MINIX = 20 for (**a**) and 15 for (**b**).

The increase of precipitation variability in the context of global warming shows some consistency in the region, but it is locally restricted to PI, RC, and VM for total annual rainfall, and to BO and RC for the frequency of rainy days. In all these cases, most of the evidence supports the homogeneity of the time series. However, global warming seems not to have a uniform effect on the rainfall regime throughout central Argentina, nor does it modify all the rainfall features in the same way.

4. Conclusions

Assessing the homogeneity of rainfall series must help to classify the available information to make it more dependable. Due to the lack of complementary information (metadata) to elucidate the influence of some extra-climatic factors that may explain a jump or break in the time series, this study analyzed the change in trend of the rainfall variables, classifying the time series by their homogeneity. The set of tests considered different procedures, criteria, and levels of statistical significance, showing that there is widespread homogeneity in the rainfall series that were used. Only at RC did the results absolutely reject homogeneity for the annual frequency of rainy days. However, a generalized trend change detected in the region for this variable could explain this lack of homogeneity as strictly climatic, instead of a consequence of weather observation change.

Unlike air temperature, which is found to increase all over the world in response to the scale of global warming, changes in rainfall have particular characteristics in each place and period. While different indicators in central Argentina between 1960 and 2012 reflect a lack of change for precipitation at some sites, the intensity and variability of rainfall at other places show significant long-term trends. These changes are environmentally and economically important, as they have a direct impact on hydrological and soil resources, as well as on the agricultural potential of the region.

For the region as a whole, the linear trend is significant ($p < 0.10$) in 18 of the total of 42 cases analyzed in an annual period (6 rainfall series $\times$ 7 stations). In only six of these cases do the series show non-homogeneous behavior. At a local scale, the rainfall regime at MJ show no long-term trend during the 53-year period analyzed, and thus rainfall at this site in the wettest area of the region presents marked stability. For PI, likewise, only the variability of total annual rainfall has increased.

Although annual total rainfall (AR) has a long-term positive trend at LB and VD, the MKS and TM procedures indicate a trend change during the period toward a current decrease. The AR trend at VM decreases for the same period. A positive AR long-term trend would explain the significant increase in mean intensity (INT) at LB, while the trend of rainy days (DPF), though positive, does not reach statistical significance. However, both MKS and TM show a breakpoint in the 1990s and a current decrease in both AR and INT values.

On the other hand, the long-term increase in rainfall intensity at VD and RC is sustained by a concurrent positive trend of both INT and AMDR, thus verifying the change seen from the two indicators used to represent extreme events. However, the complementary evaluation of trend change, using both MKS and TM, shows that INT has not grown in recent years.

Mean annual intensity is the characteristic of the rainfall regime that has changed more generally in central Argentina, with an increase that may be particularly associated with a decrease in annual DPF. However, according to the MKS sequential test and the TM method, the INT increase is currently maintained only at BO, while INT values for LB, RC and VD stopped growing in the mid-1990s.

Thus, the rainfall regime change in the central region of Argentina during the period 1960–2012 is not only a minor expression but is also strictly local in scope, in contrast to the widespread character of global warming. This behavior would require the study of atmospheric phenomena at local or regional scales, for which detailed analysis would allow a better interpretation of the influence of global warming over the rainfall regime. In addition, the complementary analysis with MKS and TM reveals that the long-term trends of the evaluated properties, whether increasing or decreasing, have now changed sign or maintain a certain constancy at present, reflecting the particular dynamics of rain variability. Finally, the increase of variability of total amounts at PI, RC, and VM and for frequency of rainy days at BO and RC may be evidence of a possible change in rainfall behavior that must be monitored in the future.

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