METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **15**: 313–323 (2008)
Published online 27 May 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/met.68

Review

Variability of low monthly rainfall in La Plata Basin

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ABSTRACT: Water resources management and agriculture planning models require a statistical synthesis of some rainfall features, in particular those representing dry atmospheric conditions. The bigger the basin, the more important these features become, as is the case of the La Plata Basin (LPB).

This paper focuses on the precipitation variability in the large LPB in South America, analysing the number of months per year with low rainfall and the sequences of months with low rainfall, their theoretical distributions and stability, which are needed as input for the models mentioned above.

Long time series are used to analyse the low-frequency variability and the relative importance of decadal variability. Changes are evident in the number of months per year with low rainfall, with a decrease of about 20% in the period after 1970.

Theoretical distribution models (binomial and geometric) are fitted to these empirical distributions, and the regional variability of the fitting parameters is shown. In practically the entire region, the goodness-of-fit of the two theoretical models considered is statistically satisfactory.

The temporal variability of the parameters of the theoretical binomial (p) and geometric (α) distributions is analysed, in excluding sub-periods of 10 and 5 years, respectively. The results show low-frequency variability overlapped on a decadal variability, with low homogeneous regional behaviour.

The distribution models have proven to be efficient for frequency adjustments of the rainfall properties studied. These results are an acceptable and necessary input to decision models in LPB. They also make it possible to infer effects of climate change. Copyright © 2008 Royal Meteorological Society

KEY WORDS rainfall; distribution; variability; management

Received 24 August 2007; Revised 5 February 2008; Accepted 6 February 2008

1. Introduction

La Plata Basin (LPB), which covers parts of Argentina, Brazil, Bolivia, Paraguay and Uruguay, is the third largest basin in the world with an area of approximately 3 200 000 km^2 (García and Vargas, 1998). The basin generates around 70% of the Gross National Product (GNP) of these five countries, and has a population of over 100 million inhabitants. The LPB is also one of the major producers of hydroelectric power in the world.

The LPB comprises the catchments of three large rivers: Paraguay, Paraná and Uruguay. The last two join to form the La Plata River, while the Paraguay flows into the Paraná a few kilometres upstream from the city of Corrientes in NE Argentina. The topography and climate of the region, as well as precipitation and human activities, strongly influence the hydrological behaviour of the rivers in the basin. An extensive list of references on the LPB can be found in García and Vargas (1999); Shi *et al*. (2000); Berbery and Mechoso (2001); Boulanger *et al*. (2005) and Nery (1993).

Assessments of global climate change impacts on economy are commonly based on averages, rather than on the analysis of variability or extremes (Adams *et al*., 1990). Climate impacts on society, however, result primarily from extreme events and their variability (IPCC, 2007). In the LPB, extreme events cause enormous losses in the agricultural and cattle-raising sectors, which can affect practically all components of the regional economy. From the hydrological perspective, small changes in the percentage of rain that evaporates or percolates into the soil can produce important changes in run-off, which should be considered when designing objective models of the basin water system.

A recent example of extreme events with large impacts on the LPB is the extensive drought that took place during part of 2003 and in 2004. This extraordinary event resulted in extremely low river levels, which had major effects on hydropower generation in the Salto Grande dam on the Uruguay River. In April 2004, the reservoir

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in Salto Grande was 5% below the required level, and only 1 of the 14 turbines was in operation (Tirso Fiorotto, 2004). This resulted in electricity shortages in Uruguay and Argentina. Rain in the province of Buenos Aires during September 2004 was less than half its historical mean for that time of the year and caused a loss of about 307 million pesos (100 million dollars) in the wheat production of the province (Galmarini, 2003).

Since the beginning of the 20th century, global land precipitation has increased by about 2% (New *et al*., 2001). However, this rise has been neither spatially nor temporally uniform. The trend of increased annual precipitation detected in a part of the study region (Castañeda and Barros, 1994; Dai *et al*., 1997; Minetti and Vargas, 1997; Penalba and Vargas, 2004; Boulanger *et al*., 2005) may have modified the theoretical models and/or the parameters adjusted for them as an influence of climate change (Groisman *et al*., 1999).

A better understanding of the spatial and temporal variations of precipitation on different timescales and the adjustment of specific theoretical models to the distribution of precipitation data are important for many applications. The resulting models will lead to a better management of a great variety of problems associated with variations in precipitation and will make it possible to improve statistical weather forecasts and climate monitoring.

This paper aims at achieving the most comprehensive analysis possible of observed rainfall events using high-quality data. Therefore, the objectives of this paper are:

- to analyse the temporal variability of the number of months *per* year with total monthly rainfall less than the mean monthly climatology (hereafter: number of months per year with low rainfall);
- to fit theoretical distributions to frequencies of (1) the number of months *per* year with low rainfall; (2) the sequences of consecutive months with low rainfall; and
- to analyse the temporal and regional variability of these adjusted theoretical distributions, using their parameters to detect climatic change.

2. Data

Long series (at least 40 years) of high-quality rainfall records with no missing data were examined to obtain more reliable results. The data were provided by the National Weather Services of the countries whose stations were involved in the study. The longest series of Brazil, i.e. Rio de Janeiro and Sao Paulo, were provided by Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) and the Sao Paulo University, respectively. The database was built in the framework of the European Community Project 'Assessing the impact of future climatic change on the water resources and the hydrology of the LPB, Argentina: ARG/B7-3011/94/25'. The monthly rainfall series were subjected to different statistical tests to detect out-of-range data, artificial peaks and trends in the monthly means (WCDMP, 2004). These demanding tests were passed by 83 rain gauge stations (Figure 1). The periods covered by the series are different, the longest records corresponding to Rio de Janeiro (22.92 °S; 43.18 °W), Observatorio Central Buenos Aires (OCBA: 34.58 °S; 58.48 °W) and Sao Paulo (23.50 °S; 46.62 °W). These cover the periods 1851–1993, 1881–2000 and 1887–2000, respectively. The 1961–1988 period is the longest covered by the stations with the best quality data.

The present study analyses total monthly rainfalls lower than the mean monthly climatology (hereafter: low monthly rainfall) recorded in rain gauges located in the LPB and adjacent regions. The stations placed beyond the LPB were used for a clearer presentation of the results.

3. Annual rainfall cycle in LPB

To understand better the results, selected features of the rainfall regime in the LPB are described in Figures 2 and 3. The total mean annual rainfall in the region is around 1200 mm. The corresponding geographical distribution shows highest values along a southwest–northeast line through northeast Argentina, east of Paraguay, Uruguay and southeastern Brazil (Figure 2). The locations with lowest annual rainfalls, approximately 300 mm, are in northwest Argentina. The highest values (above 1600 mm) are recorded in southern Brazil. Only 20% of this annual precipitation flows to the sea, while the remaining 80% evaporates, runs off or percolates into the soil (Berbery and Mechoso, 2001).

The mean annual rainfall cycle in the LPB has strong geographical variations. These range from a very well defined annual cycle (peak rainfall during the warm season) in the northern part of the basin to an almost uniform distribution with small peaks during spring and autumn in the eastern-central area, northeast Argentina and southern Brazil (Figure 3).

The results for the LPB precipitation and its seasonal cycle are consistent with those obtained by Nimer (1989) and Hoffmann (1975), who analysed shorter periods. They also corroborate the results of Shi *et al*. (2000), Berbery and Mechoso (2001) and Boulanger *et al*. (2005), which were obtained using the mean monthly Climate Prediction Center Merged Analysis of Precipitation (Xie and Arkin, 1997).

4. Results

4.1. Temporal variability of the number of months *per* year with low rainfall

Several authors have observed jumps and/or trends in the annual rainfall totals in the study region, which were generally related with the annual rainfall and some particular months or seasons of the year. Some of these studies cover shorter periods of information than in this paper (Dai *et al*., 1997; Minetti and Vargas, 1997; Penalba and Vargas, 2004; Boulanger *et al*., 2005).

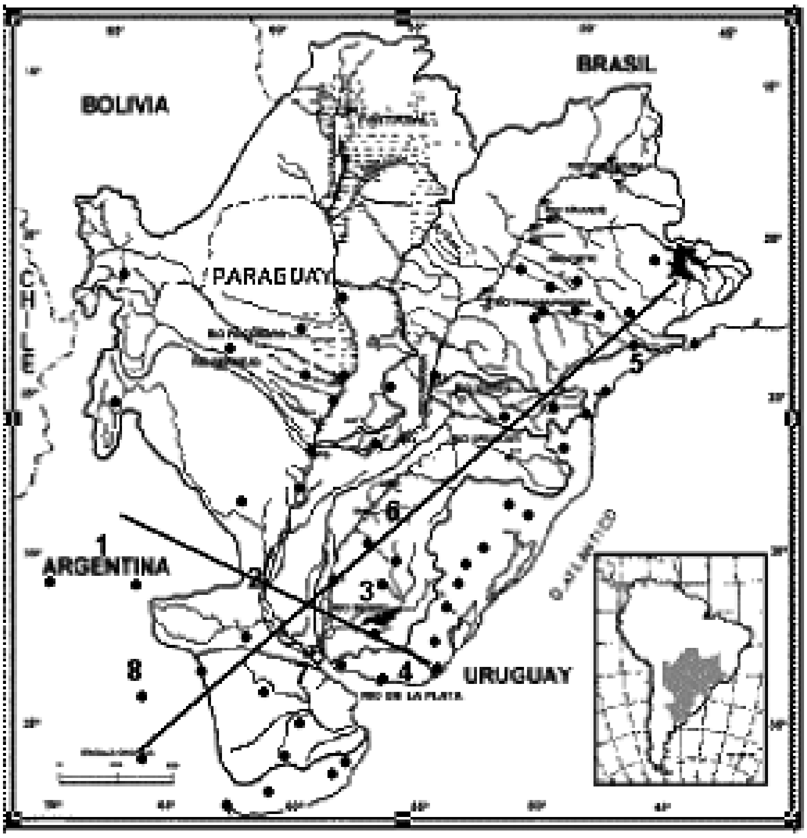

Figure 1. Location of the stations used in the study (circles) and of reference stations (numbers) in the northeast–southwest and west–east directions (lines). *Station numbers*: west–east direction: 1. Pilar: 31.4 °S:64.18 °W; 2. Paraná: 31.73 °S:60.53 °W; 3. Paso de los Toros: 32.82 °S:56.52 °W; 4. Punta del Este: 39.96 °S:55.78 °W. Northeast–southwest direction: 5. Sao Paulo: 23.5 °S:46.6 °W; 6. Alegrete: 29.76 °S: 55.78 °W; 7. OCBA: 34.58 °S:58.48 °W; 8. Santa Rosa: 36.56 °S:64.26 °W.

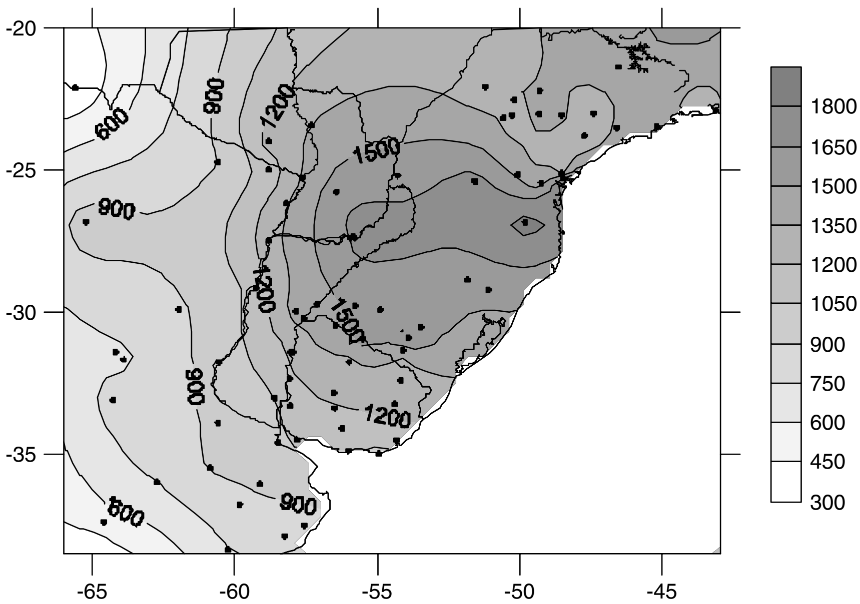

Figure 2. Total annual rainfall (mm) in the Rio de la Plata Basin.

This low-frequency variability might produce variations in the annual cycle of precipitation, as described by Rusticucci and Penalba (2000).

This section studies the evolution in time of the number of months in each year with precipitation below the respective monthly climatological mean (hereafter: number of months *per* year with low rainfall). The stations shown in Figure 4 (left) and Table I have the longest series and they represent the most characteristic features of the series in the region. First, the series were

DOI: 10.1002/met

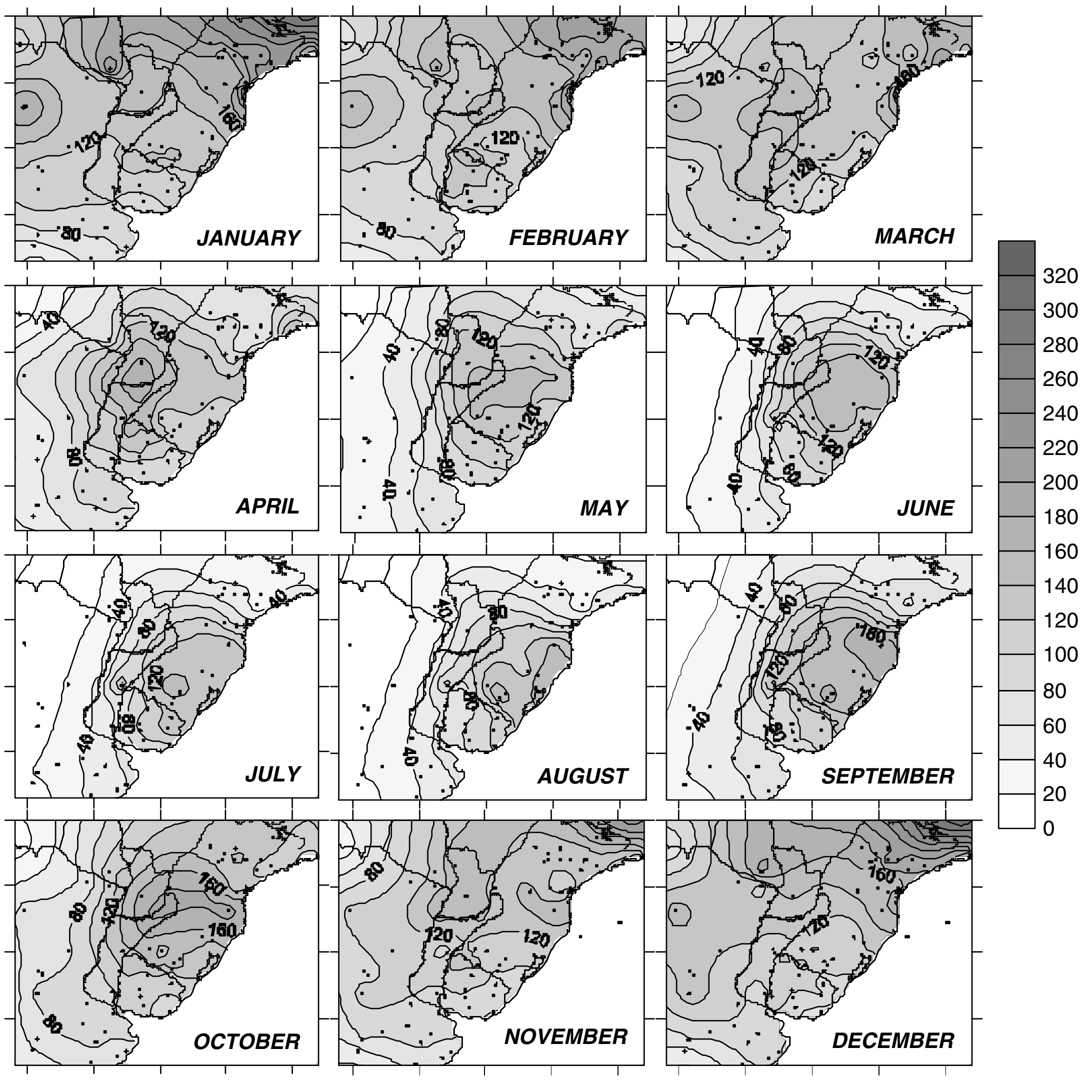

Figure 3. Total monthly rainfall (mm) in the Rio de la Plata Basin.

examined for linear trends at 95% confidence levels. Second, after applying the 11-year running mean, the inter-annual and inter-decadal variations were analysed. No homogeneous regional behaviour was observed after the analysis. The significance of the trend alone showed a progressive and marked decrease in Sao Paulo, Paraná and OCBA stations (Table I). Different inter-annual and inter-decadal variations of these series can also be seen (Figure 4, left). The inter-decadal variability component of this parameter is more evident in Rio de Janeiro and Pilar. Together with this variability, the Brazilian stations (Rio de Janeiro and Sao Paulo) show two positive 'jumps': one around 1910 and the other in 1945, the former being the one most marked. From 1955 (OCBA) and 1965 (Sao Paulo and Paraná), the number of months *per* year with low rainfall begins to decrease.

This significant temporal variability observed in some regions may be due to the above-mentioned progressive increase of the climatic mean. To test this hypothesis, the number of months in each year with precipitation below the respective mean of each month is calculated by excluding 10-year sub-periods, starting in 1851–1860.

Table I. Estimation of the correlation coefficients of the linear trend of the number of months *per* year with low monthly rainfall. Low monthly rainfall is the monthly rainfall less than the respective monthly climatological mean (column: climatic period) and than the mean of each month by excluding 10-year sub-periods (column: 10-year sub-periods).

Stations	Climatic period	10-year sub-periods
Río Janeiro	0.05	0.05
Sao Paulo	**−0.30**	0.03
Pilar	0.07	0.10
Paraná	**−0.26**	0.04
OCBA	**−0.30**	0.07

Bold: significant coefficients at 95% confidence level.

Figure 4 (right) shows the evolution in time of these series, their 11-year running means and their linear correlation coefficients (Table I). It is interesting to observe how the significance of the negative linear trend disappears along with the jumps observed in the Brazilian stations, with only the decadal variability remaining.

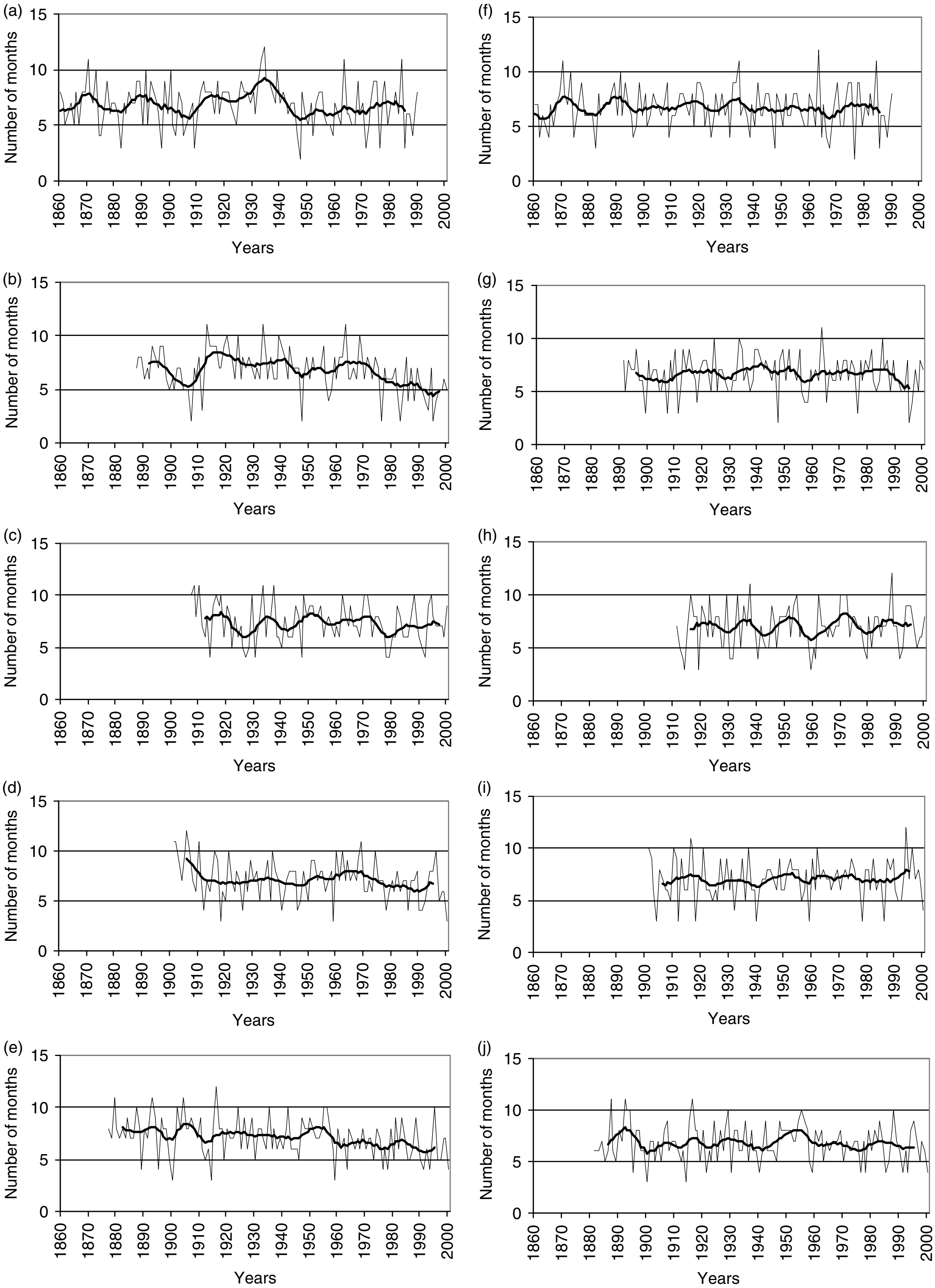

Figure 4. Time series of the number of months *per* year with low monthly rainfall. Low monthly rainfall is the monthly rainfall less than the respective monthly climatological mean (left) and than the mean of each month by excluding 10-year sub-periods (right): (a) and (f) Rio Janeiro; (b) and (g) Sao Paulo; (c) and (h) Pilar; (d) and (i) Paraná; (e) and (j) OCBA.

Indirectly, these results confirm the rise in monthly rainfall during the last decades in some stations of the region, particularly in the region of greatest impact of the LPB, and indicate that this trend cannot be due to any particular month.

Several authors have found singularities in the atmospheric circulation in southern South America around the 1970s (Barros *et al.*, 2000; Agosta and Compagnucci, 2002) as well as in other regions of the Southern Hemisphere (Gisbson, 1992; van Loon *et al.*, 1993;

DOI: 10.1002/met

Hurrel and van Loon, 1994; Trenberth, 1995). Because changes or discontinuities have been observed in annual and monthly precipitation around 1970, the following study analyses whether these changes are observed in the number of months *per* year with low rainfall (with respect to the climatological mean of each month). Therefore, to quantify the percentage change after the 1970s, the analysis is made by comparing two periods before and after this decade. To obtain a better spatial representation by including the greatest number of stations possible, the selected periods are 1962–1971 and 1979–1988. Figure 5 shows the spatial pattern of the percentage change of the number of months *per* year with low rainfall. It is worth mentioning that only a slight rise in the number of months *per* year with low rainfall in the most recent period is observed in a small region. The remaining area has a negative change, values dropping by about 20% in some parts. Although intra-annual variability is not considered in this analysis, the slight increase in the number of months *per* year with low rainfall can be inferred to be due to the winter months. This is because the area displays a drop in total monthly winter amounts (Barros *et al.*, 2000) as well as a decrease in the number of rain and intense rain days during those months (Penalba and Robledo, 2006).

4.2. Theoretical distribution

4.2.1. Model of number of months per year with low rainfall

This section analyses the theoretical distribution of the number of months *per* year with low rainfall, with respect to the climatological mean of each month. Initially, the number of years with k months ($k = 0, 1, \ldots, 12$) of low rainfall were calculated and they are plotted in Figure 6 (grey bars). These empirical distributions indicate that there is a clear spatial variability in the region. The asymmetry of the distribution of monthly rainfall totals in steppe areas and humid subtropical climates has already been demonstrated (Brooks and Carruthers, 1953; Hoffmann, 1975), and it is observed in the present analysis

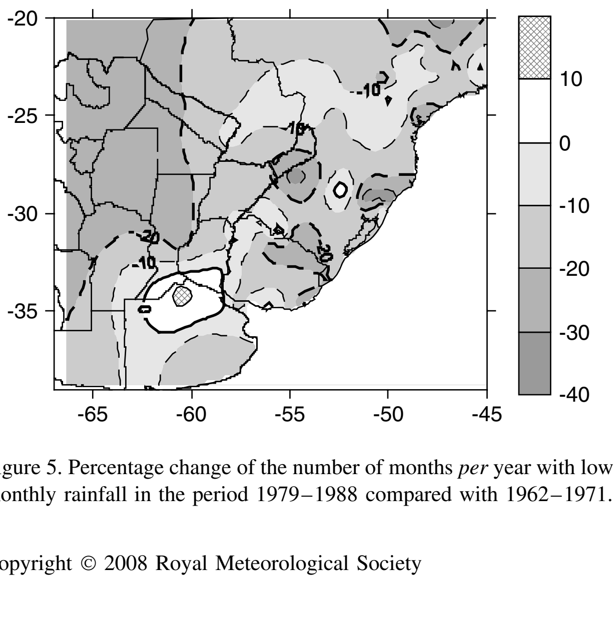

Figure 5. Percentage change of the number of months *per* year with low monthly rainfall in the period 1979–1988 compared with 1962–1971.

as well. This means that years with a large number of months with low rainfall tend to occur more often even in northwestern Argentina and Brazil (see Sao Paulo station where the highest empirical frequency occurs in 6 months). The variability increases towards dry climates, such as Santa Rosa station with the highest empirical frequency in 8 months (Figure 6, grey bars). The empirical distributions in stations located in Uruguay and south of Brazil (Punta del Este and Alegrete) are more platykurtic, tending to show two maxima, one in five months and the other in nine months. Because of the asymmetry of these distributions, the occurrence of 'extreme conditions', i.e. the right tail of the distributions cannot be neglected, meaning that the whole year presented low rainfall months (frequencies in 11 and/or 12 months). At the same time, these results define a boundary in sequence lengths as will be seen later.

As the monthly correlation coefficients were non-significant, the rainfall of each month can be considered independent of the rainfall in the remaining months of the year and the number of months *per* year with low rainfall can be assumed to have binomial distribution. Under this hypothesis, k is the number of months *per* year with low rainfall, $p(q)$ is the probability of occurrence (non-occurrence) of this event and n is equal to 12. Thus, the probability for the event to happen k times in one year is:

$$\mathrm{p_n(k)} = \frac{\mathrm{n!}}{\mathrm{(n-k)!k!}}\mathrm{p}^k\mathrm{q}^{(n-k)} \quad k = 0, 1, 2, 3, \ldots, n \qquad (1)$$

The binomial theoretical distribution was fitted to each of the empirical frequencies (Figure 6, white bars). Estimates of the parameter p were obtained with an error of 0.04. Further details on the theoretical distributions used can be found in Sneyers (1990).

The chi-square test (Von Storch and Zwiers, 1999) was applied to analyse the goodness-of-fit of the binomial model and the spatial variability of the fit (Figure 7). The fit was statistically satisfactory throughout the region (95% confidence level). Stations with higher statistic values are located in the south of Buenos Aires Province, southern Brazil, northern Uruguay and northeast Argentina.

Several papers have found links between El Niño Southern Oscillation (ENSO) events and rainfall anomalies during late austral spring and early summer in extratropical South America. Rainfall anomalies in northeastern Argentina, Paraguay, Uruguay and southeastern Brazil tend to be positive from November of El Niño years to March of the following years and negative from July to December of La Niña years (Ropelewski and Halpert, 1996; Vargas *et al.*, 1999; Grimm *et al.*, 2000; Montecinos *et al.*, 2000; Boulanger *et al.*, 2005; Penalba *et al.*, 2005). Therefore, the ENSO signal is strongest in the regions with the highest statistic values, which may be due to ENSO-related greater rainfall variability, which leads to less significant fits of the theoretical distribution.

The result shows that the same theoretical model can be used to describe the frequency distribution of the number

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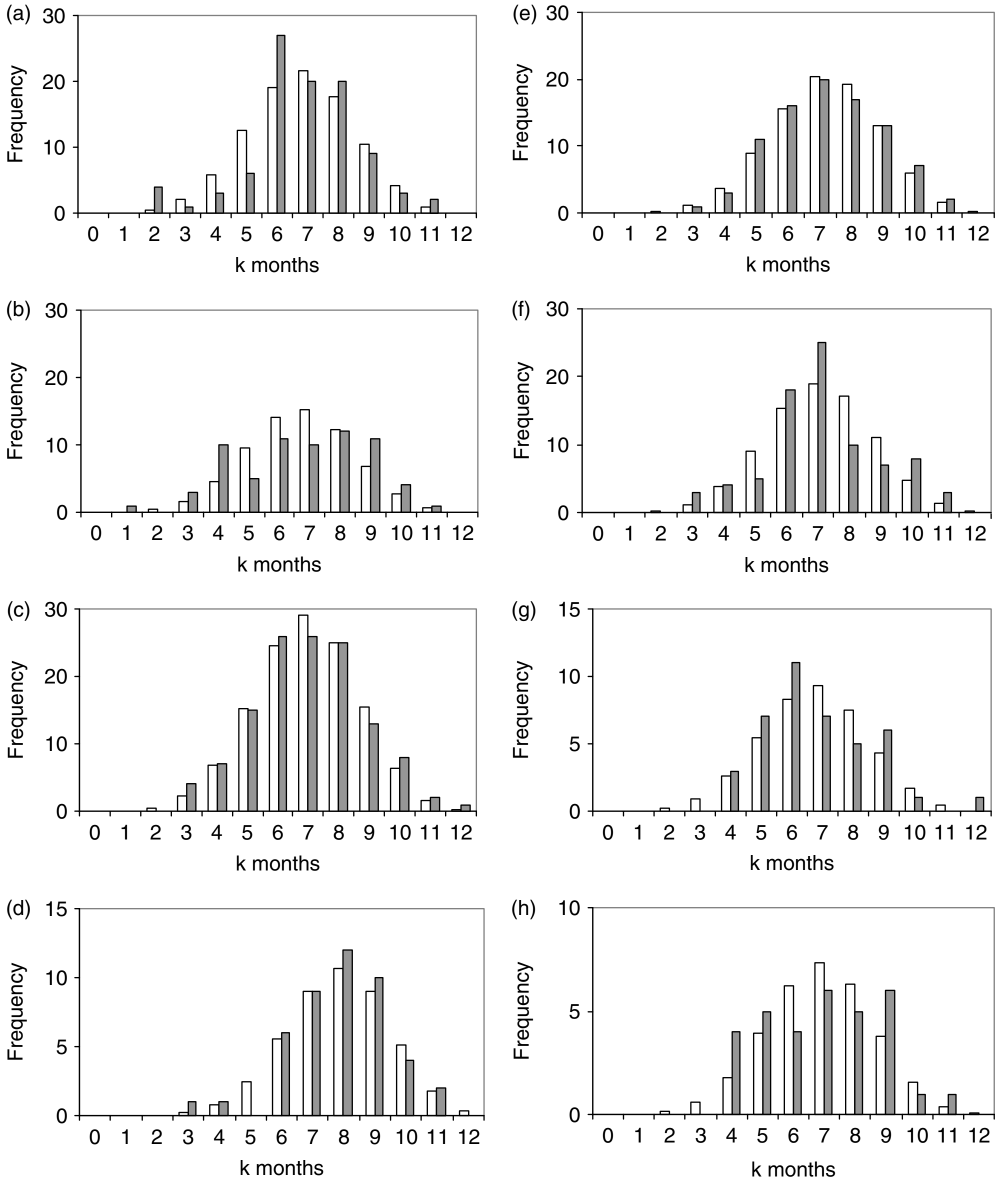

Figure 6. Absolute empirical frequency (grey bars) and theoretical binomial distribution (white bars) of the number of months *per* year with low monthly rainfall. (a) Sao Paulo; (b) Alegrete; (c) OCBA; (d) Santa Rosa; (e) Pilar; (f) Paraná; (g) Paso de los Toros; (h) Punta del Este.

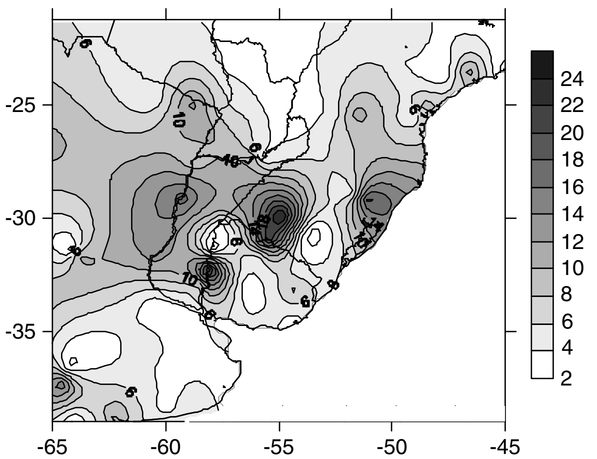

Figure 7. Empirical values of chi-squared for each station, comparing the empirical frequencies and theoretical binomial distribution (analysed event: number of months *per* year with low monthly rainfall).

of months *per* year with low rainfall. Therefore, each station can be represented by parameter p of the binomial distribution. Figure 8 shows the values of p, which are slightly greater than 0.5, according to the asymmetry of the empirical distribution. The spatial variations of p are small, with minimum values in northeast Argentina and part of Paraguay, and a maximum value in Santa Rosa. Therefore, as regards the frequency distribution of months *per* year with low rainfall, the LPB can be considered climatically homogeneous and represented by the same theoretical model and its parameter p.

4.2.2. *Model of the sequences of months with low rainfall*

A sequence of low rainfall months with respect to the climatological mean of each month is defined as a set of consecutive low rainfall months that is preceded and

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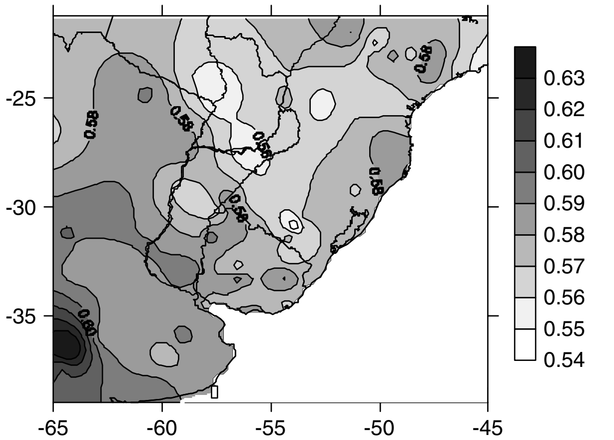

Figure 8. Estimate of the constant p of the binomial distribution for each station.

followed by no low rainfall. Figure 9 (grey bar) shows the empirical distributions of the sequence of months with low rainfall, showing that the empirical frequencies decrease rapidly for sequences longer than one month. The longest sequences with low rainfall were found to correspond to Alegrete and OCBA (13 and 15 months, respectively).

A statistical model of the sequences is analysed in this section. Considering the good fit of the previous binomial distribution, the geometric distribution appears as the complement that gives the probabilities associated with the these sequences (Feller, 1968; Sneyers, 1990). Therefore, a geometric distribution is assumed, which is a particular case of the negative binomial distribution with $\beta = 1$. The probability of occurrence of a sequence of length k is:

$$p_k = (1 - \alpha)\alpha^k \quad k = 1, 2, 3, \ldots \tag{2}$$

together with the recurrence $P_k = p_{(k-1)}\alpha$ and $P_0 = 1 - \alpha$ where the probability of a positive observation is α, which can be estimated both from the data and the empirical frequency distribution. Estimates of parameters α were obtained with an error of 0.04 (Sneyers, 1990).

The empirical sequence distributions for each station were adjusted to a geometric distribution (Figure 9, white bar). The goodness-of-fit of the sample distribution was verified by means of the chi-square test (at the 5% level). The adjustment was statistically satisfactory in the whole region, even in stations with higher chi-square statistic values (Figure 10). Again, the highest values of this statistic are observed in the regions where impacts of ENSO on rainfall are stronger. So, each station could be represented by parameter α of the geometrical distribution. The parameter α has small spatial variations, with minimum values close to 0.5 in the centre of the region and a maximum value in Santa Rosa (Figure 11).

4.3. Temporal variability of the distribution parameters

The previous section showed the spatial stability of the parameters of two theoretical distributions. In order to

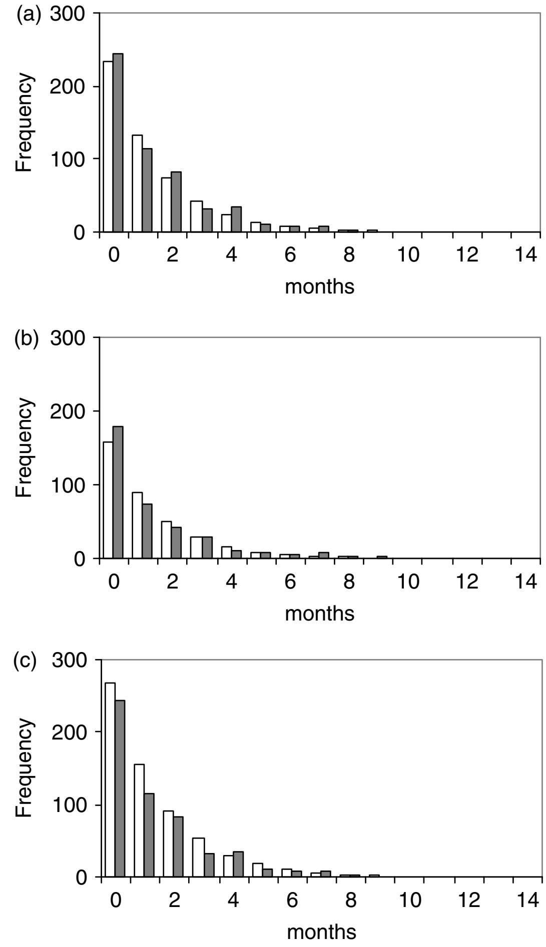

Figure 9. Absolute empirical frequencies (grey bars) and theoretical geometric distribution frequencies (white bars) of the sequence of months with low rainfall.

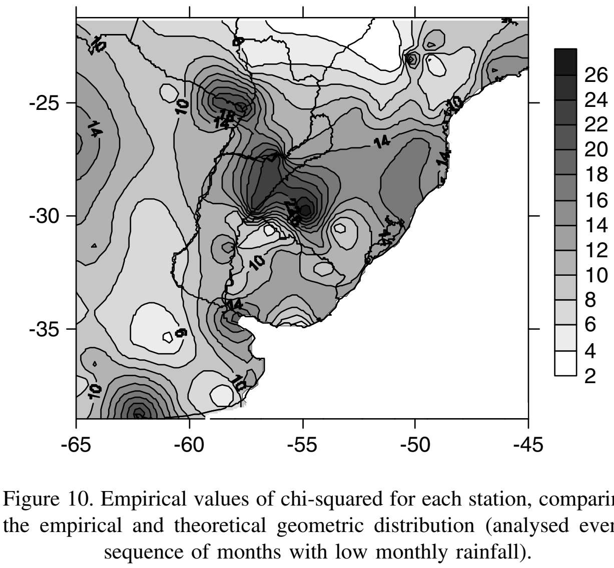

Figure 10. Empirical values of chi-squared for each station, comparing the empirical and theoretical geometric distribution (analysed event: sequence of months with low monthly rainfall).

study whether the climatic trends, jumps or changes observed in total precipitation can modify the empirical distributions studied – and therefore modify the theoretical models – the temporal variability of the theoretical distributions was analysed.

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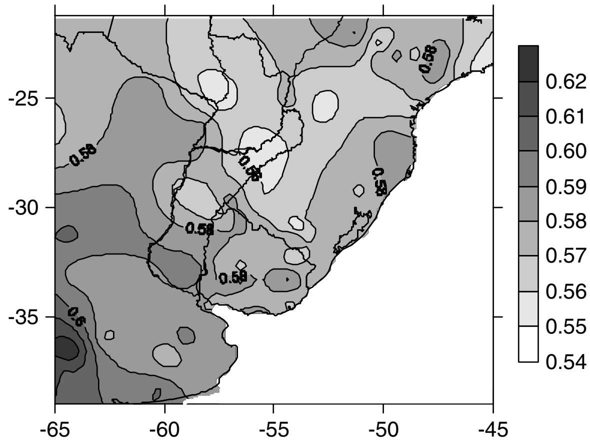

Figure 11. Estimate of the constant α of the geometric distribution for each station.

For this study, the number of months in each year with rainfall below the respective monthly mean by excluding 10-year sub-periods, starting in 1851–1860, was examined at each station. The empirical distribution of the number of months with low rainfall for each sub-period was calculated and the corresponding theoretical distribution was fitted. The adjustment was satisfactory (at the 5% level), and therefore each sub-period can be represented by the parameter p. Besides, sequences of month with low rainfall were calculated in 5-year sub-periods, starting in 1851–1855. The empirical distributions of the sequences of low rainfall months were evaluated and the geometric distribution was fitted. As the adjustment was satisfactory, each 5-year sub-period (at the 5% level) can be represented by the parameter α.

The temporal variability of the series of p and α (Figure 12, left and right, respectively, and Table II) were first examined for a linear trend (95% confidence limits). The parameter p presents a significant trend in all stations, with negative values in Rio de Janeiro and OCBA (Table II). The parameter α has a significant and positive linear trend at Brazilian stations and OCBA (Table II). The correlation coefficient of the linear trends of the remaining stations is close to and lower than the critical value. This result does not show a progressive temporal change generalized in space. Consequently, the models are preserved even though the distribution parameters vary.

The inter-decadal variability of parameters p and α is analysed to identify periods with high and low values of these parameters. Therefore, for each station, a confidence interval is calculated whose length is equal to the mean value of the parameter, plus or minus its standard deviation. The parameter p for OCBA is lower in the 1971–1980 and 1991–2000 samples, indicating that during these decades the distribution of monthly values tends to be more symmetrical or that there are more months with positive anomalies during the year. It is also the case for the 1931–1940 decade in Paraná station and for the 1911–1920 decade in Pilar station. Decades in which p is higher than the confidence interval can also be observed, e.g. Pilar in the sample 1991–2000 and OCBA. in 1961–1970. The latter station presents the largest decadal variability of parameter p in recent decades. The temporal variability of α is greater than p (Figure 12, right), which becomes evident in the first years, e.g. Sao Paulo and OCBA. before 1915 and 1920, respectively.

5. Conclusions

Some decision-making models in hydrology, as well as in other activities, need a very stable input, particularly in terms of rainfall information, which needs to be synthesized from specific features. This paper studies two such features, their probability models and variability in different time scales.

The variability of monthly rainfall in the LPB is examined using long time series from a dense network of stations with complete data in periods of at least 40 years. Two features in the monthly rainfall are considered: (1) number of months *per* year with low rainfall (total monthly rainfall less than mean monthly climatology) and (2) sequence of months with low rainfall. Binomial and geometric models are fitted to these precipitation feature distributions. The spatial behaviour of both the goodness-of-fit of specific distribution models and their parameters is studied. Finally, the temporal variability of the parameters is analysed.

The goodness-of-fit of the theoretical distributions to these rainfall properties is statistically satisfactory in practically the whole region. For northeast Argentina, southern Brazil and southeast Paraguay, lower significance levels are necessary. The estimated values of the model constants (p and α) are found to be higher than 0.5, thereby corroborating the asymmetrical distribution of monthly rainfall.

The parameter p of the binomial distribution presents a significant negative trend at all stations, indicating that in addition to the change in the average precipitation, the distributions tend to be more symmetrical. This low-frequency variability overlaps on a significant decadal variability. The parameter of the geometric model does not present temporal changes (low frequency and 5-year variability) in the whole region. This result indicates that the temporal variation of the probabilities of the different sequences is homogeneous throughout the region, particularly the extreme ones, showing that although positive trends exist in monthly rainfall, the distributions of the number of months with low rainfall remain largely unchanged. The results presented here show that parameters p and α depend on the period selected for analysis (although the distribution patterns do not).

The changes observed in the annual and monthly rainfall totals around the 1970s are also observed in the number of months per year with low rainfall with respect to the climatological mean, which drops by about 20% in almost the entire region in the most recent period.

This study is an objective analysis to estimate the magnitude and the spatial domain of rainfall variations that

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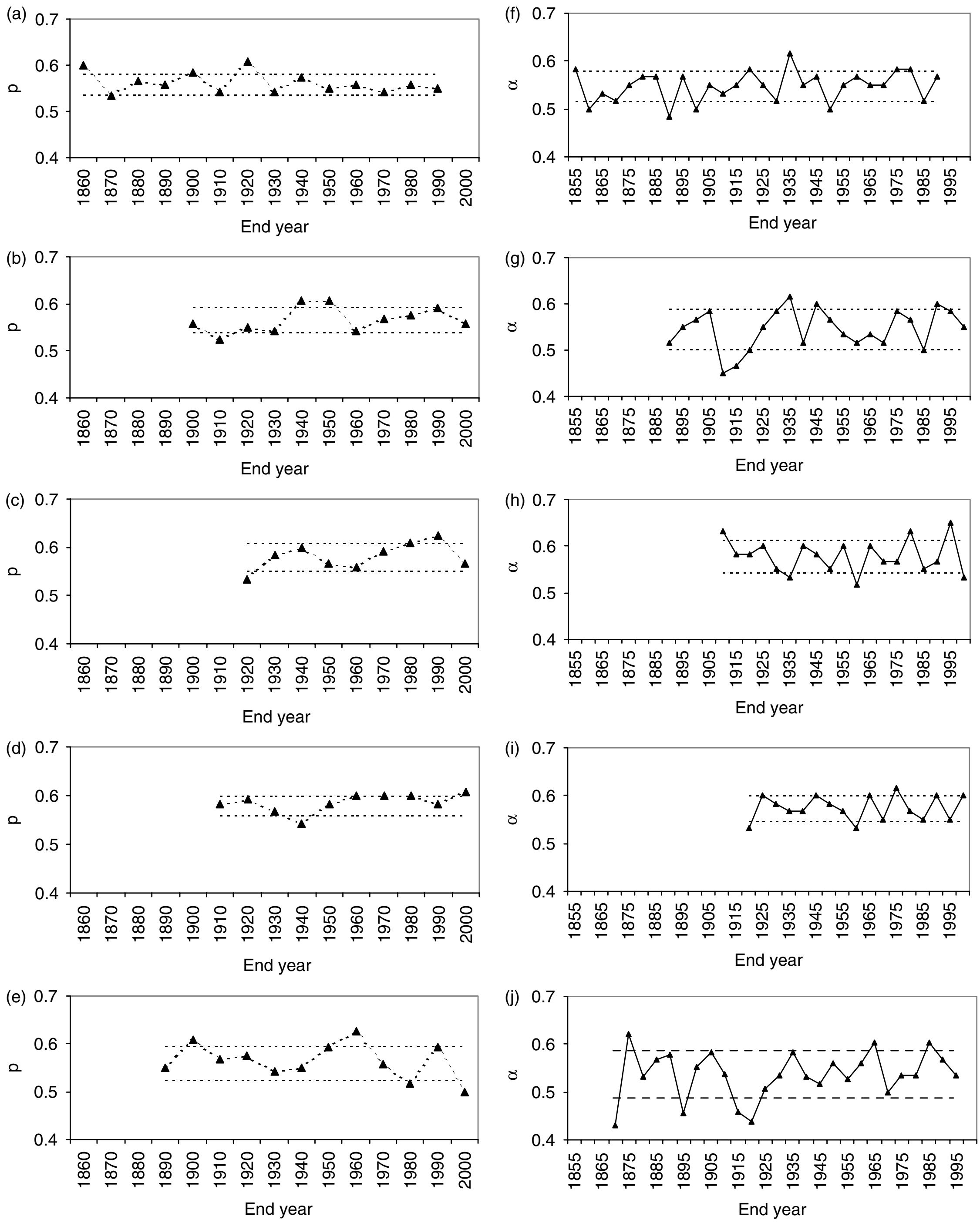

Figure 12. Time series of the parameter p for excluding samples of 10 years (left) and α parameter for excluding samples of 5 years (right), taking into account the short-term mean anomalies in both estimations.

Table II. Estimation of the correlation coefficients of the linear trend of the parameters p and α.

Stations	p	α
Rio Janeiro	**−0.30**	**0.22**
San Pablo	**0.36**	**0.24**
Pilar	**0.49**	−0.10
Paraná	**0.49**	0.10
OCBA	**−0.28**	**0.20**

Bold: significant coefficients at 95% confidence level.

can be used for hydrological applications and validation of climate models to test their ability to simulate such change.

Acknowledgements

This study was funded by the following grants: University of Buenos Aires X135 and X234, CONICET PIP 5139, BID 1728/OC-AR-PICT 38273 and CLARIS Project (European Commission Project 001454). The authors wish to express their gratitude to the anonymous referees whose suggestions enhanced the quality of this work.

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DOI: 10.1002/met