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ORIGINAL PAPER

Dry spells in the River Plata Basin: an approximation of the diagnosis of droughts using daily data

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Abstract This study addresses the dry spells observed in the La Plata Basin using daily data from 94 observation stations during sampling periods from 1900 to 2005. Dry days were defined as having less than 0.3 mm of accumulated precipitation. This definition allowed for the assessment of the dryness in the La Plata Basin and a comparison with other regions. The main purpose of this study was to analyse dry spells, especially extreme cases (meteorological droughts), and assess them on a daily basis. Trends and low frequency of droughts were analysed using a general framework to detect and compare properties of dry states based on daily and annual time scales. The trends were estimated using two different methods. Overall, the trends showed a decrease, especially in the eastern basin region during the period of 1972–1996. The results showed sporadic decreases in dry events and events of extreme dryness (droughts). Spectral structure permits an inference of low-frequency maxima and confirmed an inter-annual 2- to 3-year period of variability in drought occurrence for most of the basin. Furthermore, probabilistic distribution functions of dry spells at basin stations were analysed to confirm that they followed a geometric–binomial distribution. Additional tests were used to determine whether there was a second threshold, using the Weibull and gamma adjustment models. In order to study spatial homogeneity, the field of dry spell maxima in the basin was generated using a vector array based on the occurrence date and length of the maximum spell. Due to the dependence of spell length on the annual cycle, the longest spells were observed from April to the beginning of winter in the Argentine northwest region and in the northern and western regions of the basin. The intensity of droughts decreased in the Pampas and Mesopotamia regions. The drought of 1988 was considered to be the longest dry spell in the basin. The water deficits from this drought resulted in Argentinean economic losses of more than four billion US dollars during 1988.

1 Introduction

The study of droughts is one of the main focuses of climatology because droughts are recurring phenomena with some of the most significant global impacts. In most places of the world, dryness occurs in spells. A dry spell is generally defined as a period of multiple consecutive days with no measurable rainfall. The dry spell is preceded and followed by days with measurable rainfall.

Prolonged dry spells often coincide with the presence of specific meteorological features, such as anticyclonic systems, ridges and blocking systems (Trenberth et al. 1988; Alessandro and Lichtenstein 1996; Mo et al. 1997; Barrucand et al. 2007). Similarly, the lack of these phenomena in a region is almost tantamount to the absence

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of dryness. Therefore, it appears that more knowledge of the characteristics of dry spells may help us to better recognise certain characteristics of specific weather events and their dryness impacts. Dry spells at daily timescales are more useful for the analysis of rainfall deficit than data at a monthly timescale.

The definition of drought is controversial. In some cases, drought refers to different systems that are affected by dryness (e.g. agriculture and water resources). Other approaches consider that droughts are local phenomena that affect sub-regions and persist for prolonged periods of time. A meteorological drought is one that lasts several months or years and has reduced or absent precipitation. A meteorological drought can develop quickly and end abruptly; in some cases, the transition can occur overnight (Heim 2002).

Droughts in La Plata Basin are generally studied on a monthly basis or over longer periods of time (Minetti et al. 2008, 2010). Meteorological droughts or maximum dry spells occur over a certain number of days that may occasionally occur in the same month, or be included within it. This study took a novel approach to drought studies by defining droughts on a daily scale. For applications such as risk estimation and the impact of droughts, it is most convenient to define droughts using the length of the daily dry spell as a variable.

There are few systematic studies of droughts of the La Plata Basin. Therefore, it is not possible to typify, model or understand drought origins of the basin. Research, in general, has been aimed at specific droughts (e.g. case studies of the droughts of 1962, 1985/1986, 1988, 1995 and 2007/2008). Although these studies referred to specific droughts, they provided some characteristics of associated circulation and the behaviour of other meteorological variables.

The 1962 drought, which affected a large part of Argentina, was studied by Malaka and Núñez (1980). The study used monthly means of meteorological variables from Argentina and stations in a few neighbouring countries. Some of the distinctive features of prevailing circulation during that dry year included a weakening of the sub-polar low-pressure belt (associated with less intense and less frequent frontal systems, as well as a reduced baroclinic field) and the persistence of a blocking pattern in the south Atlantic (south of 55° S). Another outstanding case of drought occurred in 1985/1986. It was seasonal (October through January) and affected the northeastern part of Argentina and Paraguay. This drought was studied by Malaka (1987), who found that the affected region was characterised by high surface temperatures, higher geopotential heights at pressure at 500 hPa and significant subsidence in the middle and low troposphere. At the same time, floods were recorded in the south of the region and in the western centre of the province of Buenos Aires. Additionally, Alessandro and Lichtenstein (1996) studied a severe drought that mainly affected the eastern centre and northeast region of the country between May and August of 1995.

More recently, Labraga et al. (2002) and Barrucand et al. (2007) studied the atmospheric circulation anomalies associated with excess rainfall and the shortage of rainfall in the Argentine Pampas by analysing the water vapour flow anomalies in the lower and upper atmosphere. The studies found well-defined circulation anomaly patterns covering the southern region of the South American continent and the neighbouring areas of the Atlantic and Pacific oceans. The regions of the Atlantic and Pacific oceans were very similar but had opposite trends for both precipitation extremes. Months with rainfall deficits were concurrent with many meteorological phenomena, including the strengthening of the sub-tropical anticyclone in the east Pacific, abnormally high pressure in central and northern Argentina and the development of a cyclonic anomaly in the southwest Atlantic. The results of the previous studies showed that the pattern led to an anomalous southwestern flow, and the resulting water vapour flux had a maximum divergence over central and northeast Argentina.

Previous literature on the statistics of dry spells based on daily records is limited. Studies have primarily dealt with the length of dry and wet spells (Longley 1953; Williams 1952; Feyerherm and Bark 1965, 1967; Caskey 1963; Gringorten 1971; Gabriel and Neumann 1962; Naumann et al. 2008; Llano and Penalba 2010).

The goal of this study was to assess the longest dry spells in the La Plata Basin by considering daily data from reference stations in the basin and analysing their dominant structure. Thus, the main objective of this study was to characterise the most relevant statistical patterns of the longer dry spells in the La Plata Basin and to obtain their spatial and temporal descriptions. This research provides the first approach of the risk assessment of droughts on a daily basis.

The data, methodology and techniques used for the characterisation and classification of drought-associated atmospheric circulation are described in Section 2. Section 3 provides climatology of dry spells, including their temporal variability and distribution in the La Plata Basin. Section 4 is an analysis of extreme dry spells. Section 5 is an analysis of the spatial distribution and frequency of dry spells in the region and the coherence of the decade analysis of absolute minimum annual rainfall. The relationship between dry spells and El Niño–Southern Oscillation (ENSO) events are presented in Section 6. In Section 7, the special case of the year 1988 drought is analysed. Finally, results and conclusions are presented in Section 8.

2 Methods and data

Daily rainfall data collected at 94 stations in the La Plata Basin were used for this study. The stations are located in Argentina, Brazil, Paraguay and Uruguay (Fig. 1; Table 1). The data were provided by the weather services of these countries and by the Prosur Project database (ANEEL 2000).

Most of the data were provided by well-known institutions that had previously subjected the data to different coherence and homogeneity criteria. However, internal coherence at different levels was tested again in this study using various methods. For example, the WMO (1994) and Maronna and Yohai (1978) identified outliers using indirect data, such as newspapers and reports, to certify the occurrence of long periods without rainfall. Month-to-month mean isohyet fields and the monthly mean rainfall frequency fields were analysed at all stations during the same period (1959–1998). Stations showing singularities in the fields unexplainable by orography or any extraordinary phenomena were discarded. Series were accepted when less than 5% of the data were missing for the study period of 1959–1998.

Four reference stations were selected for specific analyses (Observatorio Central Buenos Aires (OCBA), Campinas, Corrientes and Tucuman). These stations have recorded daily data for at least 60 years and are located in different key locations of the basin. The Parana Region of Brazil was included for other spatial analyses. There are data for 20 years from this region.

As discussed previously, dry spells are defined as a sequence of days without measurable precipitation. In this study, days with less than 0.3 mm of rainfall were considered dry days. Distributions of the longest annual dry spells were estimated using several models in order to compare regional coherence. Probabilistic distribution functions tested included Gumbel, gamma, exponential and geometric–binomial types (Anderson and Bancroft 1952; Sneyers 1975; Wilks 2006).

Tukey spectra with a Pearson window were used to represent the dominating waves and tendencies. Chatfield (1980) used the formula:

$$S_p = 1 + 2\sum_{q=1}^{M-1} r_q \cos\left(\frac{pq\pi}{M}\right) + r_M \cos(p\pi) \tag{1}$$

where S_p is an estimate of the spectral density, r_q represents the autocorrelation function, M is the maximum value of the lag p and q is an index used in several summations. The dry spell lengths are an unevenly spaced data. Details in the calculations of unevenly data can be found in Scargle 1982.

The linear trends were estimated by calculating the regression of the variable time. The significance level of the correlation coefficient is representative of the slope, and the confidence level was 95%. The results of trend estimation were compared with the Mann–Kendall test (Sidney 1956).

The maximum dry spell for each of the N years was represented by the longest dry spell. The collection of the N longest dry spells was the extreme value data set analysed. Likewise, the second and third daily annual maximum values were defined. Extreme spells were analysed using the three maximum longest dry spells of each year, and the average length of these longest dry spells was also considered.

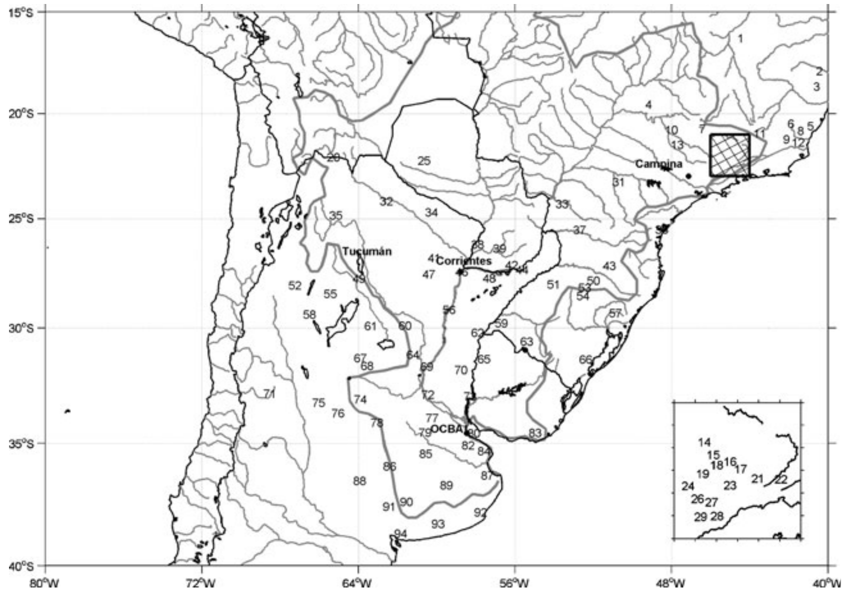


Fig. 1 Sampling stations used in this study (coded according to Table 1). The border of the La Plata basin is designated by the *grey line*

Table 1 List of stations used in this study

No.	Station	Longitude	Latitude	Start	End
1	Sao Francisco	−44.87	−15.95	1938	2003
2	Helvecia (FBM)	−39.67	−17.82	1941	1994
3	Conceiçao da Barra	−39.75	−18.57	1930	1998
4	Campina Verde	−49.48	−19.55	1941	1998
5	Castelo	−41.2	−20.6	1939	1998
6	Caiana	−41.92	−20.7	1939	1998
7	Itau de Minas	−46.73	−20.73	1941	1998
8	Rive	−41.47	−20.75	1939	1998
9	Guacui	−41.68	−20.77	1939	1998
10	Terra Roxa	−48.33	−20.78	1940	1998
11	Carandai	−43.8	−20.95	1941	1998
12	Ponte Itabapoana	−41.47	−21.2	1937	1998
13	Ponte Guatapara	−48.03	−21.5	1924	1980
14	Paraguacú	−45.67	−21.58	1941	1998
15	Monsenhor Paulo	−45.53	−21.77	1941	1998
16	Fazenda J. Casimiro	−45.27	−21.87	1941	1998
17	Conceiçao Rio Verde	−45.08	−21.88	1941	1998
18	Usina do Chicao	−45.48	−21.92	1941	1998
19	Careacú	−45.7	−22.05	1941	1998
20	La Quiaca	−65.6	−22.1	1959	1998
21	Usina Congonhal	−44.83	−22.12	1941	1998
22	Ponte do Posta	−44.47	−22.13	1941	1998
23	Cristina	−45.27	−22.22	1941	1998
24	Pouso Alegre	−45.93	−22.23	1941	1998
25	M. Estigarribia	−60.97	−22.25	1950	1999
26	Conceiçao dos Ouros	−45.78	−22.42	1941	1998
27	Brasopolis	−45.62	−22.47	1941	1998
28	Fazenda da Guarda	−45.47	−22.67	1941	1998
29	Sao Bento do S.	−45.73	−22.68	1941	1998
30	Campina	−47.12	−23	1890	2003
31	Ibiporá	−51.02	−23.27	1971	1997
32	Rivadavia	−62.9	−24.17	1959	1997
33	Palotina	−53.92	−24.3	1972	1997
34	Las Lomitas	−60.58	−24.7	1959	1998
35	Salta Aero	−65.48	−24.85	1959	1998
36	Morretes	−48.82	−25.5	1966	1997
37	Quedas do Iguaçu	−53.02	−25.52	1972	1997
38	Formosa	−58.23	−26.2	1962	1998
39	Vilarica	−57.12	−26.38	1951	1999
40	Tucumán	−65.2	−26.8	1884	2001
41	R. S. Peña	−60.45	−26.82	1959	1998
42	Encarnación	−56.5	−27.14	1950	1996
43	Joacaba	−51.5	−27.17	1943	1998
44	Posodas	−55.97	−27.37	1959	2005
45	Corrientes	−58.77	−27.45	1903	2005
46	Resistencia	−59.05	−27.45	1959	1998
47	Villa Ángela	−60.73	−27.57	1959	1991
48	Gral. Paz	−57.63	−27.75	1959	1995
49	Stgo. Estero Aero	−64.3	−27.77	1959	1998

Table 1 (continued)

No.	Station	Longitude	Latitude	Start	End
50	Erebango	−52.3	−27.85	1943	1998
51	Girua	−54.35	−28.03	1943	1998
52	Tinogasta	−67.57	−28.07	1959	1998
53	Colonia Xadrez	−52.75	−28.18	1944	1998
54	Carazinho	−52.78	−28.3	1941	1998
55	Catamarca Aero	−65.77	−28.45	1959	1991
56	Reconquista	−59.7	−29.18	1961	1998
57	Nova Palmira	−51.18	−29.33	1943	1998
58	La Rioja Aero	−66.82	−29.38	1959	1998
59	Paso de los Libres	−57.15	−29.68	1961	2005
60	Ceres	−61.95	−29.88	1959	2005
61	V. María R. Seco	−63.68	−29.9	1959	1998
62	Mte. Caseros	−57.65	−30.27	1959	1998
63	Rivera	−55.48	−30.97	1948	2001
64	Rafaela INTA	−61.55	−31.18	1959	1992
65	Concordia	−58.02	−31.3	1963	2005
66	Cangucu	−52.7	−31.38	1943	1998
67	Córdoba Obs.	−64.18	−31.4	1959	1998
68	Pilar Obs.	−63.88	−31.67	1931	2005
69	Sauce Viejo	−60.82	−31.7	1959	1998
70	Villaguay Aero	−59.08	−31.85	1959	1996
71	Mendoza Obs.	−68.85	−32.88	1959	1998
72	Rosario Aero	−60.78	−32.92	1949	2005
73	Gualeguaychú	−58.62	−33	1961	1998
74	Rio Cuarto	−64.23	−33.12	1961	2005
75	San Luis Aero	−66.35	−33.27	1960	1998
76	Villa Reynolds	−65.38	−33.73	1959	1998
77	Pergamino INTA	−60.55	−33.93	1931	2005
78	Laboulaye	−63.37	−34.13	1959	1998
79	Junin	−60.92	−34.55	1950	2005
80	Aeroparque	−58.42	−34.57	1959	2005
81	OCBA	−58.48	−34.58	1861	2005
82	Ezeiza	−58.53	−34.82	1959	2005
83	Punta del Este	−54.92	−34.91	1948	2000
84	Punta Indio	−57.28	−35.37	1959	1998
85	Nueve de Julio	60.88	−35.45	1950	2005
86	Trenque Lauquen	−62.73	−35.97	1959	1994
87	Dolores	−57.73	−36.35	1959	2005
88	Santa Rosa	−64.27	−36.57	1937	2005
89	Azul	−59.83	−36.75	1959	1997
90	Crnel. Suárez	−61.88	−37.43	1959	1998
91	Pigüé	−62.38	−37.6	1959	1998
92	Mar del Plata	−57.58	−37.93	1959	2005
93	Tres Arroyos	−60.25	−38.33	1959	2005
94	Bahía blanca	−62.17	−38.73	1959	1998

3 Daily dry spells and their temporal variation

Figure 2 shows the annual averages and standard deviations of dry spells. An east–west gradient was observed in the dry spell averages. The regional amplitude ranged from 5 to 13 days in the north–south direction within the basin. Amplitudes in the east–west direction ranged from 3 to 13 days and the gradient disappeared at the northern border of the basin. The pattern of standard deviations was similar in shape, but with higher values in the northern region.

Histograms of dry spells for some of the reference stations are shown in Fig. 3. For these histograms, precipitation was set to zero when it fell below the rainfall threshold of 0.3 mm. The pattern was similar at all stations, with the maximum of dry spell frequencies decreasing on the monthly time scale. The best fits for these types of distributions in the La Plata Basin were the gamma and geometric distributions (Sneyers 1975). To estimate the degree of fitting, the statistical chi-squared test was carried out. The null hypothesis was that the data set corresponded to each of the theoretical distributions analysed. These results agreed with previous findings in different areas around the world, such as the results of Gabriel and Neumann (1962) and Penalba and Vargas (2008).

One of the most important aspects of the probabilities shown in Fig. 3 is that spells that were at least 10 days long had less than a 5% probability of occurrence, indicating a low probability for this atmospheric state. Previous distributions were important to consider, since they aided in the adjustment of probability distribution frequencies of cycles length (defined as the sum of the length of consecutive wet and dry spells).

We analysed the series of dry spells at different reference stations in the region while trying to determine the longest dry spell. Figure 4 shows dry spell length ordered in time as a time series and its spectral power for four reference stations. The power represents cycles per total number of sequences. The series showed periodicities of approximately 1–3 weeks, and these periods seem to govern their occurrence. Another important spectral peak was found at 1- to 2-year periods.

In addition, these series of dry spell lengths showed certain climatic characteristics. For example, Tucumán, located in northwestern Argentina, presented the longest dry spell that was due to the climatic regime that causes winter droughts in the region. This occurs because Tucumán is located in the continental sub-tropical region (wet summer and dry winter seasons; Minetti 2005).

From a regional point of view and for properties based on daily and annual information, the estimation of dry spells showed a particular trend (Fig. 5). A trend towards a decrease in dry spell length was observed in southeastern Brazil, Uruguay and the northern Mesopotamian region, with the exception of a region in southern Brazil (bordering Uruguay). This result implies that the time between rains is shorter. This would imply shorter dry spells due to greater variability of circulation patterns that are more responsible for generating precipitation in the region (the passage of fronts and air masses storms).

It is also important to examine the variation in terms of the means and low frequencies of dry spells, removing high frequencies in order to highlight phenomena such as interannual variability and evidence of climate change.

4 Analysis of extreme dry spells

In order to approach the concept of drought (extreme situations of no rain), we measured the three longest dry spells per year and calculated their averages in order to establish four annual series.

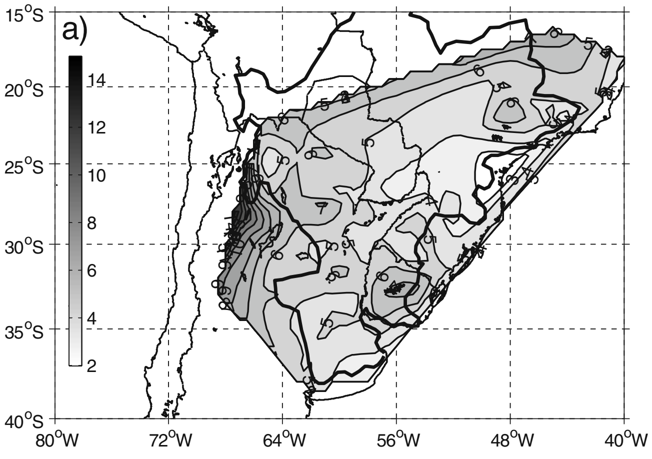


Fig. 2 Average dry spell length (in days; **a**) and standard deviation (**b**)

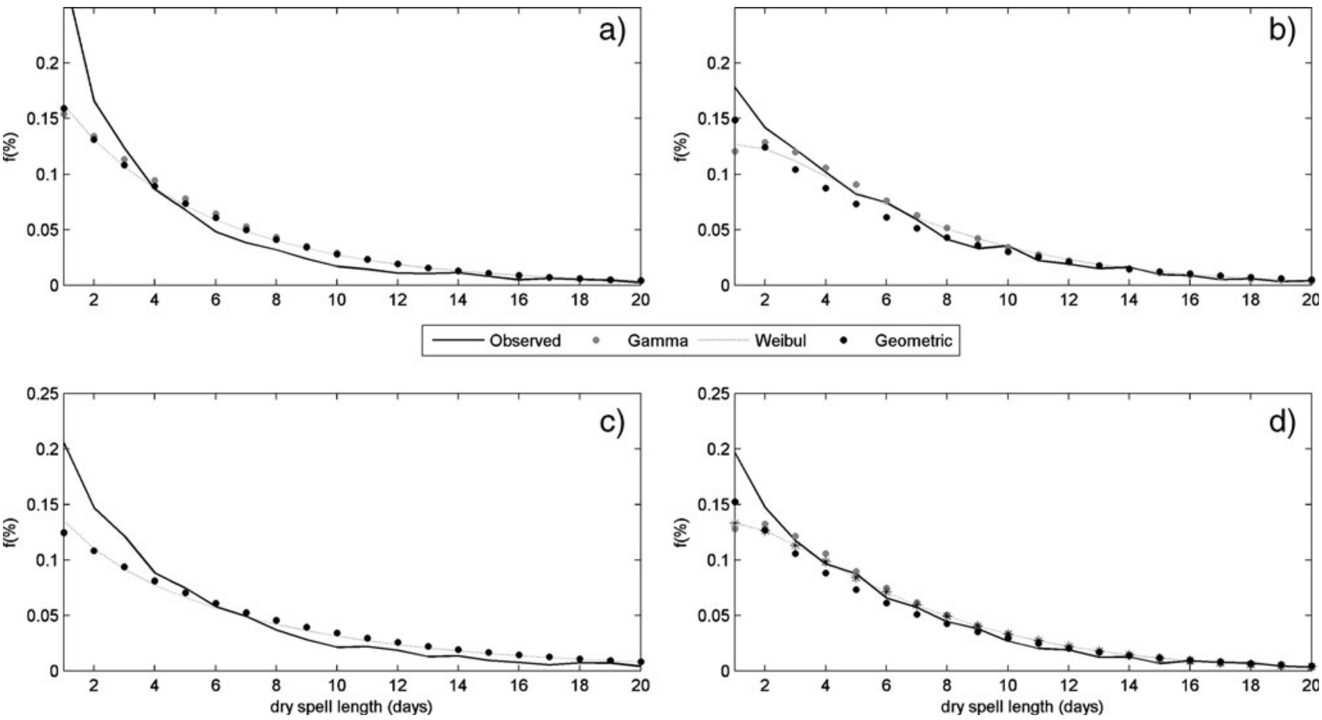


Fig. 3 Empirical probability of dry day sequences (*solid lines*) and estimated values by gamma, Weibull and geometric distributions in Campinas (**a**), Corrientes (**b**), Tucumán (**c**) and OCBA (**d**)

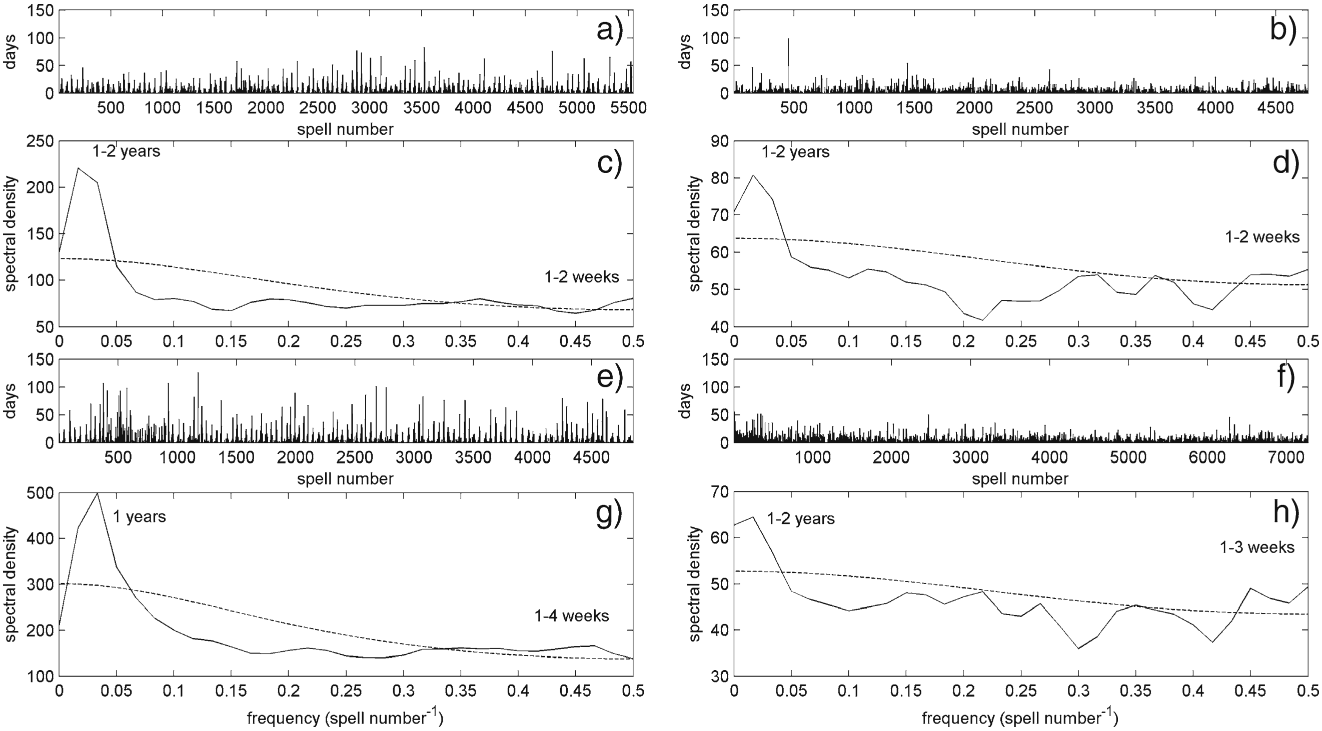


Fig. 4 Temporal evolution of dry spell length (days) and its power spectra estimation calculated according to Eq. 1 in Campinas (**a**, **c**), Corrientes (**b**, **d**), Tucumán (**e**, **g**) and OCBA (**f**, **h**). The 95% significance levels for white noise are represented by *dashed lines*

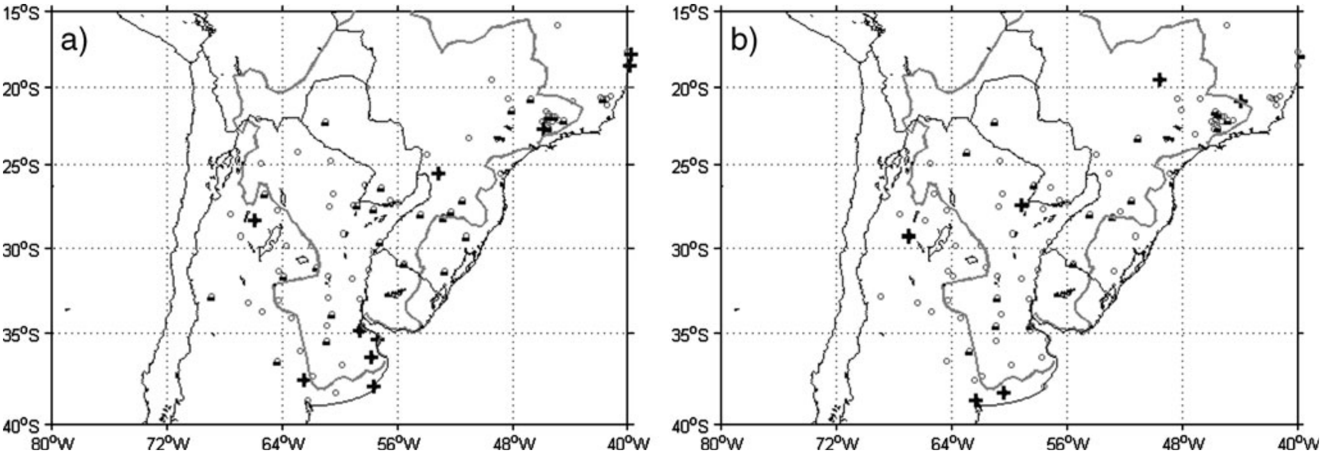


Fig. 5 Estimation of the trends of all dry spells (**a**) and the annual longest dry sequences (**b**) using the *Z* statistic with a confidence level of 5% (*plus sign* represents positive trends; *minus sign* represents negative trends)

The deficit in precipitation regimes has a particular characteristic that can be studied by the coherence between the three most prolonged droughts estimated by the correlation coefficient. Table 2 shows the sign of the Spearman correlation coefficient calculated between the lengths of three longest dry spells per year. At each station, a significant correlation existed between the three different longest dry spells of each year. This finding may imply that in years with an abnormally long longest dry spells, other long spells tend to occur as well. The same behaviour occurs for extreme wet days (Naumann et al., submitted for publication).

An analysis of the trends of the annual properties of dryness is represented in Fig. 5b. Annual longest dry spells showed significant negative trends, especially in southeastern Brazil. This suggests an increase in precipitation in the region at the expense of drought occurrence, as observed in OCBA (Fig. 6). In OCBA, the presence of low frequencies over a long period of time (140 years) is significant.

Figure 7 shows the longest dry spell per year and the power spectrum estimate for four reference stations. Significant peaks were observed at stations, with frequencies higher than 2 to 3 years. The same was observed at the other reference stations (data not shown). Similar results were also observed in Australia (Gibbs 1975). Additionally, these results agree with the findings on a daily basis, as shown in Fig. 4.

5 Regional aspects of the longest dry spells

One of the impacts and risk factors of longest dry spells is the affected surface. The adequacy of this estimate depends on the density of stations, specific parameters of coherence and the simultaneity of occurrence between stations. These data help to provide a rough estimate of the regional expansion of dry spells. For this reason, we studied the longest dry spell in each year for each station, as well as the

Table 2 Signs of Spearman rank correlation coefficients (significant at 5%) among the three annual longest-term dry spells in O. C. Buenos Aires, Campinas, Corrientes and Tucumán

	1BA	2BA	3BA	1Ca	2Ca	3Ca	1Co	2Co	3Co	1Tu	2Tu	3Tu
1BA		+	+		−					+		
2BA	+		+					+	+		+	+
3BA	+	+						+	+			
1Ca					+							
2Ca	−			+		+						
3Ca					+							
1Co								+	+			
2Co		+	+				+		+		+	
3Co		+	+				+	+				
1Tu	+											
2Tu		+						+				+
3Tu		+									+	

BA Buenos Aires, *Ca* Campinas, *Co* Corrientes, *Tu* Tucumán

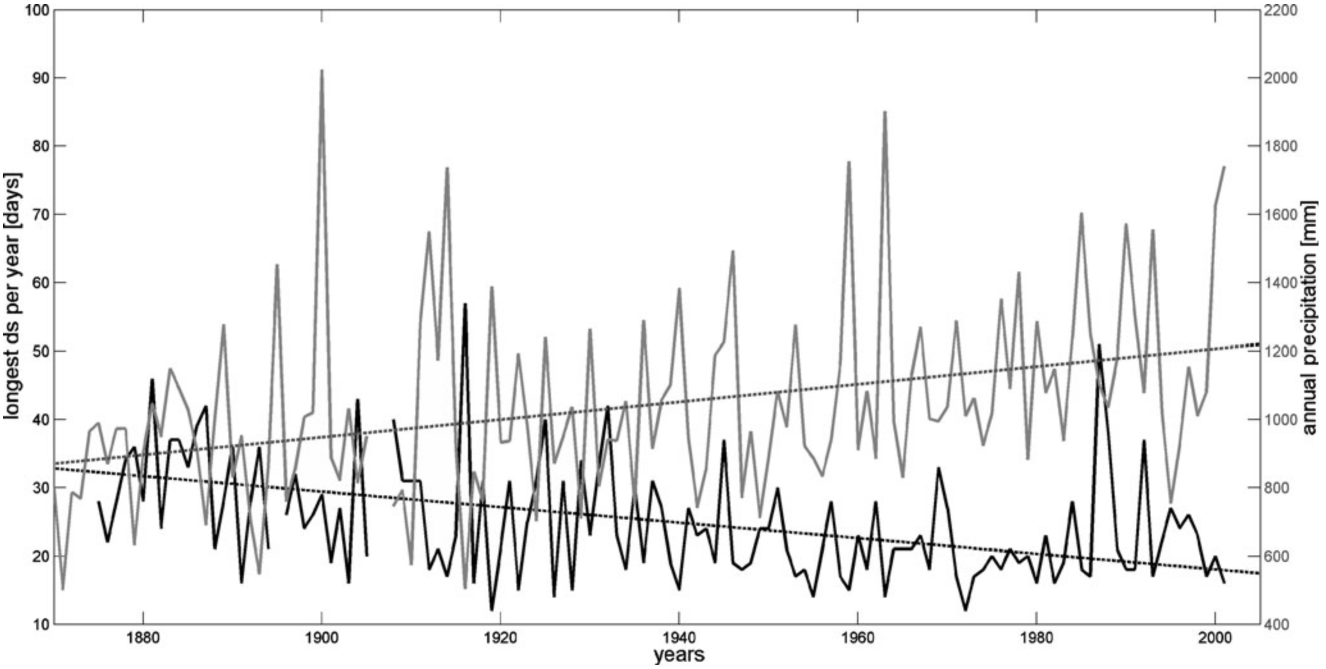


Fig. 6 Annual precipitation (*grey*) and maximum dry sequences (*black*) in OCBA. *Dashed lines* represent linear regression trends. Both trends are statistically significant at the 95% confidence level

longest dry spell recorded throughout the entire study period for each station. Priority was given to regional aspects rather than temporal aspects. For this reason, we considered the records available from the Parana Region, Brazil.

Figure 8 shows the number of stations recording their absolute longest and their second absolute longest dry spell for each year from 1972 to 1997. In 1988, the largest number of stations reported their absolute maxima of dry spells. This indicates a larger impact area than

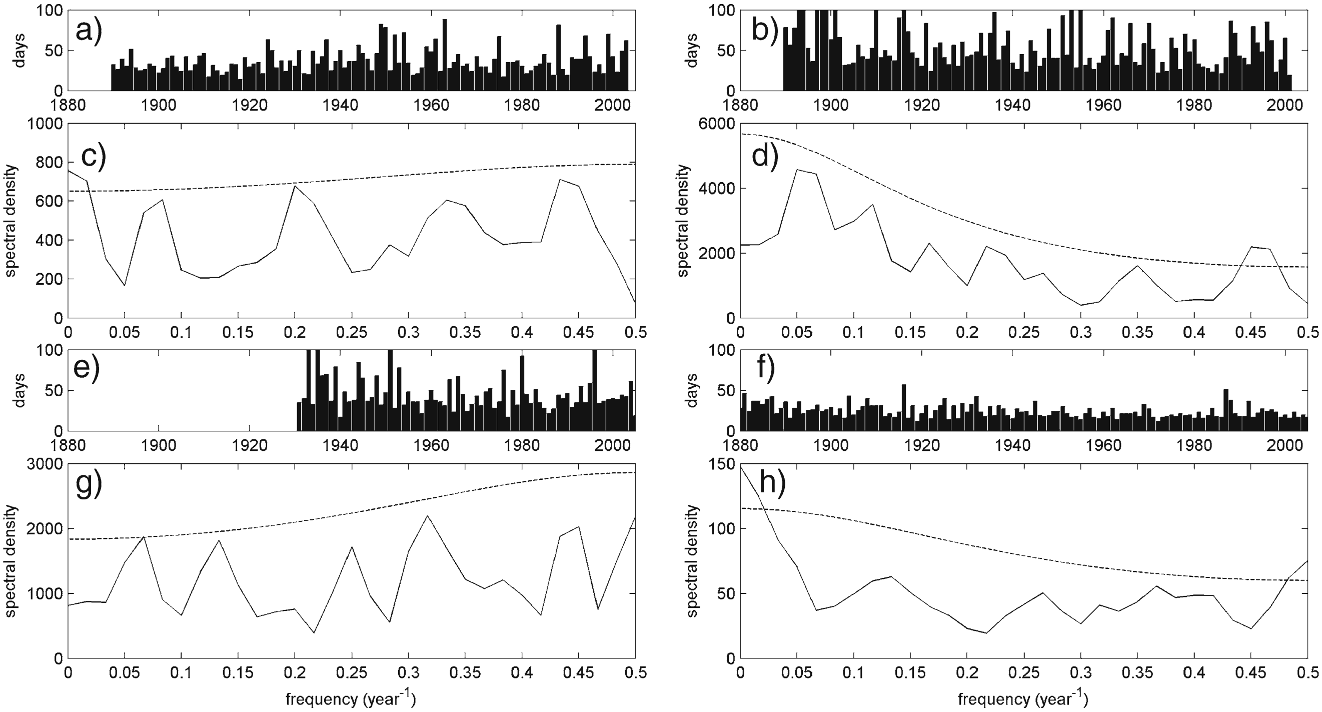


Fig. 7 Longest dry sequences per year and power spectrum estimates in Campinas (**a**, **c**), Tucumán (**b**, **d**), Rosario (**e**, **g**) and OCBA (**f**, **h**). The 95% significance levels for white noise are represented by *dashed lines*

was observed in the second most prolonged dry spell, which occurred in 1995. There have been other extreme dry periods reported from 1933 to 1951 (Minetti and Vargas 1983) and 2006 to 2008 (Minetti et al. 2008). These dry periods have been especially prevalent in Argentinean wetlands. These analyses are not discussed in this paper.

The dry spells in 1988 and 1995 both had important social and economic impacts on the region. Moreover, most of the impacts occurred in 1988. This finding supports the uniqueness of the year of 1988, since the occurrence of two extreme dry spells is possibly related to the same large-scale physical processes in areas of the region, indicating persistence. Despite this double occurrence, the probability and associated risk of the longest local dry spells occurring simultaneously in all regions is low for droughts in the La Plata Basin. In addition, this involves restricting the area of occurrence and the characteristics of dry states in the region.

An approximation field of the longest dry spell (drought) and the date of occurrence in the region are useful tools for a diagnosis. Figure 9 shows the field associated with the longest dry spells, represented by the following vector array:

$$\overrightarrow{S} = (L, \theta) \tag{2}$$

where L is the vector amplitude that represents the length of the longest dry spell (days) in the entire period and the angle θ represents the day of the year when it begins (θ= 0⇒1-January).

As expected, due to the dependence of spell length on the annual cycle, the longest spells were observed in northwestern Argentina and in the northern region of the basin from April to the beginning of winter. In central Argentina, the intensity tends to decrease and the occurrence tends to increase in July. This also occurs in the humid Pampa and Mesopotamia regions, but with shorter and more irregular spells. Moreover, in the east–southeast sector of the basin (Brazil), maximum dry spells tend to occur in April and in the beginning of winter. The gradient between the lengths in the west, the continental zone, the east and the wettest zones indicates a reduction of drought risk in this last region, which can be connected to the annual cycle of precipitation in the region.

When a station records an absolute minimum of annual rainfall, the longest dry spell is likely to occur in that year. For example, the relationship between the longest dry spell and annual rainfall at OCBA had significant negative correlations. Figure 6 shows that annual rainfall, maximum dry spell and their averages are negatively correlated. This also confirms that there are relationships between the dry spell, the areas affected and the associated rainfall at the annual scale.

Figure 10 shows the absolute minimum of annual rainfall and the period of occurrence of that minimum at 94 stations throughout the study period. This indirect analysis revealed that events occurring before 1958 were important, and they may limit the analysis of intensity and the coherence of minimum annual precipitation (as shown in Fig. 10). However, in the humid regions of Argentina, Uruguay and north of the basin, the most favourable period for the occurrence of annual rainfall minima and droughts was 1959–1965, confirming the regional restriction of the phenomenon. Greater homogeneity was observed in the analysis of the common period, particularly in the Humid Pampas, although the periods of 1959–1963 and 1975–1980 seemed to define the greatest coherence areas (and intensity).

6 The relationship between dry spells and ENSO events

Numerous studies from all over the world have used the ENSO phases to explain the longest wet and dry periods (Dai et al. 1998), but the ENSO is not necessarily the dominant influential factor. In the Parana-Plata Basin (Ropelewski and Halper 1996; Labraga et al. 2002; Silvestri 2004, 2005; Boulanger et al. 2005; Gong et al. 2005), spatial ENSO teleconnections evolved greatly from the period of 1950–1975 to 1976–2001. Moreover, there is strong modulation and displacement of the teleconnection patterns from one event to another, impeding a robust statistical relationship (impact regions) between ENSO and precipitation. Fowler and Adams (2004) encouraged a greater focus on identifying and investigating other plausible forcing factors for precipitation in New Zealand.

In this study, we analysed the frequency of occurrence of dry spells and the relationship between extreme dry spells and the occurrence of La Niña phases. The histograms of dry spell lengths at OCBA and Corrientes (Fig. 11) show that the frequencies of dry spells during El Niño and La Niña are similar for short and intermediate lengths of dry spells. The essential difference is apparent with the longest dry spells. Long dry spells seem to be related to La Niña events, particularly in Corrientes, although this can also be observed in the remaining sequences. The influence of ENSO decreases towards higher latitudes, which can be seen in the OCBA histograms. In these histograms, frequencies for both ENSO phases are similar. It seems that long dry spells can occur with both La Niña and El Niño events, although they are slightly more frequently associated with La Niña events.

The distributions of dry sequences can change substantially. The influence of La Niña events on the occurrence of intermediate or long dry spells is more evident when seasons are analysed independently, as opposed to analyses conducted across all seasons (Penalba and Vargas 2001).

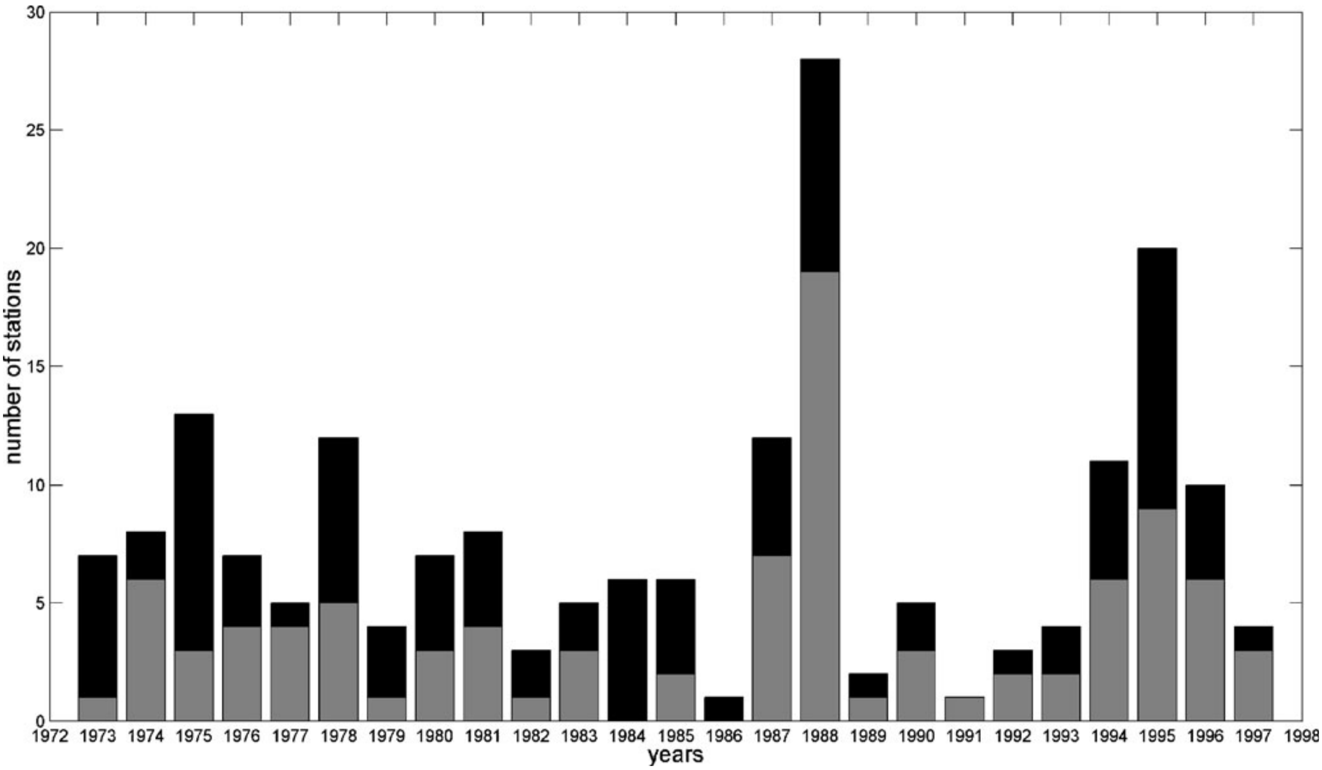


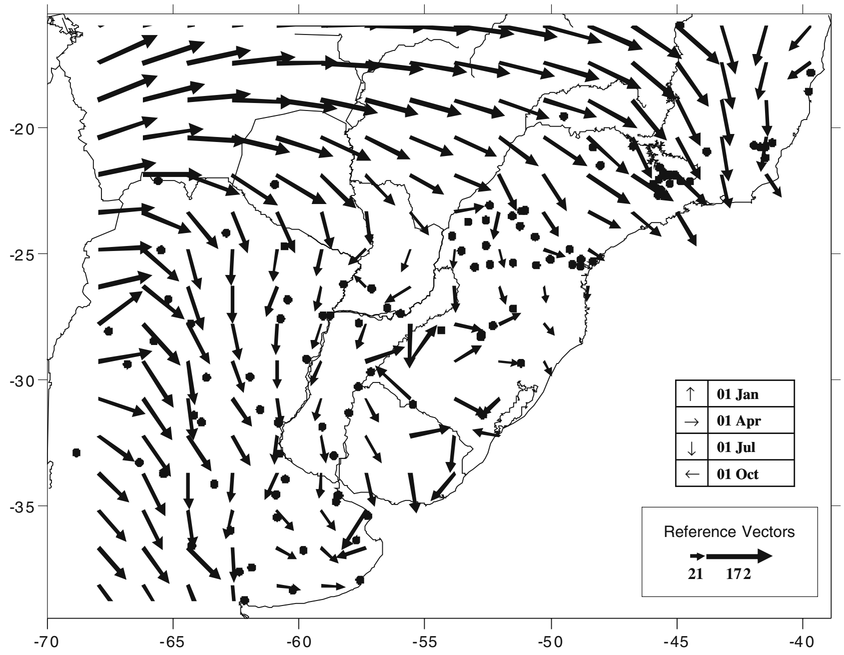
Fig. 8 Number of stations in the basin having their longest (*grey*) and second longest (*black*) dry spells in the indicated year for 1972–1997. There were 94 total stations that had data recorded during the study period

7 Drought area: the special case of the year 1988

As discussed in Section 5, 1988 had the longest dry spell on record. This dry spell had strong social and economic impacts on the region. An analysis of atmospheric circulation and global occurrence of this event can be found in Naumann et al. (2008).

Figure 12 shows the difference between the length of the longest dry sequence in 1988 and the average lengths of annual longest dry spells for the rest of the study period.

Fig. 9 Fields associated with maximum droughts, where the vector length represents the length of droughts. Order 1 represented the longest droughts and the angle θ represented the day of the year when the drought started [θ=0⇒1-January]



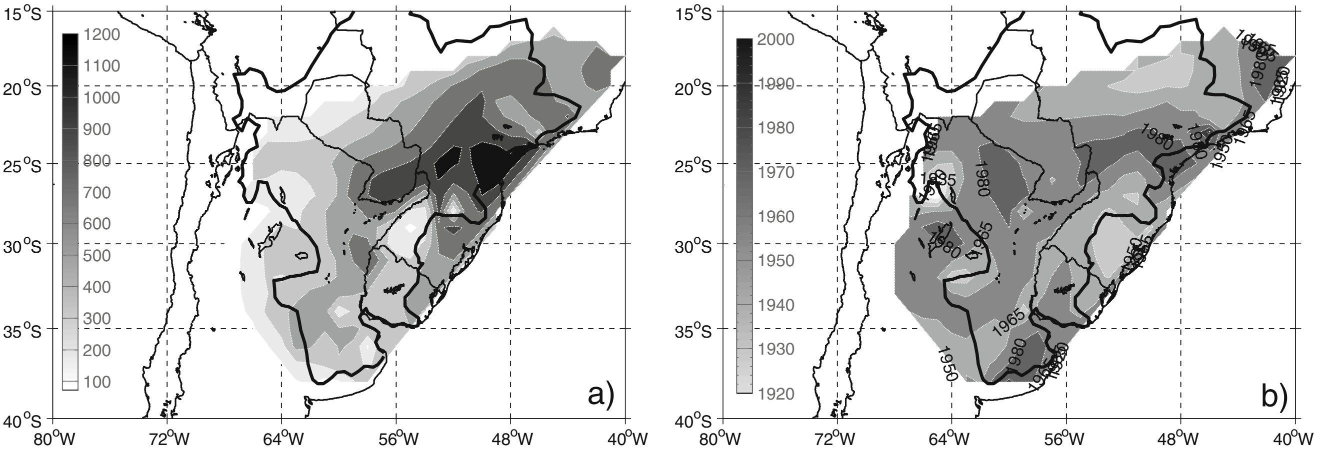


Fig. 10 **a** Absolute minimum of annual rainfall (millimetres) and **b** occurrence period (years) based on data recorded at 94 stations during the study period

Most of the area of the basin is under extreme meteorological drought conditions, and the affected area is proportional to the intensity of the dry spells. However, on an annual scale, southern Brazil, Uruguay and the centre of the province of Buenos Aires do not seem to be under drought conditions.

In order to identify the occurrence of the longest dry spell in 1988, Fig. 13 shows the beginning and end of these events in Julian days. The data show that droughts preferentially start during winter months. One exception is the area that appeared to be partially exempt from drought. Specifically, the drought in this area started in May and was therefore shorter than droughts in the rest of the basin. The end of the dry spells often occurs in early spring.

One remarkable fact is that the stations in central-eastern Buenos Aires received a cumulative input of 50–300 mm during approximately 1 week (Fig. 14). Generalised soil drying continues from March through the end of the year. This water deficit translated into economic losses in Argentina of more than four billion dollars in 1988 (Vargas and Nuñez 1991).

Cumulative anomalies of maximum and minimum temperatures and daily rainfall at four reference stations are shown in Fig. 15. The results show similarities and differences between the stations, depending on their

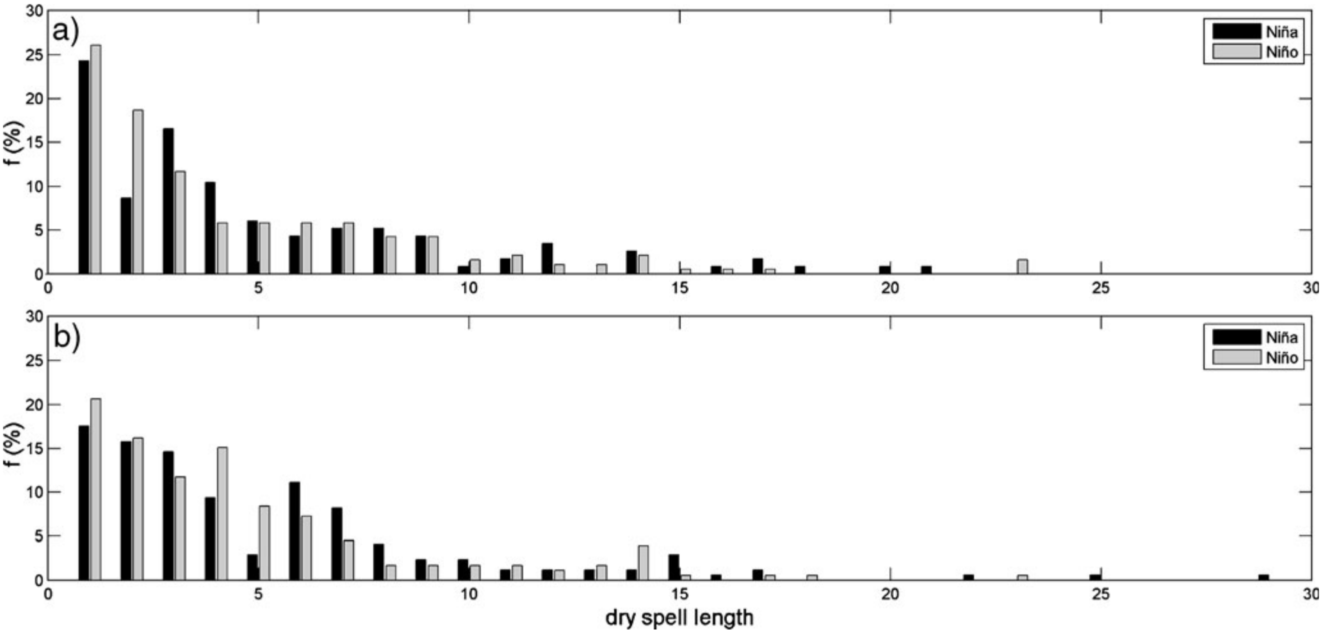


Fig. 11 Distribution of dry spells during years in which El Niño or La Niña events occurred at OCBA (**a**) and Corrientes (**b**)

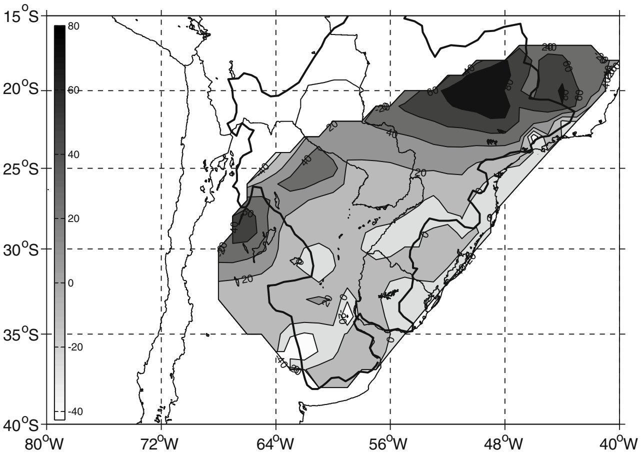


Fig. 12 The difference between the length of the longest drought sequence in 1988 and the average length of extreme annual dry sequences

locations. In the case of Corrientes, drought is clearly seen in the rainfall values. Minimum temperature values show pronounced cooling, and the maximum temperature remains close to normal values. In Campinas, only the maximum temperature seemed to accompany the lack of rainfall, with a singular event in the spring when maximum temperature rises, probably due to more effective radiation.

Tucumán seems to be beyond the drought area, and both the maximum and minimum temperature anomalies are coherent with the annual cycle. Latitude effects can be seen at OCBA, where drought starts after a significant rain episode. In this case, the absence of clouds is clear, as both the maximum and minimum temperatures undergo intense cooling. However, these temperatures also show strong stability and little thermal amplitude with respect to other stations, allowing us to infer that humidity is not low.

8 Final remarks

Many definitions of maximum water deficits, such as droughts, exist in the literature. Almost all of these definitions depend on the effects of droughts on other systems, such as water resources, agriculture and other human activities. Most of these studies analyse droughts on a monthly or annual scale. In each particular case, general comparisons are difficult because of the lack of data, especially data on soil humidity, for all countries.

This study, which relied on daily data, describes characteristics of dry spells and their extreme cases. These features are important when estimating the drought risks. Although the region selected for study is one of the major basins in the world, data were not always available at the required level of detail. As a result, the detail of the studied events depended on the data collection stations involved. This lack of data is partially compensated by the daily series. In general, this study aimed to define droughts under specific conditions in terms of dry spells. We also synthesised information for use in models of climatic risk, infrastructure damage mitigation and environmental management. The synthesis was complemented by an analysis of extreme temperatures in a pilot case involving the drought of 1988, which is considered the most important drought in the La Plata Basin due to its enormous negative impacts. This event also occurred in the plains of the USA and had the same physical occurrence process. That event was analysed in detail to provide information for professionals in other areas, especially in the social and economic sciences, and also to estimate the probability of the occurrence of such events. In conclusion, there is a trend towards a decrease in the length of annual scale dry spells, especially on the eastern side of the basin. This fact is consistent with annual precipitation trends. These results imply a lower risk of long-term droughts in the region, at the

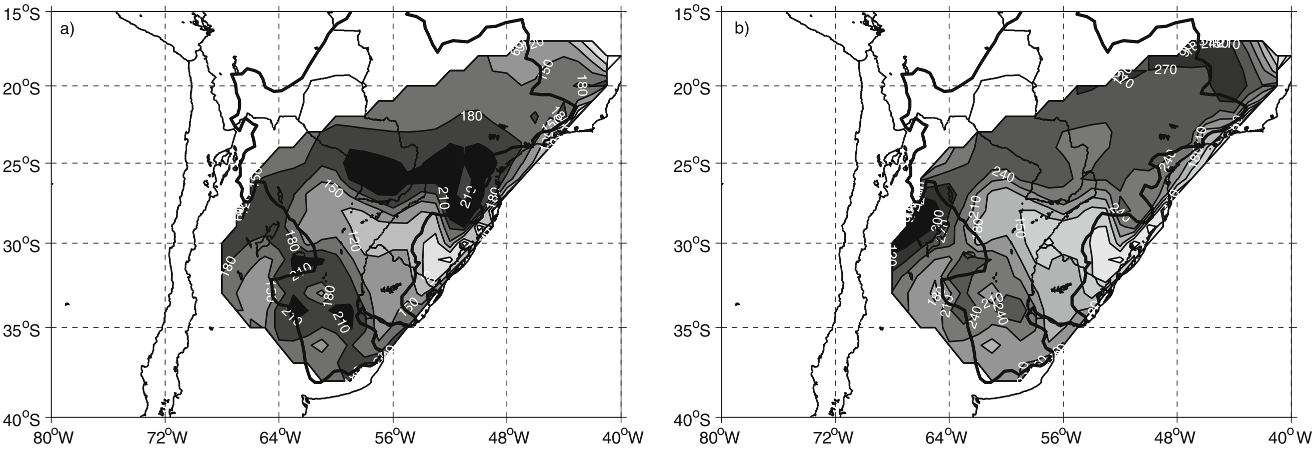


Fig. 13 Starting (**a**) and ending (**b**) days of the longest drought sequence in 1988 (Julian days)

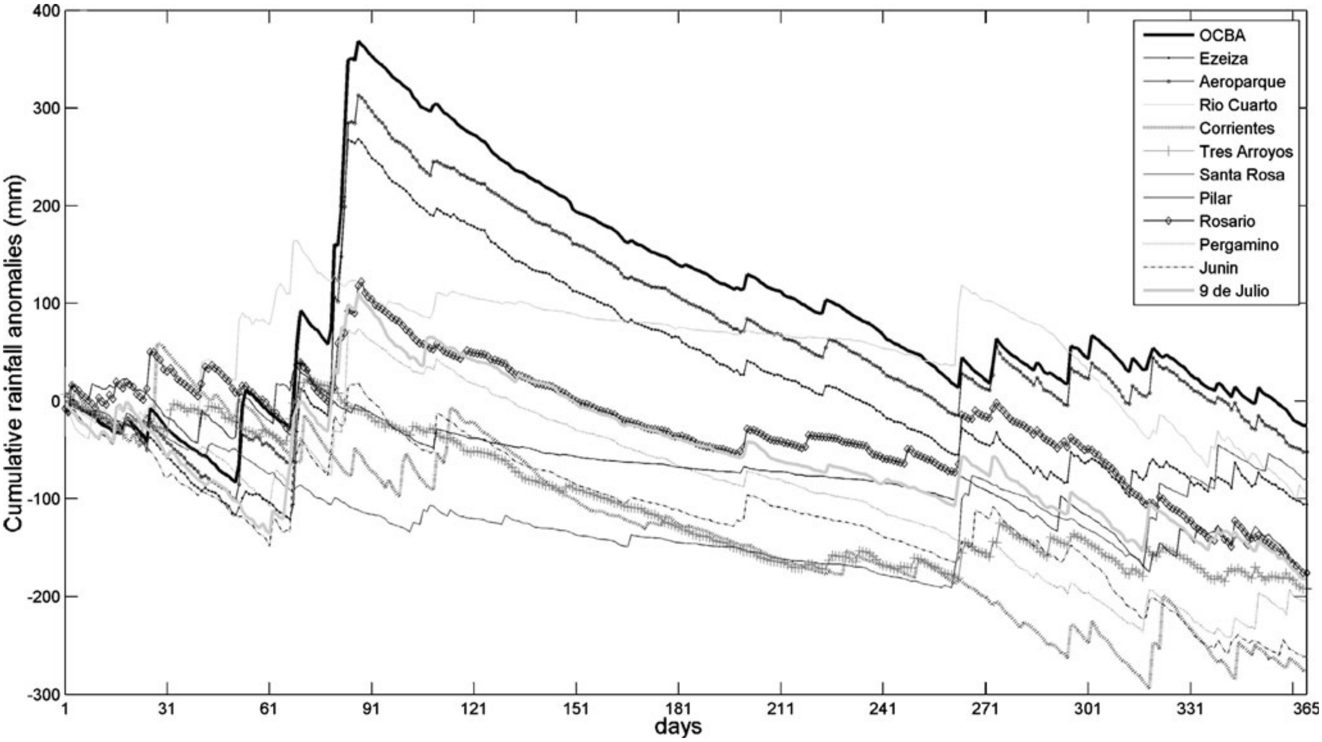


Fig. 14 Cumulative rainfall anomalies at 12 stations in Argentina in 1988

expense of increased precipitation. Spectral structure permits an inference of low-frequency maxima at a reference station, confirming an inter-annual 2- to 3-year period of variability in drought occurrence for most of the basin.

Finally, there are two inferences that may be relevant: (1) a study of the coherence of extreme dry spell (drought) occurrence shows that these phenomena occur in sub-regions, reducing the risk of occurrence throughout the entire basin, and (2) the occurrence of extreme dry spells shows a seasonal preference, suggesting that there is slight but complex dependence on the annual cycle of precipitation.

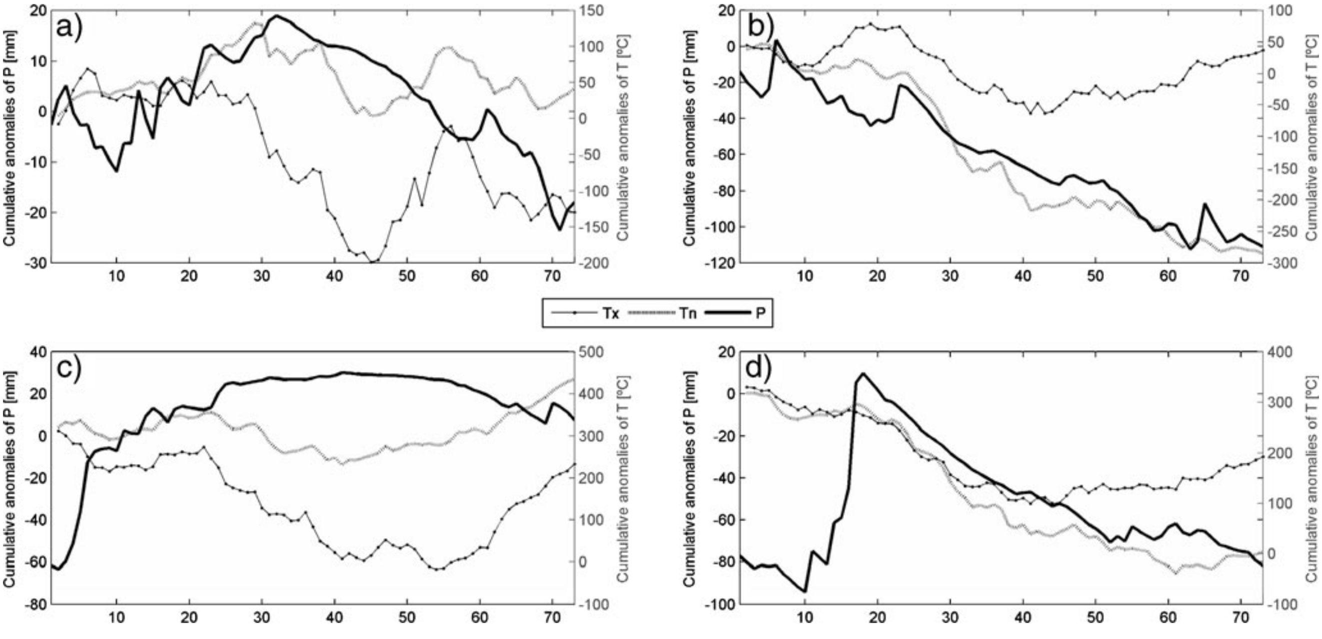


Fig. 15 Pentad cumulative anomalies of maximum and minimum temperatures and daily rainfall in 1988 at Campinas (**a**), Corrientes (**b**), Tucumán (**c**) and OCBA (**d**)

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