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Spatial and temporal variability of the frequency of extreme daily rainfall regime in the La Plata Basin during the 20th century

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Abstract We analyzed trends, interdecadal variability, and the quantification of the changes in the frequency of daily rainfall for two thresholds: 0.1 mm and percentile 75th, using high quality daily series from 52 stations in the La Plata Basin (LPB). We observed increases in the annual frequencies in spatially coherent areas. This coherence was more marked in austral summer, autumn, and spring, during which the greatest increases occurred in southern Brazil, especially during extreme events. In winter, the low and middle basins of the Río Uruguay and Río Paraná showed negative trends, some of which were significant. Interdecadal variability is well defined in the region with more pronounced positive jumps west of the basin between 1950 and 2000. This variability was particularly more marked during periods of extreme rainfall in summer, autumn, and spring, unlike in winter when extreme daily rainfall in the lower Rio Paraná basin decreased by up to 60%. The changes in the past century during extreme rainfall produced modifications in the annual rainfall cycle. The annual cycle of both indices was broader during the last period which is mainly explained by the strong decreases in winter.

1 Introduction

The Fourth Assessment Report has made progress in observing and understanding human and natural drivers of climate change, and in estimating projected future

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climate change, among other issues (IPCC 2007). Given this projected future climate change, we analyze climate variability in the region based on data from high quality stations.

Humankind and the environment are far more vulnerable to extreme climate events than to medium climate variations. Rain is one of the climate variables which had the greatest effect on land use, economic development, and practically all aspects of human activity. A comprehensive analysis of rainfall data is a crucial component in the management of water and agricultural production. This point of view is considered in the CLARIS Project framework in the context of two Work Packages 3.2 and 4.1 (WP3.2).

The study of rainfall in southern South America can serve as an important tool for the sustainable development of the region in several ways. The region under study, the La Plata Basin (LPB), covers parts of Argentina, Uruguay, Paraguay, Bolivia, and southern Brazil. LPB is a densely populated region where agriculture and hydrology have serious social and economic ramifications. This basin is the fifth largest in the world with a population of over 100 million inhabitants and an economy representing 70% of the gross domestic product of the five countries (www.brazil.gov.br). From an economic point of view various activities are rain related, particularly in South America, a continent with the highest annual rainfall worldwide. The agricultural and cattle breeding sector and the production of hydroelectric power benefit directly from rainfall. In Brazil, more than 85% of electric power consumption comes from hydroelectric dams. An understanding of extreme rainfall behavior in the different regions of the basin, together with a correct planning of the water resources, may minimize the adverse impacts owing to droughts and floods.

During recent decades many papers have analyzed annual, temporal, and seasonal rainfall variability in the different LPB regions. Krepper et al. (1987, 1989), Penalba and Vargas (1996), Minetti and Vargas (1997), Castañeda and Barros (2001), Minetti et al. (2003), among others, observed an increase in total annual rainfall in different regions of Argentina. This increase does not exhibit coherent spatial behavior. Towards the west of the LPB we can see a "jump" or discontinuity; in particular, the increase is more gradual eastward (García and Vargas 1998; Minetti and Vargas 1997; Rusticucci and Penalba 2000; Boulanger et al. 2005). Penalba and Vargas (2004) observed a strong interdecadal component in central Argentina while this variability shows a slight linear tendency in the east and northeast. The annual rainfall variability presents seasonal behavior and becomes more pronounced according to the season. For example, with respect to total summer rainfall, Liebmann et al. (2004) and Boulanger et al. (2005) identified a linear trend in southeastern Brazil and northern Argentina. These studies show that rainfall has changed considerably at least in some LPB regions over the last 40 years.

This temporal variability is usually quantified in terms of total rainfall, for example, annual, seasonal, or monthly. In some cases number of rain days appeared to be key to fluctuations in rainfall amounts; in some, variation depended on rainfall intensity; and in others, both variables played a part.

Research in changes in rainfall extremes has increased in recent years, especially since the IPCC 1st Assessment Report (Houghton et al. 1990) identified a scarcity of such studies. Few studies analyze changes in daily rainfall extremes in the region under study. Penalba and Robledo (2005) performed a climate study of the extreme daily precipitation events across southern South America from 1961 to 2000 (Fig. 1). We observed that the annual cycle of daily events largely had to do with the annual cycle of monthly precipitation. Haylock et al. (2005) examine daily rainfall data from 1961 to 2000 using 12 stations in South America. They find changes in the annual extreme rainfall indices. Pscheidt and Grimm (2006) found extensive areas in southern Brazil in which the frequency of extreme precipitation events significantly increased in November of El Niño years and decreased during the La Niña years. Re et al. (2006) analyzed the temporal variability of frequency of daily extreme precipitation events (greater than 80 and 100 mm/day), finding positive trends in central and eastern Argentina. Groisman et al. (2005) have found a systematic increase in very heavy daily precipitation in the subtropical part of Brazil since the 1940s.

At it was mentioned, changes observed in monthly rainfall may be due to changes in the number of rain days, in rainfall intensity, or both. This paper focuses on the first issue, especially extreme rainfall, and tries to provide updated information on trends and interdecadal variability in southern South America.

The objectives of this paper are: (a) to study the temporal variability of rainfall for different thresholds and (b) to quantify changes in the frequency of days of rain for different thresholds in the second half of the 20th century.

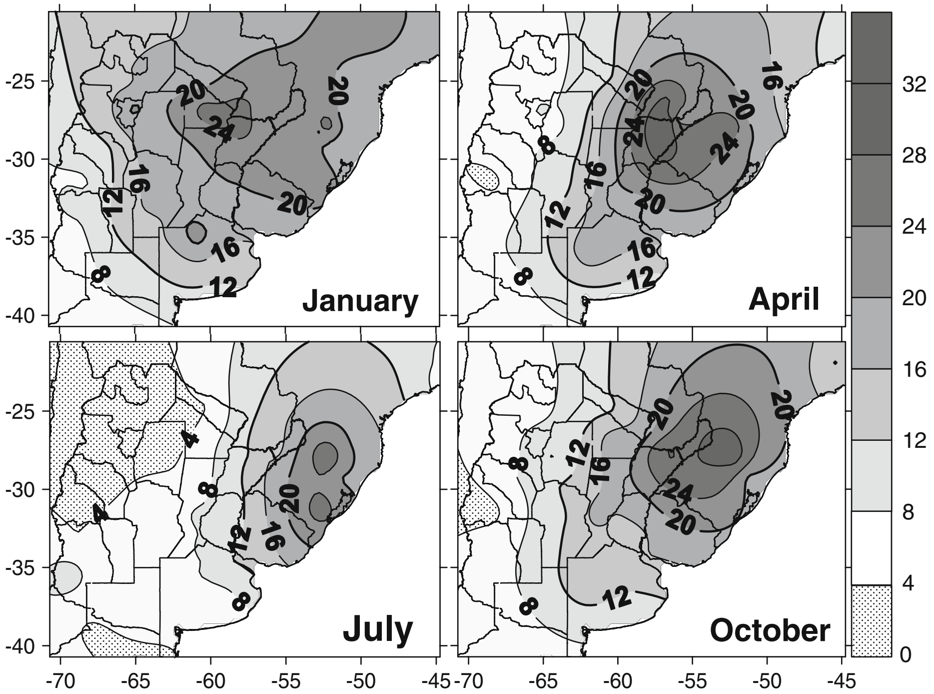


Fig. 1 Mean 75 percentile of daily precipitation (mm/day) for the 4 months of each season: January (summer), April (autumn), July (winter) and October (spring). Period considered: 1961–2000 (Source: Robledo 2007)

Section 2 describes the observational data used and the quality controls applied to them. Section 3 presents the methodology used for their analysis. The results are presented as follows: Section 4.1 describes frequency trends, Section 4.2, the decadal variability, Section 4.3, climate changes in the last decades, Section 4.3.1, the seasonal component, and Section 4.3.2 shows the percentage of change in rainfall and extreme events. Section 5 concludes.

2 Observational data and quality

Daily rainfall data used in this study were provided by different national institutions such as the Servicio Meteorológico Nacional (National Weather Service), the Instituto Nacional de Tecnología Agricola for Argentina, and the Instituto Nacional de Investigación Agropecuaria for Uruguay. For Brazil and Paraguay the daily data set was compiled by the European Community Project "Assessing the impact of future climatic change on the water resources and the hydrology of the La Plata Basin, Argentina: ARG/B7-3011/94/25".

They are distributed all across the study region: southern South America, bounded by 70° W–45° W and 40° S–20° S on the continent (Fig. 2). The distribution of gauges is relatively homogeneous, except in certain areas in western Argentina and some areas of Brazil. These stations, outside the LPB area, were used to improve spatial coverage. All stations selected registered less than 10% of daily rainfall values missing for the period in their records. The longest record is 105 years (1908–2003) corresponding to the Observatorio Central Buenos Aires (OCBA) station and the shortest is 41 years (1961–2003) belonging to numerous Argentine stations (Table 1). The period 1961–2000 is taken as the longest and common period for all the stations. The Uruguayan stations were eliminated from the study because they presented periods of less than 31 years.

Data quality assessment is an important requirement for climate research, particularly in the case of extreme rainfall. Considering the discontinuous nature of daily rainfall, the occurrence of intense rain may be considered erroneous without

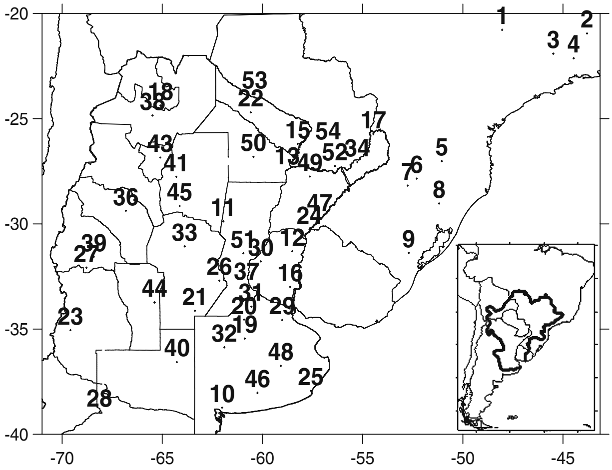


Fig. 2 Geographic distribution of the stations

Table 1 Station number relative to Fig. 2, name of the stations, country, period, longitude and latitude

No.	Station	Country	Period	Longitude	Latitude
1	Morro Agudo	Brazil	1942–1998	−48.03	−20.78
2	Carandahy		1942–1993	−43.80	−20.95
3	Ferreiras		1942–1998	−45.48	−21.92
4	Franceses		1942–1998	−44.47	−22.13
5	Videira		1944–1998	−51.05	−27.02
6	Erebango		1944–1998	−52.30	−27.85
7	Flores da Cunha		1945–1998	−52.75	−28.18
8	Coqueiros do Sud		1944–1998	−51.18	−29.03
9	Porto Alegre		1944–1997	−52.70	−31.38
10	Bahia Blanca	Argentina	1956–2003	−62.02	−38.73
11	Ceres		1956–2003	−61.95	−29.88
12	Concordia		1963–2003	−58.02	−31.30
13	Corrientes		1903–2003	−58.77	−27.45
14	Esquel		1961–2003	−71.15	−42.93
15	Formosa		1963–2003	−58.23	−26.20
16	Gualeguaychú		1961–2003	−58.62	−33.00
17	Iguazú		1961–2003	−54.47	−25.73
18	Jujuy		1967–2003	−65.08	−24.38
19	Nueve de Julio		1950–2003	−60.88	−35.45
20	Junín		1950–2003	−60.92	−34.55
21	Laboulaye		1950–2003	−63.37	−34.13
22	Las Lomitas		1959–2003	−60.58	−24.70
23	Malargue		1959–2003	−69.58	−35.05
24	Monte Caseros		1961–2003	−57.65	−30.27
25	Mar del Plata		1962–2003	−57.58	−37.93
26	Marco Juarez		1956–2003	−62.15	−32.70
27	Mendoza		1959–2003	−68.78	−32.08
28	Neuquén		1959–2003	−68.13	−38.95
29	OCBA		1908–2003	−58.42	−34.57
30	Paraná		1956–2003	−60.48	−31.78
31	Pergamino		1937–2000	−60.55	−33.93
32	Pehuajó		1959–2003	−61.90	−35.87
33	Pilar		1930–2003	−63.88	−31.07
34	Posadas		1962–2003	−55.97	−27.37
35	Río Gallegos		1960–2003	−69.28	−51.62
36	La Rioja		1960–2003	−66.82	−29.38
37	Rosario		1949–2003	−60.78	−32.92
38	Salta		1962–2003	−65.48	−24.85
39	San Juan		1967–2003	−68.42	−31.57
40	Santa Rosa		1937–2003	−64.27	−36.57
41	Sgo del Estero		1956–2003	−64.30	−27.77
42	Trelew		1959–2003	−65.27	−43.20
43	Tucumán		1911–2000	−65.10	−26.85
44	Va Reynolds		1959–2003	−65.38	−33.73
45	Va Maria		1959–2003	−64.13	−29.15
46	Tres Arroyos		1961–2003	−60.25	−38.03
47	Paso de los Libres		1959–2003	−57.15	−29.68
48	Azul		1954–1994	−59.08	−36.75
49	General Paz		1959–1994	−57.63	−27.75

Table 1 (continued)

No.	Station	Country	Period	Longitude	Latitude
50	Saenz Peña	Argentina	1959–2003	−60.45	−26.82
51	Sauce viejo		1959–2003	−60.82	−31.70
52	Encarnación	Paraguay	1951–1999	−56.38	−27.55
53	El Cuervo		1951–1999	−60.38	−23.83
54	Villarica		1956–1999	−56.72	−26.25

careful observation. The daily rainfall used in this study was first examined by *Working Group 3.2 of the CLARIS Project* (WP3.2) to determine changes in both total and extreme rainfall. For this paper, an additional assessment of data quality was necessary. All the daily data at the upper end of the empirical distribution were flagged and compared to nearby stations. To detect an anomaly or spatial singularity, the spatial field on the rain day was also analyzed. Finally, total monthly precipitation of the month in which the event occurred and its standard deviation were analyzed using the T-Student and χ^2 tests respectively (significant at the 5% level; Wilks 1995).

3 Definition of indices and methodologies

Extreme events are infrequent meteorological phenomena and their severity depends on the natural environment affected. This means that the definition of an extreme event will largely depend on the activity and region affected (Das et al. 2003). In the particular case of extreme precipitation events, their definition depends, moreover, on the nature of the rainfall in the region under study. In the LPB, as a direct consequence of the annual cycle, we can see different atmospheric circulations on the synoptic scale and mesoscale. They will be the cause of events which result in the different rainfall values observed.

We define a rain day as one on which the rainfall is greater than 0.1 mm and extreme rainfall is considered when the daily rainfall is greater than a given threshold. These thresholds are based on statistical values such as the 75th, 90th and 95th daily percentiles which were determined empirically as follows. The different daily percentiles are calculated on all the daily rainfalls for each meteorological station. This daily percentile series is clarified by smoothing the data using a 7-day running average. Symmetry of the weight distribution is applied to guarantee no phase shift in the variations in the time series after the filter has been applied (Hu et al. 1998).

The indices selected in this study are the number of days with rainfall equal to or greater than the different percentile thresholds mentioned above, calculating the percentage of events (hereafter: PE $>$ 0.1; PE $>$ 75th and so on). The selection of 0.1 mm allows us to analyze the temporal variability of the rain day, providing a clearer picture of rainfall conditions in the study area. The different indices were calculated per austral season: summer (December, January and February, DJF), autumn (March, April and May, MAM); winter (June, July and August, JJA), spring (September, October and November, SON), and the year as a whole (December to November of the following year).

The trend test applied in this study for the common period 1961–2000 is the non-parametric Kendall–Tau test (confidence level = 95%, critical $r = /0.22/$; Siegel

1985). This test is a rank-based procedure suitable for detecting non-linear trends in variables that do not have a Gaussian distribution, which is the case of the PE index.

To analyze the interdecadal PE index variations, we applied an 11-year running mean with distributed weights (Woodruff and Hu 1997). This procedure filters the smallest variability and retains the greatest variability over a 10-year period, which is the focus of this study.

To assess each season's contribution to the year as a whole, we calculated a new index. The seasonal component index (SCI), expressed in percentages, is the number of rain events in each season (DJF; MAM, JJA; SON) divided by the number of rain events in the entire year (December to November). This index is computed in two different periods: (1961–75 and 1980–96) by both thresholds 0.1 mm (SCI 01) and percentile 75 (SCI 75th).

This index was analyzed in the period 1961–2000 by Robledo (2007). During the summer SCI shows a maximum regional variability located between 35° S–60° W and 25° S–68° W and increases towards the northwest. This gradient is inverted during the winter. This result helps us to determine the region of maximum change in SCI and defines the seasonal gradient inversion axis (SGIA). The straight line in Fig. 3 indicates the location of this axis.

4 Results

4.1 Trend analysis

Figure 3 shows the sign and significance of the annual PE > 0.1 and PE $>$ 75th trends during the longest common period (1961–2000). We observed two large regions with spatial coherence in the significant trend for PE > 0.1: one to the northeast and the other to the southwest of the SGIA (Fig. 3, left). Although the lineal trend decreases in the SGIA region, few stations exhibit negative trends towards the southeast. The spatial patterns seen in PE > 0.1 trends do not persist with the same intensity as the extreme daily rainfall, PE $>$ 75th (Fig. 3, right).

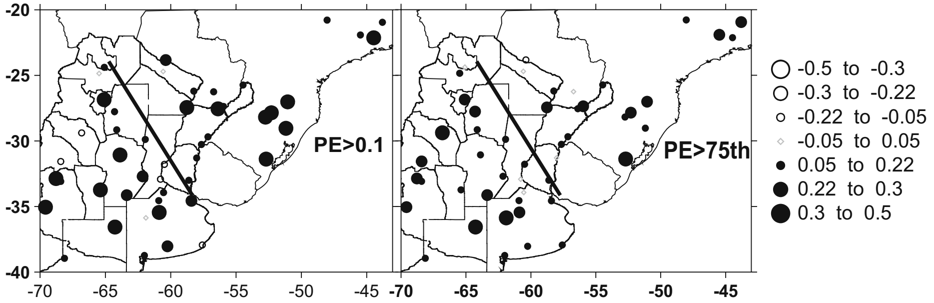


Fig. 3 Sign of the annual trend of the PE > 0.1 (*left*) and PE $>$ 75th (*right*) as measured by Kendall Tau. An increase is showed by *filled circles* and a decrease by *empty circles*. Values greater than (-0.22; $+0.22$) indicate significant $p < 0.05$. The *black solid line* represents the seasonal gradient inversion axis (SGIA)

We conducted seasonal low frequency variability analyses to determine which part of the year contributes to this annual behavior. In general terms, the spatial behavior of the positive sign for the annual PE > 0.1 and PE > 75th trends is similar to summer, autumn and spring (Fig. 4).There is little difference in the summer

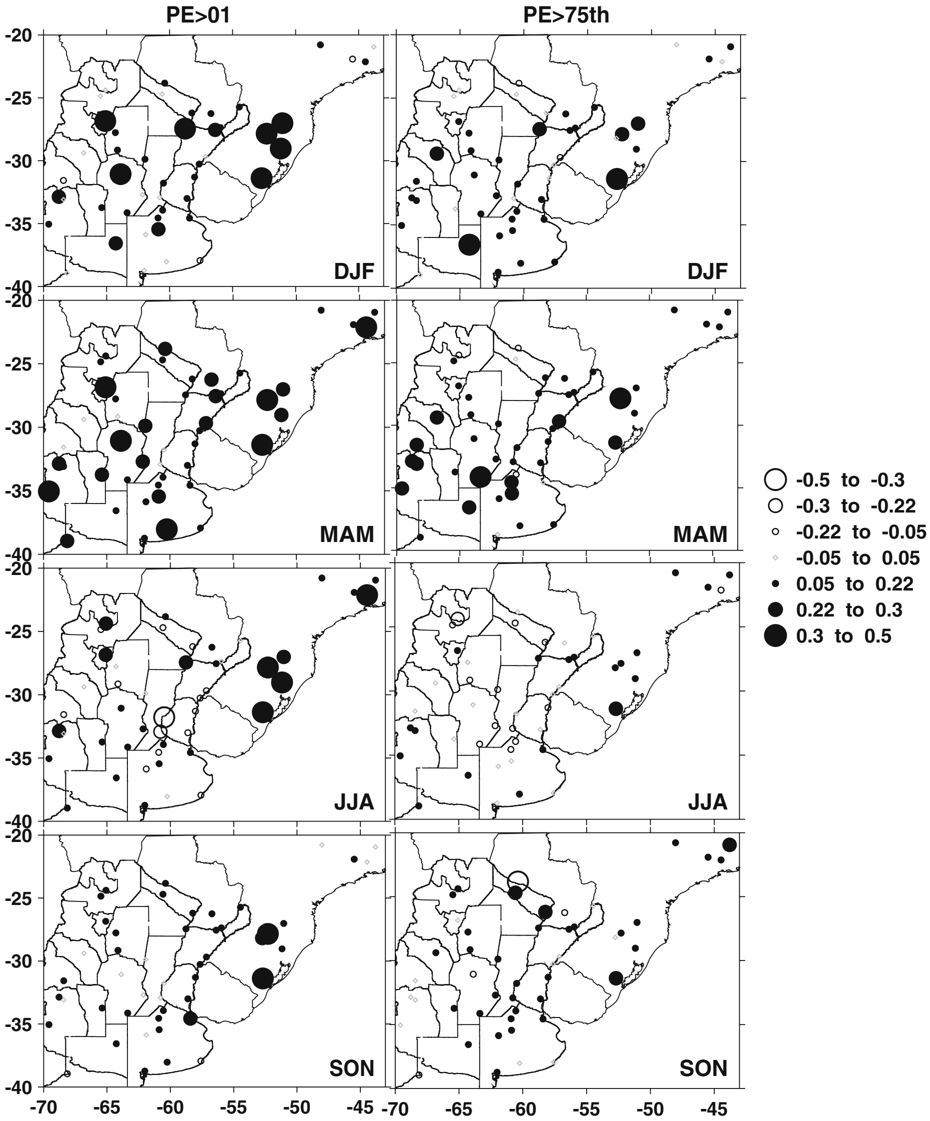


Fig. 4 Sign of the seasonal trend of PE > 0.1 (*left*) and PE > 75th (*right*) as measured by Kendall Tau. An increase is showed by *filled circles* and decrease by *empty circles*. Values greater than (−0.22; +0.22) indicate significant $p < 0.05$, summer (December, January and February, DJF), autumn (March, April and May, MAM); winter (June, July and August, JJA), spring (September, October and November, SON)

Table 2 Number of stations with significant annual and seasonal trends

	DJF	MAM	JJA	SON	Annual
PE > 0.1					
Negative	0	0	4	0	1
Positive	12	19	10	4	21
PE > 75					
Negative	0	0	0	1	0
Positive	16	11	1	4	17

To summer (December, January and February, DJF), autumn (March, April and May, MAM); winter (June, July and August, JJA), spring (September, October and November, SON), and the year as a whole (December to November of the following year)

trends for both thresholds (Fig. 4, DJF). Most of the stations in southeast Brazil show significant positive trends for both thresholds. To the north of the SGIA, we also recorded positive trends, although not all are significant. As we approach the SGIA region, the trends become non-significant and positive and some stations even present negative trends. These spatial patterns begin to differ between thresholds in autumn and winter. The entire region has positive PE > 0.1 trends in autumn, which are significant for most of the stations to the southwest and northeast of the SGIA (Fig. 4, left MAM). The winter spatial pattern shows interesting results. The positive trends are only significant at the stations in southern Brazil (Fig. 4, left JJA). In addition, all along the SGIA, a large number of stations show negative trends, particularly in the lower parts of the Paraná and Uruguay Rivers, some of which are significant. The autumn and winter spatial patterns for extreme index PE > 75th are weaker than the PE > 01 patterns (Fig. 4, right, MAM and JJA). However, the zone with a negative trend during winter months increases during extreme events. The weakest spatial pattern, in terms of significance, occurs in spring (SON) with a significant increase in PE > 0.1 only at the Brazilian stations at 20° S (Fig. 4, left SON). During this season few negative and in some cases significant trends can be observed in the north of Argentina only during extreme events (Fig. 4, right, SON).

Summarizing the temporal behavior of both indices, Table 2 shows the number of stations with significant trends (positive or negative). Nearly 50% of the stations present positive PE > 0.1 annual trends. This result is similar in summer and autumn, registering 12 and 19 positive and significant trends, respectively. Winter is the only season with negative and significant trends. Under extreme conditions (PE > 75th), positive trends increase to 16 in summer, while the number of stations with significant trends decreases in autumn and winter. The summer results indicate that the increase in the number of rain days is associated with heavy rainfall.

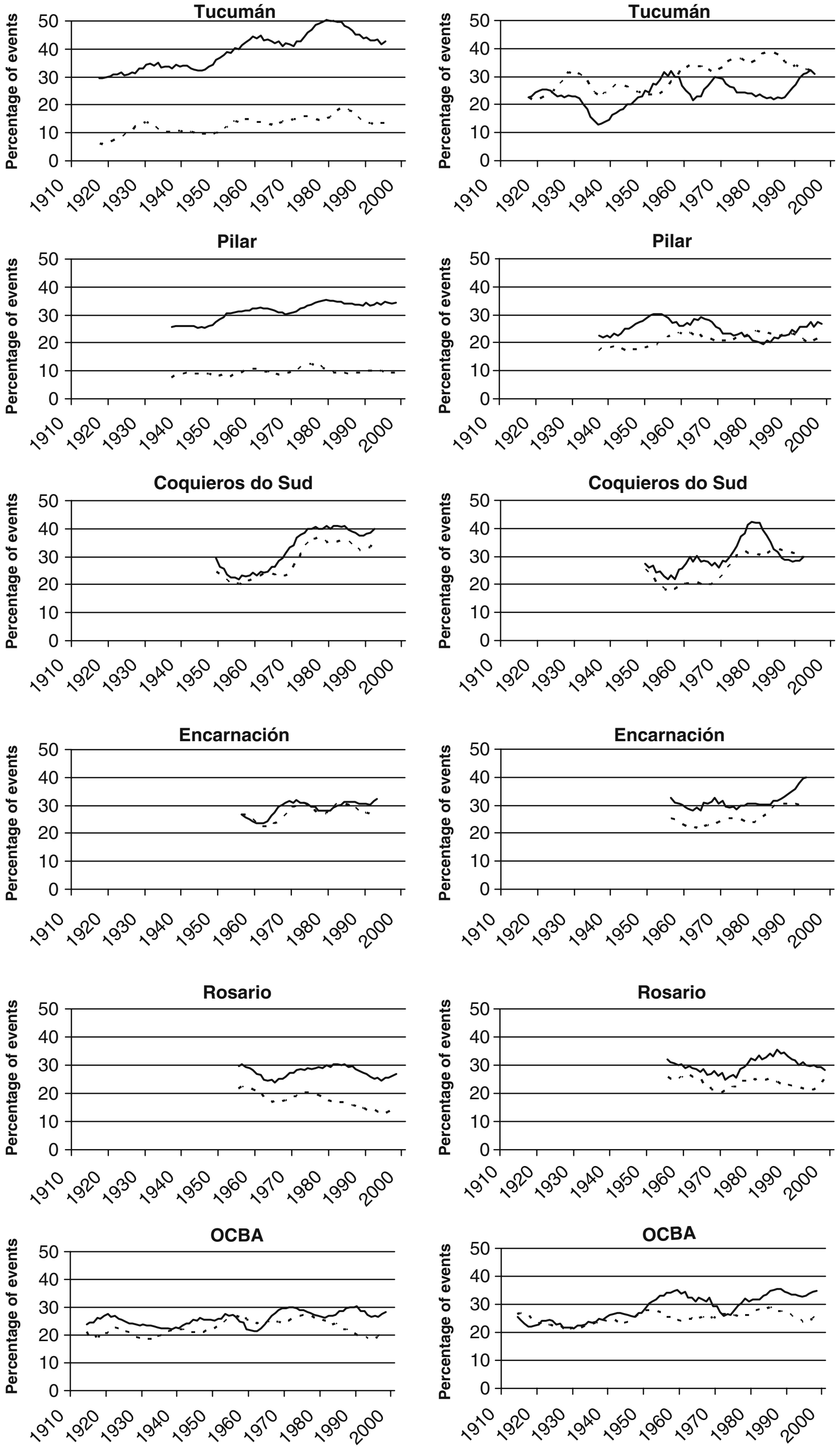
4.2 Decadal variability

The role of interdecadal variability is as important as the low frequency variability in the evolution of regional ecosystems. Numerous studies considered the possible causes of these variations and found that the sea surface temperature of the Atlantic Ocean modulates summer rainfall in the LPB, according to different patterns of moisture transport at low levels. It was not possible, however, to determine whether a change in circulation causes a change in sea temperature or vice versa (Robertson and Mechoso 2000; Doyle 2001; Doyle and Barros 2002).

Fig. 5 Time series of 11-year running mean of PE > 0.1 index for selected stations for the four seasons ▶ of the year. *Left*: summer (December, January and February, *solid line*) and winter (June, July and August, *dotted line*). *Right*: autumn (March, April and May, *dotted line*) and spring (September, October and November, *solid line*)

We analyze the different interannual and interdecadal variations of this index for both thresholds in this section. Figure 5 shows seasonal results of the PE > 0.1 series for stations covering the different features in the basin. The seasonal analysis in Tucumán (#43 Table 1) shows an increase in the percentage of rain days with a marked interdecadal variation (Fig. 5). During the summer months there is a maximum increase of 6%, between 1917 and 1940, while the increase reaches 33% from 1950 to 2000. In autumn, interdecadal variability occurs throughout the entire century with a positive discontinuity around 1960. We observed interesting behavior in spring with a significant drop of around 50% in the percentage of rain days starting around 1930 and lasting for approximately 10 years followed by a marked increase stabilizing around 1955. In winter the breaks and interdecadal variabilities are smaller. Pilar (#33 Table 1), the other western station of the basin, also exhibits interdecadal variability in summer with two positive jumps of around 40%, one in 1945 and the other in 1970. In spring, we can see a progressive decrease in the percentage of rain days in different years, 1955 to 1985. Coqueiro do Sud (#8 Table 1), in the upper Uruguay River, shows the highest positive jumps all year round. The increase in summer and winter registers 80% and a smaller variation can be observed in autumn and spring. Encarnación (#52 Table 1), located between the Paraná and Paraguay Rivers, has a bigger increase as from 1980 in autumn and spring while a more pronounced decadal variability occurs in summer and winter. In the lower part of the Paraná River, 400 km to the south of Encarnación, at the Rosario station (#37 Table 1), in winter the PE > 0.1 decreases 30% in the number of rain days between 1975 and 2000. At OCBA (#29 Table 1), a station located at the mouth of the Paraná River, the largest increases occur in spring, growing 60% between 1920 and 1990. In addition to this increase, we can a decadal variability, as occurs in summer.

The variations observed in PE > 0.1 are not only maintained for the PE > 75th but also accentuated in practically all of the regions of the basin (Fig. 6). In Tucumán (#43 Table 1), there is a 20% increase in extreme rains in summer, overlapped by a variability in jumps of larger increases in 1960 and 1980, the same as at the 0.1 mm threshold. In Encarnación (#52 Table 1), extreme events increase by 57% between 1985 and 1998 in spring (Fig. 6). In Coqueiro do Sud (#8 Table 1) a strong temporal variability exists in winter, spring, and summer. In the west of the basin (Pilar, #33 Table 1), we can observe a jump in extreme events in summer between 1970 and 1980, with a 70% increase in summer (Fig. 6). Although the jump can also be seen in autumn, it is less marked. We observed some interesting behavior in spring—PE > 75th drops by 50% between 1950 and the 1970s. This decrease of around 60% from 1950 also occurs during the winter in the lower Paraná (Rosario #37 Table 1). On the other hand, in spring and autumn increases of 30% occur between 1970 and 2000. At the mouth of the Paraná and Uruguay Rivers (OCBA, #29 Table 1), the increase is marked in spring, reaching 150% between 1929 and 1990 superimposed with a strong decadal variability in spring (Fig. 6).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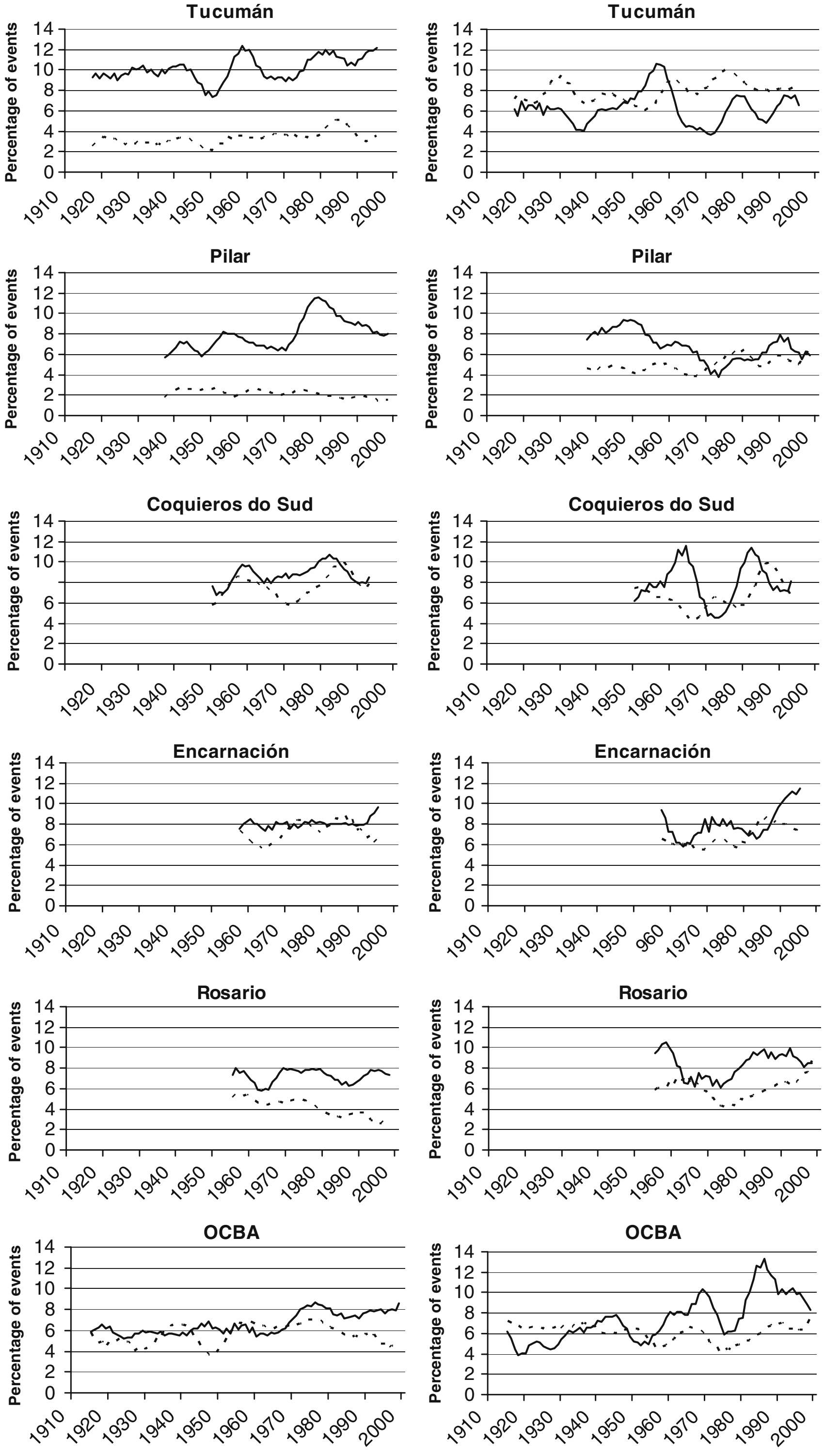
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◀ **Fig. 6** Time series of 11-year running mean of PE > 75th index for selected stations for the four seasons of the year. *Left*: summer (December, January and February, *solid line*) and winter (June, July and August, *dotted line*). *Right*: autumn (March, April and May, *dotted line*) and spring (September, October and November, *solid line*)

4.3 Climate changes in recent decades

4.3.1 Seasonal component

The summer daily rainfall maximum in the LPB is associated with the presence of convective systems. Some scientific papers report a relationship between low level jet (LLJ) events and complex convective mesosystems (Nicolini et al. 2002). Nicolini and Saulo (2000) studied the intensification of interdependence between intense rainfall and the convergence of the humidity flow in the LLJ exit region, located in northern Argentina.

The results in the previous sections indicated that low frequency variability and interdecadal variability of daily rainfall is seasonally related, producing a seasonal variability in the annual precipitation cycle. Moreover, atmospheric circulation in the different regions of the southern hemisphere and the LPB underwent important changes around 1970 (Trenberth 1995). For this purpose the SCI01 and SCI75 indices were used separately for the periods 1961–1975 and 1980–1996. The increase in SCI01 for the region as a whole in the second period as compared to the first during the summer is at the cost of a decrease in SCI01 during the second period in winter (Fig. 7). This generates greater annual PE cycle amplitude during the period 1980–1996 compared to 1961–1975. Autumn and spring also show an increase in SCI 01 for the second period but less marked than in the summer (Fig. 7).

SCI75 also shows greater annual PE cycle amplitude during the second period (Fig. 8). This expansion in the amplitude is explained mainly by strong drops of SCI75 in winter. In summer, SCI75 increase is mainly detected in the northwest and center of Argentina, while in southern Brazil SCI75 decreases in the second period (Fig. 8, right, DJF). In autumn, SCI75 increases markedly in practically the entire region. In spring, the highest SCI75 rise occurs at the mouth of the Paraná and Uruguay Rivers during the second period. In southern Brazil, on the other hand, it decreases generating strong spatial variations over the east of the basin during the same period of the year.

4.3.2 Change in the percentage of daily rainfall and extreme events

To quantify change in the indices, we calculated the variation percentage of the PE > 01 and PE > 75th for two different periods (1961–1975 and 1980–1996), before and after the change.

The annual PE > 0.1 increased in practically the entire region by more than 10% between 1980 and 1996 (Fig. 9, left), while annual PE > 75th has some negative change nuclei, located at the upper and lower Uruguay basin (Fig. 9, right). To determine which season is responsible for these changes, we evaluated the percentages of seasonal change for each index.

The summer PE > 0.1 spatial pattern (Fig. 10, DJF) resembles annual behavior with an increase of more than 10% in practically the entire region. The maximum changes, with over 25% change, occur in southern Brazil and center west of the

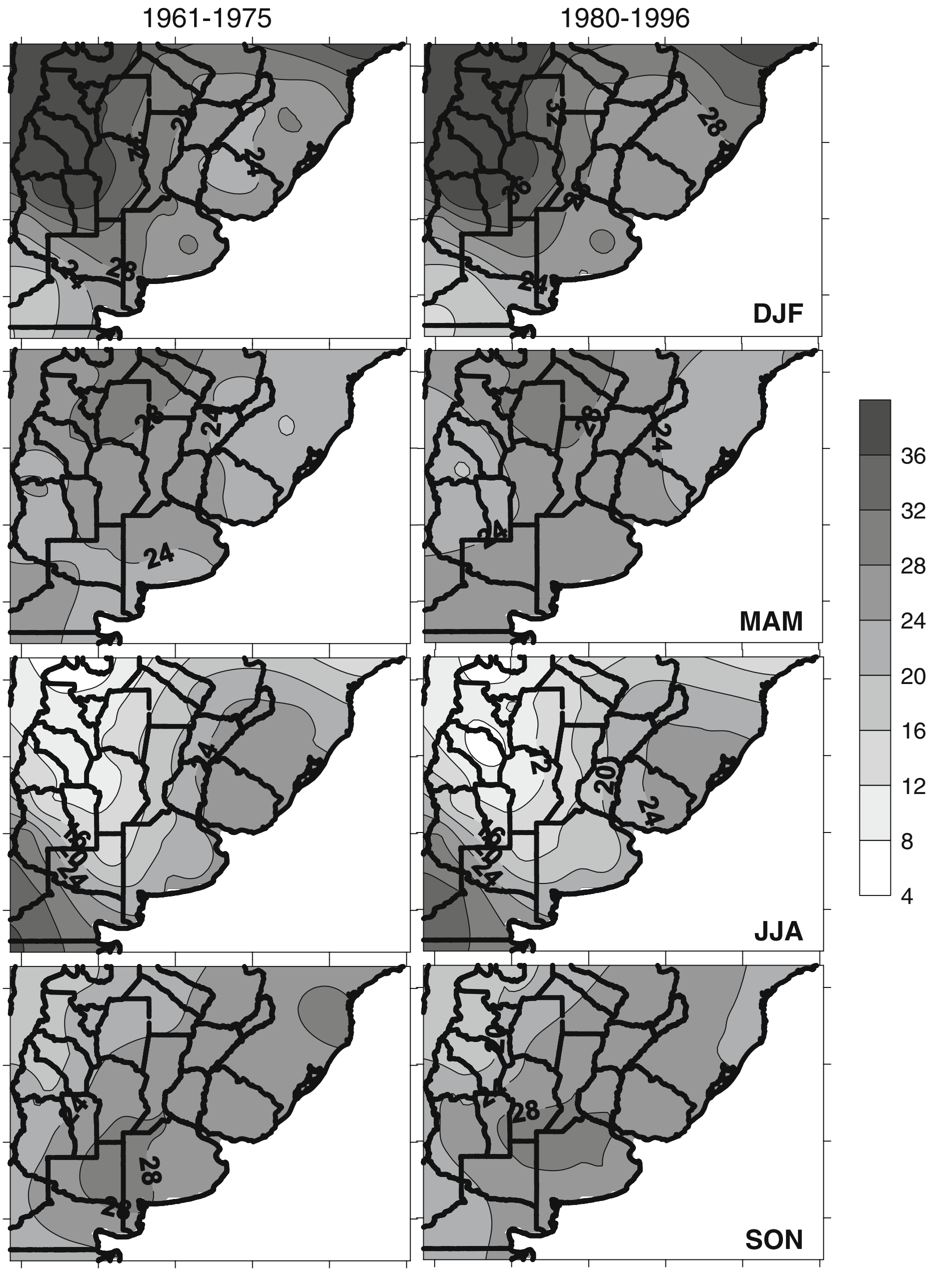

Fig. 7 Seasonal component index for PE > 0.1 (SCI 01), calculated for two periods: 1961–1975 (*left*) and 1980–1996 (*right*)

region under study. This center shifts towards the south in the autumn months and we can see a negative nucleus over the Andes Mountains (Fig. 10, MAM). In winter (JJA), this center expands towards the east and northeast of the basin and has 10%

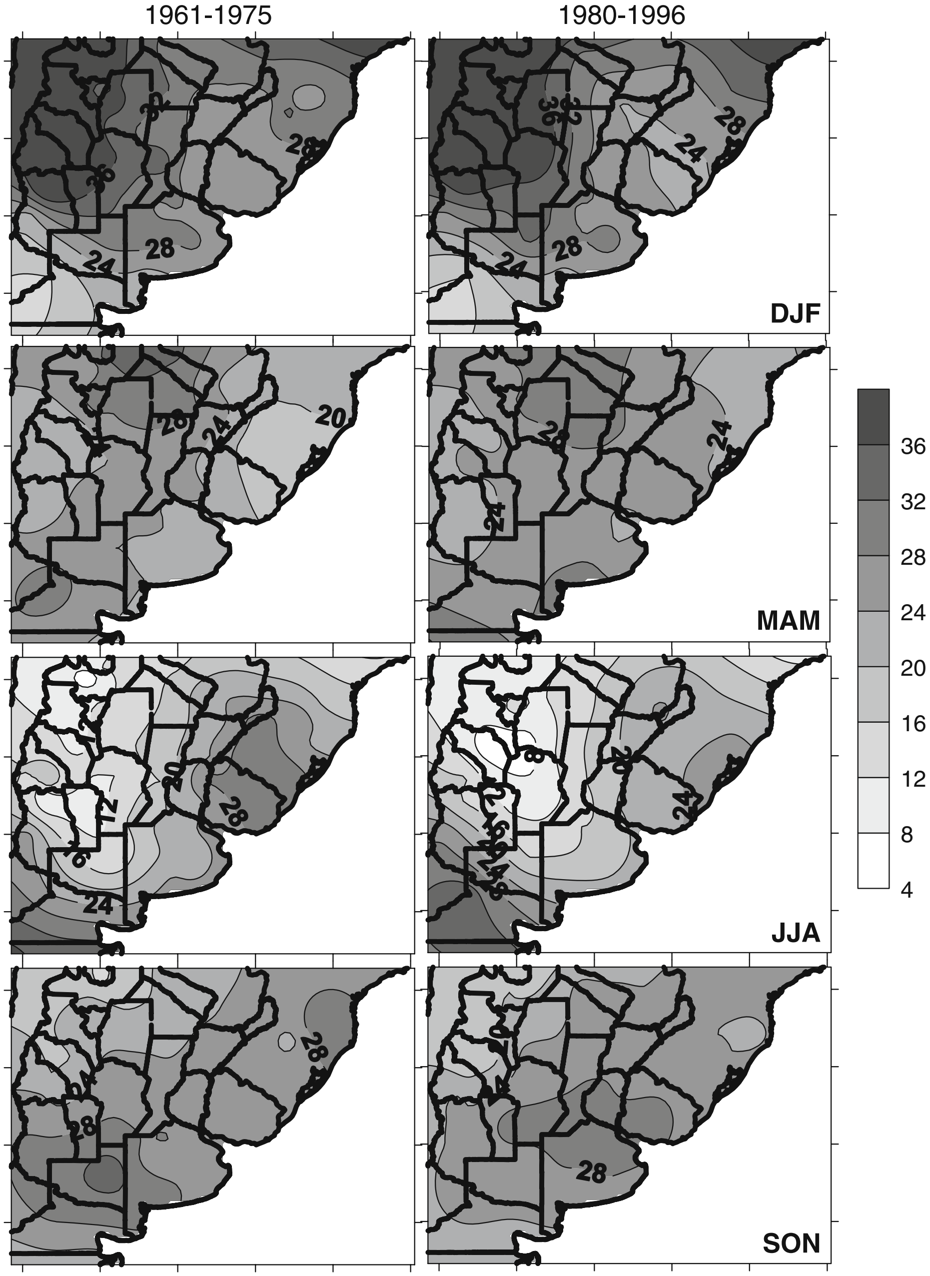

Fig. 8 Seasonal component index for PE > 75th (SCI 75), calculated for two periods: 1961–1975 (*left*) and 1980–1996 (*right*)

and 25% fewer rain events from one period to another while in spring (SON), this large negative zone practically disappears and there are small negative nuclei of change.

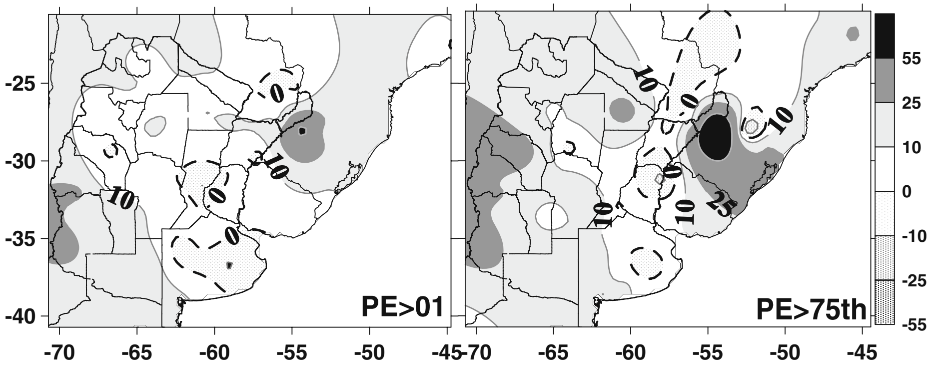

Fig. 9 Percentage of change for PE > 0.1 (*left*) and PE > 75th (*right*) between 1961–1975 and 1980–1996

The percentage changes of extreme events PE > 75th (Fig. 11) are more marked than PE > 01. Note how this extreme condition increases the spatial change during the summer and winter months. In summer (Fig. 11, DJF), a negative change occurs of more than 10% in the middle of the Paraná and Uruguay River basins, while in winter (JJA) the PE > 75th negative change area increases with nuclei higher than 25% and moves southward. In autumn and spring, there is an increase of extreme

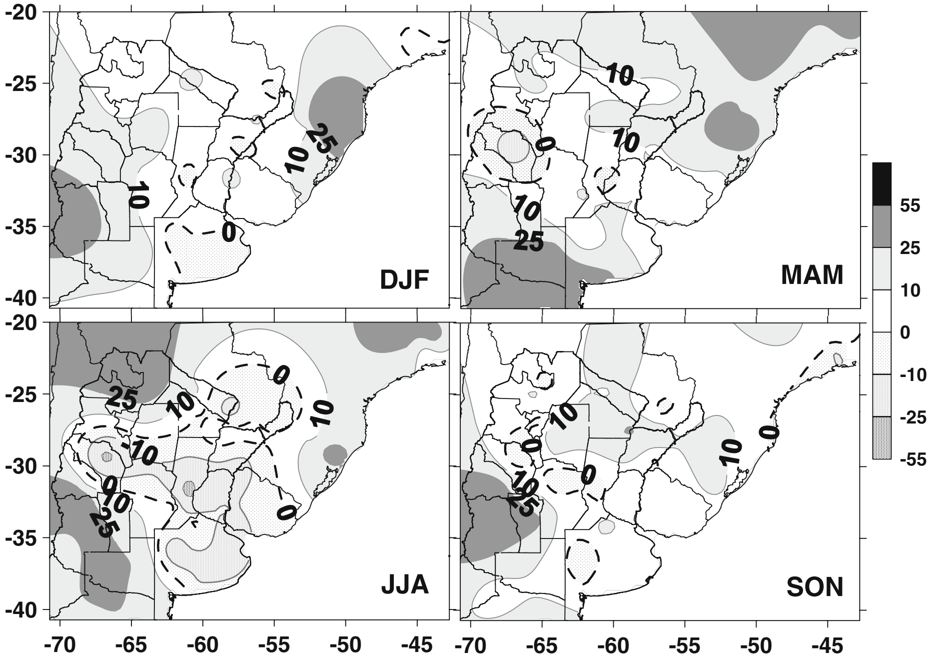

Fig. 10 Percentage of change for PE > 0.1 between 1961–1975 and 1980–1996 for summer (*DJF*), autumn (*MAM*), winter (*JJA*) and spring (*SON*)

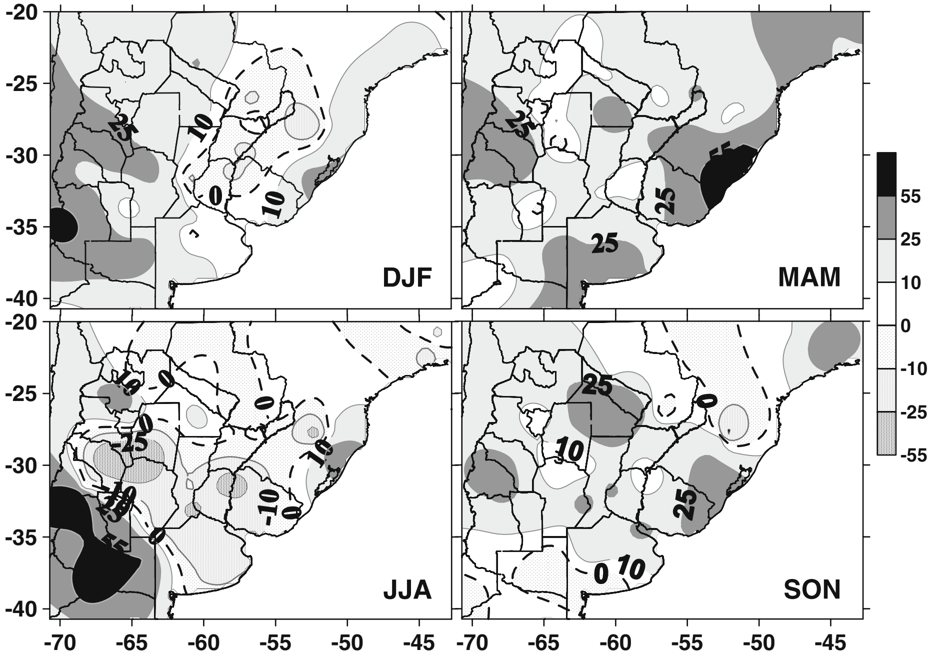

Fig. 11 Percentage of change for PE > 75th between 1961–1975 and 1980–1996 for summer (*DJF*), autumn (*MAM*), winter (*JJA*) and spring (*SON*)

events in the entire region with some areas showing more than 25%, with a maximum in the southeast of Brazil along the coast presenting an increase of more than 55% (Fig. 11, MAM and SON, respectively).

5 Discussion and conclusions

The purpose of this research was to examine the temporal variability and quantify the changes of daily rainfall and daily extreme precipitation events in stations located in La Plata Basin (LPB), the third largest basin in the world. These results can be applied to water, agricultural, and natural resources management, in addition to serving as a reference for the validation of regional circulation models. An extreme event is counted at each station for each day on which rainfall exceeds a given amount. Two indices were used in this study, the percentage of days with rainfall equal to or greater than the following thresholds: 0.1 mm (PE > 0.1) and 75th percentile (PE > 75th). Long series of high quality daily rainfall records were examined to obtain more accurate estimations of changes across the LPB region.

The low frequency variability of both indices showed regions of spatial coherence. Most of the LPB has positive annual trends, though more marked for PE > 0.1 than for PE > 75th. These annual changes are seasonally and spatial dependent. In summer, autumn and spring, the basin has a marked spatial coherence in the positive sign trends of both indices. Winter is the exception, with negative trends, some of which are significant in the lower and middle Uruguay and Paraná Rivers.

The stations located in southern Brazil show an overwhelming spatial consistency in terms of upward trends. In this region, the frequency of daily rainfall increases in the four seasons and in the extreme events during summer. This result produces immediate hydrological consequences because daily rainfall and extreme events increase.

The decadal analysis suggests positive shifts in the number of daily rainfall (PE > 0.1) of 33% between 1950 and 2000 to the west of the basin. These wetter conditions are much more marked in PE > 75th in summer, autumn, and spring. In winter, the extreme daily rainfall in the lower part of the Paraná River (Rosario) has decreased by 60% since 1950. Southern Brazil showed discontinuity in the 1970s with an increase of 80% in PE > 0.1 in summer and winter and 33% in spring and autumn. A significant temporal variability is seen in PE > 75th in the four seasons. At the mouths of the Paraná and Uruguay Rivers (OCBA) there is a 30% increase between 1910 and 1990 in summer in PE > 75th. In spring, however, the increase is very marked, reaching 150% between 1920 and 1990 is accompanied by a strong decadal variability in spring.

This temporal variability was synthesized calculating a percentage of change between two different periods. Both annual indices show an increase of around 10% for the region as a whole. The increments are caused mainly by a rise in summer, autumn and spring with over 25% in southern Brazil. In winter, at the center of the basin, the extreme events decrease by 10% with nuclei of up to 25%.

The annual PE index regime has varied, increasing or decreasing in amplitude during the past century, thus producing a variation in the seasonal contribution to the annual cycle. Like SCI01, SCI75 shows greater variability in the annual PE cycle from 1980 to 1996 as compared to the period 1961–1975. This growth in amplitude is mainly explained by the strong drop in SCI75 in winter. In SCI01, on the other hand, the decreasing winter contributes to greater amplitude of the annual cycle and summer increases are recorded in the second period.

The origin of climate variability and the relationship with rainfall across subtropical South America and, in particular, across the LPB could be found in the South American monsoon and its relationship with the South American converging zone (SACZ) and the LLJ (Nogues-Paegle and Mo 1997; Barros et al. 2002; Nogues-Paegle et al. 2002; Carvalho et al. 2004). In winter, the causes of rainfall in the LPB are the high frequency variability in latitude trajectories of the subtropical jet (30° S) which crosses South America and whose structure is similar to the baroclinical waves of middle latitudes (Vera et al. 2002).

The atmospheric phenomena of the meso and planetary scales certainly explain the low frequency variability, as well as the interannual or interdecadal variations of daily rainfall events. Consequently, once the spatial and temporal changes have been quantified, it will be possible for us to examine further the relationship between changes in the frequency of rain days and the different atmospheric scales.

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