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Extreme rainfalls in SE South America

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Abstract Heavy rainfall trends in a region of south-eastern South America during 1959–2002 were discussed using daily data of 52 meteorological stations of Argentina, Brazil and Uruguay. Changes in intensity and frequency were both studied with different statistical tests and approaches to check the significance of trends of single and regional aggregated rainfall series. There were predominant positive trends in the annual maximum rainfalls, as well as a remarkable increment in the frequency of heavy rainfalls over thresholds ranging from 50 to 150 mm. However, significant positive trends were not shown in the series of annual maximums and shown only in 15% to 30% of the series of frequencies over thresholds. This lack of significance is due to the high variability of heavy rainfalls in space and time, which makes difficult

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their capture by single rain gauges. Thus, when the assessment of the heavy rainfall indicators of intensity and frequency were conducted at the regional and sub-regional level, it showed significant trends, both in intensity and frequency over thresholds, with a clearer signal in central and eastern Argentina between 30° and 40° S.

1 Introduction

Heavy rainfall events, when lasting for one or more days, may give rise to floods, sometimes causing severe social, economic and environmental impacts. In recent times, floods have become increasingly frequent in south-eastern South America between 23° and 40° S attracting the public attention and raising the question if they were caused by a growing frequency of heavy rainfalls, or if were simply enhanced by deforestation and other changes in land use. Haylock et al. (2006) found that the pattern of the trends of extremes and of annual rainfall in South America during the last decades was generally the same. Thus, since annual rainfalls in south-eastern South America have been increasing during the last decades of the twentieth century (Barros et al. 2000, 2008; Liebmann et al. 2004), it is possible that the same could happen with heavy rainfalls.

Within a context of global warming, more intense and frequent heavy rainfalls should be expected at the global scale, as a result of more water contained in the atmosphere and, likely less thermodynamic stability (Kunkel 2003). In fact, the fourth IPCC assessment report concludes that there was an increasing rate of heavy precipitation in many mid-latitude regions during 1951–2003 that were over the expected variation due to the changes in the mean total precipitation (IPCC 2007). This implies that traditional statistical tools for flood risk assessment and infrastructure design, based on the hypothesis of stationary heavy rainfalls series, are inadequate and should be adapted considering climate projections and trends.

Extreme precipitation trends should not be expected to be uniform all over the planet, not only because warming and water vapour trends have regional differences, but because of other factors like the frequency and intensity of atmospheric precipitation systems and their respective changes. Thus, although there are several regional studies about heavy rainfalls (Mason et al. 1999; Kunkel 2003; Nadarajah 2005; among others), only few focused on southern South America, as in the case of Liebmann et al. (2004), who studied summer rainfall trends in a Brazilian part of this region, and the investigations of Khan et al. (2007) and Kuhn et al. (2007) on spatial and temporal variability of precipitation extremes.

South-eastern South America rainfall field has a general zonal gradient ranging from almost 2,000 mm in the northeast to less than 200 mm in some areas of the west. In the centre and west of the region, the precipitation regime has monsoon character with most of the rain falling in the warmer part of the year and very little in the winter. On the other hand, in the east, rainfall is more evenly distributed along the year (Grimm et al. 2000). Therefore, important differences in magnitude and seasonality of heavy rainfall between regions may be expected.

This paper analyzes heavy rainfall trends in a region of south-eastern South America, Fig. 1, during the last four decades of the past century. Changes in intensity and frequency are both studied at the regional and sub-regional level with different

Fig. 1 Regions and observation stations used in this study

statistical tests and approaches to check the significance of trends of single and regional aggregated rainfall series.

2 Data

The region of analysis is in the south-east of South America and stretches over central and eastern Argentina, south of Paraguay, south of Brazil and Uruguay. In this region, it was possible to identify and collect only 52 series of daily precipitation that were completed in the period 1959–2002. They correspond to the localities shown in Fig. 1, and are part of the networks of the National Meteorological Service (Argentina), the National Water Agency (Brazil), the Joint Technical Commission of Salto Grande (Argentina–Uruguay) and the National Direction of Meteorology (Uruguay). Some analyses were made at sub-regional level in the five areas shown in Fig. 1, where annual precipitation and regime were approximately uniform within each of these regions.

Rainfall data were not available at the hourly level, but for daily totals. Therefore, it was not possible to make analyses of 24 h maximum precipitations, which could frequently be spread in two calendar days. Consequently, since some extreme rainfalls may be distributed in two consecutive days, daily data may lose some extreme precipitations. To avoid this problem, the analyses were performed on the 2-day precipitation series. Accordingly, to convert 1-day series into 2-day series, for d_i day, the rainfall corresponding to that day plus the one of the following day $p_i + p_{i+1}$ was computed. When two consecutive 2-days fall in any category of extreme events, only the maximum of both was chosen to keep the independence between data (declustering).

3 Preliminary analysis

As a first approach to the study of trends of extreme precipitation intensities and frequencies during 1959–2002, an ordinary least-squares linear trend analysis of annual maximums was made for the 52 series. The number of series with positive trends outnumbers the negative ones by a factor of more than two (38 positives and 14 negatives). In addition, the spatial distribution of the trend signs shows a clear predominance of the positive ones, Fig. 2.

Another first approach was the assessment of changes in the frequency of heavy precipitation. Extreme events were counted when exceeding a defined threshold. The analysis for change points in the annual values of these frequencies using the non parametric method of Pettitt (1979) does not indicate a clear pattern for the changing points. Next, the ratio between the quantity of extreme events was calculated in the last 20-year period of the analysis, 1983–2002, and those in the first 20-year-period, 1959–1978. Figure 3 shows the frequency ratio for different thresholds. In most of the region, the frequency of extreme events was sensitively higher in the second period (ratio higher than 1). For the 50, 75 and 100 mm thresholds, there are large areas with ratios between one and two, with the greatest values in the south of Brazil. For the 125 mm threshold, the ratio reaches the greatest values (even more than four) in the north the region, as well as important values in central Argentina. In the case of the 150 mm threshold, the ratio reaches even higher values in the northeast of Argentina, but there is a vast region with values lower than 1 in the south of the region.

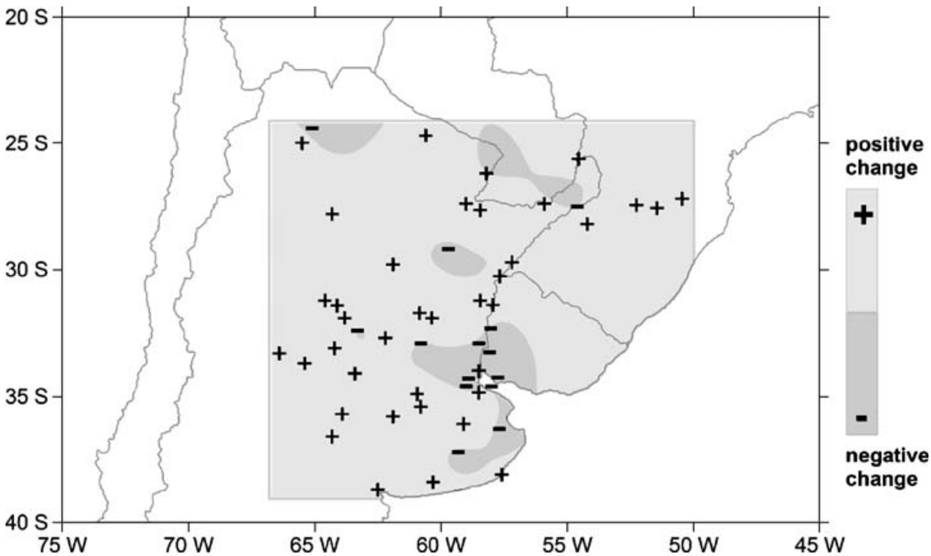


Fig. 2 Change in the intensities of annual maximum rainfall events (1959–2002)

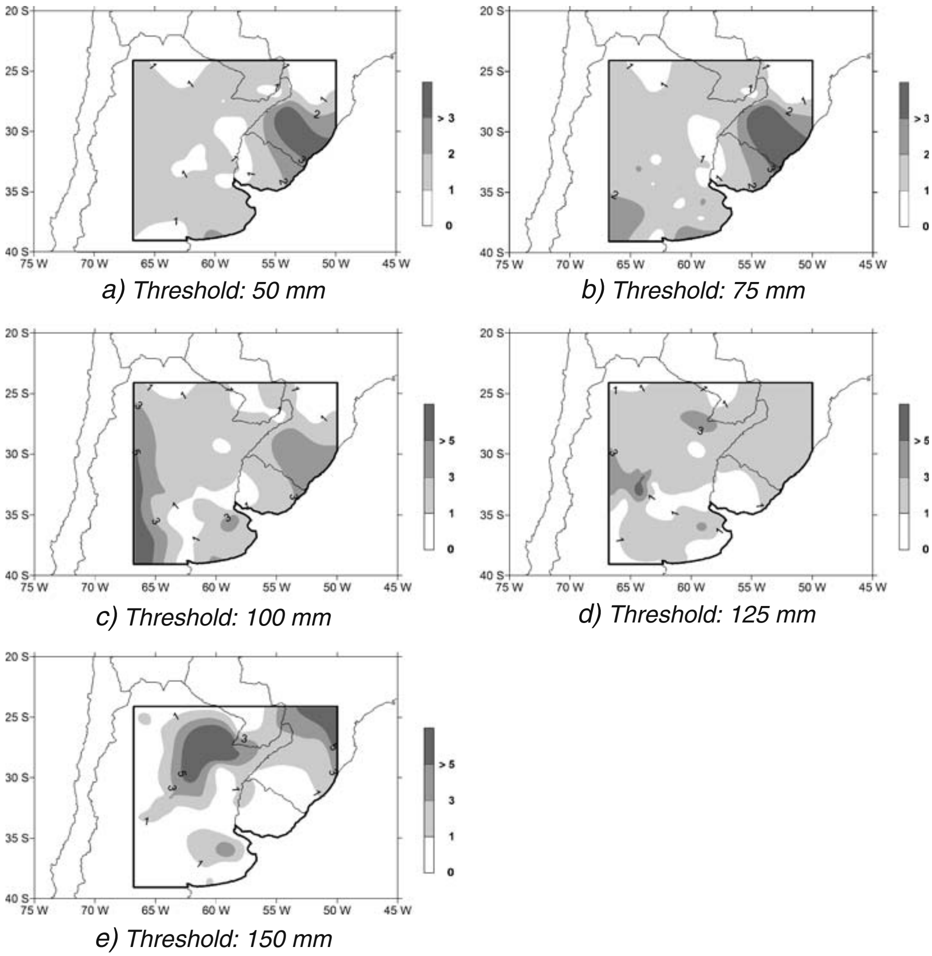


Fig. 3 Rate of frequencies over the indicated thresholds (1983–2002/1959–1978). **a** Threshold, 50 mm. **b** Threshold, 75 mm. **c** Threshold, 100 mm. **d** Threshold, 125 mm. **e** Threshold, 150 mm

This preliminary analysis indicates that there were predominant positive trends in the annual maximum rainfalls between 1959 and 2002, as well as a remarkable increment in the frequency of extreme precipitation over different thresholds ranging from 50 to 125 mm.

4 Analysis of the intensity of heavy rainfalls

4.1 Analysis of extreme values

The extreme values techniques are being widely used in many other disciplines like the insurance industry, risk assessment in financial markets or the prediction of traffic in telecommunications (Coles 2001). It is important to know the limitations of these techniques when coming to conclusions, because modeling extreme event distributions is in general associated with a large margin of error as extreme events are, by definition, rare, and therefore very few large values are available to estimate the appropriate parameters (Naveau et al. 2005).

4.2 Distributions of extreme values

The classical extreme values theory describes how, for sufficiently long sequences of independent random variables identically distributed, the maximums of n size samples can be adjusted to the Generalized Extreme Value distribution (GEV) (Coles 2001):

$$G(z) = \exp\left[-\left(1 + \gamma \times \frac{z-\mu}{\sigma}\right)^{-1/\gamma}\right] \tag{1}$$

defined on $1 + \gamma \times (z - \mu/\sigma) > 0$, where μ is the location parameter, $\sigma > 0$ is the scale parameter and γ is the shape parameter. Like the mean and standard deviation of the more familiar normal distribution, the location parameter specifies where the distribution is "centered", the scale parameter its "spread" and the shape parameter determines one of the three possible types of the distribution shape (Katz et al. 2005).

To fit GEV distributions, data are grouped in blocks of the same length, adjusting each block's maximums (rainfall annual maximums of 2 days, in this case). In this technique (BM, Block Maxima approach), the choice of the block size can be critical since small blocks can lead to bias, and blocks that are too large generate very few maximums, leading to large estimation variance (Coles 2001).

GEV distribution adjustment requires few decisions by the user, but does not make use of all the available information of the upper tail of the probability distribution. As an alternative, when considering the maximums within certain period, it is possible to consider those values of the series that go beyond a given threshold. This technique uses the values exceeding a given threshold (POT, Peaks Over Threshold) to make a more efficient use of the existing information. However, with the POT, the user must make more decisions than with the BM approach, i.e. choosing the threshold and the minimum separation between events.

An adequate asymptotic distribution to describe the behavior of events over a threshold is the Generalized Pareto Distribution (GPD) defined by Coles (2001) as:

$$H(y) = 1 - \left(1 + \frac{\gamma \times y}{\tilde{\sigma}}\right)^{-1/\gamma} \tag{2}$$

defined on $1 + \gamma \times (y/\tilde{\sigma}) > 0$, where

$$\tilde{\sigma} = \sigma + \gamma \times (u - \mu) \tag{3}$$

All three μ, σ y γ parameters have the same function that are in the GEV distributions, and y are the excesses over a selected threshold u.

The choice of a threshold implies a balance between the bias and the variance of the distributions (May 2004). Two procedures were proposed by Coles (2001) to choose thresholds: the interpretation of a mean residual life plot and the model estimation at a range of thresholds.

4.3 Rainfall series fittings

In this study, the variable of interest is the extreme rainfall intensity. The fittings to each rainfall series were performed using the Maximum Likelihood method. The principle of this estimation is to adopt the model with greatest likelihood, which is the model that assigns highest probability to the observed data (Coles 2001). This method has the great advantage of allowing the addition to the fitting of co-variables (such as trends, cycles or physical variables) (Katz et al. 2002).

4.3.1 Generalized extreme value distribution (GEV)

The GEV distribution was fitted to the 52 series of 2-day annual maximums. First, a basic model (Model 1) was fitted with the location (μ), the scale (σ) and the shape (γ) parameters unvarying in time, suggesting a stationary series. Then, to identify possible trends with time, a second model was fitted with a linear trend in the location parameter (Model 2).

$$\begin{array}{llllll} \text{Model 1}: & \mu \quad \text{const.} & \sigma & \text{const.} & \gamma & \text{const.} \\ \text{Model 2}: & \mu\,(t) = \mu_0 + \mu_1 \times t & \sigma & \text{const.} & \gamma & \text{const.} \end{array}$$

The measure of fitting of these models was examined through probability plots and Q–Q (quantile–quantile) plots (Coles 2001). Figure 4 illustrates the probability and Q–Q plots of one series, fitted according to Model 1. In all the series, fittings of this quality were observed.

To determine which of the two models fits better to each series, the Likelihood-Ratio Test was applied (Nadarajah 2005). This methodology is valid when analyzing nested models; this means that the most complex model differs from the previous model only for the addition of one or more parameters (in our case the most complex model is Model 2, which has the parameter of location variable in time). The results of the Likelihood-Ratio Test of the two models show that in all the cases the series do not have a significant trend at the 90%, 95% and 99% confidence levels in the annual maximums.

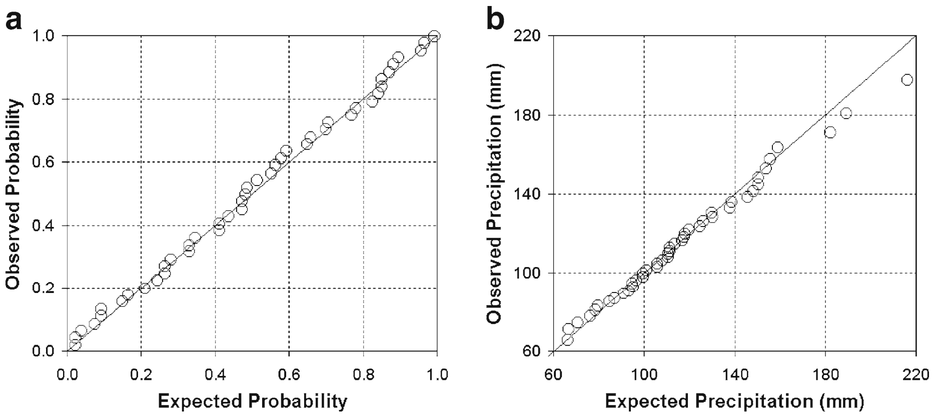


Fig. 4 Probability plot (**a**) and quantile–quantile plot (**b**) in Nueve de Julio, Model 1

This lack of significance may be caused by the high variability of the annual maximum at a given site as measured by a rain gauge. Therefore, two regional annual maximums were explored, the maximum of all the 2-day annual maximums observed within each region and the annual maximum of the 2-day average rainfall of all regional series. In neither of the two cases were there significant trends found in any of the five sub regions.

4.3.2 Generalized pareto distribution (GPD)

Although there is a general predominant positive trend, Fig. 2, the aleatory behavior of precipitation, even aggregated at sub regional scale, makes difficult to find significant trends. As explained by Coles (2001), modeling with the maximum value per block wastes other potentially useful information for the extreme value analysis. Then, considering that results can be influenced when utilizing the block method, the series were fitted to the GPD as an alternative to the GEV distribution. The selection of the most suitable thresholds for all the series was made by plotting the mean excesses and the values of the shape parameter according to a given range of feasible threshold values. May (2004) states that if the corresponding distribution provides a reasonable approach, a good practice is to adopt a threshold to be as low as possible and Clarke (2006) proposes to choose thresholds that have three or four annual excesses. Based on these criteria, following the procedures outlined in Section 4.2, a threshold selection was performed for each series.

Firstly, the GPD was fitted to each series considering a stationary behavior of the scale and shape parameters, Model 1. Then, in order to detect the presence of trends in the values of rainfall intensity, the GPD was fitted assuming a temporal variation of the scale parameter (σ), Model 2. The scale parameter stands for the energy of an extreme event and it may change with time.

$$\begin{array}{llll} \text{Model 1}: & \sigma \quad \text{const.} & \gamma & \text{const.} \\ \text{Model 2}: & \sigma\,(t) = \sigma_0 + \sigma_1 \times t & \gamma & \text{const.} \end{array}$$

The results obtained for the fitting according to Model 1 show accordance of similar quality to those observed with the GEV model, Fig. 5.

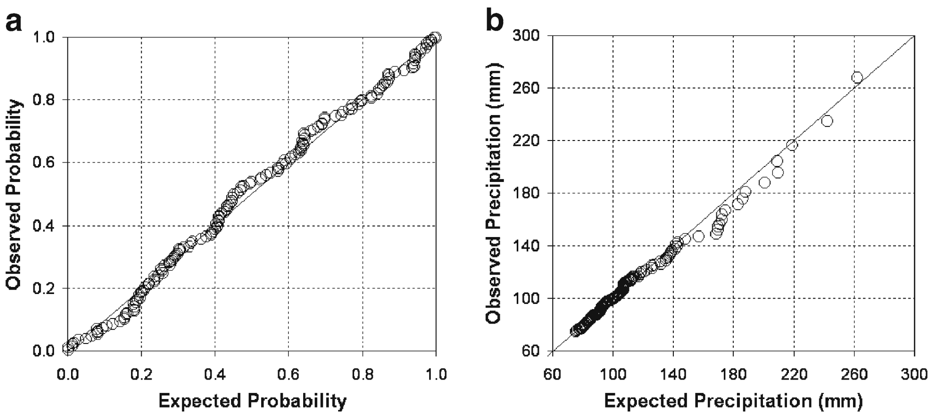


Fig. 5 Probability plot (**a**) and quantile–quantile plot (**b**) in Resistencia, Model 1

Table 1 Confidence level of positive trends in the variables indicated in left column

Variable	Region 1 (%)	Region 2 (%)	Region 3	Region 4	Region 5
Maximum of all annual rainfall maximums	95	95	–	–	–
Annual maximum of regional average rainfall	90	–	–	–	–

The Likelihood-Ratio Test was also applied to evaluate which of the two proposed models was the most adequate for the available series. Model 2 adjusted better than Model 1 showing a positive trend in intensity in 13 cases at different levels of confidence: Río Cuarto (RCU, 99%), Corrientes (COR, 95%), Dolores (DOL, 95%), La Estanzuela (ETZ, 95%), Girua (GIR, 95%), Paraná (PAR, 95%), Ceres (CER, 90%), El Palomar (EPA, 90%), Ezeiza (EZE, 90%), Laboulaye (LAB, 90%), Rosario (ROS, 90%), Tandil (TAN, 90%) and Villa Maria (VMA, 90%). Despite these results, the number of series with significant trends, 13 out of 52, is not sufficient to conclude that there was a significant positive trend of the rainfall intensity in the whole region.

To explore the regional behaviour, as in the GEV case, the trends of the maximum of all the 2-day annual maximums observed within the sub regions and the annual maximum of the 2-day arithmetic average rainfall of all the regional series were analyzed, Table 1. The POT methodology using the GPD shows that in region 1 and 2, there were significant positive trends, indicating that the significance of the heavy precipitations in those regions is sensible to the method used.

5 Frequency of heavy rainfalls

To detect trends in heavy rainfall frequency, 2-day precipitations exceeding 50, 75, 100, 125 and 150 mm thresholds were counted. Then two alternative analyses were followed, comparing stationary and non stationary Poisson processes and applying the non parametrical Mann–Kendall test.

5.1 Poisson distribution

It was firstly performed the study for each location, considering rainfalls exceeding a high enough threshold so that these rainfalls were considered extreme events. Since the Poisson distribution is an approach to the Binomial distribution for rare events, it is reasonable to assume that these events follow a Poisson process (Katz et al. 2005).

The Poison probability distribution is:

$$F(x) = \frac{e^{\lambda} \times \lambda^{x}}{x!} \tag{4}$$

λ being a positive real number, equivalent to the expected number of occurrences during a given interval. This parameter is at the same time its mean and variance. The Poisson process implies independent events, which is not always true when dealing with natural processes (Beguería 2005). However, in the case of heavy rainfall events, this is an acceptable assumption.

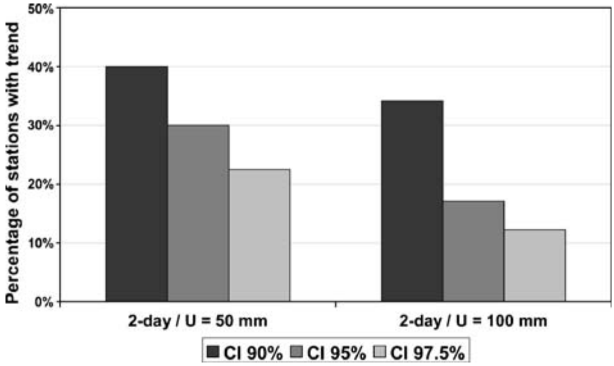


Fig. 6 Percentage of stations with significant positive trends in frequency over the indicated thresholds

The Poisson distribution fittings were performed for the annual number of 2-day rainfalls over the 50 and 100 mm thresholds. These values were chosen as representatives of a low and a high threshold, considering that rainfall variables present an important east–west gradient in eastern South America and therefore in many west locations, events over the higher thresholds are extremely rare or did not happened at all. The Chi-Square test (χ^2) was performed to assess the adjustments to the Poisson distribution. Out of the 52 series, 45 fitted well for the 50 mm threshold and 41 for the 100 mm threshold.

The series that fitted the Poisson distribution were also fitted to a non stationary Poisson process, adopting a model with the λ parameter variable with time (Katz 2002):

$$\log \lambda(t) = \lambda_0 + \lambda_1 \times t \tag{5}$$

To evaluate which of the two models is the better option (stationary or non-stationary), the Likelihood-Ratio Test was performed. Figure 6 shows that less than half of the series have significant positive trends. As already discussed for trends in the intensity of the heavy rainfalls, these events are extremely aleatory and therefore, it is hard for their trends to reach statistical significance. However, the fact that there was a considerable percentage of series with significant trends deserved further analyses, especially at the regional level.

5.2 Mann–Kendall test

The Mann–Kendall test (Mann 1945; Kendall 1975) has been widely used to estimate the significance of trends of time series. This non-parametrical test is suitable for

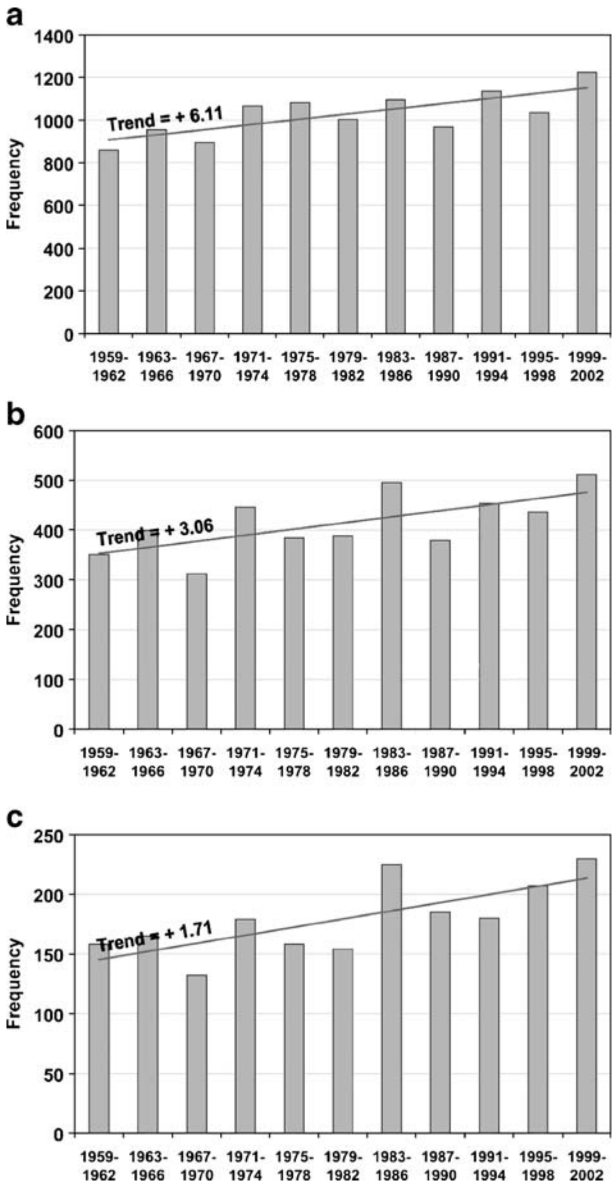
Table 2 Number of series with positive (POS) and negative trends (NEG) and respective percentage

Threshold (mm)	POS	POS %	NEG	NEG %
50	45 (11)	87 (21)	7 (1)	13 (2)
75	42 (13)	81 (25)	10 (1)	19 (2)
100	41 (16)	79 (31)	11 (1)	21 (2)
125	39 (15)	75 (29)	13 (2)	25 (4)
150	36 (7)	69 (14)	16 (3)	31 (6)

In brackets, the number and percentage of significant trends at 90% level abnormal distributions of data and measurements, which are frequently found in hydro meteorological series (Yue et al. 2002). Many studies have used this test to detect trends of heavy rainfalls (Fu et al. 2004; Houssos and Bartzokas 2006; Ramos and Martinez-Casasnovas 2006; Su et al. 2006).

As shown in Section 5.1, about 20% of the series of annual rainfalls over thresholds did not fit the Poisson distribution. To avoid the requirement of fitting a probability distribution to the frequency series of extreme rainfalls, the Mann–Kendall test was performed for each of the 52 series of annual cases with 2-day

Fig. 7 Frequency of occurrence of extreme events in the region of the study over thresholds as follows: **a** 50, **b** 75, **c** 100, **d** 125, **e** 150 mm. Trends indicated in the panels are number of cases/year



rainfall over 50, 75, 100, 125 and 150 mm thresholds. Table 2 shows the number and percentages of series of the entire region with positive and negative trends for each threshold. There is a clear prevalence of positive trends, which for low thresholds are over 80%.

The percentages of series with significant trends are not higher than 31% in any case. This result is similar to what was obtained when comparing the Poisson stationary and non-stationary distribution for each series.

5.3 Regional rainfall frequencies over thresholds

Although the series of frequencies over thresholds show positive trends, only a minority of them are statistically significant. As already mentioned, the lack of significance may be caused by the high variability of heavy precipitations at a given location. This variability comes from the fact that the areas of heavy rainfall in events that are characterized by convective activity are generally small as compared with the dimension of the total area of the rainfall event. Therefore, it makes sense to assess the heavy rainfall frequency at the regional level, because these events are more likely to be revealed by several observations than by a single one. In addition, rainfall in south-eastern South America has an important interannual variability (Grimm et al. 2000) that may contribute to reduce the significance of long-term trends when the series are made up of annual values.

Fig. 7 (continued)

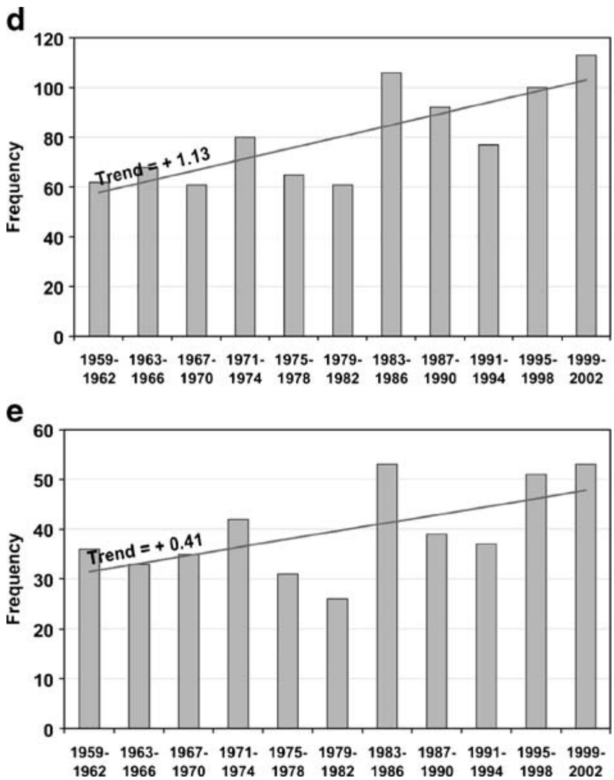


Table 3 Confidence level of positive trends of the frequency of rainfalls over the indicated thresholds

Threshold (mm)	Entire region (%)
50	97.5
75	90
100	97.5
125	95
150	–

Therefore, to assess long-tem trends, rainfall events that exceed certain thresholds for the entire region (52 stations) were counted for 4-year periods, starting in 1959–1962 and finishing in 1999–2002, Fig. 7.

The Mann Kendall test, applied to these series, shows positive trends with a 90% level of confidence, except for the 150 mm threshold, Table 3. Of course, the absolute number of cases diminishes with the value of the threshold. Then, to compare the trend over different thresholds, the percent increase between the end points should be considered. The percent trend increases with the threshold value; it is 20–30% for 50 and 75 mm, about 50% for 100 mm and almost 100% for 125 mm, and again 50% for 150 mm. This is consistent with Liebmann et al. (2004) who found, for the south of Brazil and for the period 1976–1999, that the number of extreme events (1-day rainfall over the 100 mm threshold) of the last 6 years was more than twice the one of the first 6 years.

When the entire region is considered, the frequency of extreme events is significant for all the thresholds except for 150 mm. This may happen because of the very few cases observed over that value. However, it may be also due to the fact that rainfalls over that value have some sort of physical constrains. In fact, the percent increase of the number of rainfalls over 150 mm in the period 1959–2002 was considerable lower (50%) than that of those over 125 mm (73%), a relatively not too much lower threshold; Fig. 7d, and e.

As in the case of station series, the Pettitt's test (1979) was applied to the regional series of annual frequencies over different thresholds to look for changing points. A clear point of change was not observed, except at the end of the period of the study in the second part of 1990 decade. This changing point in the late 1990s deserves further attention, but requires regional data, reaching present time, that are not still available.

The geographical distribution of the significant trends in the frequency of extreme events was explored applying the same methodology to the five sub-regions depicted in Fig. 1. The results are shown in Table 4. Region 3 appears as an area where the trends in the frequency of extreme rainfalls are highly significant. Regions 1 and 4, in addition to those cases shown in Table 3, have significant trends at a level lower than

Table 4 As Table 3 but for five sub-regions

Threshold (mm)	Region 1 (%)	Region 2 (%)	Region 3 (%)	Region 4 (%)	Region 5 (%)
50	95	–	99	90	–
75	–	–	95	–	–
100	95	–	99	–	–
125	–	–	99	–	90
150	–	–	–	–	–

Table 5 As Table 3, but for the 4 western stations of region 2

Threshold (mm)	Region 2 (4 western stations), %
50	–
75	–
100	90
125	99
150	–

90% (not shown) and contribute to the significance of the regional trend, although in a lesser degree than region 3. On the other hand, regions 2 and 5 do not seem to show significant trends in their frequency of heavy rainfalls. However, when looking in detail at region 2, the western stations of Ceres (CER), Paraná (PAR) Sauce Viejo (SVI) and Rosario (ROS) have a behavior rather similar to that of the nearby region 3, Table 5.

6 Discussion and conclusions

When considering each of the 52 complete daily series that were available, the trends of annual maximum rainfall in the southeast of South America were by large positive during 1959–2002, Fig. 2. Similarly, changes in the frequency of rainfall events over thresholds ranging from 50 to 150 mm were predominantly positive, 69% to 87% of the series. These results indicate that heavy precipitation became more frequent and intense in the last decades in the region. However, when these trends were analyzed to asses their statistical significance, results were more ambiguous. This was in part because heavy precipitation indices are highly variable, especially when they are based on measurements at a single rain gauge. Thus, it is difficult to asses if the observed trends are responding to a real change or are resulting by chance from the typical variability of the series.

Furthermore, the Block Maxima approach, applied to rainfall annual maximums, uses only a very limited part of the extreme value data and therefore does not help to identify significant trends when the series are not very long, as in the cases analyzed in this article. Thus, the Generalized Pareto Distribution (GDP), which considers values over given thresholds and consequently uses more information, was also applied. But, even when using the GDP for individual series, the number of series with significant trends is not sufficient to conclude that there was a significant positive trend of the rainfall intensity in the region. Similar results are found when frequency of precipitation over high thresholds were analyzed using the Poisson distribution.

To manage the large variability of heavy rainfalls, the use of regional indicators, as the maximum of all the maximums of individual series, the maximum of the average regional precipitation or in the case of frequency over thresholds, the number of cases reported in the region during a block of years, were explored. Since part of the interannual variability is associated to ENSO in the region, blocks of 4 years permit to filter part of this variability. With this regional approach, significance appears in both, annual maximum, regions 1 and 2 in Table 1, and frequency over thresholds trends, in Tables 3, 4 and 5. The integrated numbers of events over thresholds over the entire region are significant for thresholds ranging from 50 to 125 mm, a clear signal that there was a regional trend in heavy precipitations.

The regions that show more heavy precipitation indices with significant trends are in the south of the region, namely those numbered 1 and 3 in this article and also in the west part of region 2. Significances below 90%, not shown, indicate that region 4 (northeast) has also positive trends with high probability of not being a casual result from the interannual variability of these indices. On the other hand, the northwest, region 5, has few signals of positive trends in these indices. Therefore, it can be concluded that the region where extreme precipitations have been increasing over the 1959–2002 period is the one shown in Fig. 8.

It is not the intention of the article to identify the physical causes of the observed upward trends in the indices of heavy precipitation. However, the issue deserves a brief discussion in the context of recent literature. Barros et al. (2000) found that there was a positive trend in the annual precipitation over the whole region of this study. Haylock et al. (2006) calculated various annual indices of daily rainfall in South America over the period 1960 to 2000. They found that the pattern of the trends of extremes and of annual rainfall was generally the same, with a change to wetter conditions in southern Brazil, Paraguay, Uruguay, and northern and central Argentina. This was consistent with the results of this article, considering that they had a few, but good quality series available, and therefore could only address very large scale features.

Precipitation over most of south-eastern South America has a general response to El Niño/Southern Oscillation (ENSO), with wetter (drier) conditions during El Niño (La Niña) phase. Frequencies of extreme rainfalls hold a similar relationship as shown by correlations between rainfalls over different thresholds with the sea surface temperature (SST) in the El Niño region 3.4 and the Pacific Decadal Oscillation index (PDO), Table 6. SST temperature at El Niño regions are indicators of the ENSO

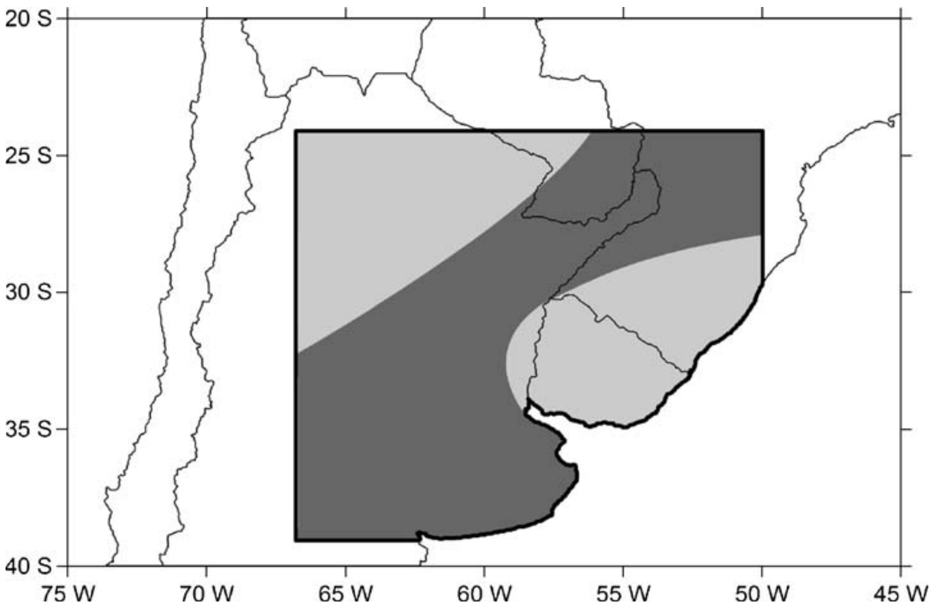


Fig. 8 In *black*, the region with increasing trends in heavy precipitation indicators

Table 6 Linear correlation coefficients between annual frequency of rainfalls over the thresholds (in the entire region of the study) and the indicated variables (confidence level in brackets)

Threshold (mm)	El Niño 3.4 SST	PDO
50	0.35 (97.5%)	0.23 (*)
75	0.33 (95%)	0.24 (*)
100	0.34 (97.5%)	0.29 (90%)
125	0.17 (*)	0.21 (*)
150	0.13 (*)	0.11 (*)

*Not statistically significant at 90%

as well as the Southern Oscillation Index (SOI). Correlations of the frequency of rainfalls over thresholds with the SOI are almost equal, but with opposite sign, to those with El Niño 3.4 SST, and therefore are not shown in Table 6.

The positive (negative) PDO phase is an indicator of high (low) El Niño activity. Its last positive phase, starting in the 1970s, could then be a factor favoring the growing frequency of extreme precipitation in the region, consistent with its positive correlation with the frequency of rainfalls over different thresholds. More generally, Haylock et al. (2006) found that the change to a generally more negative Southern Oscillation index (SOI) has had an important effect on regional rainfall trends. However, this is true for the northern part of the region of this study, but not for the southern part, regions 1, 2 and 3, where the more clear signal in heavy rainfall trends where found and where annual precipitation trends were the result of trends during the neutral phase and not during El Niño or La Niña phases (Barros et al. 2008).

Therefore, other hypotheses for the observed regional trends should be explored. There are physical reasons to expect more heavy precipitation with atmospheric warming. Kunkel (2003) discussed these reasons, arguing that in the first place, atmospheric water vapour generally increases in a warmer atmosphere as water vapour pressure increases rapidly with temperature and consequently, atmospheric precipitation systems have more water available. In fact, the special sensor microwave imager, available after 1988, provides generally positive trends in precipitable water for the 1988–2003 period, with an average of 0.4 mm per decade for the ocean as a whole (Trenberth et al. 2005). In addition, in the context of global warming, it is expected that temperatures will increase near the surface and decrease in the upper troposphere, favouring thermodynamic instability and the chances of deep convection (Kunkel 2003). Therefore, under the current global warming, the possibility of widespread enhancement of heavy rainfall intensity and frequency cannot be ruled out. In fact, there are large continental regions where the increase in heavy precipitation during the past decades was higher than that expected from the increase in the annual precipitation, and this increase occurred even in some regions where either no change or a decrease in annual precipitation was observed (Groisman et al. 2005). In addition, changes in heavy precipitation frequencies were always greater than changes in annual precipitation.

In the region of this study, there is not yet literature on trends of the factors that could influence heavy rainfalls, except in the case of surface temperature. Vincent et al. (2005) did not find trends in the maximum temperatures. However, they found significant positive trends in the minimum temperature during summer and autumn, the seasons that account for most of the annual rainfall in regions 1, 2 and 3 and where rainfall is frequently caused by convective activity. Precisely, the minimum temperature could control the amount of water vapour contained in the atmosphere and, therefore, its raise would indicate more water vapour available for the precipitation systems and in particular for convective clouds.

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