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Statistical analysis of the precipitation trends in the Patagonia region in southern South America

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RESUMEN

Este trabajo describe la climatología de la lluvia en la Patagonia Argentina y aborda el problema de las tendencias. Se usó un conjunto de datos matriciales provenientes de la Universidad de Delaware además de los observados, obteniendo resultados similares. La amplitud del ciclo anual de precipitación en la Patagonia muestra un máximo en el noroeste y revela que la lluvia en invierno, supera a la de verano, especialmente sobre los Andes. Tanto el análisis de componentes principales aplicado a las anomalías mensuales de lluvia como la aproximación lineal de la evolución de la precipitación anual calculada, muestran tendencias positivas de precipitación en el norte y el sur patagónico y negativas en el oeste y en la zona central. Se utilizó además una metodología no lineal para estudiar las tendencias y se identificaron puntos de quiebre donde el comportamiento de las tendencias cambia. En el noreste patagónico y en una pequeña región al sur de la provincia de Santa Cruz se observó un cambio en la tendencia de la precipitación en la década de 1960 mientras que al noroeste este cambio es evidente en la década de 1970. Sin embargo, en las proximidades de la Península de Valdez el cambio predomina en la década de 1990.

ABSTRACT

This paper describes the rainfall climatology in Argentinean Patagonia and faces with rainfall trends. Gridded precipitation dataset from Delaware University is used as an alternative data and they seem to reflect the same patterns that the observed ones. The mean annual precipitation shows maximum amplitude in Patagonia, winter values greater than in summer in the northwest, especially in the west and over the Andes. Both, principal component analysis (PCA) applied to the monthly anomalous precipitations and linear annual rainfall trends, show positive trends in north and south of Patagonia, meanwhile precipitation tends to decrease in the western and central zone. An alternative nonlinear methodology, a piecewise linear function, is used to detect a number of breakpoints in order to identify the moments at which the tendency changes its behavior.

Northeast of the Patagonia region and a small zone to the Southeast of Santa Cruz experienced a change in the annual tendencies of precipitation later to the decade of 1960. To the northwest, a vast region denotes a change in precipitation in the 1970 decade, whereas in the environment of the Peninsula of Valdez, the decade of 1990 is in which the change seems to predominate.

Keywords: Precipitation, nonlinear analysis, principal components.

1. Introduction

East of the Andes the Argentinean Patagonia region is located in the southeastern continental extreme of America, between 30 and 55°S and includes the provinces of Neuquén, Río Negro, Chubut, Santa Cruz and Tierra del Fuego. Situated between the southern verge of the subtropical pressure belt and the intensified subpolar low-pressure trough, Patagonia is governed by the prevailing westerlies of the middle latitudes and affected by the most characteristics disruption of troughs, wedges, cyclones, anticyclones and fronts (Prohaska, 1976).

The increase of cloudiness over the southern Patagonia region corresponds to the intensification of the westerlies in summer, while during the same season the decrease of cloud cover over the northern Patagonia must be attributed to the southward shift of the subtropical anticyclone.

A comparison between the dry Patagonian plains and the humid coast shows very slight influence of the Atlantic on the plains. The most favorable conditions for precipitation in the Patagonian mountains and its eastern slopes are stationary fronts in situations that the cold side of the anticyclone brings moist winds from the Atlantic. The result is stratiform and extended rainfall. In few cases, rainfall occurs due to blocking high pressure systems located in Patagonia or the adjacent Atlantic resulting in extended periods with cloudiness and precipitation.

The highest recorded annual totals of over 3,000 mm are found in the southern cordillera between 40 and 45° S (although situated to the lee of the rain-bearing winds). Rainfall increases suddenly south of 33° S, on the main ridge of the Andes and extends eastwards at the same time.

Studies on trends or low frequency oscillations in precipitation over Argentina have been developed since de 1950's (Schwerdfeger and Vasino, 1954; Díaz, 1959). These researches showed that precipitation tends to reduce in subtropical Argentina, in periods in which a strong index of zonal circulation exists on the Patagonia. From the 1960's precipitation increased considerably in most of the Argentine territory (Castañeda and Barros, 1994). The analysis of seasonal precipitation trends in the Argentine semi-arid region to the north of 40º S performed by Barros and Castañeda (2001) showed positive trends during summer. Regional aspects during summer were also studied by Compagnucci and Vargas (1983) in western Argentina, finding positive trends throughout the 20th Century. Barros and Doyle (1996) focused in the southeast of Brazil and north of Argentina. Barros and Mattio (1978) and Barros and Rodríguez Seró (1979) analyzed important long-term changes in precipitation over the northern plateau of the Patagonia, specially during the rainy period that occurred in the 1940's.

Usually, precipitation has been studied as an event influenced by linear trends or by discontinuities in long-term averages. During the last decades there have been a large number of papers discussing long-term linear trends of climate parameters, such as precipitation, and many of them pointed out that a linear trend is not adequate to describe its low frequency behavior. Karl *et al*. (2000) detected on global temperature time series a mean warming in two sustained periods. In order to separate the two periods of warming, they identify the discontinuities in the time series and evaluate the partial trends. On South America, Minetti *et al*. (2003) performed an analysis of nonlinear trends in precipitation over Argentina and Chile using polynomial functions and spectral estimations.

The purpose of this paper is to understand the general knowledge of precipitation behavior, including its evolution and variability in the Patagonian region. With this aim, traditional data from rain gauges have been used as other authors have done. But in this case the efficiency of a gridded precipitation dataset is evaluated to replace the traditional ones in the regions with no availability of rain gauges. Section 2 describes the methodology and datasets and section 3 contains the main results: the feasibility of using gridded precipitation data to replace the lack of measurements, the mean annual cycle of precipitation and the low frequency, lineal and non lineal precipitation changes. Finally, the main conclusions are summarized in section 4.

2. Data and methodology

Monthly precipitation data from stations were provided by the Servicio Meteorológico Nacional of Argentina (SMN). Weather stations with complete and consistent records were only considered. In order to achieve stable and representative statistical results almost 15 stations series were chosen (Table I, Fig. 1). Some other sources in this region have been analyzed but they were not considered due to their uncertain quality. The data were available for the common period of 1950-1999, and included the observed "climatic jump" during 1950's and 1960's (Minetti *et al*., 2003).

Monthly gridded precipitation data from the University of Delaware (hereinafter UDEL) (http://climate.geog.udel.edu/~climate/index.shtml) were used. These data were derived from 20,599 stations (Global Historical Climatology Network Version 1.02) and from 26,858 stations and oceanic measurements (Legates and Willmott, 1990a and b) that following the algorithm of the Shepard's distance-weighting method and they were gridded each 0.5° latitude × 0.5° longitude.

Table I. Meteorological stations selected. Significant correlation at 95% confidence are underlined.

	Latitude	Longitude		Latitude	Longitude
Bariloche	–41.15	–71.17	Puerto Deseado	–47.73	–65.92
Maquinchao	–41.25	–68.73	Lago Argentino	–50.33	–72.30
San Antonio Oeste	–40.73	–64.95	San Julián	–49.32	–67.75
Viedma	–40.85	–63.02	Santa Cruz	–50.02	–68.57
Esquel	–42.93	–71.15	Río Gallegos	–51.62	–69.28
Trelew	–43.20	–65.27	Río Grande	–53.80	–67.75
Comodoro Rivadavia	–45.78	–67.50	Ushuaia	–54.80	–68.32
Gobernador Gregores	–48.78	–70.17			

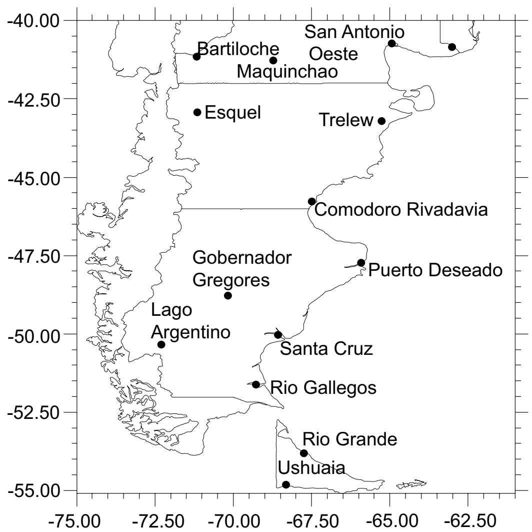

Fig. 1. The stations in the Argentinean Patagonia used in this study.

The spatial-temporal behavior of the precipitation was studied using principal component analysis (hereinafter PCA) (Green, 1978). T-Mode PCA with correlation among spatial patterns was performed on annual precipitation station data, in order to isolate subsets of fields that have similar spatial variability. In this mode the principal scores (PC) are spatial patterns and the principal loadings (PL) are time series that represent the correlation between the models and the actual spatial fields.

Precipitation changes and inhomogenities have been detected following the methodology described in WMO (1966a). Precipitation series low frequency variability was analyzed using a linear trend method of minimum squares, and statistics significance was tested using T-Student and Mann Kendall tests (WMO, 1966b). Non-linear trends were computed using the method described by Tomé and Miranda (2005), which is based in adjusting the data with consecutive linear segments, between data with great trend changes.

3. Data analysis and discussion

3.1 Analysis of precipitation gridded database

Due to the lack of data observed in the region, a second database of precipitation (UDEL) is incorporated to the study. In order to evaluate the goodness of such interpolated data in representing the precipitation observed in the Patagonian region, a statistical analysis between the time series of monthly measured data at several meteorological stations (Table I) and the closest gridpoints was performed. The high-resolution grid allows such analysis. High and significant correlations to 95% were obtained from the comparison, except for two meteorological stations, Gobernador Gregores and Lago Argentino (Table I, significant correlations underlined). Significant differences were detected in the latter during the first years of the record, which agrees with a jump already indicated by some authors (Minetti *et al.,* 2003; Barros and Rodríguez Seró, 1979). Moreover, these two stations lack information and this deficiency probably causes low correlation values. It is important to notice that the precipitation gradient is sharp near the Andes (Prohaska, 1956), where Lago Argentino is located.

As it was expected, the interpolated series of UDEL represent the behavior of the observed time series of precipitation (Fig. 2). Therefore, the interpolation method has been efficient at least qualitatively, and these data can be used to make inferences of climatic type on the period of study in the Patagonian region instead of the recorded data. However results may be carefully analyzed in high latitudes and over the Andes.

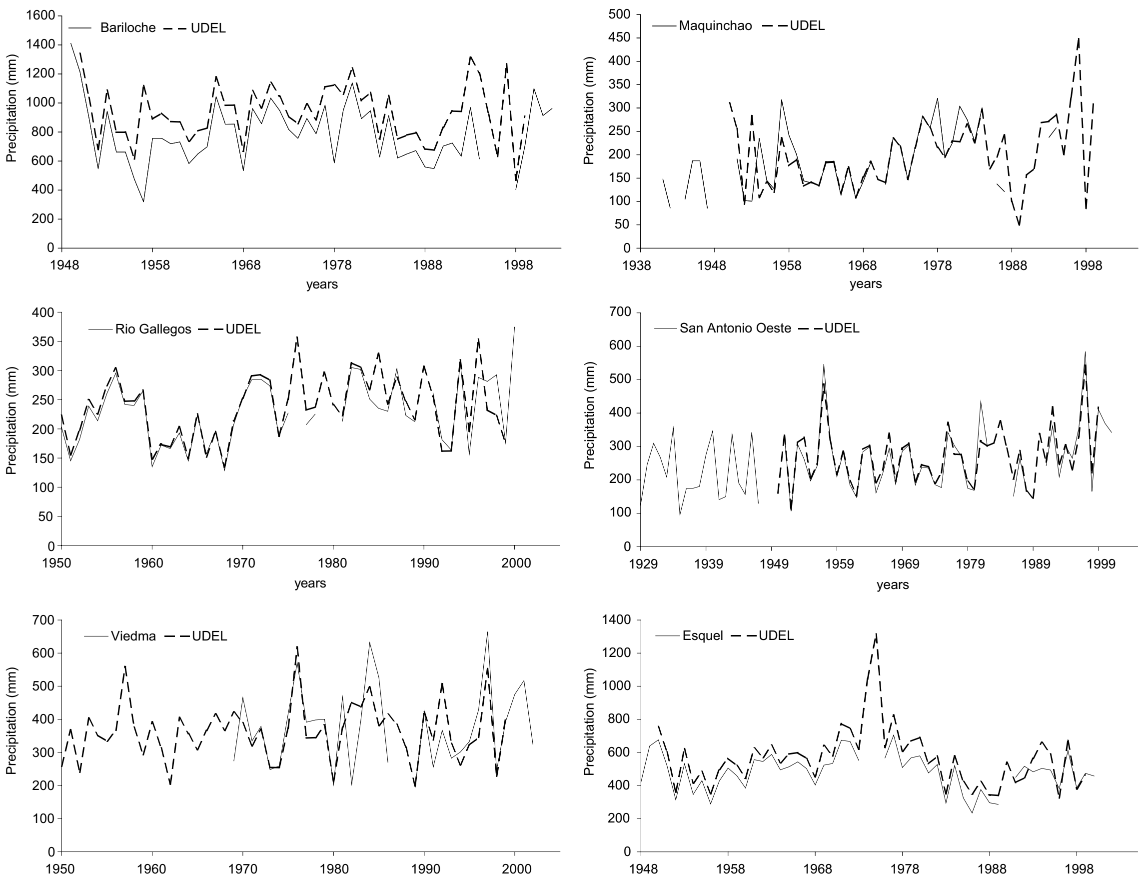

Fig. 2. Comparison between observed monthly precipitation time (solid lines) and closest gridpoints (dashed lines) of the UDEL data base. (Continues in the next page).

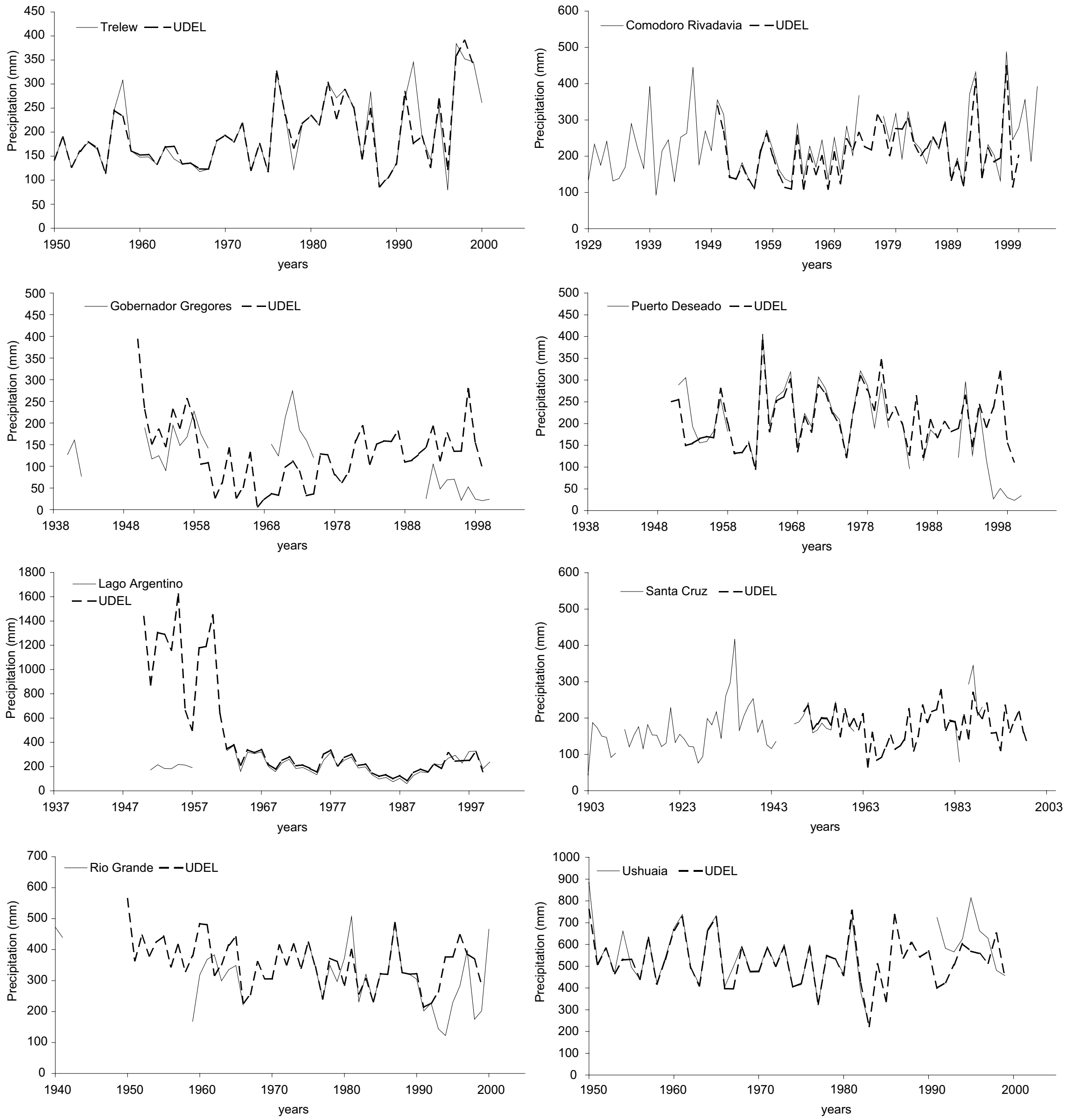

Fig. 2. Comparison between observed monthly precipitation time (solid lines) and closest gridpoints (dashed lines) of the UDEL data base. (Continued).

3.2 Precipitation mean annual cycle

Precipitation in Patagonian region shows an interesting mean annual cycle. Mean accumulated monthly precipitation data in the period 1970-2003 were used to identify regions with different mean annual cycle. This record was selected in order to describe the precipitation behavior during the last decades. A T-mode PCA was applied to these mean value, the variables considered were monthly rainfall in each one of twelve months and the cases the thirteen stations detailed in Table I. Lago Argentino and Gobernador Gregores were not considered in the analysis because of the great number of missing data in their records. The mean annual precipitation cycle in Patagonia can be described by the composition of the first three eigenvectors which explained 97% of the total variance (Fig. 3). Figure 4 shows the spatial pattern associated to them. The first eigenvector explains 67.7% of the variance and represents the mean annual precipitation with a maximum in the northwest (Fig. 4a). The second, explaining 27% of the variance, indicates that winter precipitation exceeds summer precipitation, specially in the west and over the Andes where the maximum precipitation values were registered (Fig. 4b). The third eigenvector explains 2.5% of the variance and is related to the precipitation decreasing from the north to the south in March and the opposite in December (Fig. 4c).

Precipitation mean annual cycle was filtered to analyze the temporal evolution of precipitation anomalies. A T-mode PCA was applied to the UDEL filtered data for the period 1950-1999, which was selected to be compared with the subsequent trend analysis. According to Araneo and Compagnucci (2004), no spatial weight from stations is necessary when T-mode is performed. Results showed that the first three principal components explained 60.3% of the anomalies variance (Fig. 5). The first one (Fig. 6a) explained 28% of the variance and had maximum variability in central Chubut province. The eigenvector associated to it (Fig. 5a) showed positive trend since the 90´s. The second eigenvector explained 19.8% (Fig. 6b), it showed the opposite behavior between precipitation in the northeastern and southwestern regions, with positive trends from 1980 in the northeast and negative trends in the southwest over the same period. The third principal component (Fig. 6c) had most of its variability in southeastern Santa Cruz province and the third eigenvector showed negative trends from the 80’s (Fig. 5c).

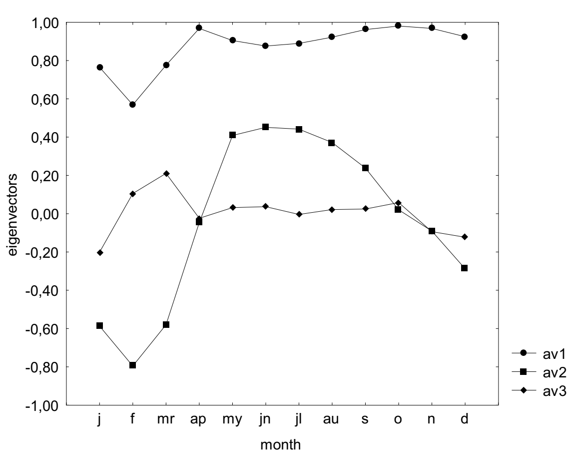

Fig. 3. First (av1), second (av2) and third (av3) eigenvectors of the mean annual observed cycle of rainfall (1970-2003).

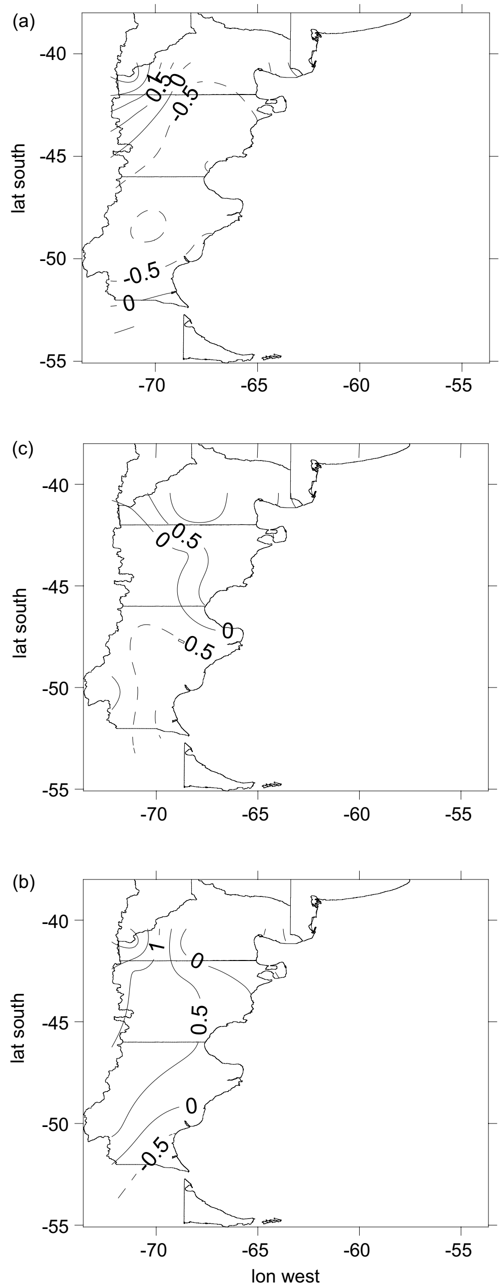

Fig. 4. Spatial patterns associated to the (a) first, (b) second and (c) third mean annual rainfall cycle eigenvectors in Fig. 3.

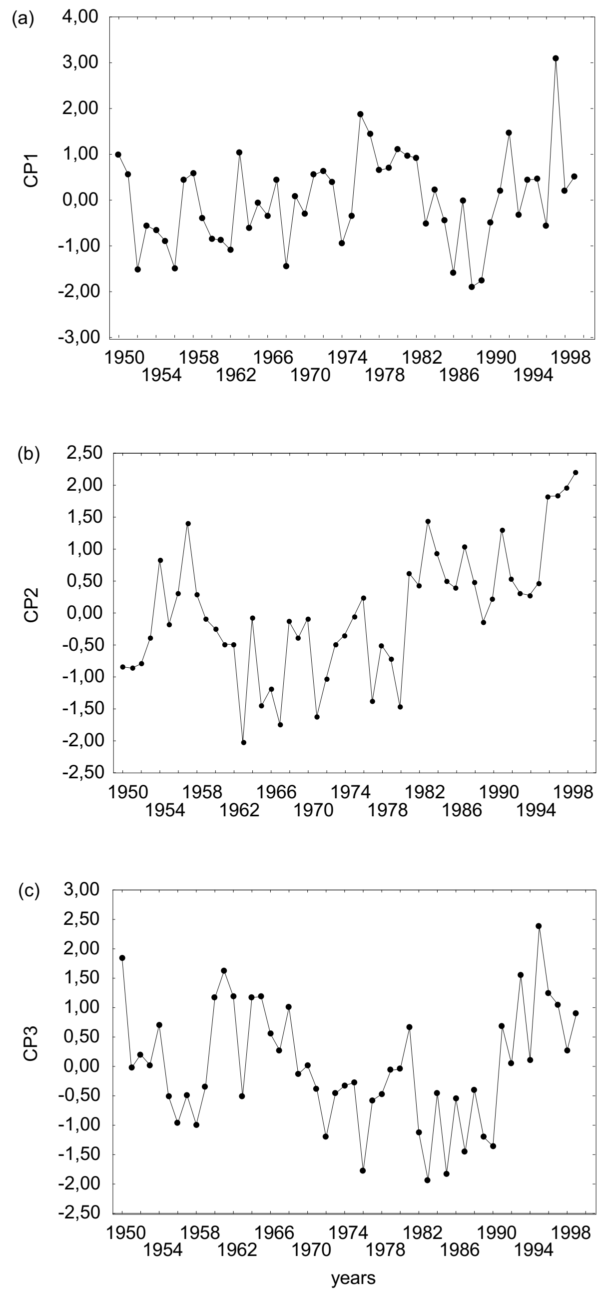

Fig. 5. First (a), second (b) and third (c) principal components of monthly rainfall anomalies during 1950-1999 from UDEL

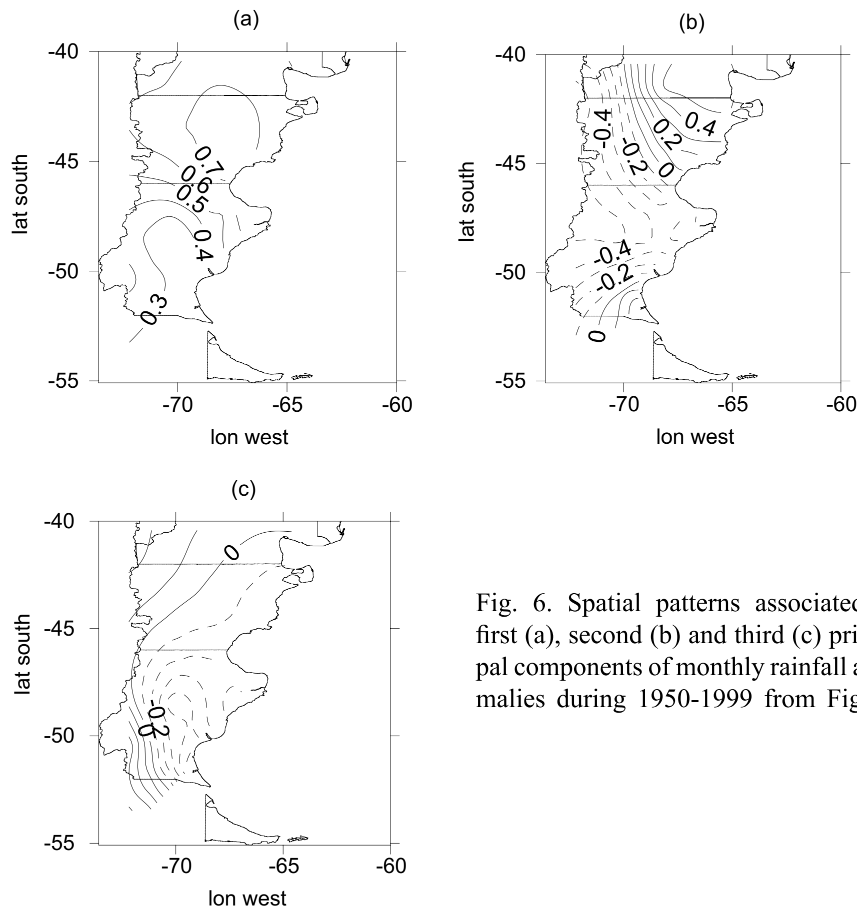

Fig. 6. Spatial patterns associated to first (a), second (b) and third (c) principal components of monthly rainfall anomalies during 1950-1999 from Fig. 5.

3.3 Precipitation linear trends

During the last century precipitation series in the Patagonian region reveal increases in some cases and decreases of precipitation amounts in others, Until this moment, linear trend approximation is the simplest way to evaluate the observed change in a time series. This approach can represent precipitation time evolution efficiently in a given time period. However, when a longer period is considered, it is necessary to use other approximations which allow representing the changes observed more accurately. Some authors have studied precipitation changes in the Patagonian region (Castañeda and Barros, 1994; Minetti and Vargas, 1997) using linear trends as a first approximation to the problem, and others have considered nonlinear methodologies, like polynomial fitting (Minetti *et al*., 2003).

Figure 7 shows annual precipitation linear trends field calculated with observed data registered in measurement stations (Fig. 7a) and using UDEL dataset (Fig. 7b) during the complete 1950-1999 period. Two maxima are detected: one is located in the northern region of Patagonia and reached 2.5 mm/year meanwhile the other is lower and it is positioned along the coast in the southeast of Santa Cruz Province. This behavior is the same as the one observed in the analysis of monthly precipitation second principal component in the previous section (Figs. 4b and 5b).

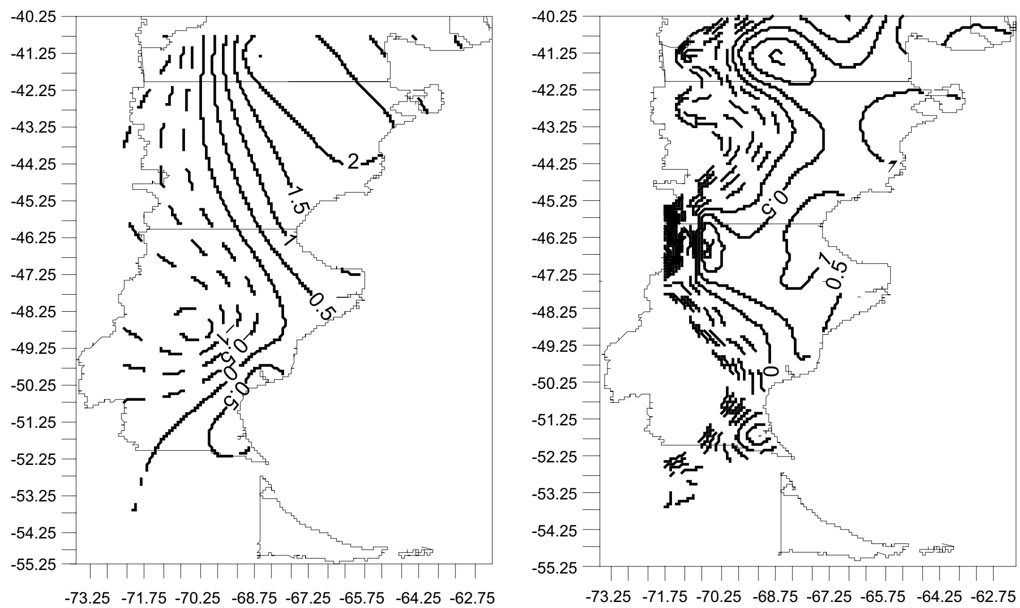

Fig. 7. Linear fit of annual precipitation trends for the period 1950-1999 for (a) meteorological stations, and (b) UDEL gridded database.

The south Santa Cruz Province is characterized by annual precipitation increase. The precipitation trend is almost linear in Río Gallegos and reaches 1.23 mm/year. Towards the north of the province, polynomial fitting better reflects time evolution of annual precipitation, as in San Julián. Positive trends are observed in northern Patagonia, too. In some cases linear trends are detected but in some others a nonlinear approach is necessary to better describe the low frequency variability, as in Maquinchao, San Antonio Oeste and Comodoro Rivadavia. Therefore, the second principal component of monthly precipitation anomalies, described in figures 5b and 6b seems to represent the linear trend behavior in annual precipitation series. A region of negative linear trends, with a decreased of 3 mm per year in average, is located between the two positive maxima already described in the west of Santa Cruz province. That is the case in Gobernador Gregores, Puerto Deseado and Lago Argentino in the Andes mountains. This fact is also reflected in the second principal component.

The analysis of Figure 7b shows that the linear trend field derived from gridded precipitation dataset, is a smoothing of the observed field (Fig. 7a), but they both depict the same pattern. The cause of the difference between them is not unique but it is important to point out the station location inhomogeneity and the difficulty to interpolate data near and over the Andes sierras.

The Mann-Kendall test is a non-parametric test for detection of trends. The theory was propose by Mann (1945) and developed next by Kendall (1975). The test does not assume any particular distribution of the data and compares each value with all the values measured in subsequent periods. The test statistic is distributed as a standard Gaussian and its significance can be tested. The test for differences of mean of Student compares in this case the average precipitation of the 10 last ones and the 10 first years of the period of study. The trends that display annual precipitation data are significant to 95% only in three stations, Esquel, Comodoro Rivadavia and Santa Cruz, according to Students' t, while Mann-Kendall's test indicates to Bariloche with significant annual tendencies.

Annual rainfall regime has changed in a different way since 1950 in some locations in Patagonia. The available data allowed detecting positive trends in north and south of Patagonia meanwhile precipitation tended to decrease in the western and central zone. It is important to mention the limitation in using the linear approach because the presence of larger cycles in which a nonlinear fitting is absolutely necessary to describe the actual behaviour is possiblility, as it will be analyzed in the next section.

3.4 Nonlinear annual precipitation trends

Throughout the last decades there have been a huge number of papers discussing long term linear tendencies of climate parameters, such as precipitation (e.g., Groisman and Easterling, 1994; Easterling *et al*., 2000; Tank *et al*., 2002). Karl *et al.* (2000), indicated that a linear trend is not enough to explain low frequency behavior on global temperature. Partial trends were identified through discontinuities in the time series, revealing the breakpoint years that separate periods of warming and cooling. Using this method enhanced by Tomé and Miranda (2005) we are able to evaluate partial trends in the Patagonian precipitation and get an improved ''trend'' through the average of partial trends, that better describes the low frequency behavior of the times series. At the same time we obtain a group of new climate parameters (breakpoints) that can offer a new approach into local climate studies.

Both annual precipitation datasets, gridded and gauges were modeled using two very simple mathematical forms, one of which is a linear fit to the data for the full record and the other employs breakpoints. This model involves fitting linear segments to the data between breakpoints, a piecewise linear function with the number of linear segments being one greater than the number of breakpoints.

The method automatically selects the best adjustment identifying the moments at which the tendency changes its behavior. This was proposed by Tomé and Miranda (2005), it was motivated originally by another study on changing trend on global warming (Karl *et al*., 2000) and the source code is freely available. Based on least-squares fitting of continuous lines segments of the data, allows to objectively locating the times of significant changes in the series tendencies. This methodology requires a huge computation time due to the large number of gridpoints involved. Once the breakpoints are found, it is necessary to discuss the physical relationship with reported events. In most cases, a simple linear model did not provide the best adjustment.

Point by point analysis of the UDEL time series shows that breakpoint year differs in a special way. Figure 8 shows the spatial distribution of the year of change in precipitation tendency–the breakpoint year. Northeast of the Patagonian region and a small zone to the southeast of Santa Cruz experienced a change in the annual trends of precipitation after the decade of 1960; this result matches with the PCA of the precipitation anomalies (Fig. 4b).

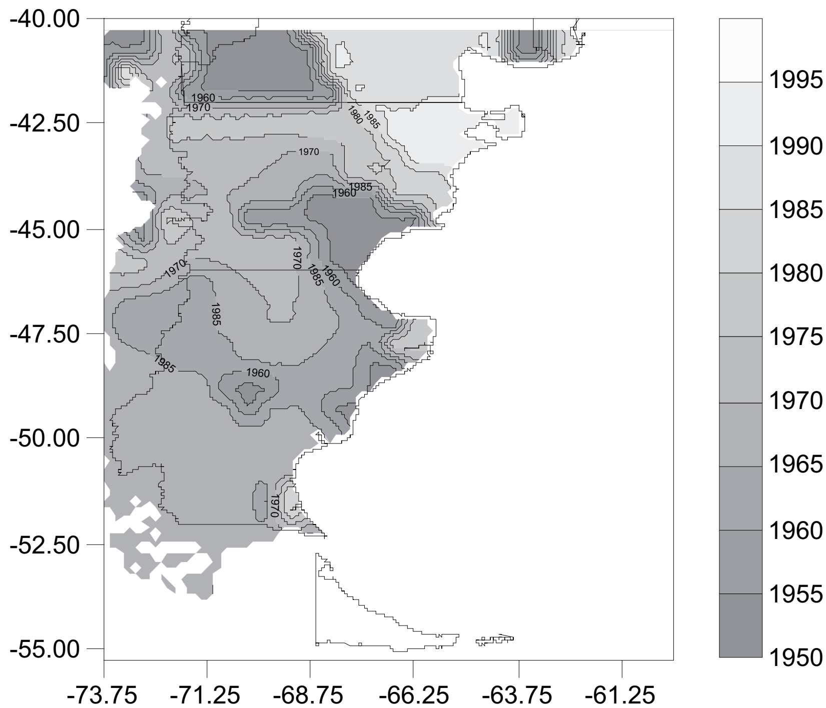

Fig. 8. Breakpoint years obtained using Tomé and Miranda method (2005) using only two consecutive line segments from UDEL dataset.

Northwestwards, it can be noticed a vast region that denotes a change in precipitation in the 1970 decade, whereas in the environment of the Peninsula of Valdez, the decade of 1990 is the one during which the change seemed to predominate. This last change was also detected in the PCA of the anomalies as it is mainly shown in Figure 4b, where an increase of precipitation in the 90s is associated to the Patagonian northeast region. The central region of the Santa Cruz province presents a decrease of the observed precipitation, according to Figures 4c and 5c, which agrees with the breakpoint at ‘50 and ‘60 shown in Figure 7.

4. Conclusions

The mean annual precipitation cycle in Patagonia was described using Mode-T PCA methodology. The winter maximum exceeds summer precipitation in the northwest, especially in the west and over the Andes where the maximum precipitation values are registered.

Both, PCA applied to the monthly anomalous precipitations and linear annual rainfall trends, show positive trends in north and south of Patagonia, meanwhile precipitation tends to decrease in the western and central zone. Gridded precipitation dataset (UDEL) is used as an alternative data and they seem to reflect the same patterns that the observed ones.

Annual precipitation gridded dataset was modeled using a piecewise linear function, a nonlinear adjustment, with the number of linear segments being one greater than the number of breakpoints in order to identify the moments at which the tendency changes its behavior. Point by point analysis of the UDEL time series shows that breakpoint year differs in a particular way. Northeast of the Patagonia region and a small zone to the southeast of Santa Cruz experienced a change in the annual tendencies of precipitation later to the decade of 1960, result that agrees with the PCA of the precipitation anomalies. To the northwest a vast region denotes a change in precipitation in the 1970 decade, whereas in the environment of the Peninsula of Valdez, the decade of 1990 is in which the change seems to predominate. This last change was also detected in the PCA of the anomalies. The central region of the Santa Cruz province presents negative trends in the annual precipitation, agrees with the breakpoint at ‘50 and ‘60.

A second important outcome can be achieved from this study and is that two different techniques allowed us to identify years of changes in annual precipitation behavior. We were able to evaluate partial trends in the Patagonian precipitation and get an improved ‘‘trend’’ through the average of partial trends, that better describes the low frequency behavior of the times series. At the same time we obtained a group of new climate parameters (breakpoints) that could offer us a new approach into local climate studies, which due to the lack of observed information has been difficult up to now.

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