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Climatic change and quasi-oscillations in central-west Argentina summer precipitation: main features and coherent behaviour with southern African region

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Abstract Summer rainfall variability (October to March) shows inter-annual to multi-decadal fluctuations over a vast area of subtropical Argentina between 28°S–38°S and 65°W–70°W. Statistically significant oscillations of quasi-period in the bands of 18–21, 6, 4 and 2 years can be found throughout the region and intra-regionally, though the latter are variable. The lower frequency variation produces alternating episodes of above and below normal rainfall each lasting roughly 9 years. This quasi-fluctuation appears to be shared with the summer rainfall region of South Africa and were in-phase related one another until mid-1970s. The teleconnection between both subtropical regions could be generated by an atmospheric-oceanic bridge through the global sea surface temperatures (SSTs), particularly those of the equatorial-tropical South Atlantic. From mid-1970s, the alternating wet and dry pattern has been interrupted in the Argentine region producing the longest, as yet unfinished, wet spell of the century. Thus, a significant change of the long-term variation was observed around 1977 toward lower frequencies. Since then the statistical model that explains more than 89% of the variance of the series until 1977, diverges from the observed values in the 1980s and 1990s. In addition the Yamamoto statistical index, employed to detect a climatic jump, reaches its major value in 1973 at the beginning of the current long wet spell. Therefore the change could be located between 1973 and 1977. Application of the *t*-student's test gives significant differences of mean values for pre-1977 and post-1977 sub-samples from both individual time series and the regional index series. The spectral analysis also shows changes in energy bands in concordance with the features of the change that occurred from mid-1970s. The change gives rise to a significant increment of more than 20% in average of normal rainfall over the region. Conversely, a drought between mid-1980s and the 1990s has been observed in the South African counterpart with severe characteristics, thereby continuing the quasi-18-year oscillation. Consequently, the low-frequency coherent behaviour between both the Argentine and South African regions is lost from the mid-1970s. The analysis of association of wet/dry spells and warm/cold, El Niño/La Niña episodes appears to be not significant at scales of year-to-year variability although at decadal to multi-decadal scales the association could be relevant. More than one process of multi-decadal variability of global SSTs could influence the Argentine summer rainfall region and the former bi-decadal teleconnection. Finally, potential hypothetical factors of change are discussed, such as the strengthening of direct and indirect mechanisms of moisture flux transport associated with global warming, low-level atmospheric circulation changes and/or to SSTs mean condition long-term variations over tropical and subtropical South Atlantic and South Pacific oceans.

1 Introduction

Long-term precipitation variations can affect vast areas and their inhabitants, negatively or positively, given the effect they produce on human activities based particularly on an intensive, weather-sensitive agriculture. The ability to determine the existence and nature of dry and wet spells favourably promotes the improvement of regional/global climatic forecasts, aiding economic regional development and the prosperity of its inhabitants. Within the southern pat of South America there exists a vast area of central-western Argentina whose semi-arid climatic features are very sensitive to low-frequency fluctuations. Here, social and farming developments during the twentieth century make the region very vulnerable to climatic variations.

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This central-western region (CWR) of Argentina extends roughly between (28°S–38°S) and (65°W–70°W) including the states of La Rioja, San Juan, Mendoza, San Luis and La Pampa. It therefore encompasses the Andean foothills, the Sierra de Cordoba and the Pampas (Fig. 1). The climate progresses from arid in the northwest to semi-arid in the southeast, with predominantly summer rainfalls throughout (Hoffmann 1992). The inner portion of the region, Cuyo, produces grapes and vegetables under river-fed channel-irrigation systems supplied by snow and glacier melt from the high Andes. Therefore inter-annual variability of local summer rainfall does not directly affect farm productivity. However, wet summer episodes affect the farming and particularly the quality of grapes, which require plenty of solar radiation to achieve sufficient quality for wine production. Moreover, wet summers are associated with a higher probability of hail damage. By contrast, the eastern and southeastern areas of CWR receive greater summer precipitation and require less irrigation. Here, both agriculture and cattle raising could be dramatically affected during dry summers.

The low-level atmospheric circulation is involved to a certain extent in weather patterns and in the regime of precipitation over CWR. Its mean conditions are dominated by the quasi-stationary South Pacific anticyclone to the west over the Andes, a thermal-orographic-dynamic northwestern low (NWL, Lichtenstein 1980) in Argentina east of the Andes, the subtropical South Atlantic anticyclone (SAA) to the east over the Atlantic, and westerlies in the most southerly latitudes of the region. The sub-tropical Andes, with a mean peak elevation of 4000 m, provide a perennial barrier to the import of humidity from the Pacific (Schwerdtfeger 1976). The interaction of NWL and SAA generates a zonal pressure gradient that when it strengthens in summer produces a northeasterly flow over eastern coastal and central regions of Argentina and a net transport of humidity from the Atlantic and southern Brazil (Barros et al. 1996). This favours the development of summer convection in CWR. However, in winter the weakening of these systems, the lower insolation and the northward displacement of the westerlies produce a noticeable diminution in winter precipitation. A detailed description of the annual precipitation cycle can be found in Hoffmann et al. (1994). Wang and Peagle (1996) used data derived over recent decades, that showed the source regions for water vapour over the subtropical Argentina (a vast continental area to the north of 40°S) are the humid lowlands and jungles of Brazil and Bolivia, as well as the South Atlantic Ocean. The Andes and the Bolivian plateau, in one case, and the highlands of eastern Brazil, on the other, favour the channelling of easterly low level flow through Bolivia towards the south and southeast, bringing humid, warm air to higher latitudes of subtropical Argentina. More recently, Saulo et al. (2000) have analysed the dynamic mechanism of import of humidity to the area by means of the low-level meridional jet using the ETA regional model integrated for the spring/summer of 1997/1998. Results showed that humidity is advected polewards through South America to the east of the Andes by the trade winds deflected by the Andes. The low-level meridional jet mechanism contributes in such a way that moisture flux approaches subtropical Argentina at 30°S.

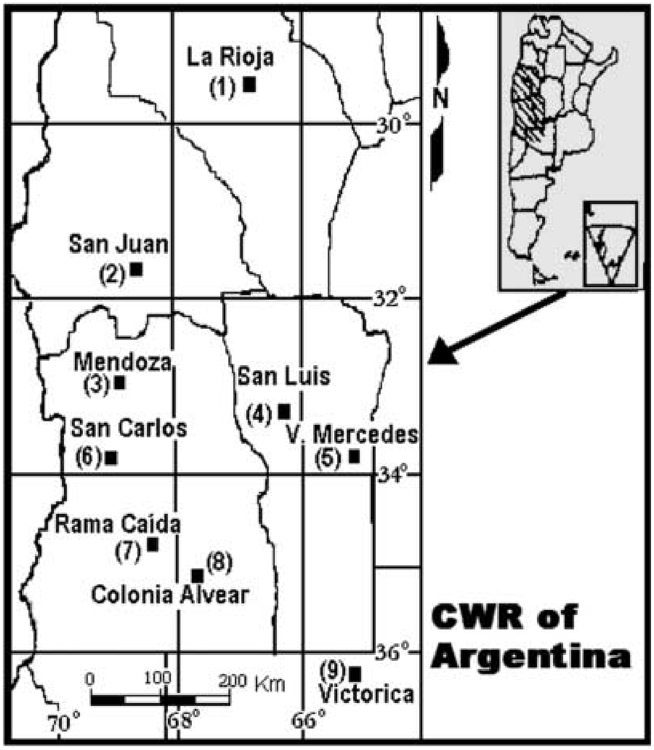

Fig. 1 Map of the central-west region (*CWR*) of Argentina (28°S–38°S and the 65°W–700°W) and the nine stations used in the current analysis

It is assumed that during wet summers this mechanism is stronger and during dry summers, it is weaker. Furthermore, anomalously warm sea surface temperatures (SSTs) over tropical and subtropical South Atlantic strengthen the low-level meridional temperature gradient and intensify the SAA and consequently the trade winds (Robertson et al. 2000). The inter-annual variability of this process influences the low-level atmospheric circulation and the humidity transport towards CWR. Therefore, low-frequency variations of the SSTs in the Atlantic would affect summer rainfall in the CWR.

Observations from the beginning of the century until 1977, formerly analysed by Compagnucci and Vargas (1983) showed that summer (October to March) precipitation totals displayed successive extended and alternating periods of above and below normal rainfall, which influence almost the entire region. These results indicated statistically significant quasi-oscillations with a period of 18 years and higher frequencies and suggested that wet and dry spells could be in-phase with those observed in the summer rainfall region (SRR) of South

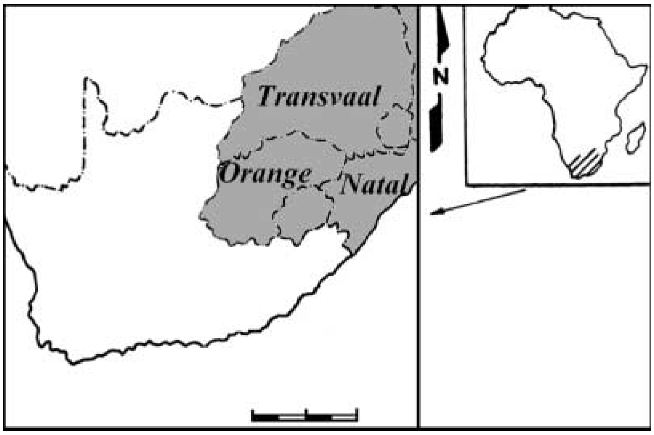

Fig. 2 Map of the summer rainfall region (*SRR*) of South Africa according to Tyson and Dyer (1975), it includes the Orange Free State, Transvaal and Natal

Africa (Fig. 2) during the same period. The SRR precipitation has been widely studied by Tyson and Dyer (1978), Tyson (1981) and Tyson et al. (1986, 1991, 1997) among others. Results suggest that there is a regional low-frequency variability of summer precipitation over CWR at least until 1977 which is useful for climatic regional forecasts. In addition this variability, apparently associated with that of the South African SRR, could be correlated with global precipitation variability and be a manifestation of climatic fluctuations related to large-scale phenomenona.

Kane and Trivedi (1986), employing results obtained by Compagnucci and Vargas (1983) and assuming the prevalence of the 18-year oscillations, forecasted below average summer precipitation totals to be observed between 1983 and 1990 in CWR. Seemingly, an extended drought was predicted in the SRR of South Africa. However, during recent years there has been much anecdotal evidence from newspapers, television and local inhabitants, of apparent increases in summer precipitation, frequency of hailstorms and flooding, both fluvial and meteorological over the CWR (Agosta et al. 1999). This failed forecast suggests an apparent change in summer precipitation owing to changes in the frequency of fluctuations for the CWR, whereas the SRR forecast succeeds for that period (Mason 1995).

Therefore, one of the our aims is to examine the low-frequency variability (interannual to multidecadal) of the summer precipitation over CWR, within subtropical Argentina, an area that has experienced relevant changes in mean atmospheric circulation over the last three decades (Barros and Scasso 1994; Camilloni 1995; Barros et al. 2000) consistently with the rest of the Southern Hemisphere (Hurrel and van Loon 1994; van Loon et al. 1993; Gibson 1992). Additionally, this research aims to provide a detailed analysis of the behaviour of summer precipitation over CWR throughout the twentieth century. In particular, an attempt is made to determine, (1) patterns of regional quasi-cycles for the whole CWR, (2) intra-regional variations through the analysis of each single summer series, and (3) whether the purported increases in summer precipitation are significant by discussing the possible causes. In addition, potential global links to the behaviour of summer precipitation in the SRR of South Africa are studied. Since Kruger's (1999) results among others suggested that there is no relationship between summer precipitation in the SRR and El Niño-Southern Oscillation (ENSO), this work also examines whether this result can also be assumed for CWR.

Section 2 introduces the data and methodologies used in the analyses of the precipitation series from CWR. In order to facilitate comparisons with SRR's reults, the methodologies from Tyson and Dyer (1978) and from Tyson (1981) and Tyson et al. (1986, 1991, 1997) are updated and employed. A description of the regional climatology of summer precipitation and temporal-climatic features is provided in Sect. 3 as well as some discussion of quasi-cycles detected regionally. The existence of an apparent summer precipitation climatic change and its low-frequency variability over CWR is discussed in Sect. 4 through a mathematical model fitted to the smoothed summer precipitation. In Sect. 5, possible teleconections between the low-frequency variations in summer precipitation over the Argentine and South African regions are tackled and the potential teleconnection with ENSO phenomenon is examined. Concluding remarks appear in Sect. 6.

2 Data and methodology

The region has few meteorological stations with reasonable periods of quality observations. Most record lengths vary from 10 to 30 years, many of which do not overlap between stations, therefore the records at only nine stations are deemed appropriate for analysis (Table 1, Fig. 1). Monthly precipitation totals are provided by the Servicio Meteorológico Nacional (National Weather Service). As temporal continuity of records is required for the analyses, a set of 10 secondary stations was used to interpolate, via linear regression (Panofsky and Brier 1958), any missing data in the primary data set. The primary stations selected met the following criteria: (1) records sufficiently complete that interpolation could be carried out without compromising their representativeness, (2) records extend until the end of the 1990s (until 1998, with two exceptions) and (3) records comprise at least 40 years of data.

The summer rainfall index series (1911–1996) for South Africa used in Mason (1995 1996) was kindly provided by Dr. Simon Mason via personal communication. In addition, data from Wright (1989), Rasmusson and Carpenter (1983), Kiladis and Van Loon (1988), Trenberth (1989), Quinn and Neal (1983) and the Climatic Diagnostic Bulletin (Climatic Analysis Center 1999) have been employed to provide a classification of years into El Niño, La Niña and Normal (neither El Niño nor La Niña) from 1909 to 1998 (Table 2).

2.1 Single series and the CWR summer precipitation index

A single regional index time series, $I(t)$ may be estimated as follows

$$Y_j(t) = (X_j(t) \cdot 100)/\chi_j$$

$$I(t) = \sum_{j=1}^{n} Y_j(t)/n \qquad 1 \leq j \leq n$$

Table 1 Stations used in the analysis of the CWR of Argentina (see Fig. 1)

Station-name	Height (m)	Latitude (S)	Longitude (W)	Record-length
Nine-set[a]				
(1) La Rioja	516	29°25′	66°52′	1904–1998
(2) San Juan	634	31°32′	68°34′	1900–1998
(3) Mendoza	769	32°53′	68°49′	1900–1998
(4) San Luis	734	33°18′	66°19′	1905–1998
(5) Villa Mercedes	514	33°41′	65°29′	1900–1998
(6) San Carlos	940	33°46′	69°02′	1938–1979
(7) Rama Caída	713	34°40′	68°24′	1927–1998
(8) Colonia Alvear	465	35°00′	67°39′	1935–1979
(9) Victorica	312	36°14′	65°26′	1905–1998
Ten-set[b]				*Interpolates to*
San Juan FC[c]	630	31°32′	68°32′	(2)
Crycit				(3)
San Rafael FC[c]	–	34°35′	68°20′	(7)
Rama Caída FC[c]	–	34°34′	68°23′	(7)
San Rafael Met.[c]	746	34°35′	68°34′	(7)
Soitué[c]	–	35°00′	67°52′	(8)
Carmensa[c]	–	35°08′	67°37′	(8)
Bowen[c]	–	34°59′	67°41′	(8)
C. Alvear FC[c]	465	34°59′	67°41′	(8)
Santa Rosa	189	36°44′	64°16′	(9)

[a] Stations used for the proper analysis
[b] Stations used for interpolation of missing data
[c] Stations with either short record or broken operation

where,

$Y_j(t)$: summer rainfall single series of station j, expressed as percentage of its long run average

$X_j(t)$: station j's summer precipitation in year t

χ_j: long run average summer precipitation at station j

$I(t)$: summer precipitation index (spatially averaged summer precipitation) in year t

j: index of stations

n: number of stations

In this way the summer precipitation index, $I(t)$, is computed for the period 1901–98. The records of two stations, San Carlos and Colonia Alvear, do not extend until 1998, therefore n is reduced in the last decade, however their records have been included in order to make the index series more representative of the entire area (Fig. 1).

In addition to the regional index series, the main statistics of summer precipitation at each station have been computed so as to determine their outstanding features.

Table 2 Classification of ENSO-year-occurrence into years El Niño, La Niña and Normal (not displayed) for 1909–1998

El Niño years			
1911/12	1930/31	1953/54	1972/73
1914/15	1932/33	1957/58	1976/77
1918/19	1939/40	1963/64	1982/83
1923/24	1941/42	1965/66	1986/87
1925/26	1951/52	1969/70	1991/92
			1997/98
La Niña years			
1909/10	1928/29	1949/50	1970/71
1916/17	1931/32	1954/55	1973/74
1920/21	1938/39	1955/56	1975/76
1924/25	1942/43	1964/65	1988/89
			1995/96

2.2 Summer-rainfall oscillation-analysis: spectral analysis and smoothing

All single station series and the regional index series of both CWR and SRR are analysed by means of Tukey's spectral analysis with Parzen's window (Jenkins and Watts 1968), in order to determine their principal periodicities. The hypothesis of the 'null continuum' (a hypothetical theoretical spectrum of either 'red' or 'white' noise) corresponds to a first order Markov process, or lag 1 autocorrelation model (Mitchell et al. 1966, details in Appendix). All series have been smoothed using a low-pass nine term binomial filter (see Appendix).

2.3 Modelling the smoothed CWR index series

In order to evaluate a possible change in the behaviour of the CWR index series evidenced around 1977, a mathematical model is fitted to the sub-period 1901–1977 for the smoothed series. A proper fitting model is the trigonometric polynomial R_j (Tyson and Dyer 1978) which is adequate for time series with significant periodicities and whose coefficients A_l and B_l are estimated by least squares. Its mathematical equation is

$$R_j = R_0 + \sum_{l=1}^{m}\left(A_l \cdot \cos\frac{2\pi j}{\lambda_l} + B_l \cdot \sin\frac{2\pi j}{\lambda_j}\right)$$

$$1 \le j \le N, \quad 1 \le l \le m$$

where,

R_j: summer precipitation index in year j

R_0: regression constant (i.e. mean of the spatially averaged series)

A_l, B_l: least squares regression coefficients

m: number of spectral peaks in the index series

λ_l: period of each single spectral peak

N: data points in the index series

Application of the smoothed CWR index series for the period 1905–1977 suggests that the number of significant spectral peaks, m, is seven. Inclusion of more waves had no significant effect upon the explained variance. Table 3 displays the values of the fitted constants. This model explains 89% of the total variance of the summer precipitation index series in the period 1905–1977. The model is used to extrapolate summer precipitation data in the sub-period 1978–1998 under the hypothesis of no change in the series. Differences between the observed data and the model are discussed in Sect. 4. The statistical significance between the predicted values and the observed in the period 1978–1998 are proved by Student's t- (Panofsky 1958) and Fisher's F- (Hoel 1964) tests and they are also employed to determine differences in the means and variances between the two portions of the summer precipitation single series.

Contingency tables (Hoel 1964) permit the identification of any statistical association between ENSO phases and positive-negative rainfall anomalies in the CWR. The application of Yamamoto's index (see Appendix) provides of an objective statistical method to determine possible climatic "jump" in year-to-year time series.

3 Summer precipitation climatology of the central-west region

3.1 Intra-regional variability within central-western region

In spite of the low density of stations available for the report, the intra-regional variations in the main statistics which define the features of the population density distribution function can be discerned (Table 4). Therefore, Fig. 3 illustrates the anomalies of the smoothed individual series from their respective means, expressed in terms of standard deviations (SD). Furthermore, spectral density functions for each single time series are analysed and shown in Fig. 4.

La Rioja, in northern lands of the CWR, has a mean summer precipitation slightly in excess of 300 mm and extremes of 81.5 mm and 588.2 mm. Alternating wet and dry periods of roughly ten year length each overlapped a 50–60 year length wave with a maximum in the 1920s and between the 1980s and the 1990s is observed in Fig. 3 top panel for the smoothed series with a decreasing tendency from the 1990s. The spectral analysis (Fig. 4a) shows the predominance of quasi-oscillations in the band of 40–50 years, near 6 years (both at 90% confidence), and near 4 years (80% confidence). The biennial quasi-oscillation is also present at the 95% confidence level.

Table 3 Regression coefficient values for the fitting constants $\mathbf{A}_1$ and $\mathbf{B}_1$ of the 7-wave model of the 9-term-smoothed summer-rainfall index for the CWR of Argentina. Series length, 73; total explained variance, 89.2%

λ_i	A_i	B_i
9.33	+0.008723	−0.709767
11.2	+4.266329	−3.596130
14.0	+2.297350	+6.759104
18.35	−3.735480	+13.669870
22.5	−1.161050	−20.008000
24.0	+21.700400	+13.714370
47.0	−6.195900	+6.323007

On the western boundary of the region, San Juan and Mendoza have the driest summer conditions averaging summer totals lower than 200 mm with little inter-annual variability. In the former, mean summer precipitation is lower than 100 mm and has not exceeded 200 mm. Individual years may receive no summer precipitation whatsoever (e.g. 1915). Figure 3, second panel, shows the smoothed series of San Juan where low-frequency oscillations of wet and dry terms predominate. It is observed that the amplification of the series decreases from the 1970s, a fact that will be examined later on. In Mendoza, in Fig. 3, third panel, the negative smoothed terms are largely predominant until the 1970s. In this dry core the quasi-18-year oscillation is dominant although lower peaks are found about 6 and 4 years. The former oscillation is significant at the 99% confidence level in San Juan (Fig. 4b) declining in confidence (85%) southwards towards Mendoza (Fig. 4c). The quasi-4-year oscillation behaves in the opposite fashion, while the biennial oscillation is only present northwards in San Juan with 95% confidence.

Further eastwards, San Luis and the easternmost Villa Mercedes both show the highest summer precipitation means of around 500 mm and also the highest maximum with more than 840 mm at San Luis. The inter-decadal variability is clearly apparent in San Luis (Fig. 3) of roughly ten-year length wet and dry terms. The spectral density function (Fig. 4d) illustrates peaks in the bands of period 18–21 years, about 4 years with 95% confidence and of the biennial periodicity with 90% confidence.

In the southern areas, San Carlos, Rama Caída and Colonia Alvear show summer precipitation means between 200 mm and 250 mm. Wettest summers may experience roughly 500 mm, and the driest close to only 50 mm. The smoothed summer precipitation in Rama Caída, (Fig. 3) indicates alternating wet and dry long-term periods with the diminution of the intensity of droughts from the 1980s. In general it is dominated by quasi-oscillations in the periods of 18–22 years and 3–4

Table 4 Main statistics for summer-rainfall single series of the nine-stations used in the analysis of the CWR

Station	Data number	Average (mm)	Minimum (mm)	Maximum (mm)	Std. deviation (mm)
(1) La Rioja	94	301.8	81.5	588.2	112.5
(2) San Juan	98	72.2	0.0	199.2	40.5
(3) Mendoza	98	158.6	17.1	381.9	71.3
(4) San Luis	92	479.6	216.0	842.9	128.2
(5) Villa Mercedes	47	551.9	305.1	796.0	121.2
(6) San Carlos	41	223.2	63.0	452.3	87.5
(7) Rama Caída	71	235.2	49.0	505.4	106.7
(8) Colonia Alvear	44	235.3	48.4	533.8	114.1
(9) Victorica	93	414.5	120.4	887.2	148.0

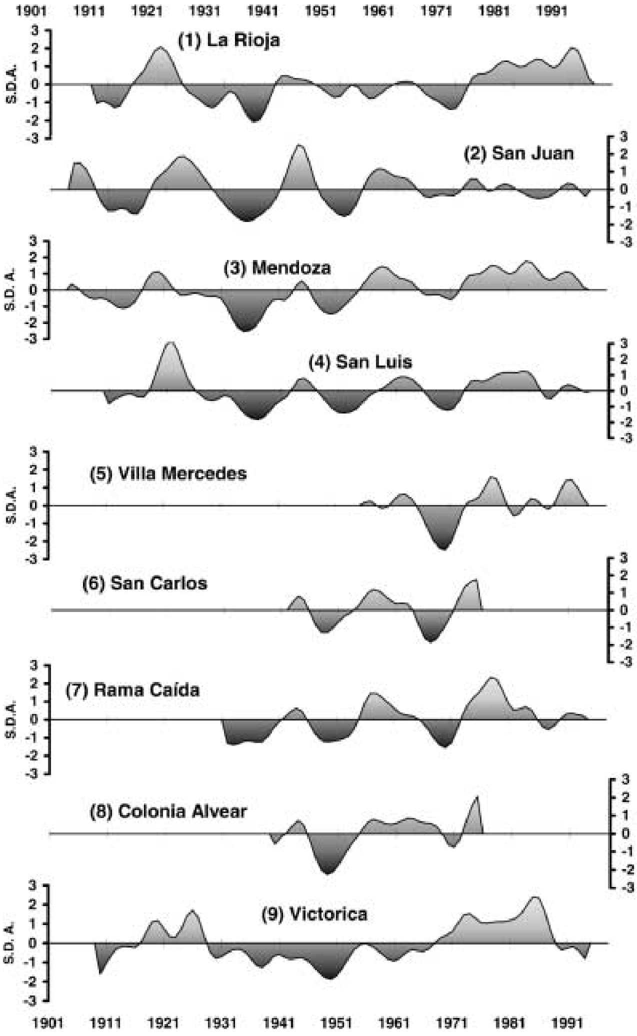

Fig. 3 Standard deviation anomalies (*SDA*) for each nine-term-smoothed individual series of summer-rainfall. *Negative values*: dry spell; *positive values*: wet spell

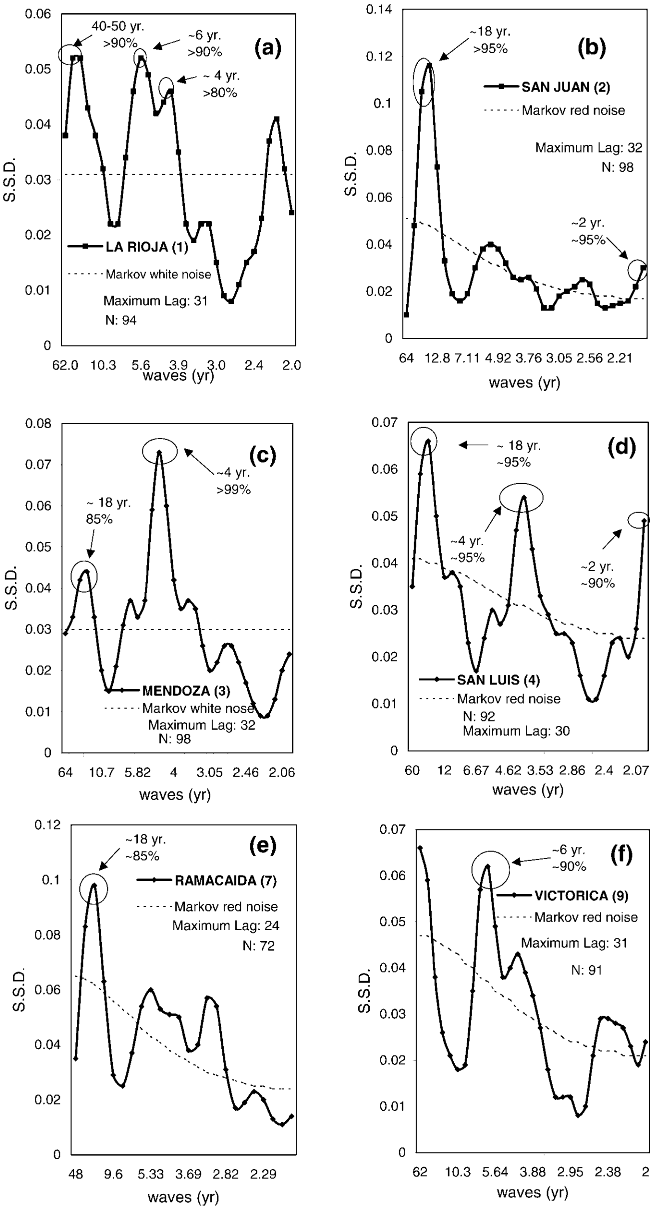

Fig. 4a–f Tukey's power spectra with Parzen's window for the main summer-rainfall individual series of CWR for the period 1901–1998. Main wave bands and corresponding significance values are indicated. *SSD* means standarized spectral density

years (Fig. 4e), significant at 85% and 90% levels of confidence, respectively. Victorica in the southeast boundary of the CWR shows mean summer precipitation of over 400 mm with the extremes of 887.2 and 120.4 mm, the highest and the lowest respectively. Hence, the major variability within the CWR is found at Victorica, denoted also by high the standard deviation at the station. In Fig. 3, ninth panel, the prevalence of below-average summer precipitation is evident between the last years of the 1920s and mid-1960s which interrupts the alternating wet and dry long-term pattern common to the rest of the region. The spectral estimates (Fig. 4f) reveal quasi-oscillations of periods 6 year with 90% confidence, of longer than 40 year and the biennial periodicity, both bands at 75% confidence level. Therefore, the decadal variability is added to the over 40-year low frequency fluctuation affecting the alternating wet and dry long-term periods.

In general it is evident that the entire region is subject to non-random quasi-oscillations in the bands of about 18–22, 6 and 4 years with different levels of confidence for each individual series.

Figure 3 confirms the clear coherence of alternating positive and negative anomalies between stations throughout the CWR. It is therefore reasonable to expect to see these features in the regional index series. The series of La Rioja, Mendoza and Victorica have a negative trend from mid-1980s, which, if extrapolated, would give rise to general dry spells in some parts of the region. Such a result could be relevant southwards, at Victorica, since it might herald another long-term drought similar to that observed between the 1920s and mid-1960s. Furthermore, the amplitude of the longer multi-decadal oscillation of Victorica is larger than that of La Rioja and it involves a difference of more than 500 mm, which represents four standard deviation, between long wet periods occurred in the 1920s and in the 1970s–1980s and that extended the long term drought of mid-century. These areas have frequently been declared to be in a 'state of agriculture emergency' due to drought. However, further analysis would be necessary to assess the validity of such a forecast in this subregion. On the other side, San Juan, San Luis and Rama Caída all seem to show a reduction of interannual variability from the 1980s.

3.2 Summer precipitation fluctuations over the CWR

The summer precipitation index and associated smoothed series is shown in Fig. 5a for the period 1901–1998, both expressed in units of percentage deviation from normal. An oscillatory pattern of alternating wet-and-dry spells is clearly apparent in both series, but there seems to be a predominance of positively anomalous rainfalls from the 1970s until mid-1990s. This phenomenon is more apparent in the smoothed record. Likewise, it is possible to identify four extended dry spells, 1907/1917, 1928/1939, 1947/1955, 1966/1972, and four wet spells, 1918/1927, 1940/1946, 1956/1965, and 1973 onwards (Table 5). A possible wet spell ending in 1906 could be discerned although its start cannot be evaluated. Each alternating spell appears to persist for about 9 years until the most recent, longest, wet spell, which seems to have started in 1973 and have extended for more than 25 years. The question of whether this formerly apparent 18 year quasi-oscillation continues in the most recent years, is discussed in later sections.

The lowest value of the regional index recorded between 1901–1998 occurred in 1934 and was 54% below normal while the highest, in 1904, was 88.6% above normal. If the post-1973 extended wet spell is excluded, then the most persistent extended wet spell is that of 1918/1927 with six consecutive years of above normal rainfall and the most persistent extended dry spell is that of 1947/1955 with nine years of consecutive years with below normal rainfall. This drought is exceptional in having no periods of above average rainfall, because, in general, every extended wet or dry spell includes about two years of opposing sign. These discontinuities in spells are generally more marked when dry years interrupt a wet spell, than during the alternate condition. For example, the largest positive anomaly in an extended dry spell occurred in 1968 and is only 7% above normal, whereas the largest negative anomaly during a wet spell is 1942 with 42.9% below normal, implying that extended dry spells are more uniformly dry than wet spells are wet. In comparison to the temporal features just described, the post-1973 extended wet spell is of an extraordinary and unprecedented length, and apparently shows no signs of cessation given the positive index values of 1997 and 1998 (Fig. 5a).

Spectral analysis of the full index series (1901–1998) reveals three statistically significant bands of maximum spectral energy at about 2, 4 and 16–21 years at 90% confidence level, and a secondary 'pseudo-peak' near 6 years with significance of only 75% (see Fig. 6, solid line). Note that lower frequency variability is located in the band 16–21 years with the maximum at 21 years. When the period 1901–1977 is analysed alone (Fig. 6, dashed line), the band of 16–21 years of low-frequency variability is shifted towards the peak of 16 years. Also, the 'pseudo-peak' of about 6 years is absent in the analysis of the pre-1977 data and the statistically

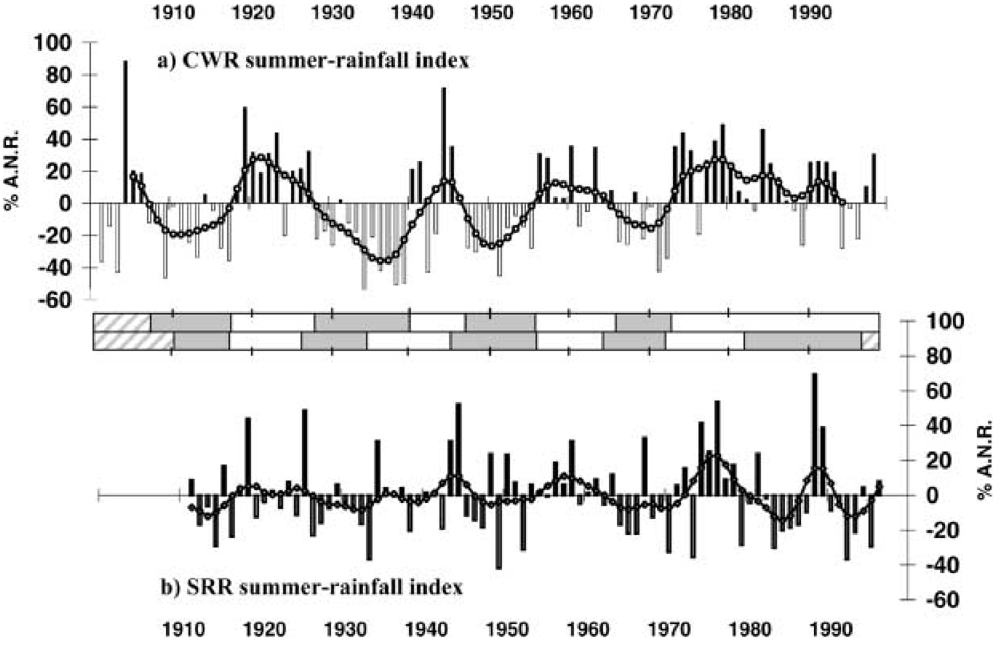

Fig. 5a Summer-rainfall index (*straight bars*) and nine-term-smoothed index (*circled line*) for the CWR of Argentina, expressed as percentage anomaly of normal rainfall (*% ANR*). **b** Summer-rainfall index (*straight bars*) and 9-term-smoothed index (*squared line*) for the SRR of South Africa, expressed as percentage anomaly of normal rainfall (*% ANR*). *Horizontal white bar*: period of extended wet spell. *Upper* for the CWR. *Horizontal grey bar*: period of extended dry spell. Lower for the SRR. *Horizontal striped bar*: undetermined period of either wet or dry spell

Table 5 Wet and dry spells in the CWR given by the spatially averaged summer-rainfall index, number of year and mean deviation for each spell, wettest or driest year and deviation within the spell and number of years with opposite rainfall-sign occurred. The year corresponds to the second three-month-term of the six-month-summer considered

Spell	Period	Number of years	Space-mean deviation (%)	Wettest or driest year	Maximum or minimum deviation (%)	Number of years with opposite sign
dry	1907–1917	11	−19.0	1909	−46.5	1
wet	1918–1927	10	+25.0	1919	+59.4	1
dry	1928–1939	12	−28.6	1934	−54.0	3
wet	1940–1946	7	+13.2	1944	+72.6	3
dry	1947–1955	9	−23.9	1951	−45.2	0
wet	1956–1965	10	+12.9	1960	35.6	2
dry	1966–1972	7	−20.3	1971	−42.4	2
wet	1973 up to date	>25	+14.7	1979	+49.1	7

significant peak at two years in the current data had previously appeared not significant. Evidently the low-frequency characteristics which dominated at least until 1977 correspond to the formerly noted 18 year quasi-oscillation. The clearly above average values of the years 1984, 1985 and 1986 (Fig. 5a) disturb the negative tendency slightly sketched from the beginning of the 1980s which would have corresponded to former 18-year quasi-oscillation. These spectral results further contribute to the notion of a possible climatic shift in the region in the mid-1970s.

4 Modelling fluctuations in the central west region index

4.1 The absence of an expected mid-1980/1990s drought

In order to evaluate the existence of a possible change in the low-frequency regime of spatially averaged summer precipitation over the CWR, the mathematical model described in Sect. 2.3 is fitted to the pre-1977 data and extrapolated until present. Figure 7 displays both the observed smoothed summer-rainfall index series and the extrapolated function, each is expressed as a percentage deviation from normal rainfall. It is apparent that the fitted model reproduces faithfully the pre-1977 series in both the amplitude and phase of the observed wet (positive) and dry (negative) periods. However, predictions for the period 1978–94 augured a sharp decline in summer precipitation, leading to a period of drought commencing at the beginning of the 1980s. The nadir would be reached in 1991, from which time values would start to increase, although remaining below average, until present. Therefore, the observed pattern of low frequency variations in summer precipitation in the region diverges from the modelled behaviour after 1978. The predicted behaviour is clearly very dissimilar to the observed pattern, and the anticipated drought of the 1980s–90s never materialised.

To assess such changes, each station's series is divided into two samples, one from the beginning of available record until 1977, and the other from 1978 onwards. Since the records at San Carlos and Colonia Alvear end in 1978, these stations are excluded from this analysis. Differences in sample means between sub-samples are evaluated by Student's t-test, however the exact formulation of this test requires the knowledge of whether the variances of the samples can be considered to equal or not. Hence, Fisher's F-test is also applied since only in the case of San Juan could the variances in the two sub-samples be considered statistically significantly different at $\alpha = 0.01$ (confidence level). Consequently, the proper application of the t-test (Table 6) indicate that mean summer precipitation totals are significantly different pre- and post-1978 at $\alpha = 0.10$ with the exception of San Juan and Villa Mercedes. The reduction from 43.9 mm to 24.8 mm in standard deviations between the two periods at San Juan is noticeable. The significance of the result at Villa Mercedes is over $\alpha = 0.10$ which could be due to the shorter series (1951–1998).

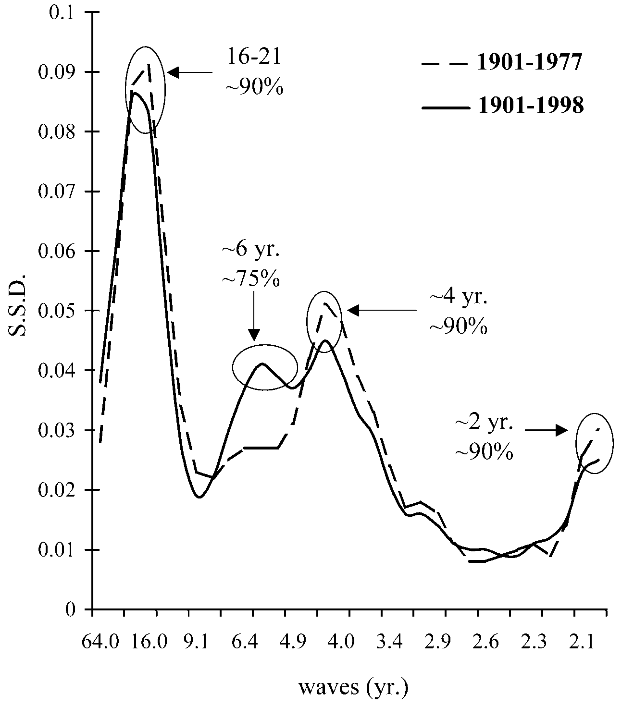

Fig. 6 Tukey's power spectra with Parzen's window of the summer-rainfall CWR index for the period 1901–1977 (*dashed line*) and 1901–1998 (*solid line*). Main wave bands and corresponding significance values between 1901–1998 are indicated. *SSD* means standarized spectral density

So far, it is highly likely (greater than 90%) that the samples obtained from before and after 1978 are drawn from different statistical populations, due to a change in the low-frequency variability of summer precipitation at about this time, evidenced by the length of the late wet spell. This implies a regionally coherent climatic change in summer precipitation regime which leads to an increment in means of about 20% averaged over CWR (Table 6). The change is strongly associated with the year 1973 corrresponding to the beginning of the current, unusually long, wet spell. Yamamotos's index, (Yamamoto et al. 1986) which evaluates objectively the year of climatic "jump" in the variable, identifies 1973 like the reference year at 95% of confidence [$\mathbf{J}_{0.95}$ (1973) = 1.10 > 1.0]. That year then marks the starting point of a statistical different population of summer precipitation. Thus between 1973 and 1977, a displacement to the bands of 18–21 years in the domaining low-frequency oscillations could be generated by one or more causes, producing a significant alteration of the summer precipitation regime over CWR. The trigger of forcing

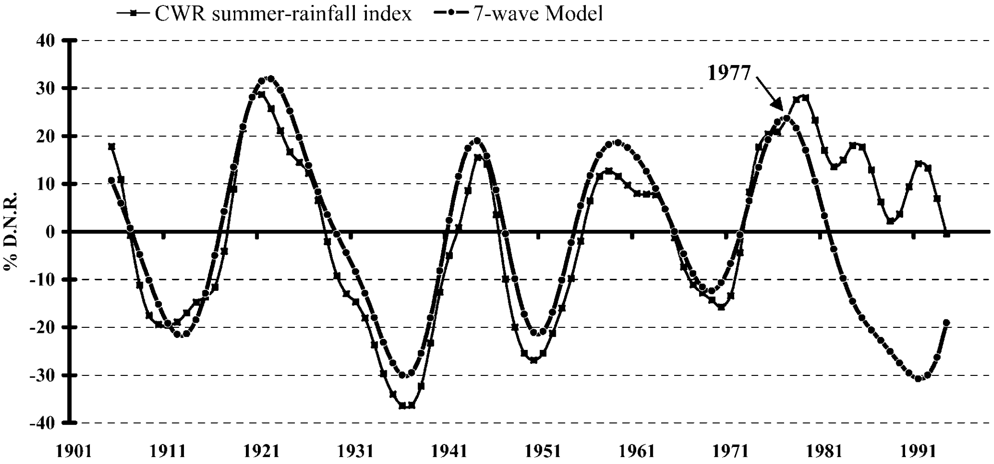

Fig. 7 Smoothed summer-rainfall index for the CWR, observed (*squared line*) between 1901–1998 and obtained by the 7-wave model (*circled line*), expressed as percentage deviation from normal rainfall (*% DNR*)

Table 6 *t*-Student's statistical test of difference of means: sampling means until 1977 and after 1977, difference between sampling means and percentage confidence of H_0-rejection. Null hypothesis H_0: samples come from equal populations respective to mean

Station	Until 1977 (mm)	From 1997 (mm)	Difference (mm)	Confidence (%)
La Rioja (1)	284.4	362.5	+78.1	99
San Juan (2)	72.3	68.4	−3.9	60
Mendoza (3)	147.4	199.8	+52.4	99
San Luis (4)	469.4	514.3	+44.9	90
Villa Mercedes (5)	525.1	582.6	+57.5	>80
Rama Caída (7)	219.1	273.5	+54.4	95
Victorica (9)	398.1	470.6	+72.5	95

mechanism(s) could be constrained between both dates and may have its source in large scale given that its influence is upon the low-frequency variability of summer precipitation. A direct hypothetical factor could be the strengthening of large-scale atmospheric circulation observable over the southern portion of South America from the 1970s that advects humidity towards the region. In turn, a potential global climatic change occurring in 1977, connected to changes in the conditions of the Equatorial Pacific and the frequency, intensity and onset of the El Niño events, is well documented (Trenberth 1990, 1995; Ebbesmeyer et al. 1991; Wang 1995), which would indirectly influence the summer precipitation regime over the CWR. The common date of change is a fact, so such a likely relationship will be examined in Sect. 5.

4.2 Changes in local fluctuations

The extent to which this apparent change in climate is reflected intra-regionally has been investigated through the application of spectral analysis to each individual time series. Two sub-samples are analysed for each station, one from the starting year of the record until 1977, and the other by eliminating 21 years from the starting year and adding data from 1978 to 1998. The maximum lag has been established at 15 years as the shortest sub-sample studied is of 50 years, and the maximum periods of oscillation upon which comparisons may be made is 30 years (for details see Appendix).

Both spectra (earlier and later) for each station are shown in Fig. 8 identified by the station name and the last year of record employed in constructing the spectrum. The La Rioja 1998 spectrum with data up to 1998, has experienced a spectral energy shift in high frequency fluctuations from about 4 to 6 years, an increment in energy of the biennial oscillation and diminution of low-frequency oscillations of period about 18 years, compared to the La Rioja 1977 spectrum. The San Juan 1977 and 1998 spectra shows no energy change in the quasi-18 year fluctuation and a slight increment close to 4 years. To the south, the compar-

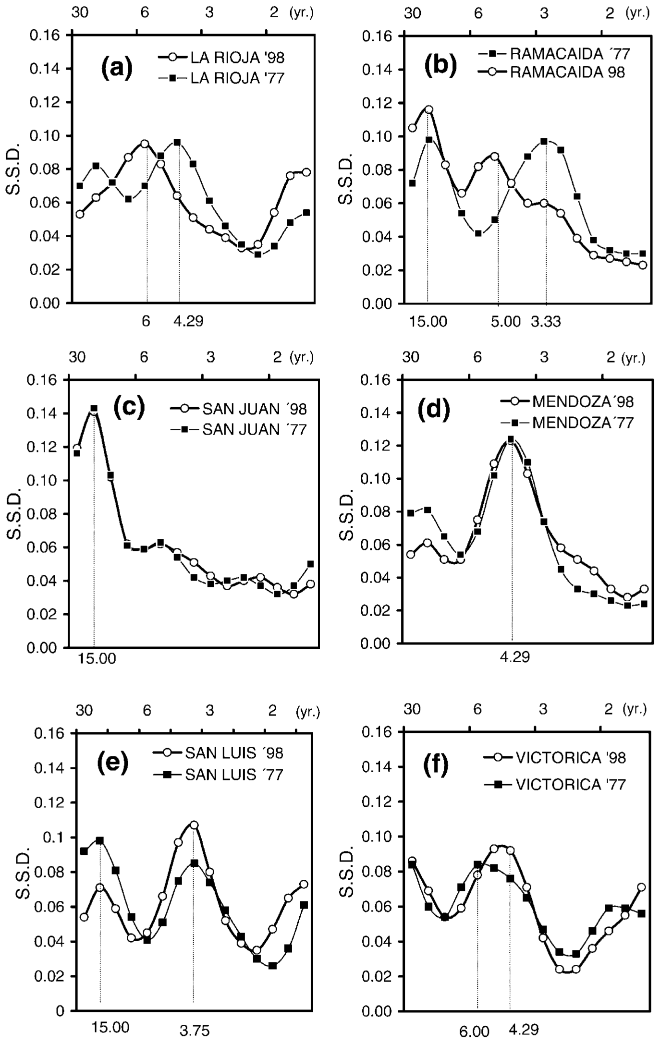

Fig. 8a–f Tukey's power spectra with Parzen's window of the samples obtained for each of the main summer-rainfall individual series of CWR for the periods ending in 1977 (*station name* 1977) and in 1998 (*station name* 1998). *SSD* means standarized spectral density

ison between Mendoza 1977 and 1998 spectra clearly illustrates a diminution of the 18 year quasi-oscillation along with an increment in the 3 year peak. Rama Caída shows spectral energy shift from the 4 year to the 6 year oscillation, and energy increments in low-frequency-oscillations in the band of about 18 to 30 years, for the spectrum with data up to 1998. Both San Luis 1998 and Victorica 1998 demonstrate an enhancement of spectral energy at a period of about 4 years, and at the biennial period, compared to the previous period. Victorica, to the southeast of the CWR, shows a clear increment in long-wave energy of the band periods of 18 to 30 years and about 6 years with the data up to 1998 (see Fig. 8).

Despite the fact that the samples containing the last 21 years of information frequently also contain observations from the pre-1977 period, the derived spectra show differences that are in keeping with the previously proposed changes for the characteristics in the regional index series of summer precipitation. The displacement of the 18 year peak towards lower frequencies is clearer in the southern areas. The 'pseudo peak' of about 6 years appears to be a shift from a previous 4 year oscillation.

5 Potential global links to the summer rainfall region of South Africa and the ENSO events

An apparent teleconnection between summer precipitation in CWR and SRR of South Africa through the 18 year quasi-oscillation in the period 1901–1978 was previously outlined by Compagnucci and Vargas (1983). Similarities in geography and location with respect to general atmospheric circulation were posited as possible explanations for this joint behaviour. Both regions are subtropical, located to the east of mountain chains, and are affected by the presence of the quasi-stationary subtropical highs, irregular irruption of cold frontal passages and synoptic cyclones. Nonetheless, such a teleconnection seems to be more complex involving atmospheric-oceanic interactions as well as inter-oceanic links (an atmospheric-oceanic teleconnection).

Results from Mason (1995), using a 80-year-long SST dataset, show that positive SST anomalies (SSTAs) southeast off the South African shore over the Indian Ocean in the Anghulas system are responsible of the major summer precipitations in the SRR. The Anghulas SSTAs reach a maximum between January and March and affect local atmospheric circulation in summer. Thus, wet conditions are associated with Anghulas warm events which enhance the tropical and middle latitude circulations by increasing the influx of warm and moist air from the east and along with the enhancement of cyclogenesis to the south of South Africa. The coupling of the tropical-temperate systems results in the formation of a trough across the SRR giving conditions of polewards transfer of heat and momentum with the subsequent enhancement of rainfalls. By analogy, a similar atmospheric connection between both CWR summer precipitation and SSTAs of the adjacent subtropical South Atlantic Ocean could be expected although further analysis is required to assess the hypothesis.

Another other relevant result obtained by Mason (1995) is the atmospheric teleconnection between the equatorial SSTs of the Atlantic Ocean and the SRR summer precipitation, though to a more minor degree than the Anghulas system. The westerly waves are affected by changes in the poleward transport of westerly momentum which originate from the South America tropical heat source. Hence, variations in the convective activity over tropical South America can influence precipitation over South Africa by its influence on westerly waves (Harrison 1986). A weakening and westward withdrawal of the 200 hPa wave is associated with wet conditions over South Africa. Such a situation can be found when the convective cloud-band is located westward of 20°W over tropical South Atlantic and the Brazilian forests leading to more convection over the continent and adjacent tropical South Atlantic.

This suggests that the SSTs of the tropical South Atlantic could be the common source for the atmospheric-oceanic teleconnection between both CWR and SRR summer precipitation regimes bearing in mind that the former is closely associated with South American tropical latitudes. This teleconnection is found to be at inter-decadal variations in the quasi-18-year fluctuation. In turn, global SSTAs of Southern Hemisphere oceans are shown to have a significant 16–21 year periodicity according to Folland et al. (1999) who link this frequency band with the periodicity of the South African summer rainfalls. This is the reason by which it does not seem to be odd to expect certain degree of low-frequency tropical-subtropical inter-continental linkage between the CWR and the SRR via the SSTs. In addition the Anghulas system also shows a 21 year quasi-fluctuation (Mason 1995; Reason and Mulenga 1999), which adds another variable to the already complex tropical-subtropical, inter-continental interactions, whose role in the former atmospheric-oceanic teleconnection must be carefully analysed. However, further work is needed to shed more light on such a link.

As discussed in Sect. 4, the CWR showed a significant change in the low-frequency variability, which is consistent with the long and persistent wet spell recorded from 1973 up to the end of the twentieth century. However, there is no documented evidence of a change in the temporal characteristics of the summer precipitation regime over South Africa. In fact, on the contrary, other studies (Tyson et al. 1986, 1991, 1997) suggest that SRR of South Africa has maintained its quasi-18-year fluctuation at least until 1996. Therefore, the former teleconnection between both regions may no longer exist. The contributions of low-frequency fluctuations, obtained by removing terms of higher frequency than nine years by filtering, to both the CWR and SRR series are shown in Fig. 5a,b. The horizontal bars illustrating wet and dry episodes indicate that the in-phase behaviour of both regions is preserved until the 1970s. The nine year alternation of wet and dry spells (i.e. 18 year oscillation) is still maintained in the SRR record until the 1990s. In fact, the SRR experienced a dry spell from 1983 that endured until the mid-1990s. The wet years of 1988 and 1989 are considered anomalous and a consequence of isolated heavy rainfalls in central South Africa (Tyson et el. 1997). Moreover, Mason (1996) states that the extended droughts, which occurred over vast areas particularly of eastern South Africa, from the beginning of the 1980s until mid-1990s, represent the longest extended dry spell of the century in SRR. Therefore comparisons between CWR and SRR indicate that the previously in-phase behaviour altered dramatically in the mid-1970s, to such an extent to be currently totally out-of-phase.

This disconnection between CWR and SRR around mid-1970s could be due to changes in the source of moisture and in the dynamic conditions involved in moisture advection and of those which favour local convection over CWR. On the other hand, the prevalence of the quasi-18-year oscillation in South Africa reveals continuity of those mechanisms and processes associated with the summer precipitation regime in that area until the end of the twentieth century.

The fundamental hypothesis which must be considered in future studies is that the moisture source for the CWR until 1977 could be mainly the subtropical South Atlantic while in the last decades of the century the major moisture source would be the equatorial-tropical South Atlantic as well as the Brazilian forests. Recent investigations confirm that in the recent years the humidity for CWR comes from tropical latitudes. The apparent South American tropical-subtropical connection seems to be the result of the meridional low level jet to the east of the Andes enhancing the influx of moisture to subtropical Argentina according to Saulo et al. (2000). Her results applied to the summer 1997/98, using the ETA model, show that the meridional low level jet splits into two branches. A minor branch of this moisture advection penetrates into CWR (see Fig. 13a, b in Saulo et al. (2000) which show mean summer stationary water vapour flux field integrated from 1000 to 800 hPa and from 1000 to 100 hPa). In particular, the wet 1997/1998 summer had above average rainfalls over CWR and was one of the wettest summers of the long-term wet spell registered in the region at one standard deviation above normal since the 1970s (see Fig. 5a). Also, positive/negative tropical SSTAs in the South Atlantic are associated with strong/weak trade-winds (Robertson et al. 2000) that are deflected polewards by the Andes to further determine the low meridional level jet. In concordance, former results obtained from the 1970s onwards determine that the Brazilian and Bolivian forests along the South Atlantic ocean provide movement of humidity southwards by channelling the low level circulation by to the Andes, the Plateau of Bolivia and the eastern highlands of Brazil (Wang and Peagle 1996). Moreover, Barros et al. (1996) found positive correlations between South American tropical convection and wet conditions over western subtropical Argentina. In turn, the tropical convection to the east of the Andes is also found to be directly correlated to SSTAs over the equatorial South Atlantic (Vuille et al. 1999) which reinforces the previous idea of a South Atlantic equatorial-tropical SSTs teleconnection bridge between both subtropical summer precipitation regimes of SRR and CWR.

In addition, the hypothesis that the increment in summer precipitation recorded since mid-1970 s in the CWR can be related to the enhancement of moisture advection from the equatorial-tropical South Atlantic and the Brazilian forests through the low level jet, is supported by two previous studies. One, the climatically provable increase of precipitation in the Pampas region, to the east of the CWR, and in the northeast of Argentina (Barros et al. 2000). The other, the positive tendency of the Uruguay, Negro, Paraná and Paraguay rivers, (part of the del Plata basin) to show increased streamflows after the mid-1960s at a rate that is approximately linear but not the same in all the rivers. These stream flows show a marked tendency toward levelling off in recent years (Genta et al. 1998). Both northeastern Argentina and del Plata basin are affected by the main branch of the low level jet. In addition, the major contribution of moisture is consistent with the positive tendency after mid-1970s in the SSTs over the equatorial-tropical South Atlantic shown by Folland et al. (1999).

On the other hand, changes in atmospheric circulation that occurred in the 1970s and 1980s over Southern Hemisphere and in particular over southern South America could be connected to the change in the CWR and responsible for the disconnection with the SRR of South Africa. van Loon et al.'s (1993) world wide survey showed that since mid-1970s and the 1980s the Southern Hemisphere circulation has changed radically compared to the 1970s and 1980s. Hurrel and van Loon (1994) determined that the change in the mean cycle of pressure, and high and middle latitude winds (circumpolar low, semi-annual wave and polar vortex) could be influenced by increasing SSTs in lower latitudes. Over the southern cone of South America, Camilloni (1995) found that the maximum of the SAA moved 5° polewards during the 1970s. Barros and Scasso (1994) encountered a positive continental pressure tendency at 45°S, consistent with the displacement southwards of the westerlies over the Patagonian region. This would bring a net increase in precipitation to the north of 40°S and east of the Andes, associated with a diminution of the north-to-south temperature gradient during the last 35 years (Barros et al. 1996).

From the 1970s it is clear that the tropical forests and equatorial-tropical South Atlantic SSTs are the sources of moisture flux for subtropical Argentina, and thus for the CWR. For the South African counterpart, the sources of moisture are mainly the adjacent southeastern Indian Ocean followed by the equatorial-tropical South Atlantic. It is evident that over the southern cone of South America the atmospheric circulation has changed significantly since mid-1970s giving rise to changes in precipitation regimes over subtropical Argentina.

In order to depict that the shift occurred between both CWR and SRR time series in lower frequency, the smoothed time series spectral density functions are shown in Fig. 9 for the whole period. Noticeably, the low frequency band significant at 90% confidence or more extends roughly from 19 to 9 years with spectral energy maximum between 18.7 and 14 years for South Africa. In CWR, this frequency band becomes wider toward lower frequencies with values between 28 to 9 years and a spectral energy peak located at around year 18.7. Additionally, the low frequency spectral energy appears to be higher in CWR than in SRR. Both results indicate a major variability of the low frequencies in CWR with a major length wave in average, which is visible in Fig. 9 through the difference between both spectral peaks. Although one must be prudent when interpreting these spectral results given that just the last 21 years of the time series of CWR have experienced the change, they are consistent with the loss of coherence between both CWR and SRR, clearly manifested in the longest recorded wet and dry episodes, respectively, in each region.

The diverging behaviours of the CWR and SRR since 1977 may be the result of varying dependence of each region's precipitation upon ENSO. However, Kruger (1999) claims no statistical association exists between precipitation in SRR and ENSO events. At most one can only expect that an extreme wet summer may occur within a extended wet (dry) spell if a La Niña (El Niño) event occurs. Additionally, Tyson et al. (1997), studying climatic teleconnections between New Zealand's glacial advances and South Africa's summer droughts, found that although the ENSO plays an important role in climatic variability, it does not seem to provide a proper mechanism to explain the New Zealand/South Africa teleconnection at inter-decadal scales.

With the intention of determining whether there exists an association between wet/dry spells in CWR and warm/cold phase of ENSO, contingency tables (Table 7) are constructed. Summer precipitation is considered as a dichotomous variable (above or below long-term mean) and years are categorised as El Niño, La Niña or Normal. Since the null hypothesis of independence cannot be rejected at the 0.05 level, it is suggested that the year-to-year summer precipitation may not be associated with the ENSO phenomenon. Nonetheless, one wonders about the kind of association existing, if any, between the change in the mean conditions of the equatorial Pacific SSTs and the change in summer precipitation regime over CWR, both around 1977. In fact, during the last decades the few observable La Niña events have been weak, in accord with a period of a few extended rather dry summers over CWR. In general for the period 1910–1998, there is a tendency to have below-average precipitation within La Niña years (ten against seven cases). Moreover, the driest summer of 1989, although not falling below one standard deviation, occurred simultaneously with a strong La Niña event. These results suggest that though the interannual variability of summer precipitation may be independent of ENSO events, it is possible to find a possible association at decadal to multidecadal variability between wet/dry spells and warm/cold ENSO events.

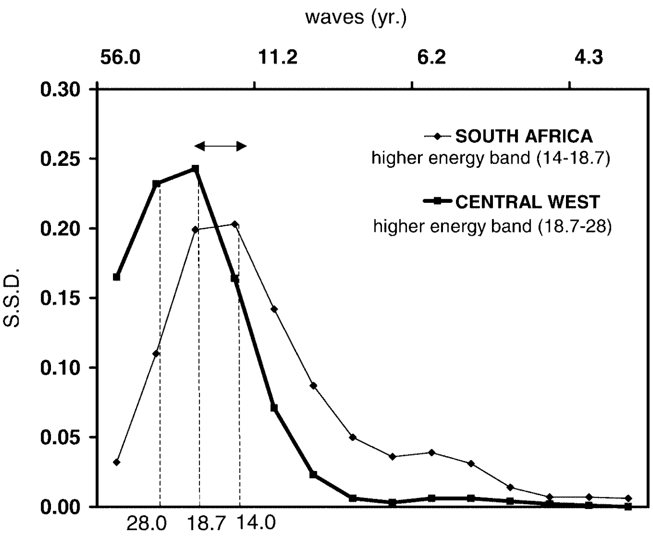

Fig. 9 Tukey's power spectra with Parzen's window of the 9-term-smoothed summer-rainfall index for both CWR and SRR in the period 1901–1998. *SSD* is standarized spectral density

Taking into account the relevant role of South Atlantic SSTs as moisture flux source, any explanation of potential relationships between ENSO events and the CWR summer precipitation needs to be sought in inter-oceanic interactions between the equatorial SSTs of the Pacific and the Atlantic oceans that indirectly could affect summer precipitation. Interactions between the equatorial Pacific SSTAs (ENSOs) and the tropical-subtropical Atlantic SSTAs have been studied (Saravanan and Chang 2000, among others). Therefore, further analysis is needed in order to understand the matter. At present, any association between both wet/dry spells in CWR and El Niño/La Niña events is, at best, inconclusive.

6 Conclusions

In spite of the fact that records are shorter than 100 years, that the density of stations in the area is low, that discontinuities and inhomogenities are present in the series, and that an important inter-annual variability of rainfall exists which may bias any discussion of fluctuation, the analysis of summer precipitation has been performed for the central-western Argentina (CWR) with the intention of identifying quasi-oscillations in the series. The study was curried out using nine stations

Table 7 Contingency table for the input variables ENSO-year and regional summer-rainfall within three categories for the former: EL Niño, La Niña and Normal; and two for the latter: wet year and dry year. Observed values and in parenthesis theoretical values according to the hypothesis of independence between variables

Year	El Niño	La Niña	Normal	Total
(+) WET	11 (9.4)	7 (7.5)	25 (23.1)	43
(–) DRY	10 (5.3)	10 (8.5)	25 (25.9)	45
Total	21	17	50	88

widely distributed over CWR with quality records throughout the twentieth century, minor discontinuities and few missing data that could be estimated by interpolation.

The driest core is located at San Juan on the middle western boundary of the region, rising towards the north, east and south. The eastern lands are the wettest and also the most variable, particularly at Victorica in the southeast, becoming the most vulnerable to climatic variations. In each individual series, decadal variations of period around 18 years and of approximately 6, 4 and 2 years are present to a varying degree, implying some sort of coherent climatic fluctuations over the region. Additionally, a long wave of approximately 40 years is mainly evidenced by the smoothed time series of La Rioja, to the north and of Victorica on the southeast, of the region. This means that decadal variability is added to that fluctuation of over 40 year affecting the alternating wet and dry patterns.

The analysis of the spatially averaged summer precipitation index for the CWR shows a fairly regular pattern of alternating wet and dry spells. On average such spells lasted for about nine years during the period 1901–1973. During such protracted conditions there were generally two years of opposing sign, although the extended droughts were more uniformly dry than the wet episodes were wet. The spectral density function of the regional index shows similar periods of oscillation to those found at each individual station, all of which are significant at the 90% confidence level, with the exception of that at six years that poorly reaches 75% confidence. In particular, the quasi-oscillation of 18 years is enhanced and corresponds to the low frequency pattern described.

In the summer rainfall region (SRR) of South Africa a similar decadal quasi-18-year oscillation with alternating wet and dry spells of approximately nine years is found in the regional index series for almost the whole century (Tyson et al. 1997; Mason 1995). During mid-1980s and mid-1990s the SRR has experienced one of the most severe drought (Mason 1996), expected by the long-term variation of around 18 years. It is found that these oscillations are in-phase related to those of CWR until mid-1970s.

The apparent teleconnection between both SRR and CWR low-frequency summer rainfall variability suggests large-scale atmospheric-oceanic factors are involved and have to be investigated. Results for SRR showed relationships with global SST variations (Mason 1995; Folland et al. 1999) so the former atmospheric-oceanic teleconnection could be concordant with them. Therefore, understanding of the former linkage between both subtropical regions and, particularly, the equatorial South Atlantic SST variations is relevant for the development of potential climatic forecasts.

However, since the mid-1970s the decadal oscillation over CWR has been interrupted by the longest, as yet unfinished, wet spell of the century giving rise to an opposing behaviour to that of SRR for mid-1980s and the 1990s. The comparison between spectra with data up to 1977 and with data up to 1998, indicates that the low-frequency band of 16–21 years has a peak of energy that has shifted from around 16 years to around 21 years, bands of around 6 years has appeared, and the biennial oscillation has become more pronounced in the analysis with data up to 1998. The analysis of comparison for each meteorological station shows slightly different individual spectra. The shift of the 18 year oscillation is most apparent at Rama Caída to the south. In La Rioja and Rama Caída, the peak of near four years appears to be shifted towards the 6 year quasi-oscillation if the last 21 years is added.

Analysing the mean of regionally averaged summer precipitation using the Yamamoto statistical index, showed that the CWR experienced a climatic 'jump' in 1973. Nonetheless, when modelling the smoothed time series of the regional index of CWR (explaining more than 89% of the variance) using the periodicities of low frequency observed until 1977 with major spectral energy, the change is clear in 1977 from which the observed values differ evidently from those of the model. From mid-1970s onward the apparent climatic change produce thereby an increase of 20% in spatial average of summer precipitation and modifies its regional fluctuation pattern.

As a consequence of this change in the low-frequency regime of summer precipitation, the long-wave teleconnection between the CWR and SRR of South Africa has been lost. The SRR appears to have continued with the 18 year oscillation, undergoing the anticipated dry spell (Tyson et al. 1997).

Furthermore, there appears to be no evidence of dependence between year-to-year above/below average rainfalls in CWR and warm/cold ENSO phases (a result also found in SRR). Nonetheless, it is possible to find a potential association at decadal to multidecadal scales between both phenomena, which could give one explanation for the former atmospheric-oceanic teleconnection between the South African and central-western Argentina summer rainfall regions.

The trigger of forcing mechanism(s) of the current regional summer precipitation regime seems to be related to the large-scale phenomena as such influence is reflected mainly in low-frequency variations. A potential hypothetical factor of change could be the strengthening of direct and indirect mechanisms of moisture flux transport associated with low-level atmospheric circulation changes and/or to the SSTs mean condition long-term variation over tropical and subtropical South Atlantic and South Pacific oceans.

A hypothesis is that the loss of teleconnection around mid-1970s between both subtropical regions could be possibly due to a change in the atmospheric circulation observed over the southern cone of South America (Barros et al. 1996, 2000). Then, it would lead to possible changes in the source of moisture advection towards the CWR from subtropical latitudes to tropical latitudes of the South Atlantic, in the strengthening of dynamic mechanisms also associated to moisture advection and/or in the atmospheric dynamics of circulation of convective processes over the area.

Finally, the current analysis encourages exploration of the essential dynamical atmospheric-oceanic interactions that affect CWR summer precipitation. Further works should consider the study of mean conditions of the SSTs of the tropical and subtropical South Atlantic Ocean in relation to the grouping of summers of both positive and negative anomaly precipitation. Moreover, studies of equivalent potential temperature fields are needed to identify the origin of air masses arriving at CWR and to determine the influence on precipitation of circulation change observed over southern South America. A first approach could be the exploration of mean pressure fields in the lower troposphere associated with wet and dry events in order to sustain the previous hypothesis.

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Appendix

Evaluation of the confidence level of the spectral estimates

The confidence level of the spectra can be evaluated using the following steps: examination of the time series regarding autocorrelation, identification of the adequate 'null' continuum, and testing of the difference between the time series spectrum and the adequate 'null' continuum.

1. If the lag 1 autocorrelation coefficient, r_1, of a time series (sample) does not differ significantly from zero, it should be assumed that this time series is free from persistence and that, the occurring periods in the spectrum are random and not transferable to the population spectrum. In this case the proper 'null' continuum is that of 'white noise', i.e. a horizontal straight line equal to the average of all $m+1$ 'raw' spectral estimates of the spectrum evaluated.
2. If the lag 1 autocorrelation coefficient, r_1, differs significantly from zero, and the autocorrelation function shows a simple exponential decline, it can be assumed that the 'null' continuum is that of 'red noise'. This is frequently the case for climatological data, then estimation of a population spectrum is generally performed using Markov generated 'red noise'. The shape of the 'red noise' is dependent upon the lag 1 autocorrelation coefficient. The computation of a proper 'null' continuum is based on the assumption that the r_1 is an unbiased estimator for the autocorrelation coefficient (Mitchell et al. 1966), which is given by:

$$\hat{S}_k = \bar{S}\left[\frac{1-r_1^2}{1+r_1^2-2r_1\cos\frac{\pi k}{M}}\right] \quad k = 1,\ldots,M \ ,$$

where $\hat{S}_k$ is the 'red noise' continuum, $\bar{S}$ is the 'white noise' continuum, $M = N/3$ number of spectral estimates (maximum lag) and N is the time series length. The selected maximum lag, M, is in accordance with suggestions (Mitchell et al. 1966) of optimising spectral detail and minimising its instability. If the autocorrelation function shows no exponential decline, the Markov 'red noise' is inappropriate.

Whether the computed spectra of the time series differ from either 'red' or 'white' continuum can be examined by means of the Chi-squared test, because the ratio of the smoothed spectral estimator $C_{xx}(f)$ to the true value $S_{xx}(f)$ is approximately distributed as χ^2 (Jenkins and Watts 1968).

$$\frac{C_{xx}(f)}{S_{xx}(f)} \propto \frac{\chi_\mu^2}{\mu} \ ,$$

where $\mu = (2\,N - M/2)/M$ degrees of freedom, M and N are defined as before.

Thus the confidence limits about $S_{xx}(f)$ are evaluated as,

$$\frac{\mu \times C_{xx}(f)}{\chi_\mu^2(\alpha/2)} \leq S_{xx}(f) \leq \frac{\mu \times C_{xx}(f)}{\chi_\mu^2(1-\alpha/2)}$$

which are valid for a particular frequency f.

Filtering of the time series

Time series $X(t)$, for $t = 1,\ldots,N$, have been smoothed using a 9-term binomial pass filter of the type recommended by Mitchell et al. (1966) in which the smoothed series is given by

$$\begin{aligned} S(t) &= 0.02X(t-4) + 0.05X(t-3) + 0.12X(t-2) \\ &\quad + 0.20X(t-1) + 0.22X(t) + 0.20X(t+1) \\ &\quad + 0.12X(t+2) + 0.05X(t+3) + 0.02X(t+4) \end{aligned}$$

The frequency response for the series $S(t)$ is approximately $R(f) = \cos^n(\pi f \Delta t)$, where n is the order of binomial expansion. This function gives ratios of smoothed to unsmoothed amplitudes of 0.928, 0.903 and 0.719 for 21, 18 and 10 years.

Objective proof of climatic 'jump'. Yamamoto's index (Yamamoto et al. 1986)

When aiming to measure the statistical significance of a climatic 'jump', the confidence limit of time mean is proposed as measurement.

Let there be a time series of year-to-year values of a climatic element x_i ($i = 1, 2,\ldots, N$), $\mathbf{M}$ is its sample time mean and S_x^2, the sampling variance both for a time interval N. Then the confidence limit C_p of probability p% for the time mean over N is given by $C_p = S_x t_q/(N-1)^{1/2}$, where t_q is the value in the t-student distribution with probability $q\% = (100 - p\%)$.

For purpose of detecting any climatic 'jump', the time means M_B and M_A and variances S_B^2 and S_A^2 are computed for samples of size N before and after a specified year which is shifted in turn. As a measure of statistical significance for the discontinuity between M_B and M_A, the J_p signal-noise ratio of probability p% is introduced as $J_p = S/N = \backslash M_B - M_A \backslash\ /(C_{pB} + C_{pA})$. Here C_{pB} and C_{pA} are the confidence limits of probability p for M_B and M_A, respectively. It is reasonable to conclude that a discontinuity of time means could be detected with p% confidence at the reference years when the value of J_p might be greater than unity.

Usually J_p is greater than 1.0 during the several years around the exact year of discontinuity. If such is the case then the year of maximum J_p is assumed as the discontinuity year.

References

Agosta EA, Compagnucci RH, Vargas WM (1999) Cambios en el régimen interanual de la precipitación estival en la región Centro-Oeste Argentina. Meteorol 24(1/2): 63–84

Barros VR, Scasso LM (1994) Surface pressure and temperature anomalies in Argentina in connection with the Southern Oscillation. Atmósferas 94(7): 1159–1171

Barros VR, Castañeda M, Doyle M (1996) Recent precipitation trends in Southern South America to the east of the Andes: an indication of a mode of climatic variability. In Rosa LP, Santos MA (eds) Greenhouse gas emission under developing countries point of view, COPPE, Río de Janeiro, Brasil, pp 41–67

Barros VR, Castañeda ME, Doyle M (2000) Recent precipitation trends in southern South America east of the Andes: an indication of climatic variability. In: Smolka PP, Volkheiner W (eds) Southern Hemisphere Paleo and Neoclimates. Springer, Berlin Heidelberg New York, pp 187–206

Camilloni I (1995) La influencia de la isla urbana de calor en las tendencias seculares de la temperatura media anual en la Argentina Subtropical. PhD Thesis, Universidad de Buenos Aires, Argentina

Climatic Analysis Center (1996) Climatic Diagnostic Bulletin US Department of Commerce, NOAA/NWS/NMC, USA

Compagnucci RH, Vargas WM (1983) Spectral analysis of summer precipitation series. Preprints, II International Meeting on Statistical Climatology, Lisbon, Portugal, Inst Nac Meteorol Geogr (eds) 11.7.1–11.7.8

Compagnucci RH, Agosta EA, Vargas MW (1999) Inter-annual variability of summer rainfall over central-west Argentina. 11th Conf Applied Climatology, 10–15 January, Dallas Texas, Am Meteorol Soc (eds) pp 297–300

Ebbesmeyer CC, Cayan DR, McLain DR, Nichols FH, Peterson DH, Redmond T (1991) 1976 step in the Pacific Climate: forty enviromental changes between 1968–1975 and 1977–1984. Proc 7th Annual Pacific Climate (PACLIM). Workshop, April 1990, Betancourt JL, Tharp VL (eds) Californian Dept Water Resources, Interagency Ecological Studies Program, Tech Rep 26: 115–126

Folland CK, Parker DE, Colman AW (1999) Large scales modes of ocean surface temperature since the late Nineteenth Century. In: Antonio Navarra (Ed) 'Beyond el Niño: decadal and interdecadal climate variability'. Springer, Berlin Heidleberg New York, 73–102

Genta JL, Perez-Irabarren G, Mechoso CR (1998) A recent increasing trend in streamflow of rivers in southeastern South America. Clim 11: 2858–2862

Gisbson TT (1992) An observed poleward shift of the Southern Hemisphere subtropical wind maximun–a greenhouse symptom? Int J Clim 12: 637–640

Harrison MSJ (1986) A synoptic climatology of South African rainfall variations. PhD thesis, University of the Witwaterstrand, 341pp

Hoel Paul G (1964) Introduction to Mathematical Statistics, John Wiley, New York

Hoffmann J (1992) The continental atmospheric pressure and precipitation regime of South America. Erdkunde. Archiv für wissenschafliche geographie. Boss, Kleve, pp 40–51

Hoffmann J, Haluszczac G, Coy J (1994) Die niederschlagscharakteristk in Nordwest- und zentralargentinien und ihre wurtschaftliche bedeutung. Geookodynamik, XV: pp 151–163

Hurrel JW, van Loon H (1994) A modulation of the atmospheric annual cycle in the Southern Hemisphere. Tellus 46A: 325–338

Jenkins GM, Watts DG (1968) Spectral analysis and its applications. Holden-Day, San Francisco, 525pp

Kane RP, Trivedi NB (1986) Are droughts predictable? Clim Change 8: 209–223

Kiladis GN, van Loon H (1988) The Southern Oscillation. Part VII: meteorological anomalies over the Indian and Pacific sectors associated with extremes of the Oscillation, Mon Weather Rev 116: 120–128

Kruger AC (1999) The influence of the decadal-scale variability of summer rainfall on the impact of El Niño and La Niña events in South Africa. Int J Clim 19: 59–68

Lichtenstein ER (1980) La depresión del Noroeste Argentino. PhD thesis FCEyN, University of Buenos Aires, Argentina 120p

Mason SJ (1995) Sea-Surface Temperature-South-African Rainfall Associations, 1910–1989. Int J Clim 15: 119–135

Mason SJ (1996) Rainfall trends over the lowveld of South Africa. Clim Change 32: 35–54

Mitchell JM, Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, Wallén CC (1966) Climatic change, Technical Note 79, WMO 80pp

Panofsky H, Brier G (1958) Some applications of statistics to meteorology. College of Mineral Industries, Pennsylvania State University, 223pp

Penland C, Matrosova L (1998) Prediction of tropical Atlantic sea surface temperature using linear inverse modelling. J Clim 11: 483–496

Prieto R, Gimeono L, García R, Herrera R, Hernández E, Ribera P (1999) Interannual variability of hail-days in the Andes region since 1885. Earth Plane Sci Lett 171: 503–509

Quinn WH, Neal VT (1983) Long-term variations in the Southern Oscillation, El Niño and the Chilean subtropical rainfall. Fish Bull 81: 363–374

Reason CJC, Mulenga H (1999) Relationships between South African rainfall and SST anomalies in the southwest Indean Ocean. Int J Clim 19(15): 1651–1673

Rasmusson EM, Carpenter TH (1983) The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. Mon Weather Rev 111: 516–528

Robertson AW, Mechoso CR, Kim Y-J (2000) The influence of Atlantic sea surface temperature anomalies on North Atlantic Oscillation. J Clim Am Meteorol Soc 13: 122–138

Saravanan R, Chang P (2000) Interaction between tropical Atlantic variability and El Niño-Southern Oscillation. J Clim 13: 2177–2194

Saulo AC, Nicolini M, Chou SC (2000) Model characterization of South American low-level flow during the 1997–1998 spring-summer season. Clim Dyn 16: 867–881

Schwerdtfeger W (1976) The atmospheric circulation over Central and South America. In: Climates of Central and South America. World Survey of Climatology 12, Elsevier, pp 2–12

Trenberth KZ (1989) Toga and atmospheric processes. In: Berger A, Dickinson RE, Kidson JW (eds) Understanding climate change Geoph Monogr 52, IUGG 7: 117–125

Trenberth KZ (1990) Recent observed interdecadal climate changes in the Northern Hemisphere. Bull Am Meteorol Soc 71: 988–993

Trenberth KZ (1995) Atmospheric circulation climate change. Clim Change 31: 427–453

Tyson PD, Dyer TG (1978) The predicted above normal rainfall of the seventies and the likelihood of droughts in the eighties in South Africa. S Afr J Sci 74: 372–377

Tyson PD (1981) Atmospheric circulation variations and the occurrence of extended wet and dry spells over South Africa. J Clim 1: 115–130

Tyson PD (1986) Climatic change and variability in Southern Africa. Oxford University Press, Cape Town, p 220

Tyson PD (1991) Climatic change in Southern Africa: past and present conditions and possible future scenarios. Clim Change 18: 241–258

Tyson PD, Sturman AP, Fitzharis BB, Mason SJ, Owens IF (1997) Circulation changes and teleconnections between glacial advances on the west coast of New Zealand and extended spells of drought years in South Africa. Int J Clim 17: 1499–1512

van Loon H, Kidson JW, Mullan AB (1993) Decadal variation of the annual cylce in the Australian dataset. J Clim 6: 1227–1231

Vuille M, Bradley RS, Keimig F (2000) Climate Variability in the Andes of Equator an its Relation to Tropical Pacific and Atlantic Sea Surface Temperature Anomalies. J Clim 13: 2520–2535

Wang B (1995) Interdecadal changes in El Niño onset in the last four decades. J Clim 8: 267–285

Wang M, Peagle J (1996) Impact of analysis uncertainty upon regional atmospheric moisture flux. J Geospfys Res 101: 7291–7303

Wright PB (1989) Homogenized long-period Southern Oscillation Index. Int J Climatol 9: 33–54

Yamamoto R, Iwashima Y, Sanga T (1986) An analysis of climatic jump. J Meteorol Soc Japan. 64(2): 273–280