Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30-43º S

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RESUMEN

Se analiza la evolución de la precipitación a lo largo de la costa occidental de América del Sur entre 30 y 43º S (Chile central) durante el periodo 1900-2007. Investigaciones previas han documentado la existencia de una persistente tendencia negativa en la precipitación anual en esta región. Este estudio se focaliza en los cambios y fluctuaciones en la escala de tiempo decadal, explorando posibles vinculaciones con anomalías en la circulación atmosférica regional relacionadas con modos oscilatorios de gran escala del sistema océano-atmósfera. Específicamente, la condición relativamente seca que predominó entre la década de 1950 y principios de los años setenta en el sector norte de Chile central (30-35º S) es consistente con un anticiclón subtropical intensificado en el Pacífico sur-oriental durante un período en que predominó la fase positiva de la Oscilación del Sur (SO) y la fase fría de la Oscilación Decadal del Pacífico (PDO). El cambio de la PDO hacia la fase cálida a mediados de la década de 1970 fue seguido por un aumento de frecuencia de la fase negativa de la SO y de episodios El Niño asociados. El concurrente debilitamiento del anticiclón subtropical favoreció un aumento en la frecuencia de años relativamente lluviosos en esta región. Más hacia el sur, la tendencia negativa de precipitación que ha prevalecido entre 37 y 43º S desde la década de 1950 se intensificó a fines del siglo XX. Los cambios en el gradiente meridional de presión atmosférica a nivel del mar entre latitudes medias y altas en el Pacífico suroriental, que se vinculan parcialmente con la Oscilación Antártica (AAO), tienen un rol significativo en la modulación de la variabilidad interanual de la precipitación en Chile central, particularmente durante el semestre de invierno austral (abril-septiembre). De este modo, un gradiente de presión intensificado (reducido) favorece un desplazamiento hacia el sur (el norte) de la banda latitudinal de sistemas de bajas presiones migratorias extratropicales y de los sistemas frontales asociados. La significativa tendencia positiva que muestran desde la década de 1950, tanto el índice de AAO como su contraparte regional en el Pacífico suroriental, puede explicar en parte la tendencia negativa que se ha observado en la precipitación anual en el sector sur de Chile central, como resultado tanto de una reducción en la frecuencia de días de precipitación como en la intensidad de la misma. La mayoría de los modelos climáticos globales y regionales utilizados para evaluar escenarios climáticos futuros asociados a la intensificación del efecto invernadero indican que la precipitación en esta región continuará disminuyendo, lo que es consistente con la tendencia positiva de la AAO que dichos modelos pronostican.

ABSTRACT

The evolution of annual rainfall along the west coast of South America from 30 to 43º S (central Chile) is analyzed for the period 1900-2007. A prevailing negative trend in annual rainfall has been documented for this region in several previous studies. Here we focus on the significant changes and fluctuations occurring at the decadal time scale, exploring the links with regional atmospheric circulation anomalies associated with large-scale oscillatory modes of the ocean-atmospheric system. In particular, the relatively dry condition that prevailed from the 1950s to the early 1970s in the northern part of central Chile (30-35º S) is consistent with an intensified subtropical anticyclone in the southeast Pacific during a period characterized by a prevailing positive phase of the Southern Oscillation (SO) and the cold phase of the Pacific Decadal Oscillation (PDO). The shift of the PDO toward the warm phase by the mid-1970s was followed by an increased frequency of the negative phase of the SO and associated El Niño episodes. Concurrent weakening of the subtropical anticyclone favored an increased frequency of wet years in this region. Further south the negative trend in annual rainfall that prevailed since the 1950s in the region from 37 to 43º S intensified by the end of the 20th century. Changes in the meridional sea level pressure gradient at mid-latitudes and high-latitudes in the southeast Pacific, which are partially connected to the Antarctic Oscillation (AAO), play a significant role in modulating the interannual rainfall variability in all central Chile, especially during the austral winter semester (April-September). Thus, an intensified (reduced) meridional pressure gradient in that region favors a southward (northward) displacement of the latitudinal band of migratory extratropical low pressure systems and associated fronts. The significant positive trend that both the AAO index and its regional counterpart in the southeast Pacific exhibit since the 1950s may partially explain the observed downward trend in annual precipitation in the southern portion of central Chile, resulting from a reduction in both the frequency of wet days and the intensity of precipitation. Most of the global and regional climate models used to assess future climate scenarios associated with an enhanced planetary greenhouse effect, also call for a reduction of rainfall in this region which is consistent with the positive trend in the AAO predicted by those models.

Keywords: Southern Oscillation, Pacific Decadal Oscillation, Southeast Pacific Subtropical Anticyclone, Antarctic Oscillation.

1. Introduction

The region along the extratropical west coast of South America spanning from the extremely arid Atacama desert in the north to the very wet domain at midlatitudes corresponds to the central portion of Chile, that concentrates more than 90% of its population and most of the economic activities of the country. The rainfall regime along this transitional region is quite different from that in the rest of the southern portion of the continent, not only regarding the annual amount as shown in Figure 1, but also in its seasonality and the associated mechanisms. The Andes cordillera that isolates this region from the Atlantic influence is the major factor explaining the marked contrast in the mean and the seasonal cycle on both sides of the mountains. Thus, in the subtropical domain along the West coast of the continent more than 50% of precipitation falls during austral winter (JJA) and is mostly associated with extratropical cold fronts that reach this region when the subtropical anticyclone in the southeast Pacific and the midlatitude band of migratory low pressure systems are at their northernmost position (Montecinos and Aceituno, 2003). At the same latitudes eastward from the Andes up to around 60º W the wet season coincides with austral summer (DJF) when the advection of air masses bringing moisture from the Amazon basin reaches its maximum strength in the annual cycle (Vera *et al*., 2006). In the eastern portion of subtropical South America, including southern Brazil, eastern Paraguay and northeastern Argentina, an active meridional

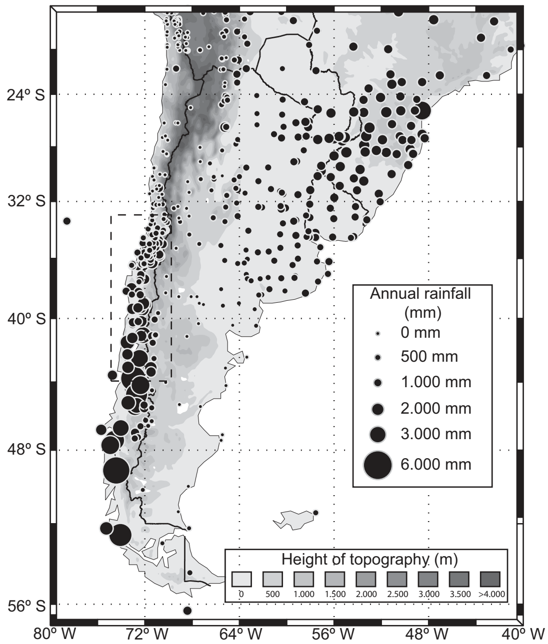

Fig. 1. Mean annual rainfall in southern South America for the period 1960-1990, calculated from records available to the authors or obtained from National Weather Services within the region.

interaction between warm and humid air masses from the tropics and relatively colder and drier ones from midlatitudes explains the relatively weak amplitude of the rainfall annual cycle in this region (González and Barros, 1997; Grimm *et al*., 2000). The southern tip of the continent is under the permanent influence of extratropical disturbances embedded in the midlatitude westerlies, but as shown in Figure 1, the Andes cordillera defines a sharp contrast between the very wet conditions on the windward side of the mountains (due to the forced uplift of the prevailing westerly flow) and the much drier condition in the region east of the mountains (Patagonia).

In central Chile annual precipitation increases southward from a few mm a year along the Atacama desert in northern Chile, to more than 3 000 mm along the islands facing the Pacific in the southern part of the country (Fig. 1). As explained earlier, in the region stretching from the southern margin of the Atacama Desert (23º S) to around 36º S precipitation occurs predominantly during austral winter. In contrast, south of 42º S in the area dominated by the permanent influence of midlatitudes fronts, rainfall episodes are common all year long. In the transitional region from 36 to 42º S rainfall is larger during winter, but a significant precipitation amount is also observed during the summer semester (October-March).

Regarding the interannual rainfall variability, several studies have documented the tendency for above normal rainfall in central Chile during the negative phase of the Southern Oscillation (SO) or during El Niño episodes, with opposite conditions being reported for the positive SO phase or La Niña events (Pittock, 1980; Quinn and Neal, 1983; Aceituno, 1988; Grimm *et al.*, 2000; Montecinos *et al.*, 2000a, b). Changes in the intensity of the subtropical anticyclone and in the atmospheric circulation at higher latitudes in the southeast Pacific (blocking) have been mentioned as key factors explaining those rainfall anomalies (Rutllant and Fuenzalida, 1991; Montecinos and Aceituno, 2003).

The prevailing negative trend in annual rainfall along the subtropical west coast of South America during the 20th century in contrast with a marked increase in the southeastern portion of the continent have been documented in several previous studies (Krepper *et al.*, 1989; Aceituno *et al.*, 1993; Hulme, 1996; Dai *et al.*, 1997; Minetti and Vargas, 1997; Barros *et al.*, 2000; Montecinos *et al.*, 2000a, b; Minetti *et al.*, 2003; Haylock *et al.*, 2006; Folland *et al.*, 2001; Trenberth *et al.*, 2007). Considering that the assessment of slow climatic changes based on linear trends is relatively limited and sometimes misleading, the objective of this paper is to document the decadal and long-term variation in the rainfall regime in central Chile, and to explore some mechanisms that explain it. This is achieved through the analysis of changes in annual rainfall along the 30-43º S latitudinal band for the period 1900-2007, and its links with changes in regional and large-scale atmospheric circulation indices.

2. Data

Annual rainfall series from stations having a reasonable operational record (less than 5% of missing data) were compiled for the region 30-43º S in central Chile, considering available data from 1900 onwards. Rainfall data was subjected to a careful scrutiny, searching for obvious discrepancies of values at nearby stations. An homogeneity test (Alexandersson, 1986) based on the analysis of the ratio between rainfall at neighboring stations was applied. Series whose values had to be modified by more than 5% were excluded, unless the source of inhomogeneity was clearly identified as resulting from a change in the station location. The list of selected stations is presented in Table I. A clustering technique was used to combine these series into eight spatially homogeneous annual rainfall indices covering the region 30-43º S (Fig. 2). Moreover, annual rainfall for two stations at higher latitudes (Balmaceda and Punta Arenas) during the period 1976-2007 was considered for some specific aspects of the study. The grouping was considered adequate to characterize the regional changes in the rainfall regime from the semi-arid condition in the north to the very wet condition in the south. Each rainfall index was calculated as the average of the standardized rainfall series within the group, using 1971-2000 as the reference period. Since most of rainfall episodes are associated with cold fronts, rainfall variability is highly coherent within each group. For the period 1900-1929 rainfall indices are based on fewer stations due to reduced data availability (see Table I). In group 8, annual rainfall corresponding to station Futaleufu during 1930-1950 was estimated from data at a neighboring station in Argentina (Esquel).

In this study we also analyze the changes in the frequency of rainfall events and in the intensity of precipitation in order to assess how they relate to slow changes in annual rainfall. We examine this matter by analyzing daily precipitation data compiled for a few stations in central Chile, including La Serena, Santiago, Concepción, Valdivia and Puerto Montt (Table I and Fig. 2).

In order to assess the link between slow changes in the intensity of the southeast Pacific subtropical anticyclone (SEP-High) and those in annual rainfall in central Chile, an annual surface pressure index was calculated for the period 1970-2007 as the 1st principal component of mean surface pressure at eight stations located within the domain of the anticyclone (Fig. 2): Arica (18.3º S, 70.3º W), Iquique (20.5º S, 70.2º W), Antofagasta (23.4º S, 70.4º W), La Serena (29.9º S, 71.2º W), Santiago (33.5º S, 70.7º W), Concepción (36.9º S, 73.0º W), Juan Fernández (33.7º S, 79.0º W) and Easter Island (27.2º S, 109.4º W). Problems with data availability for some of these stations prevented the calculation of this index for the period before 1970. Description of other regional and large-scale circulation indices and specific methods used for analysis are explained in the sections where those indices and methods are applied. In the northern part of central Chile the assessment of

Table I. Meteorological stations for which annual rainfall series were considered. Stations in bold indicate those for which daily rainfall data was compiled during the period 1930-2007.

Group	Station	Lat. (º S)	Lon. (º S)	Annual rainfall (mm)	Period
1	**La Serena**	29.9	71.2	78	1900 - 2007
	Vicuña	30	70.7	92	1918 - 2007
2	Puerto Oscuro	31.4	71.6	163	1911 - 2007
	La Ligua	32.5	71.3	322	1912 - 2007
	San Felipe	32.8	70.7	224	1925 - 2007
	Limache	33	71.3	434	1929 - 2007
	Valparaíso	33	71.6	386	1900 - 2007
3	**Santiago**	33.5	70.7	335	1900 - 2007
	La Obra del Maipo	33.6	70.5	664	1915 - 2007
	Aculeo Pintue	33.9	70.9	596	1913 - 2007
4	Pumanque	34.6	71.7	618	1922 - 2007
	San Fernando	34.6	71	699	1910 - 2007
	Curicó	35	71.2	704	1918 - 2007
	Talca	25.4	71.7	646	1907 - 2007
	Cauquenes	36	72.3	392	1919 - 2007
5	Bullileo	36.3	71.5	2134	1930 - 2007
	Concepción	36.9	73	1102	1900 - 2007
	Atalco	36.9	71.6	2410	1930 - 2007
	San Cristóbal	37.2	72.6	984	1914 - 2007
	El Tambillo	37.6	72.7	1199	1930 - 2007
6	Temuco	38.8	72.6	1197	1911 - 2007
	Valdivia	39.6	73.1	2138	1900 - 2007
	Panguipulli	39.7	72.3	2246	1914 - 2007
7	La Unión	40.3	73.1	1159	1925 - 2007
	Osorno	40.6	73.1	1276	1927 - 2007
	La Ensenada	41.2	72.5	1875	1921 - 2007
	Puerto Montt	41.5	72.9	1678	1930 - 2007
8	Castro	42.5	73.8	1814	1930 - 2007
	Futaleufu (*)	43.2	73.7	2033	1930 - 2007
	Puyuhuapi	44.3	72.6	3512	1938 - 2007
	Balmaceda	45.9	71.7	612	1976 - 2007
	Punta Arenas	53	70.9	376	1976 - 2007

(*) Annual rainfall for the station Futaleufu during the period 1930-1950 was estimated from precipitation at Esquel (42.9º S, 71.3º W) in Argentina. Rainfall records at stations Balmaceda and Punta Arenas were considered for the analysis of interannual variability presented in section 5.

links between rainfall and atmospheric circulation indices calculated on an annual basis is somewhat affected by the fact that rainfall concentrates during the winter semester (April-September), with prevailing dry conditions during the rest of the year.

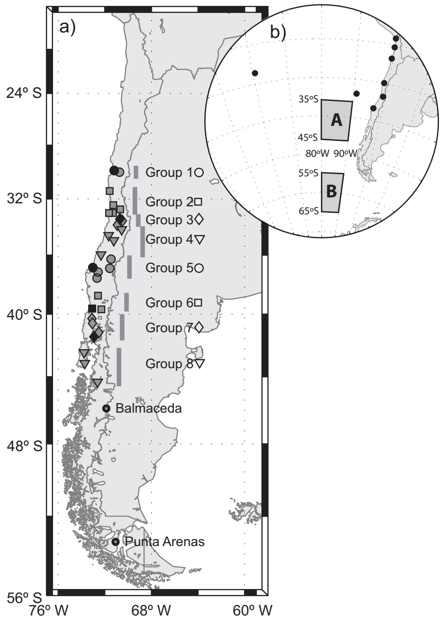

Fig. 2. Station network. a) Symbols represent stations with monthly (gray) and daily (black) rainfall data. The different symbols separate the stations into the groups 1-8 as detailed in Table I. Locations of rainfall stations Balmaceda and Punta Arenas are indicated. The inset map b) indicates stations for which surface pressure was used to calculate an annual index for the intensity of the SE Pacific subtropical anticyclone. A meridional SLP gradient between mid- and high-latitudes was calculated as the difference of standardized SLP over regions A and B.

3. Changes in annual rainfall

Evolution of the annual rainfall in central Chile is presented in Figure 3 as 11-years moving averages of the regional rainfall indices described in the previous section. Each index is identified by the mean latitude of the stations whose normalized rainfall series were averaged. In the northern sector (30-37º S), but especially in the regions corresponding to indices 2, 3, 4 and 5 (Fig. 3a, b, c), a prevailing negative trend that persisted from the beginning of the 20th century was interrupted by a relatively abrupt increase in the 1970s. During recent decades the annual rainfall regime within this region has shown a considerable decadal variability and the absence of a well defined trend. In the region around 39º S (rainfall index 6 in Fig. 3c) the sustained negative trend that prevailed throughout the 20th century intensified during the 1980s and early 1990s. This feature was also described by Rusticucci and Penalba (2000) regarding the evolution of annual rainfall in Valdivia (39.6º S, 73.1º W). The increase that exhibits rainfall index 6 during recent years (Fig. 3c) is a common feature for the whole region from 30 to 39º S. The rainfall indices 7 (41º S) and 8 (43º S) in the southern part of central Chile do not cover the early part of the 20th century, but both of them indicate that a rainfall increase in the 1930s and 1940`s was followed by a persistent negative trend since the 1950`s that in the case of index 8 (43º S) was modulated by significant decadal variability.

The linear trends in annual rainfall at individual stations in central Chile for the periods 1900-2007, 1930-2007 and 1950-2007 are presented in Figure 4. The statistical significance of each trend was assessed through the application of a standard bootstrap method. Thus, linear trends were calculated for a total of 1000 series composed each of them by randomly chosen elements from the original series. The trend of the original series was considered statistically significant if its value was in the lower or upper 5% of the sample of 1000 trends. Considering the substantial low frequency variation in the rainfall series, a block resampling approach was also applied, using 4-year blocks in the bootstrap method. However, the statistical significance of the trends did not change much using this approach, as only in one case (station Osorno, rainfall series during the

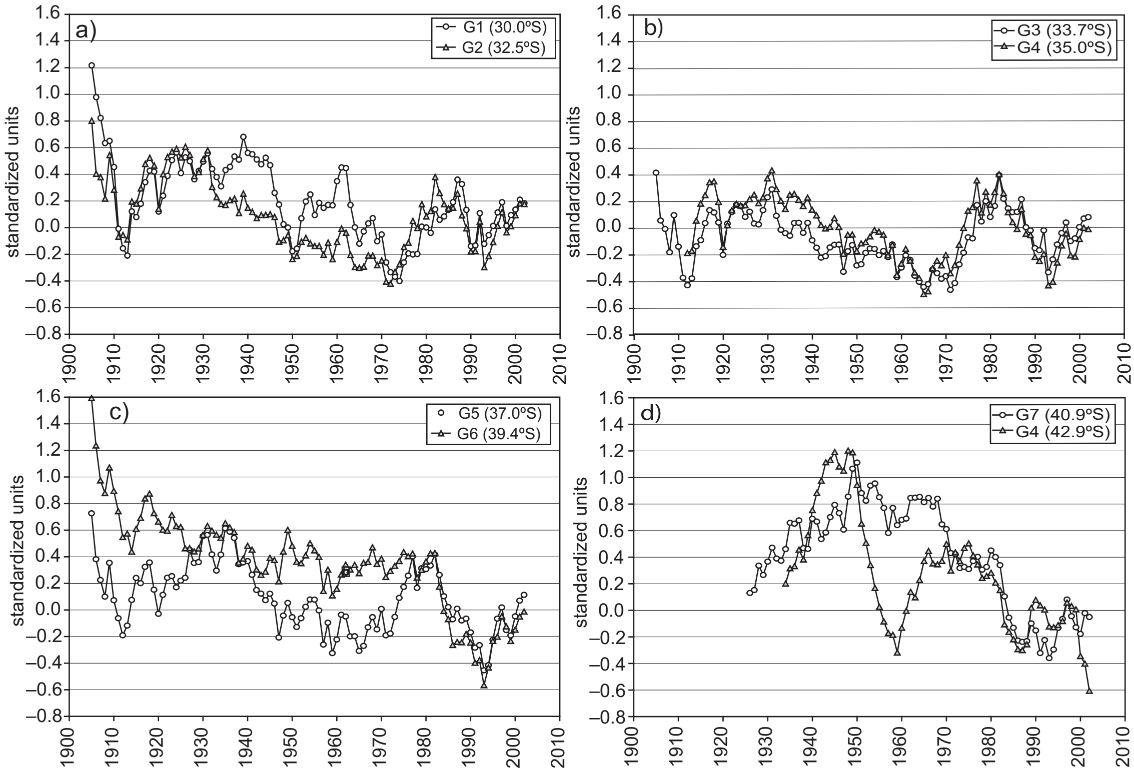

Fig. 3 Evolution of 11-years moving averages of regional annual rainfall indices in central Chile. The horizontal scale indicates the middle year of the respective 11-years interval. Indices were calculated as the average of standardized annual rainfall at individual stations within each group (mean latitude is indicated) regarding the period 1971-2000. For station locations see Table I and Figure 2.

period 1950-2007) the linear trend was significant according to the standard bootstrap method, but it was not according to the block resampling approach. The relatively large negative trends in the northern part of this territory for the period 1900-2007 are conditioned to a large extent by the occurrence of very wet conditions at the beginning of the 20th century (Fig. 3a, b, c). This effect, combined with the increased precipitation after the mid-1970s, explain the weakening of the

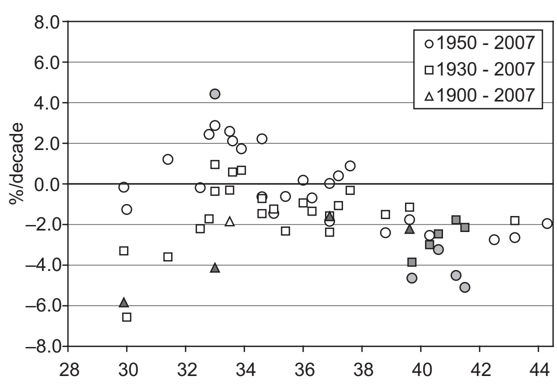

Fig. 4. Linear trend in annual rainfall at individual meteorological stations in central Chile, indicated as the change per decade during indicated periods, and expressed as percentage regarding the 1971-2000 mean value. Symbols in gray denote statistical significance at the 95% level according to a standard bootstrap test.

negative trend that is apparent in Figure 4 when more recent and shorter periods are considered. Furthermore, results presented in this figure suggest that the rainfall regime was quite stationary in the region 30-37º S during the period 1950-2007, with the exception of the area around 33º S where increases of the order of +2 %/decade to +3 %/decade are noticed. Regarding the region southward from 37º S, Figure 4 shows that the trend in annual rainfall is consistently negative for the three periods considered, with values ranging from –2 %/decade to –5 %/decade during 1950-2007.

Since slow changes in annual rainfall characterized by moving averages can be significantly distorted by the occurrence of extremely wet or dry years, the rainfall variability at the decadal time scale was also analyzed by examining the changes in the frequency of dry and wet years. Wet (dry) years were defined as those when the corresponding rainfall index was in the 3rd (1st) tercile of its empirical distribution during the period 1930-2007. Then, the frequency of dry and wet years were calculated for 11-years moving periods. Assuming a stationary climate, for any 11-years period, around one third of the years (3 o 4) should be classified as wet, and a similar situation should occur with respect the occurrence of normal or dry years. Moreover, according to the binomial distribution, under the null hypothesis that the series are randomly sorted, frequencies of 0, 1, and equal to or larger than 5 for any of the three categories (dry, normal, wet) during a 11-years period are statistically significant at around the 90% level.

Results presented in Figure 5 indicate that linear trends presented in Figure 4 are modulated by significant changes occurring at the decadal time scale. Specifically, relatively low frequency of wet years prevailed during the 1950s and 1960s in the 32- 38º S latitudinal band in contrast with the relatively large frequency during the late 1970s and 1980s. It is also apparent in Figure 5a that in the southern portion of central Chile changes in the frequency of wet years were broadly opposite to those described for the northern part, particularly when considering the latitudinal bands 40-43º S and 32-39º S, during the periods 1940-1970 and 1975-1990. Thus, the frequency of wet years that was relatively high during the 1950s and 1960s in the region southward from around 39º S decreased significantly during the 1980s and 1990s. Regarding the frequency of dry years (rainfall in the 1st tercile of the distribution), Figure 5b shows the occurrence of anomalies that prevailed in most of central Chile, as the low frequency in the 1930s as well as in the late 1970s and early 1980s, and the relatively high frequency during the 1990s. Furthermore, during the 1960s the frequency of dry years was relatively high in the northern portion of the territory (30-38º S) and anomalously low in the region southward from around 40º S. The increase in the frequency of wet years during the most recent years shown in Figure 5a is consistent with the rainfall increase that is apparent in Figure 3 for rainfall indices 1 to 6.

4. Changes in the frequency and intensity of rainfall events

Long-term changes in annual rainfall described in the previous section could be associated with changes in the frequency of rainfall episodes. To analyze this matter, time series of daily rainfall at 5 stations from 30 to 43º S were analyzed (locations are indicated in Fig. 2 and Table I). In the northern part of central Chile the annual frequency of wet days is highly correlated ($r > 0.80$) with the annual rainfall amount. This close relationship is illustrated in Figure 6 for Santiago (33.5º S). Although the strength of the correlation weakens at higher latitudes (+0.73 for Valdivia (39.6º S) and +0.71 for Puerto Montt (41.5º S)) they are large enough to suggest that the slow changes described in previous sections are partially associated with changes in the frequency of wet days.

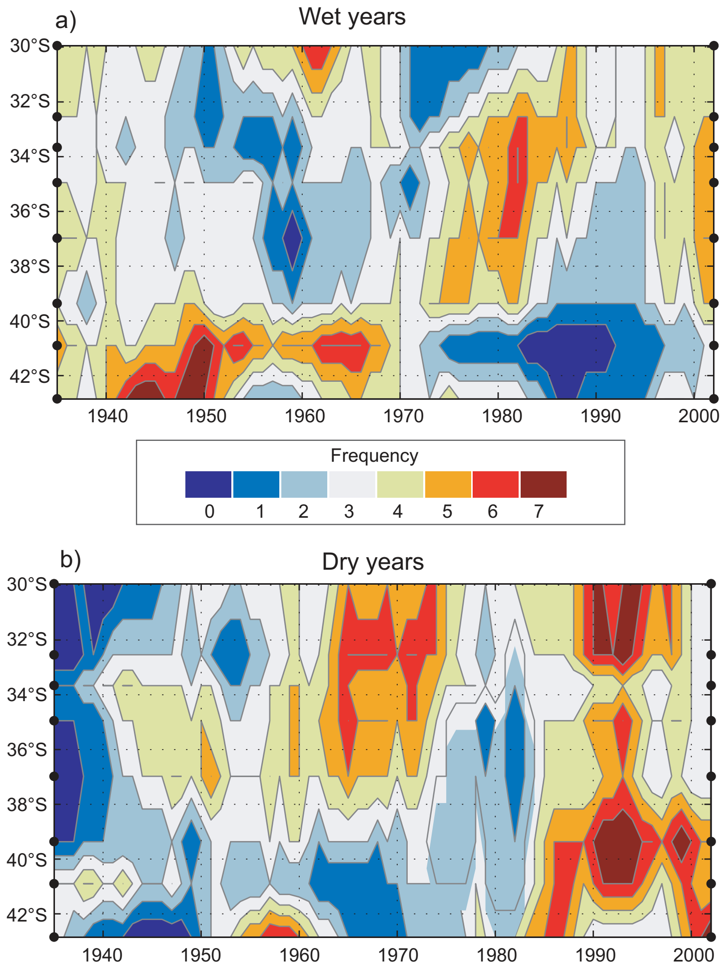

Fig. 5. Frequency of wet (a) and dry (b) years in central Chile for 11-years moving intervals during 1930-2007, calculated from annual regional rainfall indices. Dry and wet years are those with rainfall in the 1st and 3rd tercile of the 1930-2007 distribution, respectively. Frequencies 0, 1 and equal or larger than 5 are significant at approximately 90% the level. The horizontal scale indicates the middle year of the respective 11-years interval. Black dots on the y-axis indicate the mean latitude of stations defining each regional rainfall index.

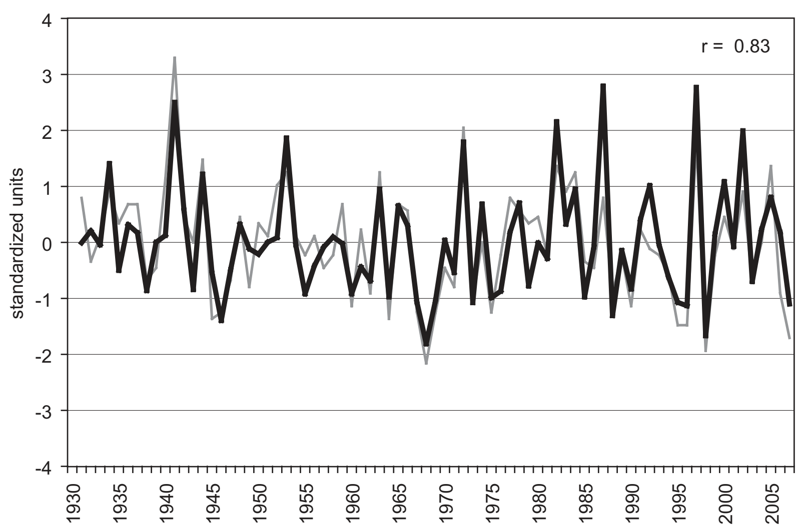

Fig. 6. Standardized values of annual rainfall (dark line) and annual frequency of wet days with precipitation equal to or above 1 mm at Santiago (33.5º S, 70.7º W) during 1930 -2007.

Changes in the intensity of rainfall episodes may also contribute to changes in annual precipitation. This was assessed through the analysis of slow changes in the distribution of daily rainfall. Thus, the percentages of wet days with precipitation in the lower and upper tercile of the distribution of daily rainfall were calculated for moving 11-year intervals, considering all days with precipitation equal to or larger than 1 mm. Assuming a stable rainfall regime, these percentages should remain close to 33%. Results are presented in Figure 7 for three stations in the region 37-42º S (Concepción, 1942-2007; Valdivia, 1941-2007; and Puerto Montt, 1931-2007) where the negative trend in annual rainfall has been more persistent during recent decades. The percentage of wet days with rainfall in the 1st tercile (Fig. 7a) does not depart significantly from 0.33, except during the late 1980s and 1990s when it reached values around 0.37 at the three stations. Regarding the percentage of wet days with precipitation in 3rd tercile of the distribution, Figure 7b depicts a predominant downward trend until the 1990s followed by an upward trend in recent years. These results, suggesting that the predominant negative trend in annual rainfall described for the southern portion of central Chile during the second half of the 20th century was partially conditioned by a reduced intensity of the rainfall events, are coherent with those in Haylock *et al*. (2006) documenting the existence of a negative trend in indices related with the intensity of

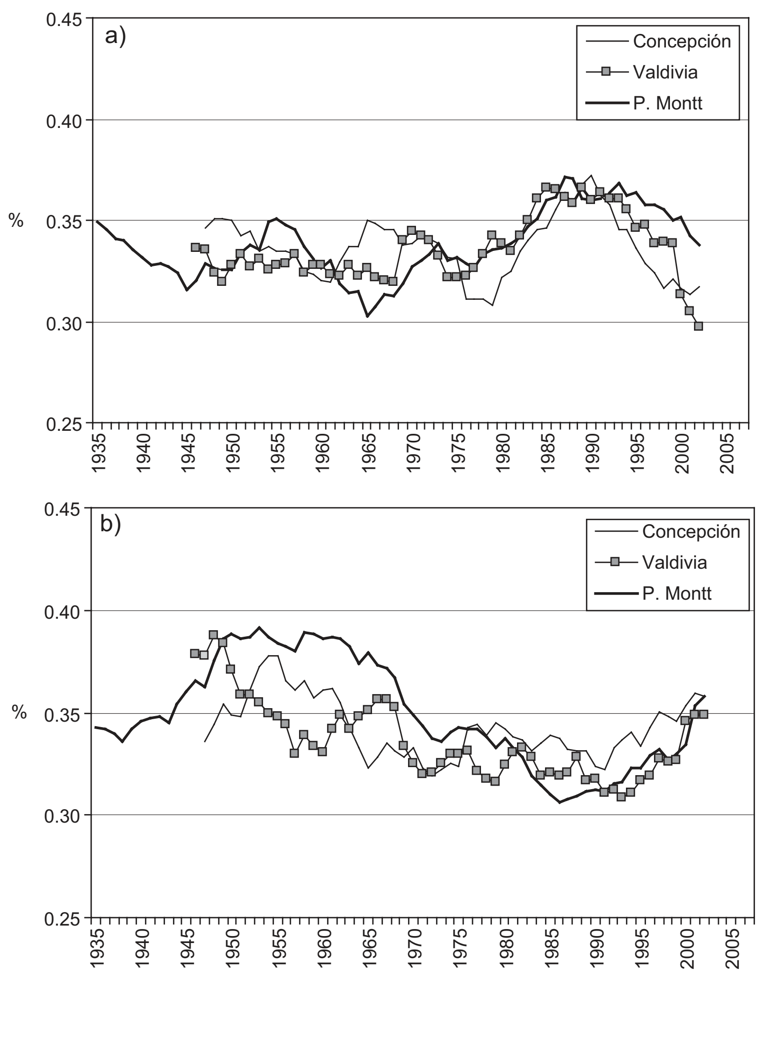

Fig. 7. Percentage of wet days with rainfall in the 1st tercile (a) and in the 3rd tercile (b) of the distribution of daily rainfall for 11-years moving intervals at Concepción (36.9º S; 1942-2007), Valdivia (39.6º S; 1941-2007) and Puerto Montt (41.5º S; 1930-2007). The horizontal scale indicates the middle year of the respective 11-years interval. Only days with precipitation equal to or above 1 mm were considered.

daily precipitation at stations in the southern portion of central Chile, such as the annual frequency of days with rainfall above 10 and 20 mm during the period 1960-2000. During the most recent years the decrease (increase) in the frequency of daily precipitation in the 1st (3rd) tercile of the distribution, that is apparent in Figure 7, is consistent with the increase in annual rainfall that is noticed in Figure 3 for the region northward from 40º S.

5. Discussion

Changes in the intensity of the southeast Pacific subtropical anticyclone have a significant impact on the variability of annual rainfall in central Chile at all time scales. Long-term changes in the intensity of this anticyclone are shown in Figure 8a as 11-years moving averages of an annual surface pressure index during 1970-2007 and of the mean annual pressure at Santiago (33.5º S)

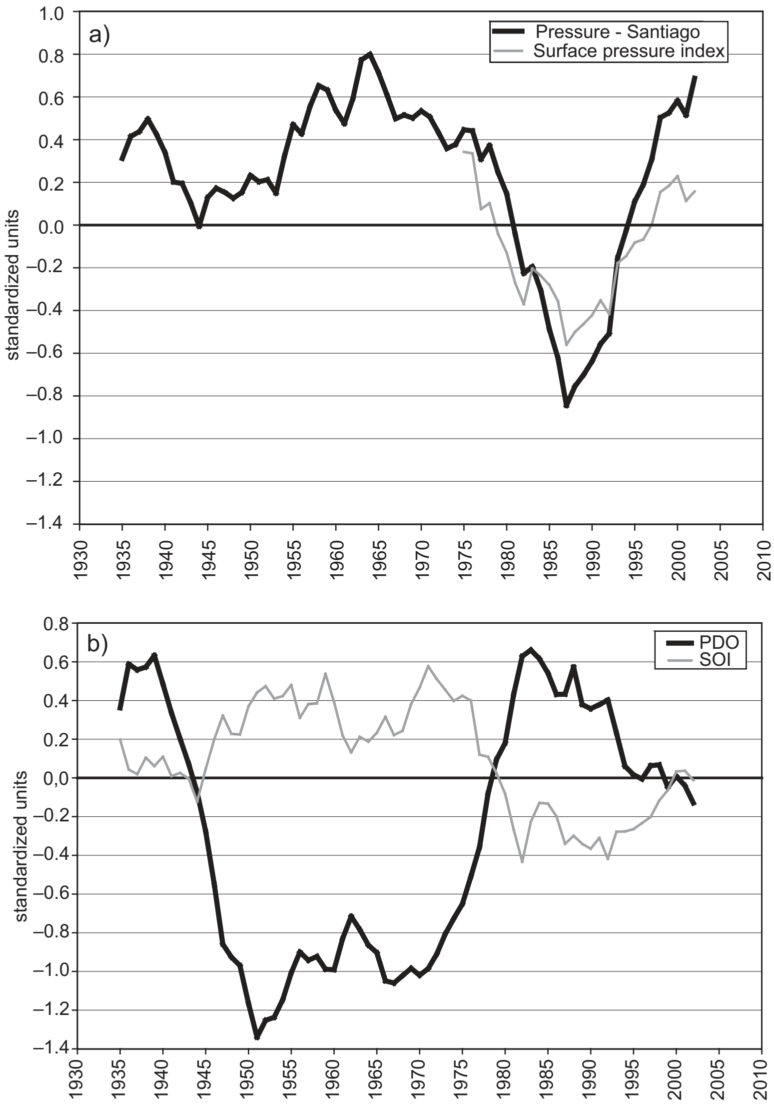

Fig. 8. 11-years moving averages of standardized annual values (Ref. 1971-2000) of surface pressure over the southeast Pacific anticyclone, the Pacific Decadal Oscillation and the Southern Oscillation indices: a) Surface pressure index calculated as the first principal component of pressure at 8 stations (locations in Fig. 2) for 1970-2007 and surface pressure at Santiago (33.5° S) for 1930-2007; b) Southern Oscillation Index calculated as the standardized sea-level pressure difference between Tahiti and Darwin (source http://www.bom.gov.au/climate/current/soi2.html) and a PDO Index derived as the leading PC of the monthly SST anomalies in the North Pacific Ocean poleward of 20° N (Mantua *et al.*, 1997) (Source: http://jisao.washington.edu/pdo). The horizontal scale indicates the middle year of the respective 11-years interval.

during 1930-2007. Both series are closely correlated (r = 0.80) during the common period. The index for the intensity of the southeast Pacific subtropical anticyclone (SEP-High) was calculated as the first principal component of mean annual surface pressure at eight stations within the domain of the anticyclone (locations are indicated in Fig. 2b). The southeast Pacific anticyclone was relatively intense during the 1960s and early 1970s. The weakening that followed lasted until the 1990s when the anticyclone strengthened again.

The strength of the SEP-High is closely linked to the Southern Oscillation (SO). The correlation between annual series of the SOI and of the SEP-High Index is +0.86 for the period 1976-2007. This is coherent with the fact that Walker and Bliss (1932) included surface pressure at Santiago among the set of variables defining the SO index for austral winter. Several studies have also documented the existence of a significant tendency for above (below) average rainfall in central Chile during the negative (positive) phase of the SO (Pittock, 1980; Quinn and Neal, 1983; Aceituno, 1988; Montecinos *et al*., 2000). In particular, the mechanisms explaining the enhanced winter rainfall in central Chile (30-35º S) during El Niño episodes have been associated with changes in large-scale atmospheric circulation in the southern hemisphere, including increased frequency of blocking episodes at mid-latitudes in the southeast Pacific (Karoly, 1989; Rutllant and Fuenzalida, 1991; Grimm *et al.*, 2000; Montecinos and Aceituno, 2003). As shown in Figure 8b, the functioning of the SO at the decadal time scale is linked to the Pacific Decadal Oscillation (PDO), which is a basin-wide oscillation of the Pacific ocean-atmosphere system. During the positive (negative) phase of the PDO, relatively warm (cold) conditions prevail in the tropical Pacific, while opposite temperature anomalies are dominant at high latitudes, particularly over the northern Pacific. For a complete description of this large-scale oscillatory mode see Zhang *et al*. (1997) and Garreaud and Battisti (1999).

Considering the aforementioned coherent changes in the functioning of the PDO, the SO and the SEP-High, particularly after the mid-1940s, it is expected that they have some influence on the evolution of the rainfall regime in central Chile, particularly in the northern portion of this territory (30-35º S) where the influence of the SO on the rainfall interannual variability is largest (Montecinos and Aceituno, 2003). In fact, the relatively sharp increase in precipitation during 1970s documented in Figure 3 for rainfall indices in this region, which interrupted a long-lasting negative trend observed during previous decades, could be at least partially explained by the switch of the PDO toward the positive phase by the end of the 1970s and concurrent weakening of the SEP-High and increased prevalence of the negative phase of the SO, as shown in Figure 8. The evolution of the PDO toward the negative phase and the intensification of the SEP-High since the late 1990s shown in Figure 8 suggests that the Pacific ocean-atmosphere system is evolving to conditions similar to those before the mid-1970s. In particular, the remarkable strengthening of the subtropical anticyclone during the 1990s (Fig. 8a) is consistent with a significant increase of the frequency of dry years during that period in all central Chile (Fig. 5b). During the most recent years rainfall has increased in the region to the north of 40º S, as revealed in Fig. 3a, b, c. This seems to be at odds with the results of Figure 8 that do not show a reversal in the evolutions of the SOI, the PDO and the intensity of the SEP-High during the most recent years, suggesting the existence of other unknown factors shaping the changes in rainfall in central Chile at the decadal time scale.

Changes in the atmospheric circulation at higher latitudes in the southeast Pacific affecting the latitudinal position and strength of the extratropical storms embedded in the mid-latitude westerlies may also contribute to the rainfall variability in central Chile (Thompson *et al*., 2000). A potential influencing factor is the Antarctic Oscillation (AAO) or Southern Hemisphere annular mode (SAM), corresponding to a year-round leading mode of low-frequency variability characterized by an exchange of air masses between mid- and high latitudes with an equivalent barotropic and approximately zonally symmetric structure. During the positive phase of the AAO, the sea level pressure and geopotential height are anomalously high along the latitudinal band northward from around 50º S while negative anomalies prevail at higher latitudes. Consequently, the mid-latitude migratory low pressure systems and the poleward limit of the Hadley cell move southward from their climatological mean positions. During the negative phase of the AAO the strongest meridional gradient in sea level pressure and geopotential height moves northward from its mean position favoring an intensification of the westerlies near the core of the subtropical jet stream.

We correlated 1976-2007 detrended series of annual rainfall indices with three annual AAO indices based on sea level pressure (SLP) data, defined as the leading principal component of SLP from NCEP-NCAR reanalysis in the region to the south of 20º S (Mitchell AAO Index, available from http://jisao.washington.edu/data/aao/slp/), the difference in SLP between 40º and 70º S, also from NCEP-NCAR reanalysis (N&L AAO Index) (Nan and Li, 2003), and the difference in SLP between mid- and high-latitudes in the southern hemisphere estimated from observations at meteorological stations (Marshall Index) (Marshall, 2003). As it was expected, negative correlations were obtained, with largest values between –0.35 to –0.45 for the correlation between the SLP difference 40-70º S (N&L AAO Index) and the rainfall indices 1 to 7 corresponding to the region north of 41º S. The weakest negative correlations were obtained with the Marshall AAO index with values between –0.15 and –0.30. In the three cases the magnitude of the negative correlation was significantly lower for the rainfall index 8 (42.9º S). Considering that rainfall in central Chile could be more directly linked with meridional pressure gradient between mid and high latitudes in the southeast Pacific we defined a regional AAO index (SEP-AAO) calculated as the difference in standardized mean SLP over the region 35-45º S, 90-80º W minus that over the region 55-65° S, 90-80º W (Fig. 2b) for the period 1948-2007, with information from NCEP-NCAR reanalysis. These two regions were considered adequate to characterize the regional characteristics of the AAO signal.

Although the quality of the NCEP-NCAR reanalysis at high latitudes in the Southern Hemisphere for the period prior to 1979 has been questioned (Marshall, 2002) the relative proximity of these two regions to southern South America and the Antarctic Peninsula, where SLP is routinely measured at meteorological stations, adds credibility to the SLP data from NCEP-NCAR reanalysis at high-latitudes in the southeast Pacific used to calculate the SEP-AAO. Specifically, the SEP-AAO Index has a relatively high correlation (r = +0.66) with the difference in SLP between stations Puerto Montt (41.4º S, 73.1º W) and Eduardo Frei (62.4º S, 58º9º W) in the Antarctic Peninsula. The positive correlations between detrended series of the SEP-AAO and the three previously described AAO indices during 1976-2007 (when the positive phase prevailed in the PDO) are moderate in magnitude for the cases of the Mitchell AAO Index (+0.48) and N&L AAO Index (+0.59), and considerably weaker for the case of the Marshall Index (+0.25), indicating that the interannual variability of the meridional SLP gradient between mid- and high-latitudes in the southeast Pacific differs considerably from that of the corresponding hemispherical average.

Although the link between the three AAO indices and the SOI is weak during the period 1976-2007 (the largest correlation between detrended series is +0.25 between the N&L AAO Index and the SOI), the relatively large correlations between detrended series of the SEP-AAO Index and the SOI

(+0.62) and the intensity of the southeast Pacific subtropical anticyclone (SEP-High Index) (+0.65) during the same period, indicate that these tropical and extra-tropical factors affecting rainfall in central Chile are not independent. Thus, the positive (negative) phase of the SO and a strengthened (weak) subtropical high tend to be associated with an increased (reduced) baroclinicity at mid-latitudes in the southeast Pacific. These results are consistent with previous findings, documenting the occurrence of circulation anomalies characterized by positive surface pressure and geopotential height anomalies (blocking) in the region westward from the Antarctic Peninsula and a weakened southeast Pacific subtropical anticyclone during warm events in the tropical Pacific (Karoly, 1989; Rutllant and Fuenzalida, 1991; Sinclair, 1996; Renwick, 2005). Other studies have shown that the strength of these anomalies exhibits a significant decadal variability depending on the phases of ENSO and AAO (Genthon and Cosme, 2003; Fogt and Bromwich, 2006).

Linear correlations of regional annual rainfall indices in central Chile with the SOI, the meridional sea level pressure gradient at midlatitudes in the Southeast Pacific (SEP-AAO), and the strength of the southeast Pacific subtropical anticyclone (SEP-High), are shown in Figure 9 for the period 1976-2007 following the climate shift in the Pacific domain. Since the objective was to assess the relationships at the interannual scale, all series were detrended before calculating the correlations. In order to show the overall weakening of the relationships at higher latitudes, Figure 9 includes the correlations with annual rainfall at Balmaceda (45.9º S) and Punta Arenas (53.2º S). The statistical significance of the correlations was assessed through the application of a standard bootstrap method, with the rainfall series being resampled 1000 times. Results from this assessment remained unchanged when a block resampling approach was applied, using 4-year blocks in the bootstrap method, to consider the potential impact of the lag correlation in the annual rainfall on the statistical significance of correlations. The statistical significance of the correlation remained the same when using this approach. The correlation of nearly –0.60 between the SEP-High Index and precipitation from 30-35º S illustrate the relevance of the strength of the southeast Pacific subtropical high on the interannual rainfall variability in the northern portion of central Chile. Changes in the intensity of the anticyclone are partially modulated by the SO, whose index (SOI) also exhibits significant negative correlations with rainfall indices over this region as indicated in Figure 9 and documented in many previous studies. Correlations between the meridional sea level pressure gradient at high-latitudes in the SEP-AAO and annual rainfall indices are also negative, with increasing magnitudes from around –0.47 at 30º S to nearly –0.74 at 41º S. At latitudes southward from around 42º S negatives correlations weaken considerably, indicating that other factors modulate the interannual rainfall variability in that region.

In order to assess the impact of correlating annual atmospheric circulations indices with annual precipitation in a region characterized with a marked annual cycle in the rainfall regime, we repeated the analysis at the seasonal time scale, considering raw rainfall data for the austral winter (Apr.-Sep.) and austral summer (Oct.-Mar.) semesters and the corresponding seasonal values for the SOI and the SEP-AAO index. During the rainy season in central Chile (Apr.-Sep.) both the SOI and the SEP-AAO Index are negative correlated with rainfall in the region 30-42º S (Fig. 10a), with largest negative values or the order of –0.50 in the region 30-35º S in the case of the correlation with the SOI, and between –0.6 and –0.7 from 33 to 42º S in the case of the correlation with the SEP-AOO index. Further south 43º S, neither the SOI nor the SEP-AAO are significant factors in the interannual rainfall variability during this part of the year. For the dry season in central Chile (Oct.-Mar.), correlations were calculated only for the region southward from around 37º S, where significant rainfall is observed during this part of the year. Then, significant negative correlations between the SOI and rainfall are restricted to the region around 37º S (Fig. 10b). However regarding the spacial SEP-AAO/rainfall correlation pattern, significant negatives correlation of the order of –0.50 prevail from around 37º S up to 42º S. The fact that the SEP-AAO is a significant factor for the interannual rainfall variability in this region, both during the winter and summer semesters, may explain the relatively large magnitude of the negative correlation between annual rainfall and annual SEP-AAO index shown in Figure 9.

According to results presented in Figures 9 and 10, the Southern Oscillation, the strength of the SE Pacific subtropical anticyclone, and the meridional pressure gradient between mid and high latitudes in the southeast Pacific have a negligible influence on the interannual rainfall variability in the region southward from around 42º S, both at the annual and seasonal time scales. Furthermore, the fact that the spatial patterns of correlation shown in Figures. 9 and 10 are reproduced quite well in the analysis of data from climate models, particularly regarding the weakening of the correlation in the region southward from around 42º S (Pizarro, 2011), indicate that the relationships presented in those figures are not statistical artifacts, but they reflect the physical mechanisms connecting the changes in the meridional pressure gradient between mid and high latitudes in the southeast Pacific and the rainfall variability in central Chile.

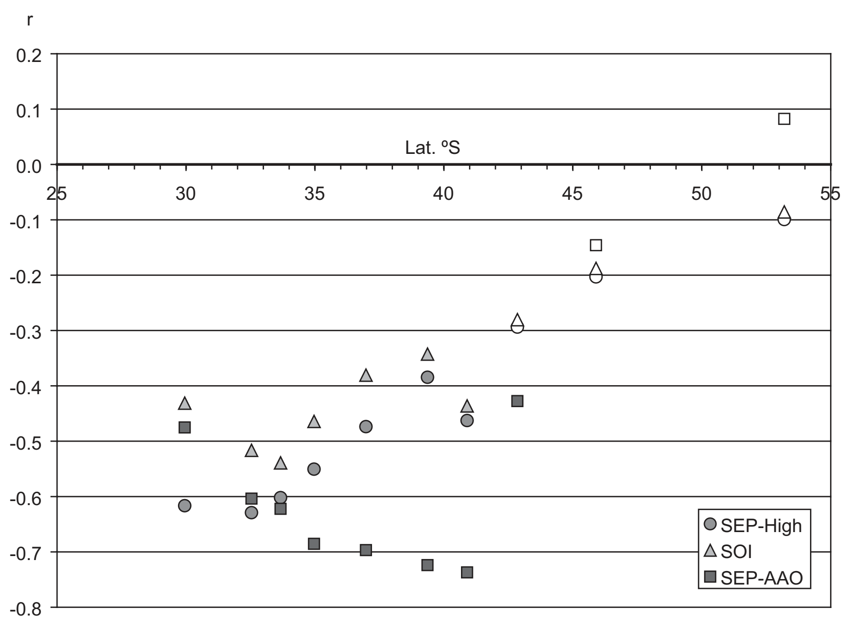

Fig. 9. Correlation (r) of annual regional rainfall indices in central Chile and annual rainfall at Balmaceda (45.9º S) and Punta Arenas (53.2º S) with annual indices for the strength of the SEP-High, calculated as the first principal component of surface pressure at 8 stations within the domain of the anticyclone (locations indicated in Fig. 2 and Table I) (triangles); the Southern Oscillation Index (SOI) (circles); and the meridional gradient of sea level pressure at high latitudes in the SE Pacific (SEP-AAO) (squares). Correlations are calculated for the period 1976-2007 after the series were standardized and detrended. Standardization was performed with respect to 1971-2000. Symbols in gray denote statistical significance at the 95% level according to a standard bootstrap test.

Regarding the close association shown in Figures 9 and 10 between the regional AAO index in the SEP-AAO and annual and seasonal rainfall in central Chile at the interannual time scale, it is worthwhile mentioning in the context of this study the positive trend that has characterized the evolution of the AAO Index during recent decades (Thompson *et al*., 2000a, b; Arblaster and Meehl, 2006), and the evidence about a widening of the Hadley cell and an associated poleward displacement of the subtropical dry zones during recent decades (Johanson and Fu, 2009). Then, the positive trend of the regional AAO index in the southeast Pacific (SEP-AAO), that is shared by its hemispheric counterpart as shown in Figure 11, could partially contribute to the persistent negative trend that have been observed in the southern portion of central Chile since 1950 (37-41º S; Fig. 3c,

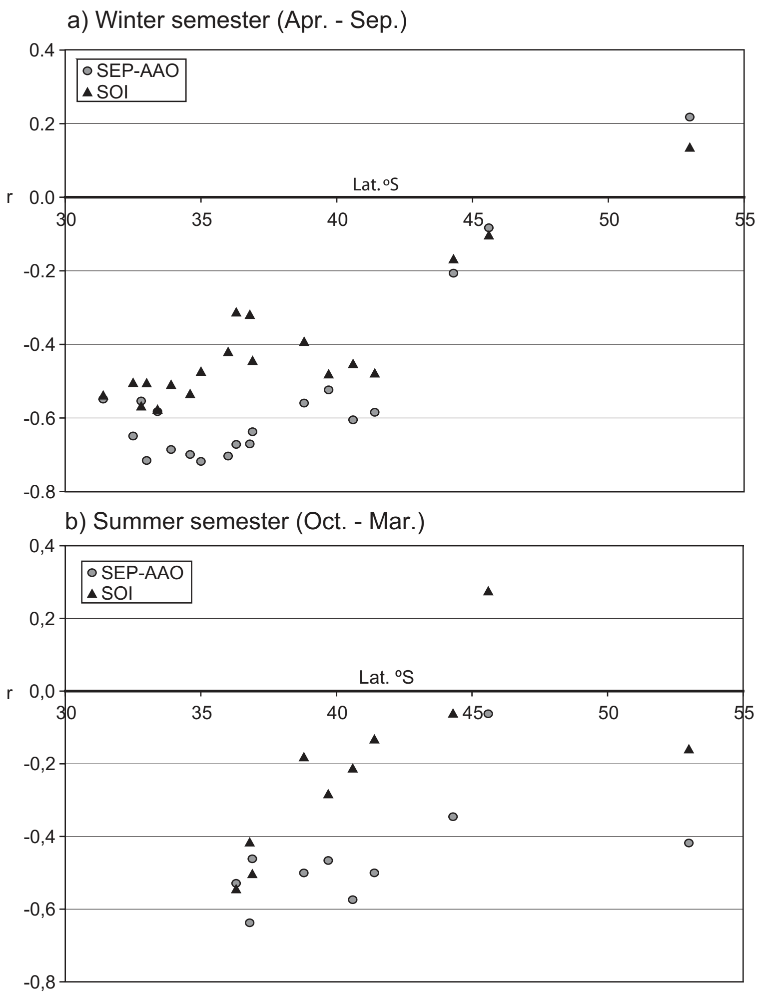

Fig. 10. Correlation (r) between seasonal rainfall at individual stations and seasonal values of the Southern Oscillation Index (triangles) and of the meridional sea level pressure gradient at high latitudes in the SE Pacific (SEP-AAO) (circles), for the period 1976-2007. a) winter semester (Apr.-Sep.); b) summer semester (Oct.-Mar.). Correlations with a magnitude larger than 0.35 are statistically significant (95% level; Student test).

d). With respect to this ongoing trend, it should be reminded that most of the global and regional climate models used to assess future climate scenarios associated with an enhanced planetary greenhouse effect suggest that rainfall should decrease in the southern portion of central Chile (Trenberth *et al*., 2007), due to a southward displacement of the midlatitude storm track in the Southern Hemisphere. This regional future climate scenario is coherent with results from several studies indicating that a positive trend of the AAO is consistent with an increased greenhouse gas (GHG) concentrations in the atmosphere (Fyfe *et al*., 1999; Kushner *et al*., 2001; Cai *et al*., 2003; Arblaster and Meehl, 2006), and also with results from other studies indicating a weakening and poleward expansion of the Hadley cell and the associated subtropical dry zones in response to increased GHG forcing (Lu *et al*., 2007; Vecchi and Soden, 2007)

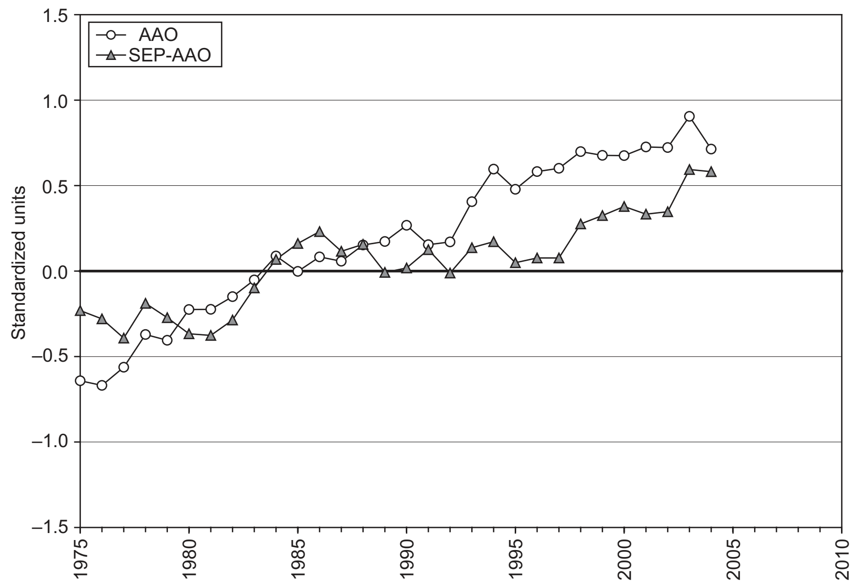

Fig. 11. 11-years moving average of standardized values (Ref. 1971-2000) of the Antarctic Oscillation Index calculated from sea-level pressure (SLP) anomalies south of 20º S (data available from http://jisao.washington.edu/data/aao/slp/) and the meridional gradient of sea level pressure at mid-latitudes in the southeast Pacific (SEP-AAO) during the period 1970-2009. The horizontal scale indicates the middle year of the respective 11-years interval.

6. Conclusions

Slow changes in the annual rainfall regime in central Chile (30-43º S) have been described in the context of the evolution of major regional and large-scale factors controlling rainfall variability along the extratropical west coast of South America: the strength of the Southeast Pacific subtropical anticyclone (SEP-High), the Southern Oscillation (SO), the Pacific Decadal Oscillation (PDO) and the meridional gradient of sea-level pressure and geopotential height at mid-latitudes in the southeast Pacific, which is regionally linked to the Antarctic Oscillation.

In the northern part of this territory (30-35º S) annual rainfall showed a persistent negative trend from the beginning of the 20th century until the mid-1970s, followed by a significant increase in the 1980s (Fig. 3a, b). Since then, the rainfall regime has exhibited a marked decadal variability in the absence of a well defined trend. The strength of the SEP-High, which is closely linked to the SO, is one of the key regional factors that modulate the interannual rainfall variability within this region. Then, it is postulated here that coherent slow changes in the SEP-High and in the SO, modulated by the PDO, are partially responsible for the observed changes in annual rainfall during recent decades. Thus, relatively dry conditions persisted from the mid-1950s to the mid-1970s, when the SEP-High was relatively strong in association with a prevailing positive phase of the SO and a negative phase of the PDO. Furthermore, the significant and relatively abrupt increase in rainfall during the 1970s indicated in Figure 3a, b broadly coincides with the evolution of the PDO toward the positive phase, together with a weakening of the SEP-High and with an increased frequency of the negative SO phase, shown in Figure 8. The weakening of the positive phase of the PDO and the strengthening of the SEP-High during the 1990s, that is apparent in Figure 8, suggest that the Pacific ocean-atmosphere system is evolving to conditions similar to those before the mid-1970s, favoring a decrease of rainfall in this region.

In the southern portion of central Chile (37-43º S) a significant downward trend in annual rainfall prevailed since the 1950s (Fig. 4), as a direct result of a decreasing frequency of rainfall episodes and a weakening of daily precipitation intensity that lasted until the 1990s (Fig. 7b). The meridional gradient of sea-level pressure between mid- and high-latitudes in the southeast Pacific seems to be a key factor of the interannual rainfall variability in this region. Thus, the prevailing negative trend in rainfall may be partially influenced by the continued strengthening of that meridional gradient of sea-level pressure during recent decades, favoring a poleward shift of the westerly jet and of the mid-latitude migratory low pressure systems and associated fronts. This slow change in the atmospheric circulation at mid-latitudes in the southeast Pacific is coherent with the trend in the AAO toward its positive phase during recent decades reported in several papers (see for example Marshall, 2003) and shown in Figure 11 for the AAO index calculated as the leading principal component of SLP in the region to the south of 20º S, revealing a strengthening of the baroclinicity and a southward shift of the midlatitudes stormtrack over the whole Southern Hemisphere circumpolar region that has modified the rainfall regime in other extratropical regions such as South Africa, Australia and New Zealand (Gillett *et al.*, 2006; Hendon *et al.*, 2007; Silvestri and Vera 2009; Ummenhofer *et al.*, 2009). Regarding future climate scenarios, it is likely that this process will continue in the future. In fact, most of the global and regional climate models used to simulate the impacts of an enhanced greenhouse effect indicates a reduction of rainfall in southern central Chile during the 21st century (CONAMA, 2007; Trenberth *et al.*, 2007). In the discussion of future climate trends affecting the Southern Hemisphere storm track and trends in the AAO, it should be noted that there are competing influences in the summer season from increasing greenhouse gases and from recovery of the Antarctic ozone hole. The net effect of these two influences on trends in the AAO in summer is uncertain (Arblaster *et al.*, 2011, and references therein).

The processes described earlier are probably more complex as other unknown factors may also contribute to shape the long-term changes observed in annual rainfall in central Chile. To this respect, it is worth noticing that in spite of the intensification of the subtropical high and the evolution of the PDO and the SO toward the negative and positive phases, respectively, during the most recent years as it is apparent in Figure 8, there are evidences that during this period both the rainfall amount (Fig. 3) and the frequency of anomalously wet years (Fig. 5) have increased in the region to the north of 40º S. A detailed analysis of changes at the seasonal (3-months) scale is necessary to improve the understanding of the mechanisms shaping the long-term evolution of the rainfall regime in central Chile.

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