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RECENT TEMPERATURE VARIATIONS IN SOUTHERN SOUTH AMERICA

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ABSTRACT

Results from a critical appraisal of surface mean air temperature in Chile and Argentina and extreme air temperature in Chile during the present century are presented. Observations were homogenized to produce a set of time series as reliable as possible. Linear trends computed for the period 1933–1992 resulted in warming rates from 1·3 to 2·0 °C 100 years^{-1}; during the last three decades warming rates are twice as large. The generalized warming is not present around 41°S, where a cooling period from the 1950s to the 1970s prevails. Both positive and negative trends are due mostly to changes in minimum temperatures. The influence of El Niño–Southern Oscillation on surface temperature along the Pacific South American coast from 18°S to 53°S was estimated and found to decrease southward. When its effect is extracted, warming trends become more uniform through time. In particular, the Southern Oscillation Index change around 1976 is felt in minimum temperatures at almost all stations, starting a period with higher values along the Chilean Pacific coast. Trend corrections for autocorrelation in the series introduce only small local changes.

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KEY WORDS: ENSO; air temperature; long-term variations; South American region; Argentina; Chile

INTRODUCTION

Climatic variations have been the subject of numerous studies during recent decades because of suspected anthropogenic influences. Among the least known areas of the world are austral latitudes, where the South American region appears to have very little information available. This is due to the poor quality of data and its inadequate dissemination. In Chile, long time series suffer from serious drawbacks due to inadequately documented instrument and siting changes. Furthermore, because of complex terrain many microclimates exist across the country and not too distant stations may show little correlation, a fact aggravated by the paucity of the observing network. As a result, standard procedures to verify or correct the data are not applicable because reliable or master records in most cases do not exist, or are contaminated by urban growth. In spite of all these problems, an effort to produce reliable time series of temperature for Chile is underway and the first results are presented here. Some Argentinian data is included in order to assess the regional extent of temperature variations.

Continental Chile spreads over a wide latitudinal range, from 18°S to 56°S, mostly on the west slope of the Andes, covering a wide range of climatic regimes from extreme aridity in the north, through mediterranean type with a dry summer in its central part, to all year rainy climates in the south. Furthermore, Chile is part of the only continental area approaching Antarctica, providing a natural bridge to link middle with high latitudes in the Southern Hemisphere.

The Southern Hemisphere instrumental record of mean surface temperatures has been analysed by several authors, with fairly similar results (Boden *et al.*, 1994). The following discussion on the annual temperature anomalies (with respect to the period 1950–1979) is based on data from Jones *et al.* (1994). Under visual inspection the updated series seems to present two significant changes around the years 1936 and 1976. Before 1936, negative anomalies prevailed with average values around −0·3°C; between 1936 and 1976 the average value moved to around zero, and later on became positive with a value close to 0·25°C during the last decade.

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This series was studied by Ghil and Vautard (1991) by means of singular spectrum analysis, separating a secular warming trend and a few oscillatory modes from background noise. The trend was flat before 1910 but from this year on the Southern Hemisphere temperature increased at a fairly constant rate by 0·4°C from 1910 to 1990. However, if a different method is used to identify singularities, additional dates appear. For instance, when the method suggested by Alexandersson (1986) is applied, changes in 1936, 1956, 1968 and 1976 appear. Therefore, it is not clear if warming has proceeded in discrete steps or with a smoother positive trend since 1910. Independently of the way the warming is occurring, the linear trend is a simple and useful way to characterize the long-term climatic variation, although discrete changes may appear in a more detailed description.

The temperature change around 1976 is a long established feature also present in the Southern Oscillation Index (SOI: twice-normalized Tahiti minus Darwin pressure anomalies), which has shown frequent negative values and rare excursions to the positive side in recent decades. In the Northern Hemisphere the surface temperature change after 1976 was noticed as a cooling in the northern Pacific Ocean and as a warming over Alaska by Trenberth (1990), who, due to the prominent role of quasi-stationary planetary waves in this hemisphere, characterized this change as an eastward shift of a deeper Aleutian Low during winter. Because such a shift is compatible with the teleconnection pattern described by Wallace and Gutzler (1981) for the Northern Hemisphere during El Niño years, the extratropical temperature changes appear to be linked with El Niño–Southern Oscillation (ENSO) phenomena. Analogous teleconnection patterns have been presented by Karoly (1989) for the Southern Hemisphere both in winter (developing phase) and summer (mature phase). For the extratropical Chilean coast the most relevant anomalous winter feature is an anticyclonic circulation over the Bellingshausen Sea advecting cold polar air over the austral part of South America. Also, Ghil and Vautard (1991) point that since 1976 interannual and interdecadal oscillations give positive contributions, keeping the resulting composition above the secular trend. In a more detailed study of global warming in recent decades, Jones (1994) subtracts both ENSO and volcanic eruption effects, obtaining a residual series in which the present warming begins in 1975. Removing the ENSO signal from the data is an artefact not free from criticism, because ENSO phenomena are part of the climate internal variability and indeed their variations in magnitude or frequency can be an expression of an enhanced greenhouse effect.

Regional analyses have been presented by Rosenblüth and Fuenzalida (1991) and Rosenblüth *et al.* (1995) for mean annual temperature in Argentina and Chile between 1930 and 1988, and Hoffman (1990) for decadal means for Argentinian stations. In Rosenblüth and Fuenzalida (1991), monthly mean temperatures provided by the Chilean Weather Service were used as basic data. Such mean temperatures are computed as the average of observations taken at 1200 GMT (0600 to 0900 mean solar time), 2400 GMT (1800 to 2100 mean solar time) and the daily maximum and minimum temperatures. This local procedure was chosen in 1930 to agree with previous methods used since the mid-nineteenth century. This formula, which has not been compared with the true mean daily temperature in recent times, was extended to new stations without further analysis. Hence, daily mean temperature for Chile, and derived statistics such as the monthly mean temperature, are not strictly comparable with similar values from other countries, although the difference between the result obtained with this method and the true daily mean is probably small. Extreme temperatures, although noisier, do not share this objection and are more informative with regard to physical processes responsible for their variation.

Recently, Karl *et al.* (1993) performed a global analysis of extreme temperatures including only 10 per cent of the Southern Hemisphere (Australia and South Africa). The main result is that minimum temperatures increased three times faster than maximum temperatures, a result that has been related to an increase in cloudiness or an increment of atmospheric water vapour due to global warming. On the other hand, Jones (1995) finds that over the Antarctic continent the diurnal temperature range (maximum–minimum) shows regions of increase and decrease with no continental trend between 1957 and 1992, although a decrease seems to prevail over the Antarctic Peninsula.

2. DATA

A set of 20 Chilean stations from 18°S to 53°S was selected because of the quality and extent of their temperature records. Time series of monthly mean temperature and monthly mean extreme temperatures were included. The longest record starts in 1912 and the shortest one in 1940, with the exception of Quintero, El Belloto, and Osorno,

Table I(a). Chilean stations' data: location, record and site changes

Station	Data Period	Present Location			Missing Data		Site changes
		Latitude (S)	Longitude (W)	Height (m)	*T* max.	*T* min.	
Africa	1930–1992	18°20′	70°20′	58	31(2), 34(7), 35(7), 36(3), 48(3), 49, 50(6), 55(6), 56–57	55(9), 56(11)	50,57
Iquique	1900–1992	20°12′	70°11′	6	30, 31, 46–49	30, 31, 46–49	46, 58, 74, 81
Antofagasta	1930–1992	23°26′	70°26′	135		44–45	44
La Serena	1930–1992	29°54′	71°12′	142	46, 48, 49, 56, 59–62	46, 48, 49, 56, 59–62	67, 70, 72
P. Tortuga	1920–1992	29°55′	71°21′	25	48–52, 67, 85	48–52, 67, 85	
Ovalle	1920–1970	30°27′	71°13′	220	34–41, 66–68	34–41, 66–68	
Quintero	1952–1992	32°47′	70°32′	8	62(11), 63–64, 76(3), 83	62(11), 63–64, 76(3), 83	
P. Angeles	1912–1992	33°01′	71°38′	41	88(3)	88(3)	
El Belloto	1963–1988	33°06′	71°24′	121	76(3)	76(3)	
Concepción	1942–1992	36°46′	73°03′	12			58,68
Temuco	1930–1992	38°45′	72°38′	114	55(6), 55–58, 61(5)	54(6), 55–58, 61(5), 63(9)	71
Valdivia	1930–1992	39°37′	73°05′	19	52(4), 60(8), 61–63, 71–78	52(5), 60–63, 71–78	54,66
Osorno	1960–1992	40°36′	73°03′	65			
P. Montt	1930–1992	41°25′	73°05′	85	63(6)	63–64	64
I. Guafo	1908–1989	43°34′	74°45′	140	18(6), 49(4), 50(4), 51(5), 53–54, 55(8), 64(10), 69–74, 78(11), 83(11), 89(4), 85(6), 88(5)	49(4), 50(4), 51(5), 53–54, 55(9), 56(6), 68(5), 69–73, 74(11), 78(6),, 82(5), 83, 89(5), 88(5)	
Aysen	1932–1992	45°20′	72°40′	11			
I. Evangelista	1900–1992	52°24′	75°06′	60	12(11), 36(8), 37–40, 45(6), 46, 47(4), 48, 49(10), 51(11), 52, 53(5), 59(10), 60(5), 75–79, 82(11), 90(8), 91–92	12(4), 36(8), 37–40, 48(7), 51(4), 52, 56(8), 57(3), 58(6), 59(7), 60(5), 62(7), 63–64, 65(3), 71(11), 81(6), 82(11), 90(9), 91–92	
P. Dúngenes	1900–1990	52°24′	68°26′	32	07(9), 08–09, 10(10), 24(7), 28(5), 42(3), 45(6), 52(5), 53–64, 65(3), 82(4), 85(3), 89	11(9), 47(4), 48, 52(5), 53–64, 65(3), 77(11), 78–79, 82, 83(3), 85(3), 89	
P. Arenas	1905–1992	53°00′	70°51′	37	20(6), 51(4), 52(4), 54(8), 55, 63, 71(7), 87(6)	20(6), 43(3), 51(4), 52(7), 63, 71(7), 72(5), 83(4), 87(6)	64
M. Fagnano	1900–1992	53°10′	70°55′	32	42, 43(7), 54, 59	42, 43(7), 54, 59	

Table I(b). Argentinian stations: location and record

Argentinean Stations			
Station	Period	Latitude(S)	Longitude(W)
La Quiaca	1911–1988	22°06′	65°36′
Salta	1901–1987	24°54′	65°30′
Corrientes	1931–1987	27°30′	58°48′
Posada	1931–1987	27°24′	56°00′
La Rioja	1931–1987	29°24′	66°48′
Ceres	1931–1987	29°54′	62°00′
San Juan	1931–1987	31°36′	68°24′
Córdoba	1931–1987	31°24′	64°12′
Pilar	1931–1987	31°42′	63°54′
Mendoza	1906–1987	32°54′	68°48′
Río Cuarto	1931–1987	33°06′	64°18′
Dolores	1931–1987	36°24′	57°30′
Mar del Plata	1931–1987	37°54′	57°36′
Bahía Blanca	1931–1987	38°42′	62°12′
Neuquén	1931–1987	39°00′	68°06′
Bariloche	1931–1987	41°12′	71°12′
Esquel	1931–1987	42°54′	71°12′
Comodoro Rivadavia	1931–1987	45°48′	67°30′
Río Gallegos	1931–1987	51°36′	69°18′
Ushuaia	1931–1987	54°48′	68°18′

which were used to fill recent gaps at the other sites. All series extend up to 1992. Some long temperature series, such as Santiago's were excluded because of urban growth influence. In the Argentinean sector monthly mean temperature was available for 20 stations covering the latitude interval between 20°S and 54°S. Most of them start in 1930 and end in 1988; the only information available to us on extreme temperatures is for Río Gallegos on a decadal basis. Chilean records were obtained from the National Weather Service (Dirección Meteorológica de Chile), and most of the Argentinean records were extracted from the World Weather Disc in its version 2·0 15 May, 1990).

Table I(a) describes characteristics of the time series of extreme temperatures for Chile, including for each station the geographical coordinates, period covered by the record, missing data, and years when there was a known site change (additional information on stations is given in Appendix I). Missing data are indicated by the year only (last two digits) if the whole year is missing and the number of months without data (in brackets) otherwise. Years separated by a dash are used when the whole interval is missing. Table I(b) contains information on data period and geographical coordinates for Argentinean stations. The map in Figure 1 shows the location of Chilean and Argentinian stations. Across Chile two geographical gaps are evident, the first between 24°S and 30°S and the second between 46°S and 53°S. In both sectors there are a few stations on the coast but their records are either too short or fragmented by interruptions.

A preliminary visual inspection of each series was performed on a monthly basis. Individual station records were compared with nearby stations and apparent outliers were deleted. A regression with the closest record was used to fill missing values if the simultaneous record length was long enough, otherwise the value of the closest station corrected by the average difference between stations was used. The stations with the longest gaps were Punta Tortuga (1948–1952), filled with La Serena, and Temuco (1955–1958), filled with Valdivia. Most of the Argentinian stations had complete records and only isolated months had to be filled in.

Site changes occurred mainly when stations were moved from urban locations to airports during the 1950s and 1960s. Homogeneity was attained by applying Alexandersson's test to temperature difference between not too distant stations on a monthly basis. Reported site changes were verified by means of this test and corrections applied as follows. Arica was corrected by comparing with Antofagasta; Concepción and Puerto Montt were corrected comparing with Temuco; and Punta Arenas by comparing with Monseñor Fagnano. Punta Angeles presented discontinuities although no site change was reported for this station. They were corrected using

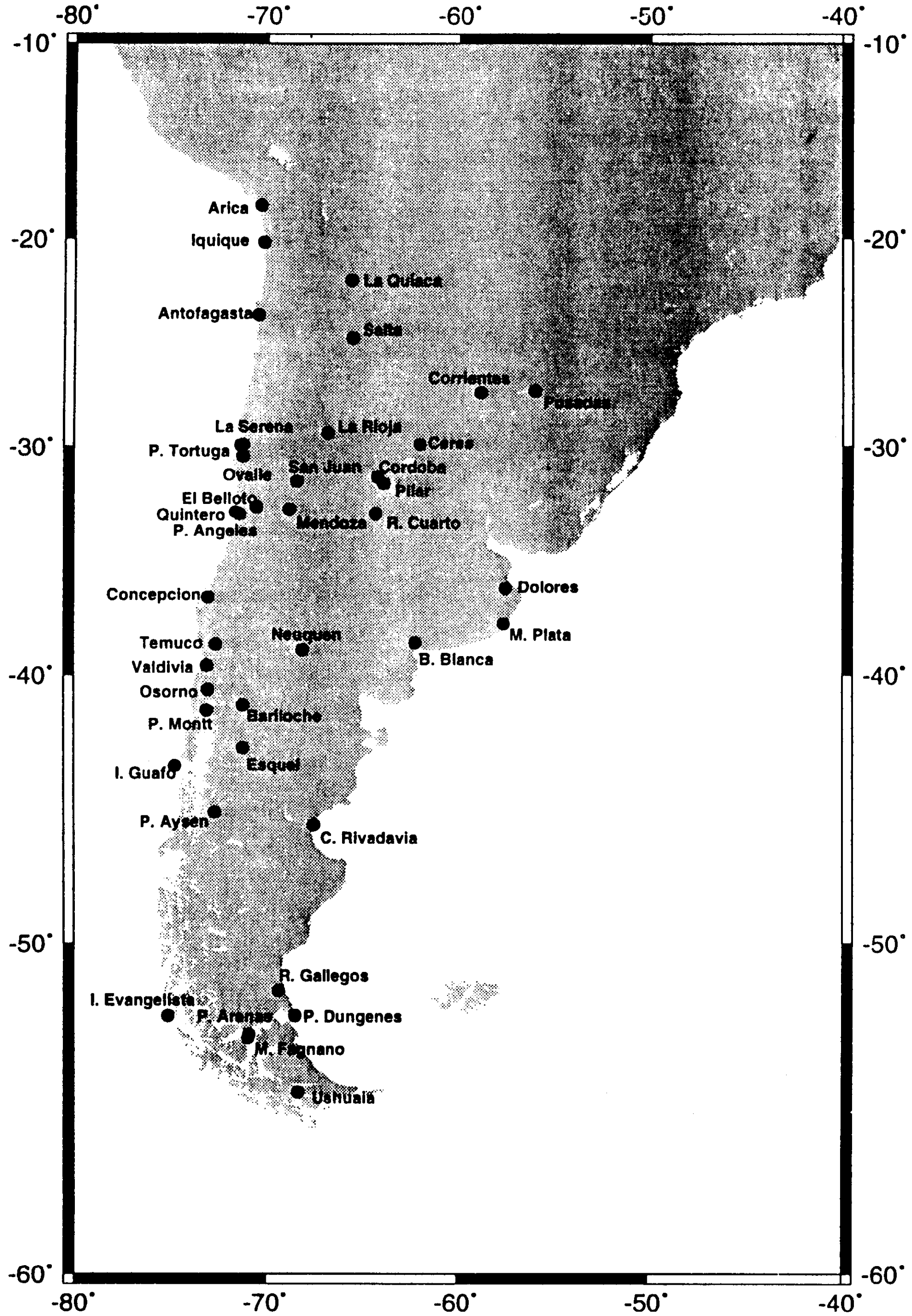


Figure 1. Station location map

observations at El Belloto and Quintero. Puerto Aysen record was the only one left without correction. Discontinuities were removed by displacing the older record to the level of the more recent period.

To illustrate the kind of difficulties faced with the observations and the impact of site changes, two specific cases will be commented on. The first example corresponds to Puerto Montt extreme temperatures. This station was moved sometime during 1964 from a site close to the sea to an inland airport with a height change of about

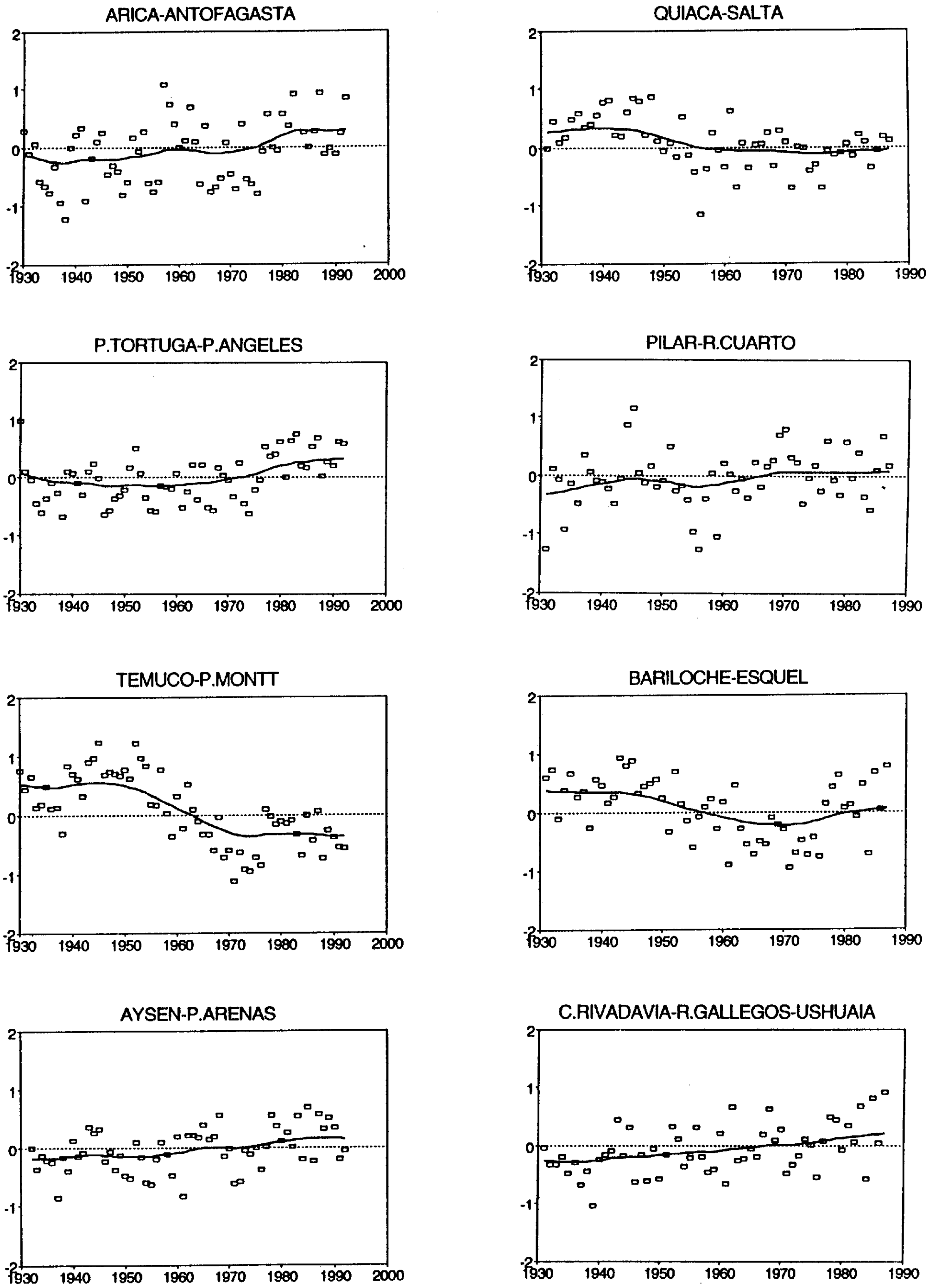


Figure 2. Annual mean temperature anomalies (open rectangles), with respect to the period 1940–1988, and smoothed variations (solid line) for selected Chilean (left) and Argentinian (right) composites

60 m without simultaneous records on both sites. This change introduced a discontinuity of about 2°C in minimum temperature and a smaller one in maxima. The second example illustrates a case of inhomogeneity where no station change was reported. It corresponds to Punta Angeles (Valparaiso's lighthouse) where the record of maximum temperature exhibits a 3°C jump in the late 1970s. This change was not observed at El Belloto and Quintero.

3. RESULTS

3.1. Mean temperature

A sample of annual mean temperature variations is shown in Figure 2, including eight composite cases. Four of them, along the Pacific Coast (left), illustrate the climatic meridional gradient along Chile. The first, a mean of Arica and Antofagasta, represent the extremely arid northern coast with frequent low cloudiness; the second, a mean of Punta Tortuga and Punta Angeles corresponds to a steppe type of climate, still dry but with some winter rain; the third, formed by averaging Temuco and Puerto Montt represents the temperate mediterranean climate with winter rains, and the fourth, a mean of Puerto Aysen and Punta Arenas, is a mixture of colder climates with rainfall well distributed throughout the year, although the first place is much moister than the second, being located on the lee side of the Andes. On the right side of Figure 2 there are four composites made from Argentinian stations centred at latitudes similar to the Pacific composites. Two cases on the eastern slope of the Andes: La Quiaca-Salta, centred around 22°S, and Bariloche-Esquel, around 42°S; one inland composite (Pilar-Río Cuarto), centred around 32°S; and one on the southern Atlantic Coast (Comodoro Rivadavia–Río Gallegos-Ushuaia) centred around 50°S.

Deviations from the mean value for the period between 1940 and 1988 are indicated by open rectangles and a smoothed version is indicated by a continuous line. Smoothed versions are obtained by applying twice an exponential filter with damping coefficient 0·11: forward and backward to preserve phase (Appendix II: Essenwanger, 1986). For this filter the amplitude frequency response decays monotonically, damping the amplitude of the 50-year cycle by 50 per cent, approximately. Its response follows closely that of a Gaussian filter with $\sigma = 10$ up to frequency 0·02, decaying slower beyond this point.

Chilean records have been corrected for site change, so they represent a revised version of those communicated previously (Rosenblüth and Fuenzalida, 1991; Aceituno *et al.*, 1993; Rosenblüth *et al.*, 1995). Trends, represented by the smoothed variation, can be assessed from this figure.

Starting from the north, temperature fluctuations on the arid coast of Chile (Arica–Antofagasta) are correlated negatively with the Southern Oscillation Index (SOI) (see below) so that ENSO explains part of the variance of annual mean temperature anomalies. The influence of ENSO decreases towards higher latitudes. The outstanding feature in the smoothed version is a warming starting in the late 1930s that peaks in 1960, followed by a second warming from the mid 1960s up to the early 1980s and levelling off thereafter. This contrasts with an opposite variation on the eastern slope of the Andes (La Quiaca–Salta), where a cooling is present from the 1940s to the 1970s. Here the Andean Altiplano reach 5000 m, separating hyper-arid climates controlled by the Pacific subtropical anticyclone on the west from climates with summer rainfall associated with moist air of Amazonian origin on the eastern slope. Further south between Punta Tortuga and Punta Angeles (31°S approximately) there is a slight cooling in the first decades followed by a rise from the early 1960s to the early 1980s levelling off in recent years. In the central part of Argentina at roughly the same latitude (Pilar–Río Cuarto) warming periods are interrupted by a cooling from the mid-1940s to the mid-1950s and a stable interval from 1970 up to the present. Over the mediterranean climate belt in Chile, Temuco–Puerto Montt (40°S), the main feature is a marked cooling from the 1950s to the 1970s. This is also present on the east side of the Andes in the composite Bariloche–Esquel, followed by a warming afterwards. Here the Andean summits are lower, rarely reaching 2000 m. In the south, between Puerto Aysen and Punta Arenas (53°S) there is a mild warming beginning in the 1950s that levels off in the 1980s. Most of the warming occurring in the southern sector. On the Argentinian side the composite of Comodoro Rivadavia–Río Gallegos–Ushuaia exhibits a similar trend that starts a little earlier. Note that in the southern half of Chile there is a significant cooling in 1991–1992 that coincides with the period when aerosols from the Pinatubo and Cerro Hudson eruptions (in June and August 1991, respectively) were present in the stratosphere; however this feature is not apparent in the northern sector.

Table II contains annual mean temperature trends evaluated for the periods 1933–1992 and 1960–1992, showing that during the most recent period positive trends are larger, but at Puerto Montt, the only place where cooling is observed, the trend is still negative.

A regional map for linear trends, expressed in degrees per century, in the most recent period (1960–1962) is presented in Figure 3. Statistically significant values at 95 per cent (*t* test) are indicated with asterisks. There is a generalized warming except for an inland sector over Argentina centred around 30°S and the latitude belt centred around 41°S on the Pacific coast. In general, the Pacific continental coast has experienced a warming that attains

Table II. Annual mean temperature trends (°C/100 $years^{-1}$)

Station	Latitude S	1933–1992	1960–1992
Arica	18°20′	1·5*	2·0*
Antofagasta	23°26′	1·4*	2·7*
P· Angeles	33°01′	2·0*	3·8*
P· Montt	41°25′	−2·2	−1·1
P· Arenas	53°00′	1·3*	2·1*

*Significant at the 5 per cent level

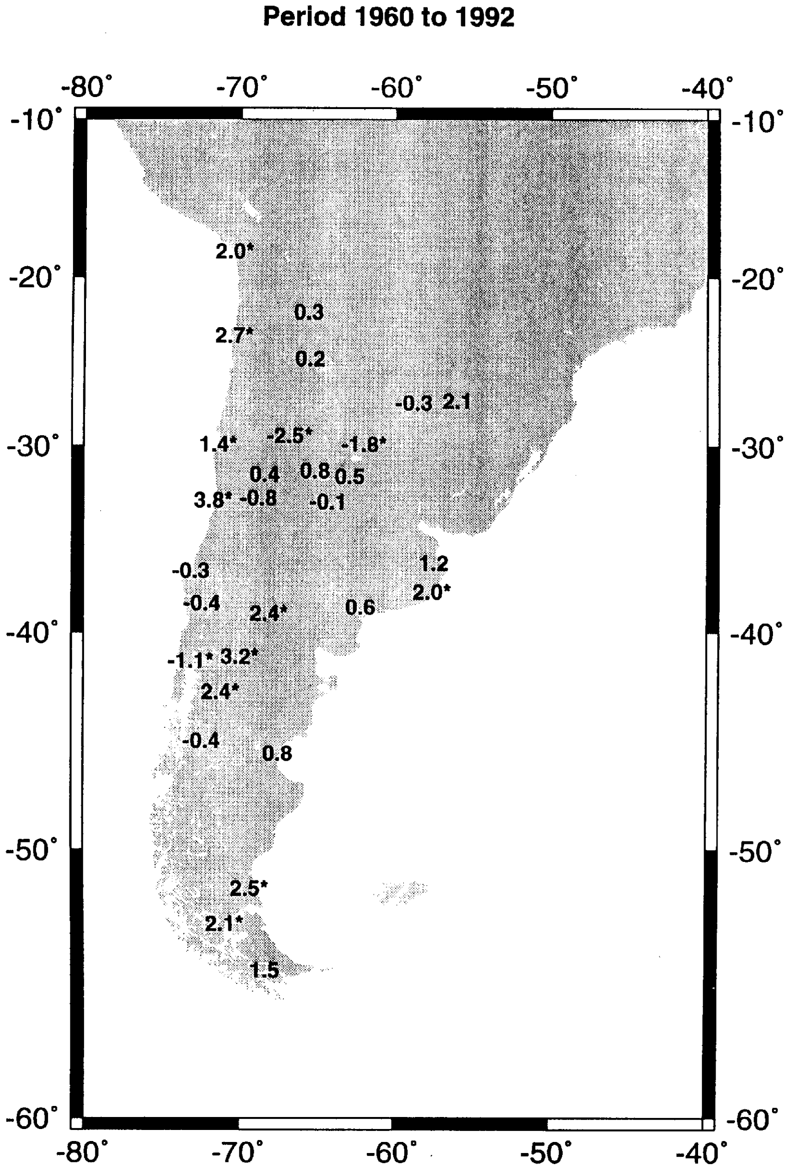


Figure 3. Distribution of annual mean temperature trends for the period 1960–1992 (°C 100 $years^{-1}$). Asterisks indicate significant values at the 5 per cent level in a two-tail Student *t* test

the largest magnitudes in the northern sector associated with ENSO phenomena (see discussion). Close to 41°S, where cooling along the Pacific coast is observed, Argentinian stations exhibit a positive trend due to a temporary recovery in recent years that is not present on the Pacific coast. Towards the most austral sector a warming increase occurs again, in agreement with larger values reported by King (1994) for the Antarctic Peninsula. The two previous decades, 1940–1959 (not shown), exhibit a generalized cooling, which is statistically significant at very few stations. When summer and winter temperatures are considered separately (Figures 4 and 5), it becomes apparent that, for the southern part of the region, warming is more intense in summer compared with winter. Significant values appear in the southernmost stations whereas in winter they occur in the northern stations along the Pacific coast. Because El Niño has been unusually active in the most recent period (Trenberth and Hurrel, 1994) this suggests that ENSO phenomena might be responsible, at least partially, for this warming pattern.

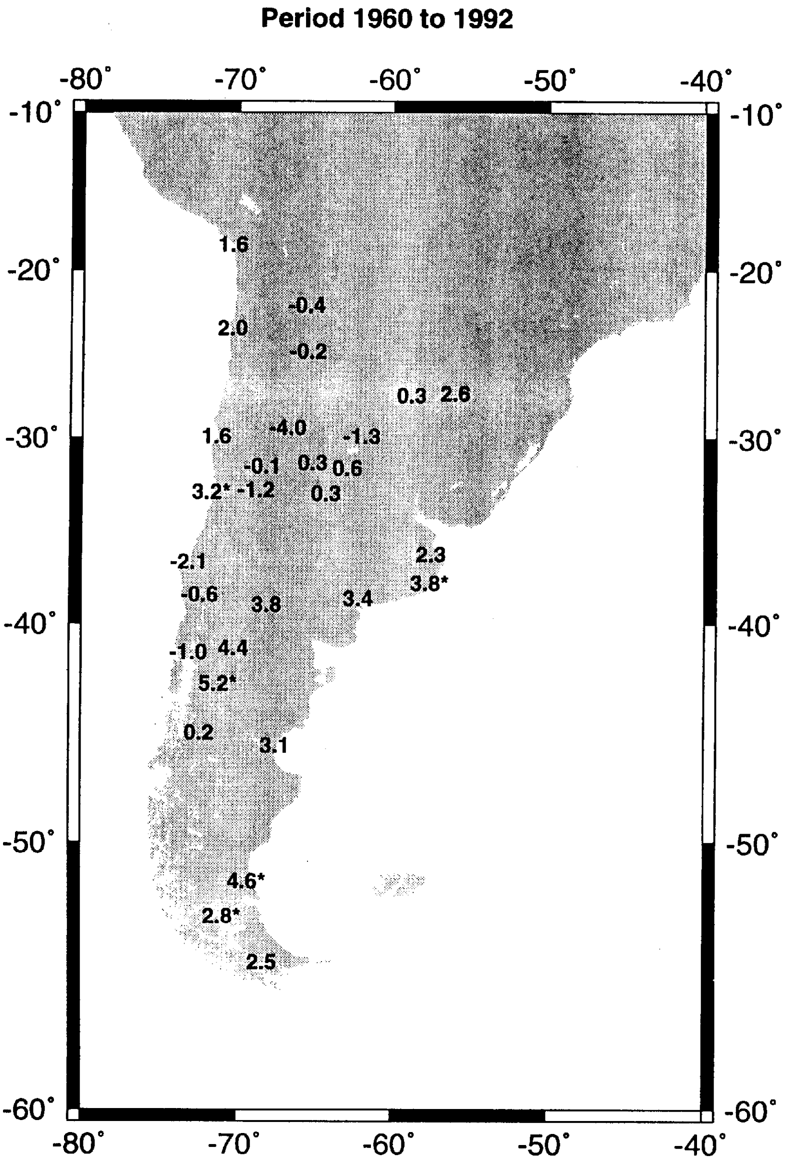


Figure 4. Distribution of summer mean temperature trends for the period 1960–1992 (°C 100 years^{-1}). Asterisks indicate significant values at the 5 per cent level in a two-tail Student *t* test

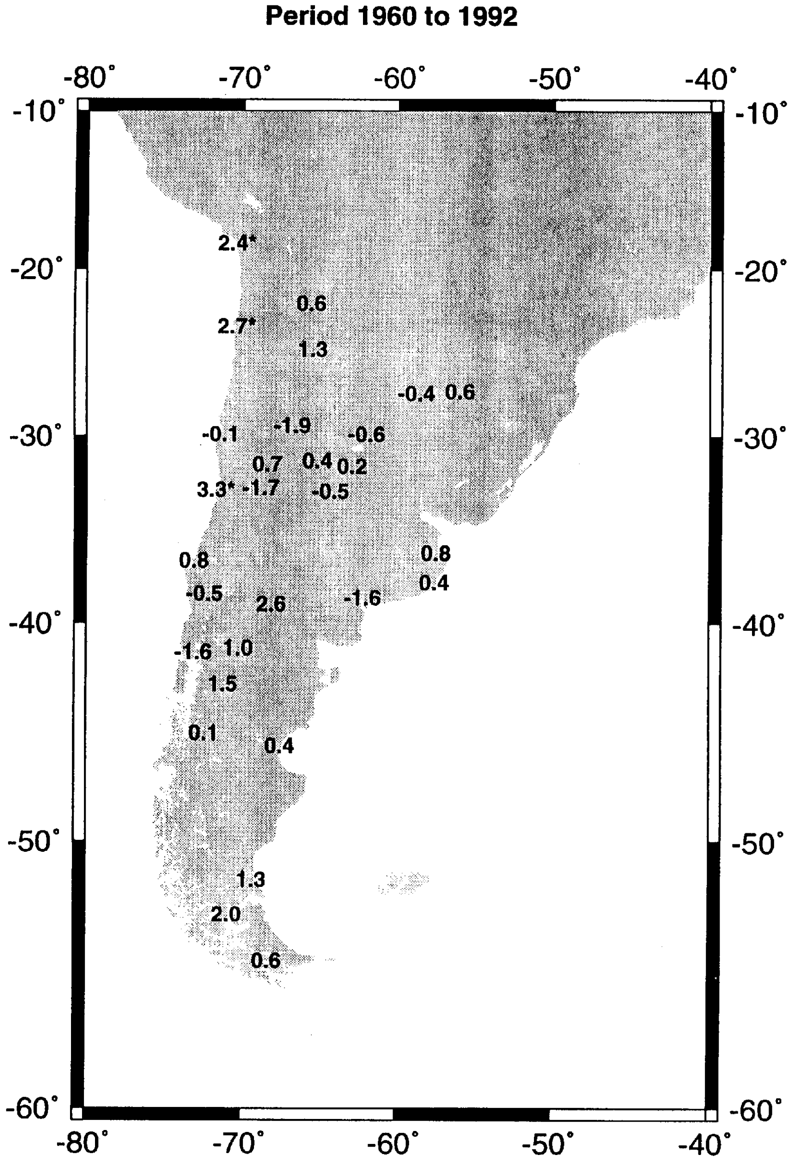


Figure 5. Distribution of winter mean temperature trends for the period 1960–1992 (°C 100 years^{-1}). Asterisks indicate significant values at the 5 per cent level in a two-tail Student *t* test

3.2. Extreme temperatures

Minimum and maximum temperatures for Chilean stations were subject to the same homogenizing procedure described above. Corrected annual time series for the same composites along the Pacific Coast as in Figure 2 are shown in Figure 6. In agreement with the findings of Karl *et al.* (1993) for land stations, minimum temperatures exhibit a larger warming compared with maxima, with the exception of Temuco and Puerto Montt, where cooling prevails.

In the northern sector, from 18°S to 33°S, minimum temperatures warmed since the 1950s up to the present, whereas maximum temperatures oscillate around an almost invariable mean value. In the austral sector there is a warming beginning in the 1950, mainly in minima. In mid-latitudes the cooling period extending from the 1950s to the 1970s is shared by both extreme temperatures with a somewhat larger role played by maxima. Table III includes trends in extreme temperatures for the period 1960–1992. A large seasonal warming in minimum

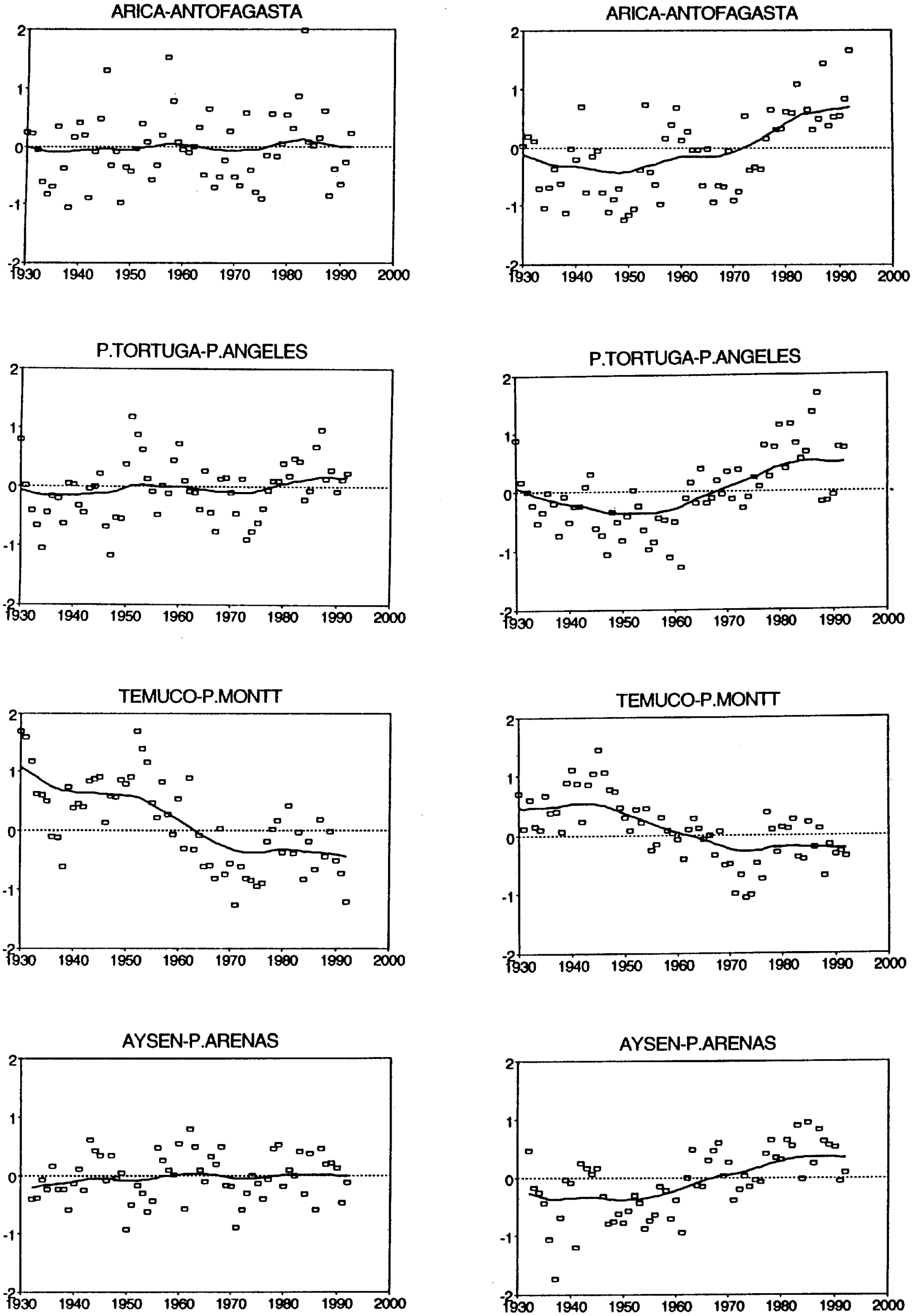


Figure 6. Annual extreme temperature anomalies (open rectangles), with respect to the period 1940–1988, and smoothed variations (solid line) for Chilean composites: minimum temperature (right) and maximum temperature (left)

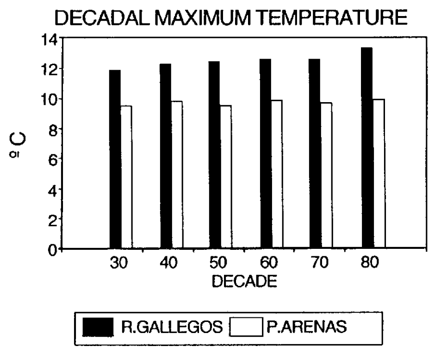
Table III. Extreme temperature trends 1960–1992

		Minimum temperature (°C 100 years^{-1})					Maximum temperature (°C 100 years^{-1})				
Latitude (S)	Station	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring	Annual
18°20′	Arica	4·3*	4·8	5·2*	4·2*	4·7*	1·0	1·4	1·3	1·8	1·3
23°26′	Antofagasta	4·6*	5·8*	6·0*	5·9*	5·6*	−0·7	0·5	0·6	0·9	0·3
29°55′	P. Tortuga	1·0	4·6*	2·8	4·4*	3·2*	0·2	0·6	−1·9	−0·5	−0·4
33°01′	P. Angeles	3·4*	3·1*	3·1	5·3*	3·7*	2·7	4·3		3·1	3·1
36°46′	Concepción	−0·3	1·7	0·1	1·6	0·8	−2·5*	−1·3	0·7	0·5	−0·6
38°45′	Temuco	−0·7	−0·8	−0·5	−0·1	−0·1	−0·5	−2·0	−0·2	−0·3	−0·8
41°25′	P. Montt	−1·8*	1·0	−0·7	−0·6	−0·1	0·0	−2·8	−0·1	−0·4	−0·1
45°20′	Aysén	1·2	0·0	0·9	0·4	0·6	−1·2	−1·6	1·3	−0·1	−0·6
53°00′	P. Arenas	4·6**	4·7*	3·3*	2·7*	3·9**	0·2	−1·0	−0·5	0·4	−0·4

* Significant to 5% level
** Significant to 1% level

temperature appears in the northern sector and Punta Arenas; there are statistically significant values for most places. Near 40°S there is a slight cooling covering a wider latitudinal belt in summer. Increases in maximum temperatures are smaller by a variable factor, including cooling at places south of 36°S. During the previous period (not shown) there is a generalized cooling except for the northern region.

Hoffman (1990) has reported an analysis of mean decadal temperatures from Argentinian stations in the sub-antarctic region. He shows that south of 45°S there is a significant warming, especially at Río Gallegos and Orcadas. At least at Río Gallegos, warming is larger in minimum temperatures, as can be seen from Figure 7, in which decadal means of extreme temperatures for Río Gallegos and Punta Arenas are compared.



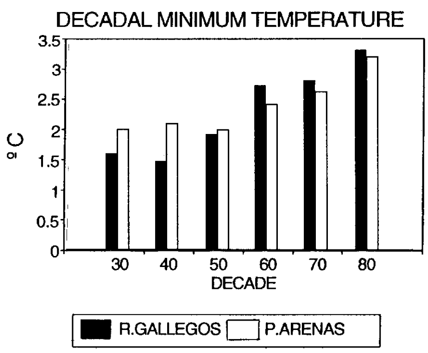


Figure 7. Decadal mean extreme temperatures for Río Gallegos, Argentina (51·6°S) and Punta Arenas, Chile (53°S)

DISCUSSION

The influence of ENSO on air temperatures along the coast of Chile can be summarized through correlation with the Southern Oscillation Index at various stations. They are presented in Table IV for the years 1933 to 1992, for summer, winter, and annual values at five stations. It can be seen that correlations decrease from north to south, becoming non-significant somewhere between Punta Angeles and Punta Arenas. In the northern sector correlations are larger in winter, whereas in the southern region they are larger in summer, although with no statistical significance. Also, in the northern sector, correlations for the whole year are better than for a particular season. Related to this, Figures 4 and 5 show that warming trends have statistical significance during summer in the southern region whereas in winter significant trends are in the northern sector.

Analogous information for mean annual extreme temperatures are presented in Table V showing that minimum temperatures attain significance over a larger latitudinal belt than maxima. On a seasonal basis (not shown) this asymmetry becomes more evident, with a significant relationship between SOI and minimum temperatures extending up to Puerto Montt in spring. Another feature observed in the seasonal decomposition is the appearance of weak positive correlations in the austral sector (Puerto Aysen and Punta Arenas), which for spring maximum temperatures become significant at Punta Arenas. In the recent decades (1960–1992) this behaviour becomes better defined in winter and spring. For the period 1948–1983 mean temperature cooling at high latitudes during ENSO years was detected by Aceituno (1988) in winter and spring. Its geographical extension becoming larger, with a statistical significance of 5 per cent, in September and October. Therefore, the austral cooling is due mostly to lower maximum temperatures. Its origin can be traced to the frequent presence, in ENSO years, of a blocking anticyclone over the Bellingshausen Sea advecting cold air over the region (Rutllant and Fuenzalida, 1991) in agreement with the teleconnection pattern found by Karoly (1989). However, this anticyclone was also present during the very cold 1995 austral winter when relatively small values of SOI prevailed.

The ENSO signal was extracted from the seasonal temperature series by means of regression, with the SOI averaged over each season. Following Jones (1994) the best lag for regression was verified, finding that in all cases except for Punta Arenas the simultaneous series correlated best. The linear relation was subtracted from

Table IV. Mean temperature–SOI correlation for the period 1933–1992

Station	Latitude (S)	Summer	Winter	Annual
Arica	18°20′	−0·45*	−0·54*	−0·59*
Antofagasta	23°26′	−0·54*	−0·60*	−0·67*
P. Angeles	33°01′	−0·43*	−0·37*	−0·53*
P. Montt	41°25′	−0·16*	−0·14	−0·10
P. Arenas	53°00′	−0·20	−0·11	−0·19

*Significant at the 5 per cent level

Table V. Annual extreme temperatures–SOI correlation for the period 1933–1992 (°C 100 years^{-1}

Station	Latitude (S)	Minimum Temperature	Maximum Temperature
Arica	18°20′	−0·54*	−0·54*
Antofagasta	23°26′	−0·53*	−0·48*
P. Tortuga	29°55′	−0·29*	−0·29*
P. Angeles	33°01′	−0·47*	−0·37*
Concepción	36°46′	−0·26*	−0·01
Temuco	38°45′	−0·32*	0·02
P. Montt	41°25′	−0·18	−0·04
P. Aysen	45°20′	−0·14	−0·13
P. Arenas	53°00′	−0·25*	0·09

*Significant at the 5 per cent level

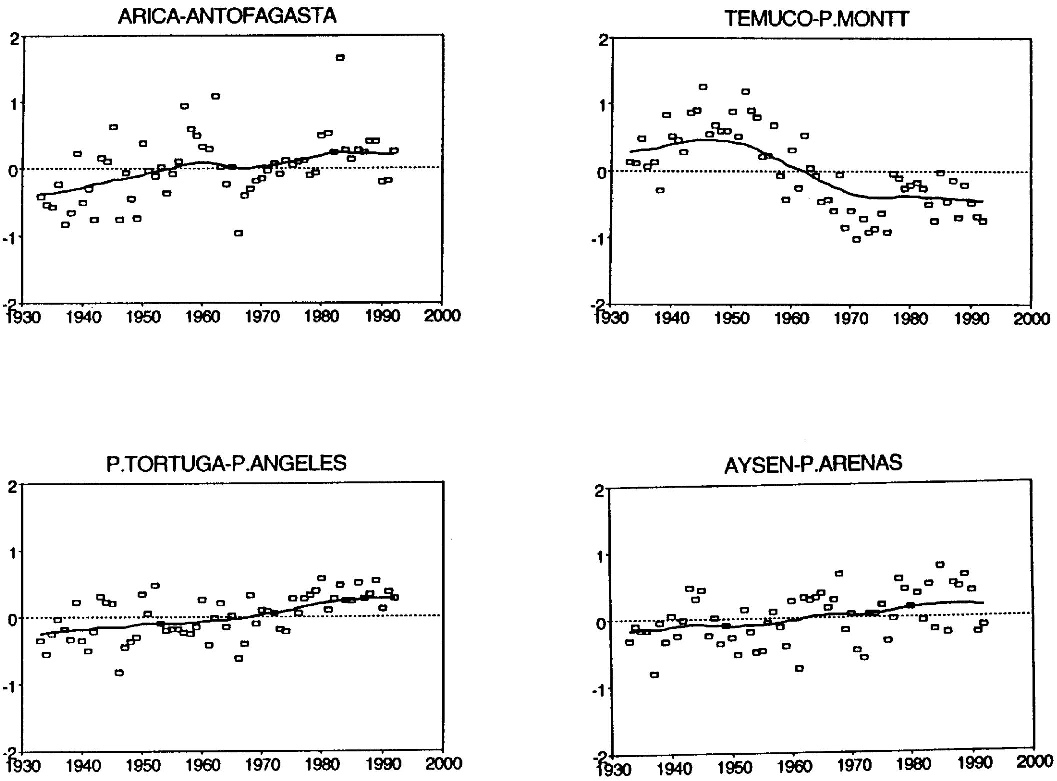


Figure 8. Annual mean temperature anomalies, SOI component extracted (open rectangles), with respect to the period 1940–1988, and smoothed variations (solid line) for selected Chilean composites

observations, obtaining the annual mean values shown in Figure 8 for the same composites as in Figure 2. They reveal a more regular warming in all regions with the exception of Temuco–Puerto Montt, where the cooling from the mid-1950s to the 1970s still prevails. Linear trends determined by least squares for individual stations are presented in Table VI for the period 1933–1992 and 1960–1992. A comparison with Table II indicates that trends do not differ much in the complete record but decrease substantially in the recent decades, particularly in the northern sector where ENSO influence is important. The largest positive trend occurs at Punta Angeles.

Singularities in the minimum temperature, where most of the warming occurs in the period 1960–1992, were explored at nine Chilean stations in the latitudinal interval 18–53°S by Alexandersson's (1986) method, including a Monte Carlo significance test. In all cases a break between 1975 and 1977 was found, which was statistically significant in three of them (Antofagasta, Punta Angeles, and Punta Arenas). Therefore, the change in the SO regime around 1976 affected minimum temperatures at all latitudes along the Pacific coast of Chile. On the other

Table VI. Annual mean temperature trends with SOI subtracted (°C 100 years^{-1})

Station	Latitude (S)	1933–1992	1960–1992
Arica	18°20′	1.2*	0.5
Antofagasta	23°26′	1.1*	1.2*
P. Angeles	33°01′	1.8*	2.8*
P. Montt	41°25′	−2.3	−1.4
P. Arenas	53°00′	1.3*	1.8*

*Significant at the 5 per cent level

hand maximum temperatures do not show any break around this date. Year 1910, where Ghil and Vautard (1991) claim a first-order discontinuity is beyond the record available, and year 1936, when another break is apparent in the Jones *et al.* (1994) hemispherical record, is too close to its beginning to be detected.

Sansom (1989), working with mean temperature series for Antarctica, has blamed serial autocorrelation for spurious linear climatic trends. A correction due to autocorrelation in the residuals was applied to linear trends using the method of Cochrane and Orcutt (1949). Table VII shows trends of mean and extreme temperatures corrected for autocorrelation for the recent decades. Comparing with Tables 2 and 3 it is verified that modifications vary in sign and magnitude from place to place but no major change occurs and the increase in minimum temperature keeps on taking the larger part of recent variations. Therefore, for annual mean values, autocorrelation is a minor factor introducing no qualitative change in the general conclusions.

The cooling period experienced in mid-latitudes from the 1950s the 1970s (Temuco–Puerto Montt and Bariloche–Esquel in Figure 2 and Temuco–Puerto Montt in Figure 6) received special attention. Ghil and Vautard (1991) did not find this cooling in the mean temperature of the whole Southern Hemisphere. Table 8 shows annual and seasonal temperature trends for the period 1950 to 1965 at stations between 33°S and 41°S. Most of them are negative, particularly for maximum temperature. In summer, minimum temperature cooling attains statistical significance at the three southern stations. This cooling, which is present in both extreme temperatures, as shown for Puerto Montt in Figure 5, is not present in the radiosonde observation at this location at 700 hPa and above, so that, judging from this partial evidence, it is restricted to low tropospheric levels. However, Angell (1994) does report a cooling in the zonal mean temperature of the 850–300 hPa layer between 1959 and 1964. Therefore, this cooling seems to be a local feature of South American mid-latitudes, encompassing a shallow layer near the surface mostly on the Pacific side.

In closing, air temperature records along the Pacific coast of South America, with the ENSO signal extracted, have experienced a fairly sustained increment during the present century of the order of 1°C in 100 years, except around 41°S where a cooling period between the 1950s and 1970s dominates. This general warming intensified in the 1960s to slow down during the 1980s. Both general warming and local cooling are due mostly to the changes

Table VII. Annual and extreme temperature trends corrected for autocorrelation for the period 1960–1992 (°C 100 years $^{-1}$)

Station	Latitude (S)	Minimum	Maximum	Annual
Arica	18°20′	4·1*	1·6	2·2*
Antofagasta	23°26′	7·1*	0·4	3·1*
P. Tortuga	29°55′	3·2*	0·6	1·4*
P. Angeles	33°01′	3·3*	3·7*	3·8*
Concepcion	36°46′	2·2*	0·0	0·6
Temuco	38°45′	0·1	−0·3	0·2
P. Montt	41°25′	0·0	−0·4	−0·8
P. Aysen	45°20′	0·6	−0·6	−0·4
P. Arenas	53°00′	3·4*	−0·1	1·9*

*Significant at the 5 per cent level

Table VIII. Extreme temperature trends for the period 1950–1965

	Minimum temperature (°C 100 years $^{-1}$)						Maximum temperature (°C 100 years $^{-1}$)				
Latitude (S)	Station	Summer	Autumn	Winter	Spring	Annual	Summer	Autumn	Winter	Spring	Annual
33°01′	P. Angeles	7·2*	5·8*	7·8*	4·9*	6·5*	0·9	−1·4	−6·0	−4·0	−2·6
36°46′	Concepción	−9·2*	−1·2*	−2·7	−4·7	−7·3*	−14·9	−11·0*	−8·0*	−1·3*	−12·0*
38°45′	Temuco	−2·5*	−7·1*	3·8	4·1	−0·6	−9·3	−14·7*	−6·2*	−3·1	−8·4*
41°25′	P. Montt	−4·3*	−1·1	3·0	1·3	−3·1**	−15·0	−13·6*	−8·7*	−10·1*	−12·7*

*Significant at the 5% level
**Significant at the 1% level

in minimum temperature. Inclusion of the ENSO signal makes warming more erratic, particularly in the northern sector. Warming trends reported here are substantially smaller than those observed on the western side of the Antarctic Peninsula (King, 1994), indicating that the largest warming is occurring close to the sea-ice boundary, at least in this region. After the abrupt change in the SO regime in 1976, minimum temperatures along the Chilean coast warm up significantly.

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APPENDIX 1

General Information on the stations

Stations included in this study can be grouped in three types. First, those belonging to a large city, inland and on the coast, that in the early part of the present century were located in the city centre and later moved to an airport out of town, sometimes more than once as new air facilities were built. Second, stations at lighthouses that have stayed at the same location during the whole period although they might have had changes in exposure. Third, stations of small towns where no airport has been built and have not been moved to new environments although gradual changes may have occurred due to moderate urban growth. Large inland cities, such as Santiago, although having the longest records in the country, have been omitted because of significant urban warming. The stations in italics in the following groupings are included in tables in the main text.

In the first group are: *Arica*, Iquique, *Antofagasta*, La Serena, *Concepción*, *Temuco*, Valdiva, *Puerton Montt*, and *Punta Arenas*. Among these the only one that is located inland is Temuco.

In the second group are: *Punta Tortuga* (Coquimbo), *Punta Angeles* (Valparaiso), Isla Guafo, Islote Evangelista, and Punta Dungeness. All of them are open to the Pacific Ocean except for Punta Dungeness, which is on the Atlantic entrance to the Magallan Strait.

In the third group are: Ovalle, Osorno, *Puerto Aysen*, and El Belloto. Puerto Aysen is located at the east end of an Andean fiord.

Monseñor Fagnano, Punta Arenas city centre, was included because of its long records and, due to strong winds and open surroundings, the urban effect must have a small impact on temperature. Quintero, in a small bay with records starting in 1957, was used only to fill gaps in the Punta Angeles series.

APPENDIX II

Exponential and Gaussian filtering

The exponential filter was applied twice, once forward and once backward in time. Thus the process for an input series x_t can be described by the sequence

$$\begin{aligned} y_t &= cx_t + (1-c)y_{t-1} \qquad && t = 2, 3, \ldots, N \\ z_t &= cy_t + (1-c)z_{t+1} \qquad && t = (N-1), (N-2), \ldots, 2, 1 \end{aligned} \tag{1}$$

where y_t is an intermediate series and z_t is the output of the process. The value of c determines the degree of smoothing. A value $c = 0{\cdot}11$ was used. This filtering process requires initialization in both applications. In the forward stage the initial value y_1 was taken as the average of the first five values. In the backward stage z_N was taken as the final value of y. Therefore, the final value in the output inherits the previous behaviour in the intermediate variable.

The frequency response of filter (1) is

$$H_e(f) = \frac{c^2}{2(1-c)(1-\cos 2\pi f) + c^2} \tag{2}$$

As a reference the Gaussian filter with standard deviation σ has a frequency response

$$H_g(f) = \exp\left[-\frac{\sigma^2}{2}(2\pi f)^2\right] \tag{3}$$

In the limit of very low frequency both filters have the same response for $c = c_0$ satisfying

$$\sigma^2 = 2\frac{1 - c_0}{c_0^2} \tag{4}$$

However, because the exponential response decays slower, both responses will separate further for frequencies not close to zero. A compromise must be made to make both filtering processes similar for intermediate frequencies taking a value of $c = c'$. The following table compares c_0 with c' for several values of σ, indicating also the minimum period P over which both responses differ by less than 0·1.

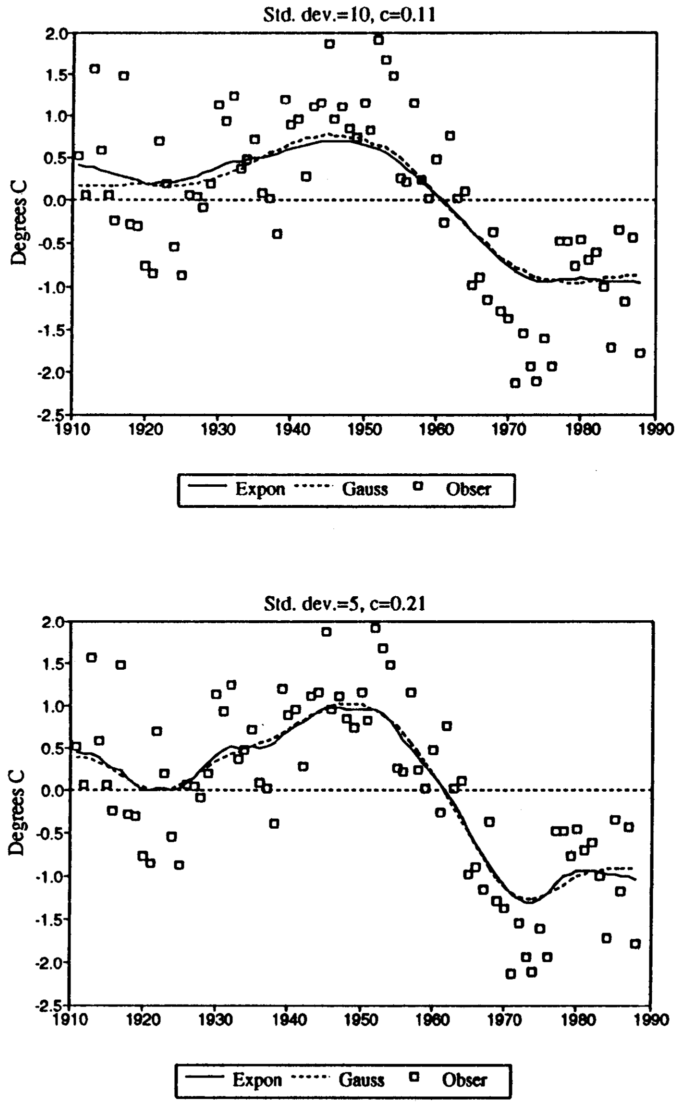

Figure A1. Filter comparison (Gaussian versus exponential) for a sample series. Above: $\sigma = 10$, $c = 0 \cdot 11$, Below: $\sigma = 5$, $c = 0 \cdot 21$

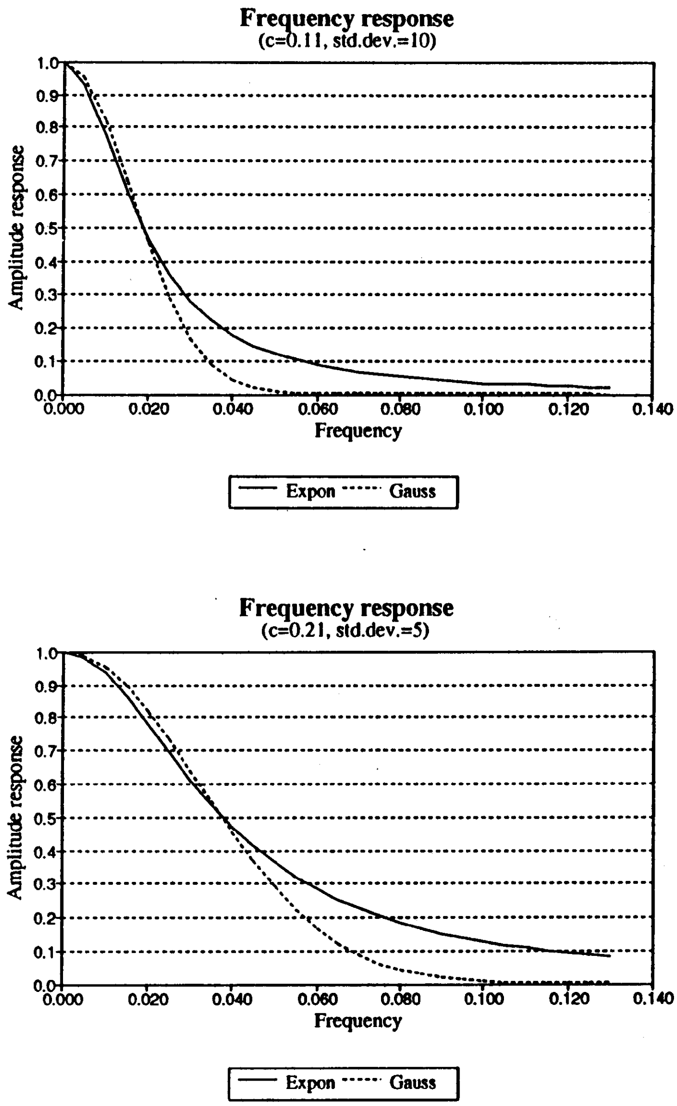

Figure A2. Frequency response for Gaussian and exponential filters used in Figure A1. Above: $\sigma = 10$, $c = 0 \cdot 11$, Below: $\sigma = 5$, $c = 0 \cdot 21$

σ	2	5	7	10
c_0	0·50	0·24	0·18	0·13
c'	0·50	0·21	0·16	0·11
P years	11	18	28	33

Figure A1 compares the exponential and Gaussian filters for a sample series (original mean temperatures at Puerto Montt) that was previously normalized to zero mean and unit standard deviation, for the cases $\sigma = 5$, 10 and $c = 0{\cdot}24$, 0·11, respectively. Frequency responses for the same filters are shown in Figure A2. From Figure A1 it can be seen that both outputs are very similar except for the beginning, where initialization is relevant. The exponential filter has some advantages in terms of easy use in spreadsheets and simple initialization but Gaussian filters provide a smoother output, because of the rapid decay of its response, and because of its wider use.

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