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Latitudinal positioning of the subtropical anticyclone along the Chilean coast

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In the past various authors have investigated climatic change (CC) by using the latitude of the subtropical ridge in the mean sea-level pressure (MSLP) for a range of geographic regions. In this paper the index L is defined as the latitudinal position of the subtropical anticyclone along the Chilean coast. This L index on the South American coast of the South Pacific is analysed using an instrumental record, covering the 1901-2004 period. An objective methodology is proposed for estimating L, and the physical consistency is assessed with the SOI and pressure at sea level in Valdivia, Chile. The analysis of a shorter period is compared with other authors' results. The L variable can be useful in CC studies or in the analysis of low-frequency fluctuations in climate variability, and it is analysed as a dependent and independent time series. L was displaced towards the south over the last century but not to a statistically significant extent. Natural fluctuations of 50 years and another, shorter, of 16-22 years were also observed. In this paper, the greatest persistence and distant associations between anomalies of monthly L are shown; these associations can be useful for climate forecasting.

Introduction

In the past Pittock (1973, 1975), Minetti and Vargas (1983, 1990), Thresher (2002) and others have used an index of circulation (L, based on MSLP) for studies of climatic change and climatic variability in Australia and South America. This index L is defined in this paper as the latitudinal positioning of the subtropical anticyclone along the Chilean coast. The above authors have studied the L index, making use of daily data during the period of 1948-2002 (NCEP-National Centers for Environmental Prediction; NCAR-National Center for Atmospheric Research) (Kalnay et al. 1996; Kistler et al. 2001) and monthly data for 1890-2000 (National Climate Centre (NCC) of the Australian Bureau of Meteorology and NOAA). Other studies into the relationship of pressure between the centre of the anticyclone in the South Atlantic Ocean to that at the coast, and between a range of variables of circulation with L, were carried out by Minetti and Vargas (1990, 1999).

The latitudinal position of the subtropical anticyclone along the Chilean coast is very important due to its north-south seasonal and interannual movements. These displacements explain the changes in the Mediterranean rainfall regime, with maximum winter precipitation in central Chile and the upper Andes. Albeit in a less definite manner, the displacements also affect the Argentine plain, whose rainfall regime presents a maximum in summer (Prohaska 1952; Pittock 1980).

As different methods have been used to obtain the L index, the series obtained in other works cannot be compared

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with the sub-periods of the ones studied here (Kidson 1925, period 1890-1923; Das 1956, period 1909-53; Pittock, 1971, 1973, 1980, period 1941-80 and period 1941-62; Minetti and Vargas, 1983, 1990, period 1941-80). These analyses were made for different geographical regions during the aforementioned periods, and the evolution of the methodology has become a matter of concern when comparisons and statistical time-analyses are made (Drosdowsky 2005). Furthermore, in past studies where the effects of CC due to global warming are discussed using the position of the subtropical anticyclone (L), in most cases relatively short series of climatic data (less than 50 years) have been used.

From a theoretical point of view, global warming would be expected to cause a displacement of the subtropical jet and the subtropical anticyclone axis to higher latitudes. This phenomenon was explained using the basic equations of Smagorinsky (1963) when describing models of atmospheric circulation. This would have impacts on the variability of regional precipitation (Pittock 1980; Minetti and Vargas 1998; Rusticucci and Penalba 2000; Minetti et al. 2004). Attempts at using the L index of the South American Andes region to explain its influence on interannual climate variability are found in Pittock (1980), Minetti et al. (1982), Radicella et al. (1989) and Minetti and Vargas (1990). These authors analysed the interannual variability of rainfall and temperature in the Argentina-Chile region in relation to the L index. In all cases, these studies of the impacts of the location of L on other climate variables included a few decades of data and resulted in conclusions related to CC. In addition, on both sides of the Andes, long-term changes of opposite sign were recorded in the last century for interdecadal rainfall averages, consistent with the hypotheses of CC generated by global warming (IPCC 2001). CC studies should involve analyses of extended temporal and spatial variables (large scale), which is difficult to achieve given the length of climatological series in the region. Long-term analyses can be made for some variables after homogeneity and consistency tests (WMO 1966). Homogeneous and consistent data of L are important for diagnosis and application to other disciplines, such as dendrochronology and hydrology, which use extended records to explain phenomena such as river flooding and the width of tree rings.

This paper estimates the L index along the western South American coast based on long time series of monthly mean sea-level pressure data, which are subject to homogeneity and consistency checks. Later, an analysis of the seasonal and inter-annual variability of the index is carried out, with emphasis put on long-term changes possibly associated with global warming.

Data and methods

Monthly climate data were first published by the Smithsonian Miscellaneous Collections (1929, 1934, 1947) and then by WMO, US Department of Commerce (1959, 1966, 1982, 1991 and 1997). Together, they complete the period of 1901-90. The recent world monthly climate data extend the record from 1991-2004 (WMO 1991-2004). The availability of data varied along the Pacific Ocean coast during the last century, with a gradual increase in the number of localities that either record sea level atmospheric pressure or reduce atmospheric pressure records to the mean sea level pressure measured at other meteorological stations. In order to obtain a long series of the L index, it has been proposed to use (i) a fixed number of localities with long records, which benefits the first decades to the detriment of precision in the latter ones (Pittock 1980), or (ii) a variable number of localities treated with an appropriate methodology not disproportionately affected by certain decades. The authors adopted the second option, and made a strict control for physical consistency, in addition to a comparative analysis with other results from previous estimations, which are discussed later.

The method adopted for the monthly estimate of L in geographical degrees is made by the following means:
(a) the adjustment of a third degree polynomial using least squares (Eqn 1) to the set of monthly data of atmospheric pressure reduced to mean sea level. This was applied to meteorological stations located along the western South American Coast of the Pacific Ocean. A few additional inland stations were used in some cases to complete the information.

$$P = a + b\,L + c\,L^2 + d\,L^3 + E \qquad \ldots (1)$$

where:

P is the mean monthly pressure at sea level for a specific month and year

a, b, c, d are polynomial coefficients

L is latitude in °S

E is estimate error

(b) by setting the tangent of P equal to zero, we obtained the location of the maximum or minimum pressures reported by this function, which were examined in each case for selection. The third degree polynomial was used to smooth irregularities in the data due to: (i) natural and (ii) artificial effects. In the first case, the smoothing by the polynomial filters removes a known effect caused by the intense radiation in the Atacama Desert that affects air density and causes pressure to drop in the warm season. This is known in Chile as the "continental depression" (Saavedra 1983), though the actual continental depression in South America is the one observed over the northwest of Argentina (Schwerdtfeger 1951, 1954; Lichtenstein 1983). The same effect, at a larger scale, is noted in data from some Chilean valleys when compared with

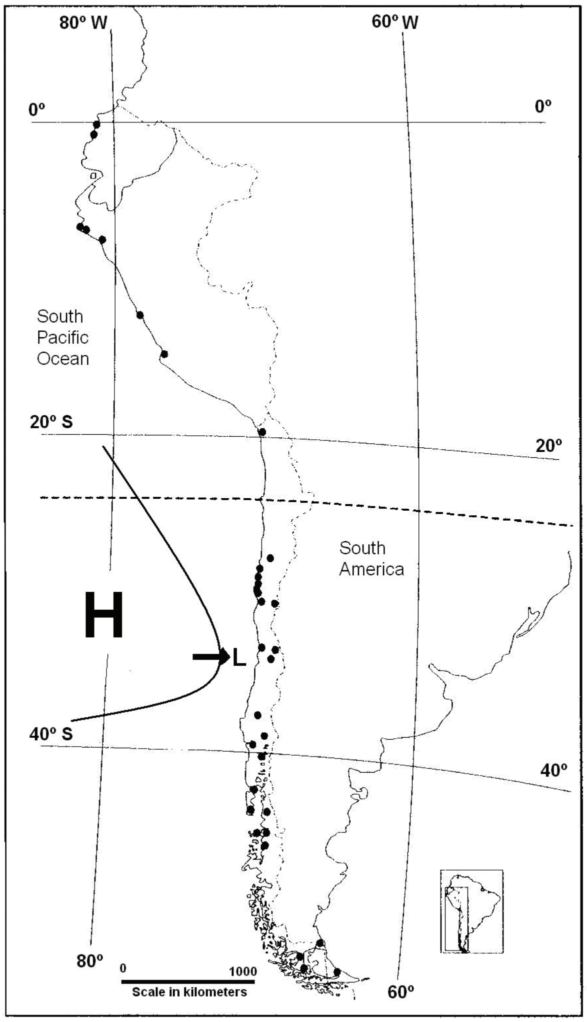


Fig. 1 Study region. Chile, Peru, Ecuador, and Argentina. Location of meteorological stations used to estimate L. Schematic of the South Pacific anticyclone (H) and location of maximum atmospheric pressure over the coast (L).

coastal values at mean latitudes, which causes some irregularities in the latitudinal pressure profile (Saavedra 1983). Other errors, caused by the addition of a hydrostatic column affected by temperature, add to these natural phenomena and are related to the reduction of atmospheric pressure to the mean sea level (SMN 1952). These errors result from the application of different methodologies for the calculation of pressure at sea level, i.e. temperature measured at the time of the observation, daily average temperature or the use of tables corresponding to seasonal heights that are not very accurate.

There are also other unknown errors from the generation of data. This lack of homogeneity in the criteria for the correction and/or reduction has generated different errors in the same chronological time span. Other errors, already mentioned by Pittock (1980), are related to the increasing amount of data available during the last decades. To address this aspect, the L index was checked against the one obtained by Pittock (1980) for the period of 1941-62 as a test of the accuracy of the estimation method.

A physical consistency test was applied to validate the information (WMO 1966). This was carried out with monthly rainfall data from sites located to the south of the climatic position of L, where rainfall is more responsive to anticyclonic interannual variability (Minetti et al. 1982), and also with other variables such as the SOI (Troup 1965), all of them for a typical month. In all cases, the correlation coefficients ("r") between variables have been estimated after applying the Fisher transformation of the two-tailed Student "t" test, with the significance indicated in each case. The algorithms proposed by WMO (1966) were used to estimate autocorrelations of the L anomaly and their significance.

Once the monthly information of the L index was obtained and its consistency checked, the index was studied on a monthly, annual and interannual basis in the form of a time series (Uriel 1985) in order to relate the position of the L index with time. Linear trends were tested by means of the t-Student, Kendall and Spearman tests (Yue et al. 2002) and the spectral analysis of Tukey (1950).

The monthly rainfall used for consistency of L in this work was obtained from meteorological stations in the region and published by decade by the WMO-NOAA, and in Chile by CORFOP (1969).

Analysis and results

Nature of the L index

Figure 1 shows the Pacific South American coast with the location of the meteorological stations used in this study and a sketch of the location of the eastern edge of the South Pacific anticyclone (H) and the latitude of the maximum coastal value of the mean sea level pressure (L). The number of points observed does not necessarily coincide with data from the full century. An inspection of the data used per decade over the period 1901-2004 shows that the number of sites used has varied from nine to twenty, the initial number (nine) being repeated in the first three decades (1901-30). Another important feature is the similarity of latitudinal pressure profiles in the summer and winter, with the exception of a pressure increase at low-subtropical latitudes in the winter.

Therefore, the main latitudinal changes of the pressure maximum over the South American coast can be assumed to be due to pressure fluctuations over mid-high latitudes (above 40°-50°S), while the remaining profiles would be rather stable through the years. The justification for the application of a third degree polynomial to the pressure profiles may be seen in Figs 2(a) and 2(b) for January and July, and for climatic pressure data from Taljaard et al. (1969) along the

Fig. 2 Second and third degree polynomial fits of monthly averaged atmospheric pressure data of Taljaard et al. (1969) for (a) January and (b) July at 70°W.

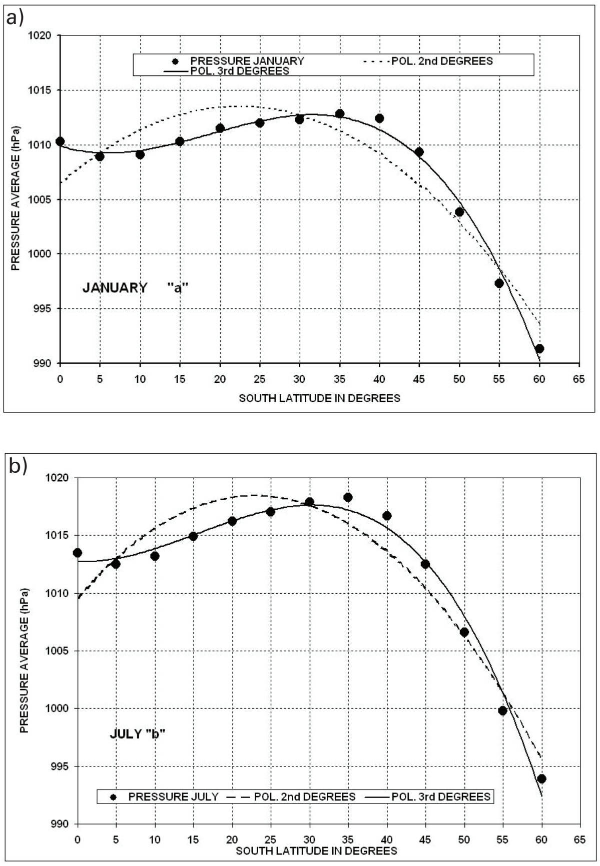


Fig. 3 Fits of second, third and fifth degree polynomials to pressure data on the Pacific coast for (a) January and (b) July 1976.

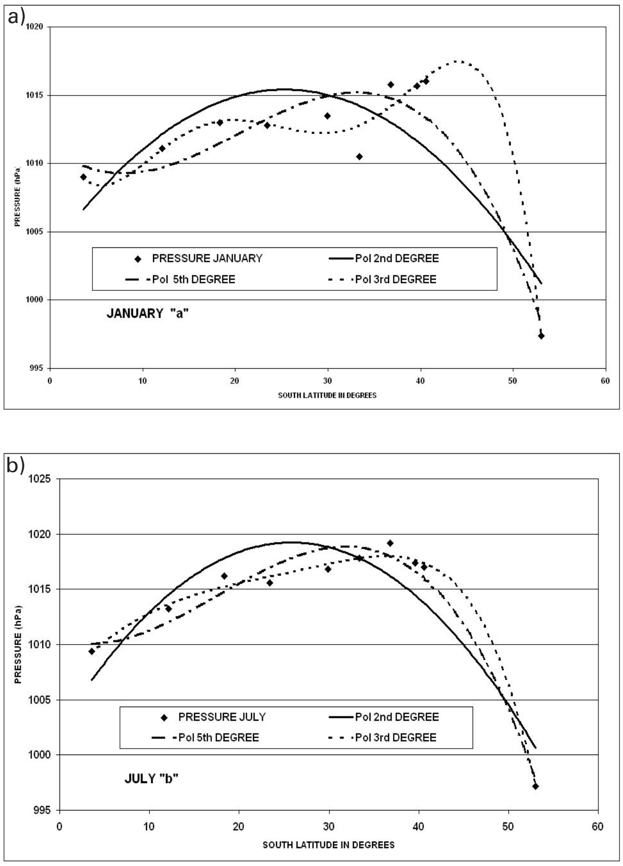
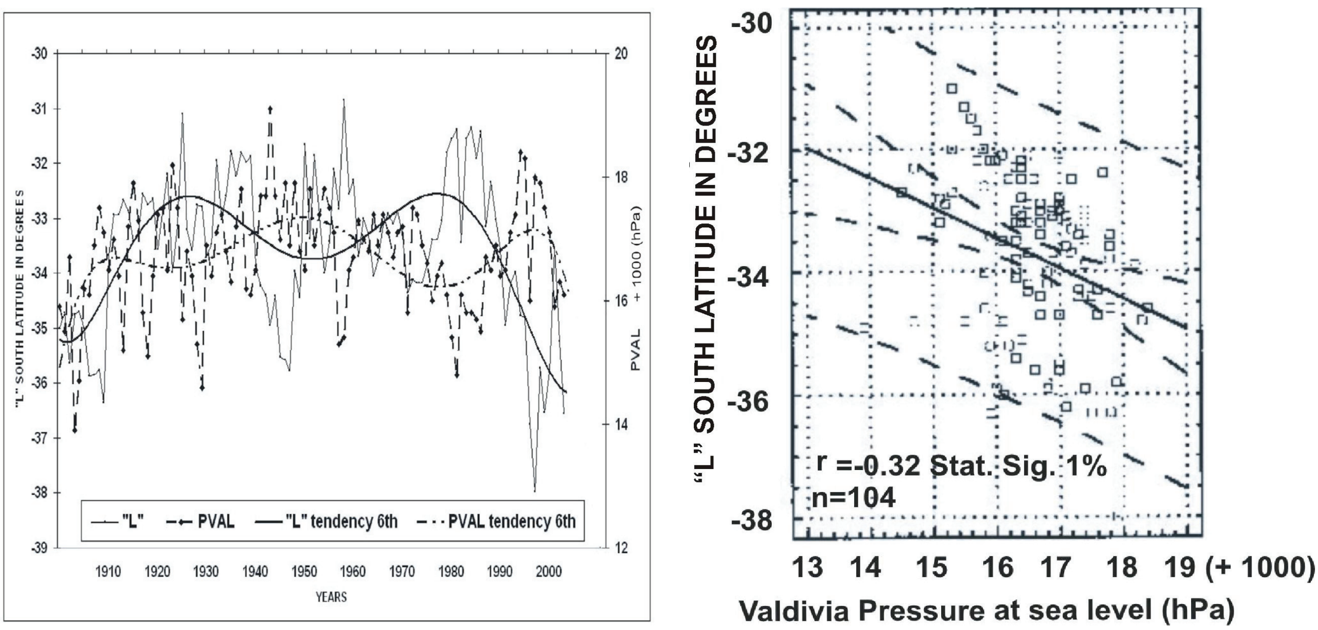


Fig. 4 (a) Annual sea level atmospheric pressure in Valdivia – Chile (PVAL) and annual position of L. Trends as indicated by a sixth degree polynomial fit are included, (b) regression between both variables.



70°W meridian, near the South American coast. An excellent fit with third degree polynomials to the latitudinal means stated by Taljaard et al. (1969) is seen for July, and a lower adjustment in January, where the fitted value of L is slightly lower than that suggested by the latitudinal means. Second degree polynomials were not considered, as the distribution of mean sea level pressure is not symmetrical with latitude. The third degree polynomial improves the adjustments to the physical properties that are being described while higher degree polynomials, e.g., the fifth, introduce undesirable spatial fluctuations (see Figures 3(a), (b), for January and July 1976). We note that in the individual months the variability of the pressure is greater than the average of the set. Nevertheless the averages represent the sample, and in low and mid-latitudes (Equatorial-Tropical and Subtropical zone) the variability of the pressure is low (Harnack and Harnack 1984) and the fit is appropriate. The fitting is more problematic in high latitudes, which are not normally relevant to the calculation of L. In this zone of high variability of pressure the changes cannot always be adequately simulated by a polynomial of third degree. In a few daily cases, under situations of blocking of the westerly circulation in high latitudes (Rex 1950; Grandoso and Nuñez 1955), the pressure profile separates considerably, but this does not occur in the monthly data that we studied. The pressure at the position indicated by L over the coast of Chile reflects the maximum anticyclogenesis in agreement with standard development theory (Gordon 1965) and is correlated with the pressure in the centre of the anticyclone (Berlage 1957, 1966; Minetti and Vargas 1999). Coastal data are used for the calculation of L, as older information is only available for the coast with no offshore data except for Juan Fernández Island in the eastern South Pacific Ocean. Additional offshore data have been recently made available by NCAR-NOAA (Kistler et al. 2001), but these do not cover a sufficiently long time period for the analysis proposed here (climatic trends). Minetti and Vargas (1990) showed that the L index summarizes a set of properties of the eastern edge of the anticyclone, such as the curvature, pressure intensity as well as the more synoptic meridional and zonal circulation. Figures 4(a) and (b) show the relationship between annual L and atmospheric pressure in Valdivia-Central Chile, indicating an opposite connection, especially at decadal timescales.

Fig. 5 Basic monthly statistics of L.

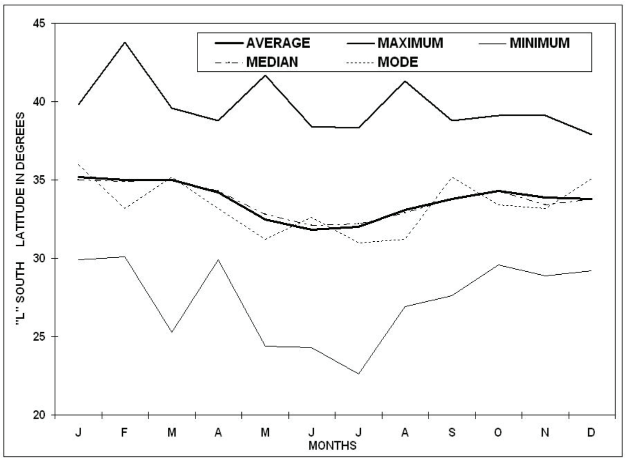


Table 1 Basic statistics of the L index for the period 1901-2004.

Month / Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Average (°S) (X)	35.2	35.0	35.0	34.2	32.5	31.8	32.0	33.1	33.8	34.3	33.9	33.8	33.7
Standard deviation (S)	2.13	2.09	2.29	2.05	2.96	2.96	2.82	2.70	2.21	1.79	1.95	1.80	1.32
Coeff. Var. % S/X 100	6.1	6.0	6.5	6.0	9.1	9.3	8.8	8.1	6.5	5.2	5.8	5.3	3.92
Maximum (°S)	39.8	43.8	39.6	38.8	41.7	38.4	38.3	41.3	38.8	39.1	39.1	37.9	43.8
Minimum (°S)	29.9	30.1	25.3	29.9	24.4	24.3	22.6	26.9	27.6	29.6	28.9	29.2	22.6
Amplitude	9.9	13.7	14.3	8.9	17.3	14.1	15.7	14.4	11.2	9.5	10.2	8.7	21.2
Median	35.0	34.9	35.0	34.3	32.8	32.1	32.2	32.9	33.8	34.3	33.4	33.8	33.5
Mode	36.0	33.2	35.2	33.2	31.2	32.6	31.0	31.2	35.2	33.4	33.2	35.1	33.2
1st Tercile Percentile 33.3	33.8	33.4	33.6	32.6	30.6	29.4	30.7	31.2	32.5	33.2	32.6	32.6	33.0
3rd Tercile percentile 66.6	36.8	36.4	36.3	35.6	34.2	33.4	34.0	34.7	35.2	35.4	35.2	35.1	34.3
Skewness	–0.02	0.79	–0.59	0.06	0.30	–0.01	–0.50	0.16	–0.42	–0.09	0.40	0.10	0.53
Kurtosis	–0.58	2.37	2.29	0.64	0.96	–0.39	0.52	0.29	0.49	0.44	0.27	–0.23	0.01

Monthly and annual statistical properties of the L index

The proposed methodology made it possible to calculate the monthly L index over the period 1901-2004. The basic statistics are shown in Table 1 and the main statistical quantities (average, maximum, minimum, median and mode) are presented graphically in Fig. 5.

For all months, no significant differences exist between the averages, medians and modes of L, which indicates an approximately normal distribution of L data, and thus that the data are appropriate for use in diagnosis or forecast of other climate variables using tools such as bi-varied - or multi-varied - correlations. The most extreme monthly values of L occurred in February (highest latitude) and July (lowest latitude). The largest interannual variability of L occurs in the months of autumn-winter (May and July), which is the beginning of the rainy season in the Mediterranean climate of central Chile (Prohaska 1952). This variability peaks in June, and reaches its minimum in October, which is the start of the summer dry season in central Chile. The seasonal mean of L has its minimum in June (31.8ºS) and maximum in January (35.2ºS). There is a secondary maximum in October (34.3ºS) and a secondary minimum in December (33.8ºS). These secondary peaks and troughs have not been mentioned before in literature (Prohaska 1952; Pittock 1980).

Temporal series and homogeneity analysis

Figure 6 shows the monthly trend of the L index for the period 1901-2004. This figure shows that the L index has a very weak trend (equivalent to –144 km/104 years), which has no statistical significance ("t-Student", Kendall and Spearman test). Some detail of the interannual variability may be seen in Fig. 7. According to Smagorinsky (1963), global warming would be expected to cause a displacement of the subtropical anticyclone to higher latitudes. The observed trend over the century is far less than what results from analysis of a short series of L from the mid-20th century to the present (Pittock 1980; Minetti and Vargas 1990; Camilloni et al. 2005). The higher degree polynomials do not seem to represent this low-frequency change, but a parabolic fit is consistent with an increasing (positive) trend from the beginning of the series to the middle of last century and a decreasing (negative) trend during the second half of the series. Rapid changes in L were observed in the 1970s, consistent with the observations made by Hare and Mantua (2000) among others.

At this point, it is useful to make a physical-statistical consistency analysis of the L index, due to the assumptions applied in the temporal changes of the number of meteorological stations used. As the Southern Pacific anticyclone is strongly associated with sea surface temperature (SST) conditions of the ENSO cycle (Walker 1923, 1924; Arkin et al. 1980 and Rasmusson and Carpenter 1981), the relationship between SOI and L was obtained for two periods between

Fig. 6 Monthly L and linear trend for the period January 1901 – December 2004.

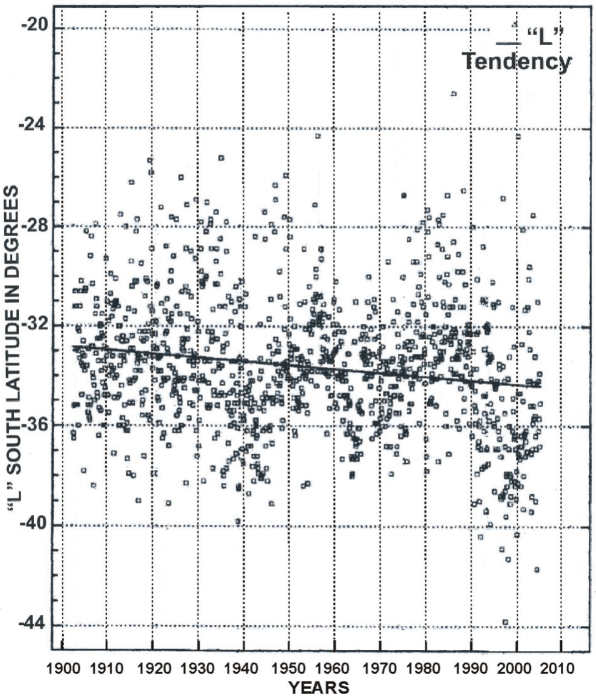
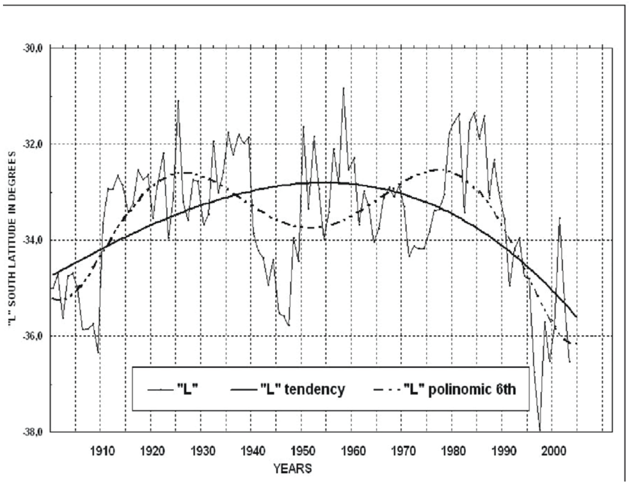
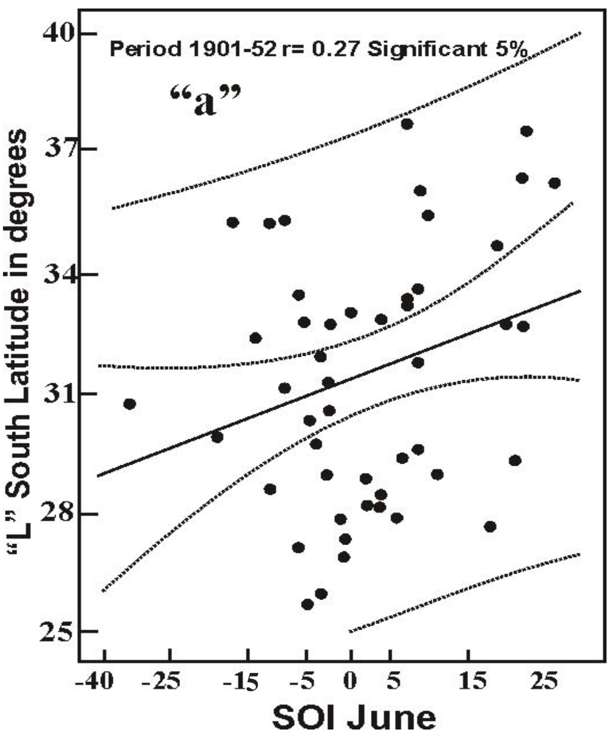


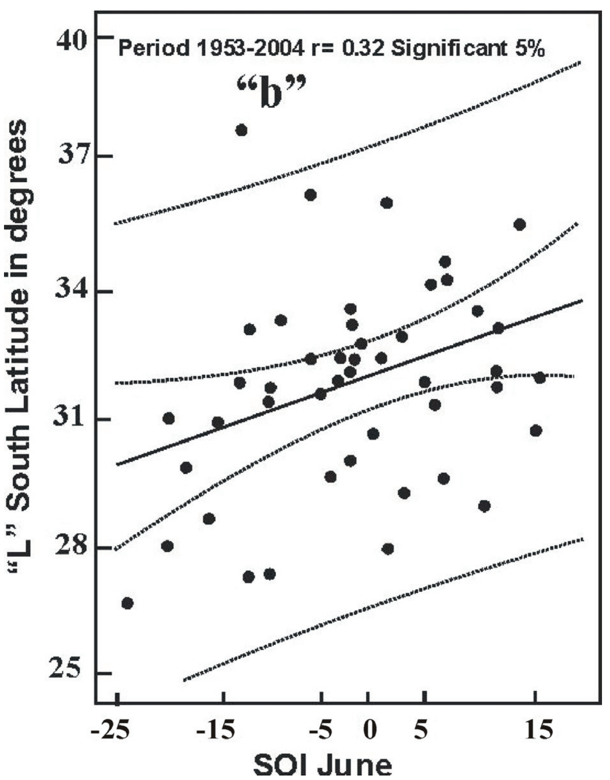
Fig. 7 Annual values of L with second ("L" tendency) and sixth degree polynomial fits.



1901 and 2004. The regressions for June corresponding to the selected periods 1901-52 and 1953-2004 can be seen in Figs 8(a), (b). The correlations for both periods (r = 0.27 and r = 0.32) are similar and indicate the consistency of the relationship between the L index and the SOI (Troup 1965). It is worth mentioning that as the SOI is closely related to SST in the equatorial Pacific, the oscillation appears to be inverted in the long term (Federov and Philander 2000). In this case, the change in the number of meteorological stations

Fig. 8 Regressions and correlations between the SOI (Troup 1965) and L for June in (a) 1901-1952 and (b) 1953-2004.





involved in the estimate of latitudinal pressure profiles and the different quality of the data mentioned by Pittock (1980) does not appear to have influenced the quality of the L index proposed here.

Another comparison was made between the L data in this paper and that proposed by Pittock (1980) for the period of 1941-62. A comparison of Pittock's methodology with that used here shows that when the subtropical anticyclone moves towards low latitudes in June, migrating transient anticyclones have little influence on the location of the pressure maximum. In this case, the correlation between both indices is r = 0.53, significant at the 1 per cent level. In January, when migrating anticyclones are significant near Puerto Montt (Chile), the location of the pressure maximum proposed by Pittock appears greatly displaced towards high latitudes due to the weight given to individual station data. In this case, the maximum obtained by means of polynomial adjustment is located at lower latitudes and the correlation between the two indices is significant at the 5 per cent level, with r = 0.46. An objective method, such as the one presented here, allows us to overcome network and data quality related problems by means of the filter employed in the methodology.

Table 2 shows the major differences in the average L index estimated by both methods. For comparison purposes, the climatic values of Taljaard et al. (1969) are also included. This table shows that the values of L estimated with this methodology lie between those of Taljaard et al. (1969) and Pittock (1980) in July, January and for the year as a whole. The greatest differences are observed with Pittock's (1980) results, mainly in January.

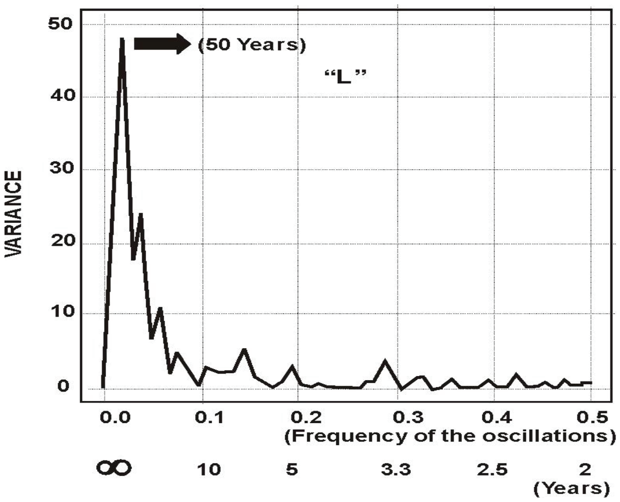
L trends over Australia estimated using monthly data by Pittock (1973) and Das (1956), and with daily data by Thresher (2002), showed a movement of the subtropical anticyclone from high to low latitudes in the first half of the last century and from low to high latitudes in the second half. This suggests a similar behaviour to that observed along the South American coast. This behaviour along the South American coast generates the power spectrum seen in Fig. 9 where we can see that the greatest percentage of the variance is explained by an oscillation of approximately 50 years.

The evidence of changes in the sign of the trend over the last century does not make it possible to assume that the increased latitude of L during the last half of the century was due to global warming (Gibson 1992; Barros et al. 1996, 2000; Camilloni et al. 2005). Rather, it appears that this slow fluctuation is describing natural long-term low frequency changes. The medium-frequency oscillations in annual L, described by a fifth degree polynomial, show fluctuations of around 16-26 years. Such fluctuations are observed in the rainfall over Cuyo-Argentina and neighbouring regions (Compagnucci et al. 2002; Minetti et al. 2004 and Agosta 2005) as well as in the humidity advection toward the continent (Vargas et al. 2001).

Table 2 Mean values of L obtained by three methods; differences between the results of Pittock (1980), this paper and Taljaard et al. (1969).

Author / Period	Pittock (1980) (A)	Taljaard 70°W (B)	Actual proposed (C)	Difference (D) = A – C	Difference (E) = A – B	Difference (F) = B – C
Year	36.8°S	31.3°S	33.8°S	3.0°	5.5°	2.5°
January	39.5°S	32.5°S	35.1°S	4.4°	7.0°	2.6°
July	33.1°S	30.0°S	32.6°S	0.5°	3.1°	2.6°

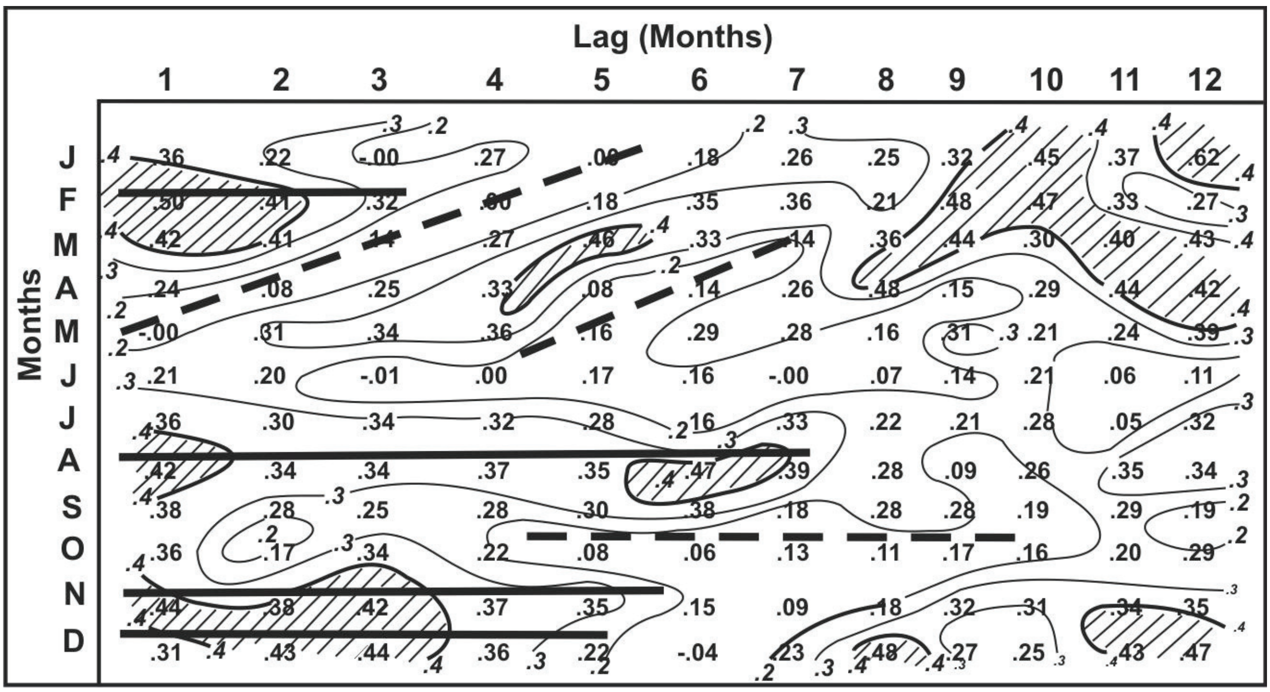
Fig. 9 Power spectrum of annual L.



Intra- and inter-seasonal relations of L

Figure 10 shows the temporal isocorrelations between the values of L in a given month and those in up to twelve consecutive subsequent months. The position of L is strongly persistent in August, November, December and February from seven to three months forward (full lines). The only non-persistent month is May. Between August and March, the persistence seems to be dominant, with secondary minima in the months of October and January. In addition, during the first six months, there are distant relationships with the alternation of non-correlated periods represented in Fig. 10 by dotted lines. The first period that interrupts the persistence occurs in the southern hemisphere (SH) autumn. This is described by Minetti et al. (1993) when studying the inter-seasonal behaviour of the edge of the anticyclone along the coast of Chile. Distant associations relate the summer with

Fig. 10 Correlations between vectors of L for the months of January to December (1901-2003) and the vectors of twelve later months; persistent behaviour shown by full line, thick dashed lines indicate low correlations or breaks in persistence. Obliquely striped areas indicate correlations statistically significant to 1 percent.



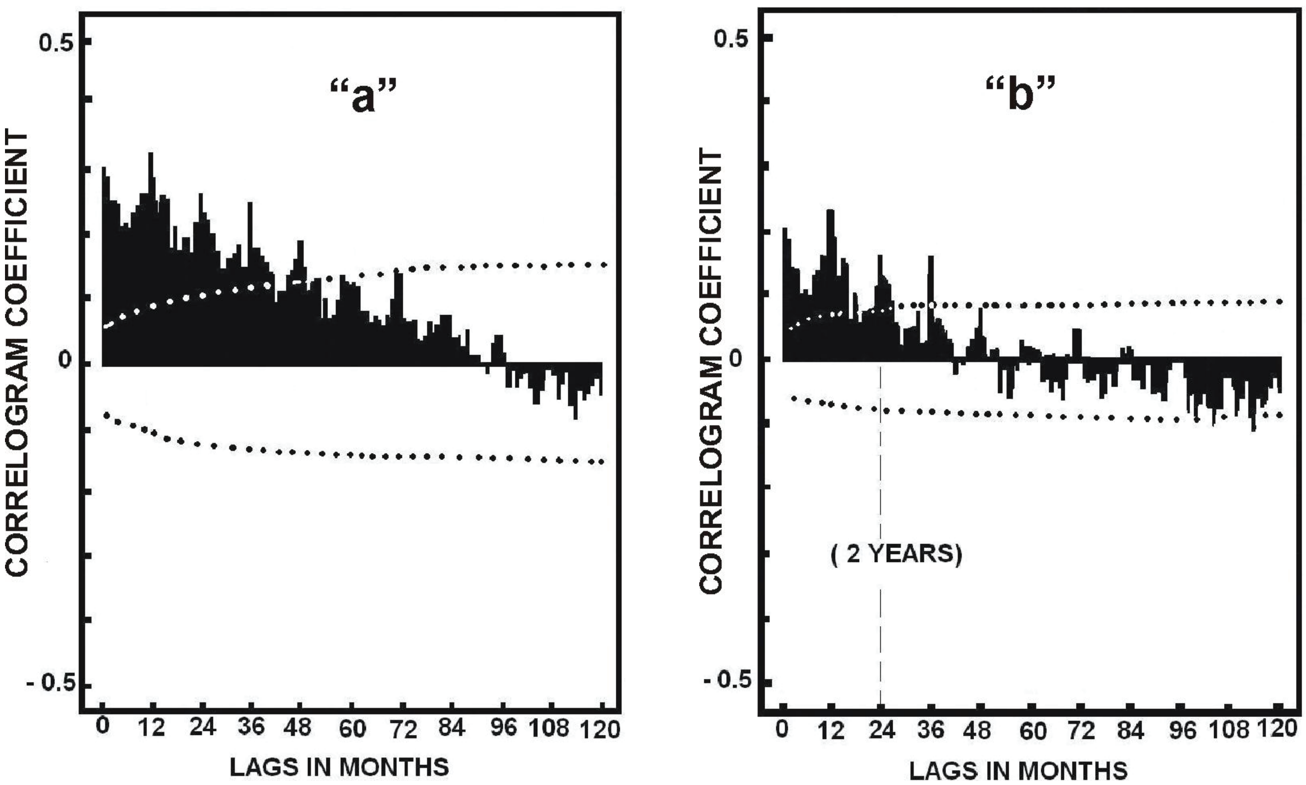
August and summer with the following spring, the sign of the relationship being maintained in both cases, which indicates a high distant persistence occasionally interrupted in some months. This self-variation of the South Pacific anticyclone is related to SST and the SOI, and has already been described when analysing the consistency of data. The implication of this relationship is evident due to the occurrence of the maximum persistence of SST anomalies in the South American coast (Peru), during the SH autumn (April), shown by Minetti et al. (2003). In the atmosphere, the maximum persistence of L appears in August, i.e. four months thereafter. In the sea, the maximum persistence was 11 months (April of year "t" to March of year "t+1") and in the atmosphere the maximum persistence was 7 months (from August of year "t" to March of year "t+1). In both cases, the persistence disappears in March of year "t+1".

Figures 11(a) and (b), show the correlogram of monthly L anomaly extended to 10 years (lag = 120 months), considered as monthly anomalies. They show that the trend of monthly anomalies is similar to that of the annual changes of L. This implies an important dependence between monthly data vectors of approximately four years (Fig. 11(a)). The correlations after removing the trend with a 5th degree polynomial are shown in Figure 11(b). This explains the dependence pattern of about two years and the existing correlation between summer and spring of one year in the SH. This important autocorrelation of the L index along the Chilean coast has a considerable impact on other regional circulation variables in subtropical latitudes.

Conclusions

A database has been prepared of the latitudinal position L of the South Pacific subtropical anticyclone along the South American coast using an objective method. The consistency of this information has been checked with other regional variables of great importance in the Pacific Ocean such as the SOI. The absolute homogeneity has been studied. The main conclusion of this study is that there is no significant southward movement of the subtropical anticyclones during this study period, but that there are shorter-term cycles, with the most important one having a period of around 50 years. Low-frequency fluctuations were observed, with oscillations of 16 years or more, and this could contribute to explanations of the regional climatic jump observed in other atmospheric and oceanic variables. The importance of the persistence of the L index is shown for the second half of the year, lagging four months behind the largest persistence in the tropical Pacific, and non-persistent distant associations exist between summer, winter and spring in the SH; these associations may be useful for climate forecasting.

Fig. 11 Correlogram between the anomalies of monthly L values from 1 January 1901 - 31 December 2004 (a) with trends and (b) detrended. Dots above and below the time axis (months) indicate 95 per cent significance levels. Vertical dashed line indicates the end of the two year persistence.



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