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MONTHLY MEAN RAINFALL FREQUENCY MODEL FOR THE CENTRAL CHILEAN COAST: SOME CLIMATIC INFERENCES

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ABSTRACT

A simple empirical model giving the annual evolution of monthly mean rainfall frequency for any location along the central Chilean coast is proposed. Model hypotheses are discussed with reference to a climatic scenario, which has been found of value in developing simple empirical climatic models for coastal stations in Chile. Equations giving monthly mean rainfall frequency for any latitude as a function of the latitude of the location of maximum monthly mean pressure in Chile are presented. It is concluded that the proposed model adequately describes the observed annual evolution. Moreover, the model allows qualitative inferences to be made regarding the interaction mechanisms between the main meteorological centres of action on a regional scale, which may prove of value in identifying trends of regional climatic change. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: rainfall frequency model; surface pressure; Chile

1. INTRODUCTION

The main meteorological centres of action in Chile are: (i) Pacific anticyclone (PA), (ii) sub-polar frontal-wave cyclones, here denoted Polar lows (PLs), (iii) coastal low (CL), which relates to differential heating of the continent and ocean, and (iv) what has been called enhancement of coastal low (ECL). The latter is a nucleation of the CL frequently observed during summer in central Chile. All four centres can be identified in typical surface isobar patterns. A detailed description of this meteorological scenario has been discussed by Saavedra and Foppiano (1992a). In particular, the 'high wedge' observed on the continent, whose location and maximum pressure can vary considerably from day to day, has been considered representative of the coupling between the four centres. Weatherwise, 'good weather' is to be found north of the wedge, and 'bad weather' occurs south of it.

A detailed description of a climatic scenario (see Figure 1), keeping the corresponding features of the meteorological scenario, has also been given before by the same authors. The main characteristics of the now monthly mean 'high wedge' are expressed, to a first approximation, in terms of the location of maximum monthly mean pressure in Chile (LMP). Saavedra (1980) first precisely defined the LMP on the basis of monthly mean values of pressure published by Wittaker (1943), who used observations for the 1911–40 interval (this interval includes 14 El Niño events: four strong, six moderate and four weak; Quinn *et al.*, 1978). This location can be used as a pointer that divides the country into two regions. The climatic properties of these regions may be associated with the meteorological properties already mentioned. Moreover, the LMP can then be considered as an index of the monthly mean spatial interaction of the meteorological centres.

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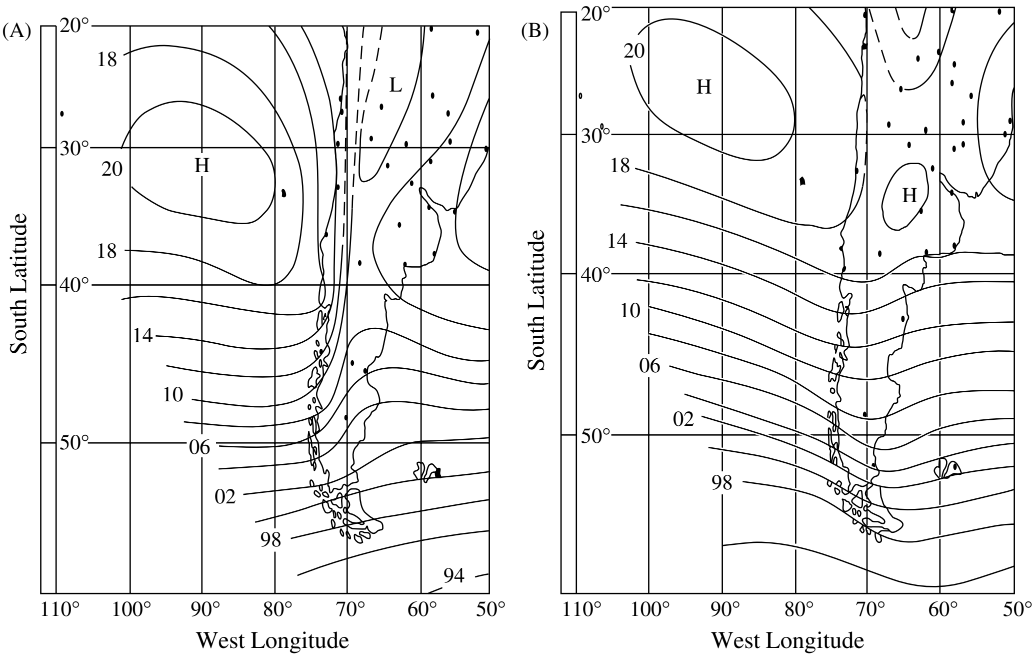

Figure 1. Climatic surface pressure fields (adapted from Schwerdtfeger, 1976). (A) December–February (20 = 1020 hPa), 'high wedge' centre at Chilean coast at about 41 °S. (B) June–August (98 = 998 hPa), 'high wedge' centre at Chilean coast at about 33 °S

The annual evolution of the LMP's latitude and pressure have been discussed by Saavedra and Foppiano (1992b) in terms of empirical Fourier components. Figures 2 and 3 reproduce some of these results. As can be seen, for both latitude and pressure evolution, the annual component (solar) is, as expected, the most significant (it explains more than 90% of the variance). The latitude's annual component is almost in phase with solar declination, whereas the pressure's annual component lags by about 1 month, the latter being a feature probably associated with surface thermal inertia. By contrast, both semi-annual components follow the semi-annual component of the sub-Antarctic trough determined by van Loon (1971), although the association may not be a direct one. These components give the observed evolutions their characteristic shapes, i.e. a faster (slower) change from summer to winter than from winter to summer. In particular, they are associated with the long lag between the equatorward-most latitude and highest pressure (nearly 2 months) and the short lag between the poleward-most latitude and the lowest pressure (only 5 days).

Details of the LMP's capacity as a climatic descriptor for Concepción (36°48′S; 73°02′W) are given in Saavedra (1985, 1986). Similar indicators have been used for various purposes by Prohaska (1952), Pittock (1971, 1980), Minetti *et al.* (1982), and Minetti and Vargas (1983, 1992).

Compagnucci and co-workers (e.g. Compagnucci and Salles, 1997) have analysed daily surface pressure values for South America corresponding to the 1972–83 interval (which includes three El Niño–southern oscillation episodes), using a principal component technique. They conclude that the first six components account for more than 90% of the total variance and that the same climatological pattern is found for all months. The most important difference between months is a north-to-south shift of the synoptic systems from winter to summer. This strongly confirms the approach followed in the present paper.

There are perturbations that cause inter-annual and inter-monthly variability of meteorological variables such as, for example, those related to El Niño/La Niña and blocking conditions (Berbery and Nuñez, 1989; Rutllant and Fuenzalida, 1991). In general association with these phenomena, very occasionally, cyclonic activity is observed in the north of Chile (Minetti and Sierra, 1989; Vuille and Ammann, 1997; Garreaud and Wallace, 1998). These do not significantly change the climatological scenario considered here. Indeed, the

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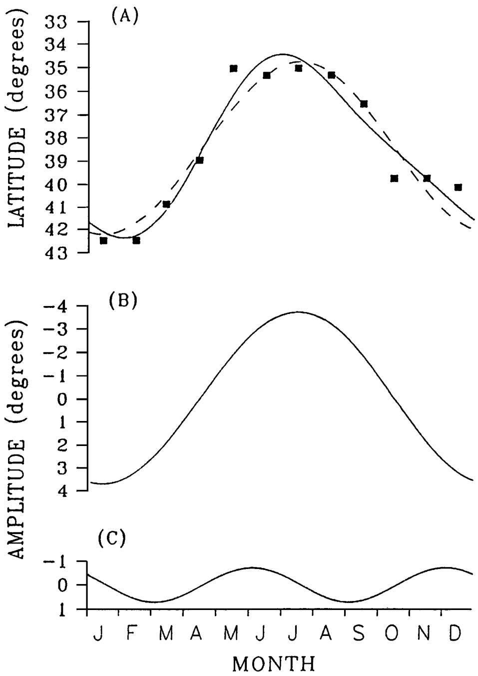

Figure 2. Annual evolution of the latitude of the location of maximum monthly mean pressure, along the Chilean coast (LMP). (A) Observed and modelled (empirical Fourier components) values. (■) Observed values corresponding to the 1911–40 interval (adapted from Wittaker, 1943); there are 14 El Niño events during this interval: four strong, six moderate and four weak; Quinn *et al.*, 1978). (- - - -) One-component model. (———) Two-component model. (B) Annual component. (C) Semi-annual component. (Saavedra and Foppiano, 1992b: Figure 2)

scenario is considered to be the result of using only monthly mean values, which do include the special cases indicated above. The approach is to try to quantify aspects of the standard descriptive Chilean climatology (e.g. Romero, 1985). Furthermore, only coastal climatology is considered, although it may be possible to infer what would be the case along the central Chilean Andes using the coastal results presented here. Finally, it should be noted that the basic climatological scenario relates directly to climate defined as monthly mean values of frequency variables (expressed as a percentage) rather than intensity variables, which also basically depend on other mechanisms.

The purpose of this paper is to show how knowledge of only the LMP's latitude permits a simple model to be developed giving the annual evolution of monthly mean rainfall frequency for any location along the Chilean coast. The goodness of fit of this model to measured values, as was the case with the pressure model (Saavedra and Foppiano, 1992a), confirms the main properties of the LMP as a descriptor of Chile's climate. Some qualitative aspects of the climatic scenario are given in Section 2. In Section 3, observed annual evolutions of rainfall frequency are presented, and the proposed model for these is described in Section 4. Section 5 gives the main model results and the validity of the model is discussed in Section 6. Finally, Section 7 deals with speculative model implications on the quantitative dominance of the PA and PL actions and on climate change.

2. QUALITATIVE ASPECTS OF THE CLIMATIC SCENARIO

As is well known, the nature of the PA and the PL actions are not the same. Whereas the PA is quasi-permanent and its presence is felt almost over the whole South Pacific, the PL are episodic and their effects are noticeable at a given time on localized areas. Thus, the climatic PA domain, which is characterized by regular, solar declination associated changes, can be considered as a dominant feature that is 'perturbed' by

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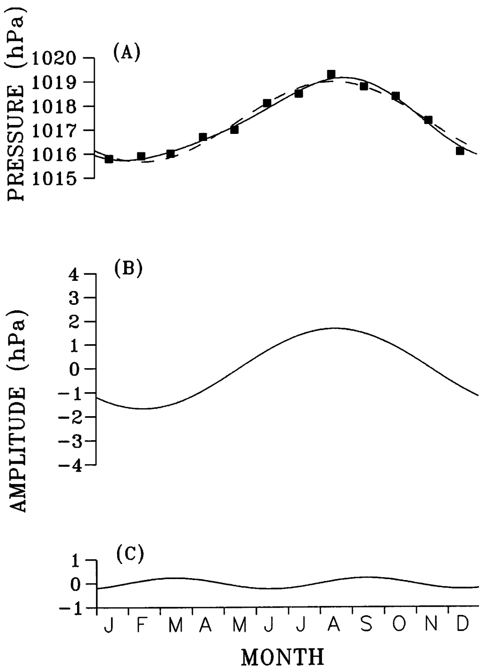

Figure 3. Annual evolution of pressure at the latitude of the location of maximum monthly mean pressure, along the Chilean coast (LMP). (A) Observed and modelled (empirical Fourier components) values. (■) Observed values corresponding to the 1911–40 interval (adapted from Wittaker, 1943); there are 14 El Niño events during this interval: four strong, six moderate and four weak; Quinn *et al*., 1978). (- - - -) One-component model. (———) Two-component model. (B) Annual component. (C) Semi-annual component. (Saavedra and Foppiano, 1992b: Figure 3)

the climatic PL domain. The latter can only have a precise meaning on statistical terms when due account is taken of frequency of occurrence, duration and spatial extension of individual PLs. Indeed, the climatic PL signature on a monthly mean sea-surface pressure field is an array of zonal pressure contours, along which the westerlies prevail (see Figure 1).

It should also be noted that, in Chile, rainfall is almost always of frontal origin, except in the northern high plateau (Altiplano), and at other latitudes during occasional convective mountain storms which are very localized. There are also rainfall events during a transition from PL to PA actions; however, these PA- and PL-associated rainfalls can be considered as compensating each other on a climatic time scale. Moreover, meteorologically speaking, precipitation is an all or nothing variable, and since it is only present when a PL-associated front sweeps the rather narrow country from west to east, its climatic description in terms of the LMP must take into account the statistical nature of the LMP.

On the basis of the above climatic scenario, the proposed rainfall model allows qualitative inferences to be made regarding the interaction mechanisms between the main meteorological centres of action on a regional scale, and on their effect on the description of the Chilean climate. For instance, estimates of likely climate change could be determined for a given long-term change of the LMP location, assuming the climatic scenario does not change. These inferences should prove of value when addressing the problem of identifying trends of regional climatic change.

3. OBSERVED ANNUAL EVOLUTIONS OF RAINFALL FREQUENCY

The annual evolution of monthly mean rainfall frequency were determined for 18 locations, covering most of coastal central Chile. Values are computed for each location from records corresponding to 1931–60, a 30 year interval (OMC, 1966). Monthly mean rainfall frequency is defined as the ratio of

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number of days for a given location and month for which rainfall is greater than 0.1 mm to the total number of days for which there are observations in the interval, expressed as a percentage. Thus, there is only one value for each location and month for the whole 30 year interval, including all types of inter-annual and inter-decadal variability. There are 12 El Niño events during the interval: three strong, two moderate, five weak and one very weak according to Quinn *et al.* (1978). It could be argued that the intervals used to derive the LMP are not the same as those used here for rainfall frequency determinations. Unfortunately, the corresponding data sets were not readily available at the times the studies were performed. However, both intervals are long enough to be considered representative of a basic state of the variables concerned for climatic studies. Moreover, they even include similar numbers and intensities of El Niño events.

The rainfall frequency values used here are given in Table I, and Figure 4 shows sample annual evolutions. Two features are particularly significant. The evolutions share a common shape from La Serena to Puerto Aysen, the amplitude of the variation increasing with latitude up to a location between Concepción and Valdivia and then decreasing in a sort of symmetric fashion. North of La Serena and south of Puerto Aysen the rainfall hardly shows any change from month to month; the frequency is almost nil in the north and is largest in the south. Furthermore, the common shape resembles that of the LMP's latitude annual evolution. These two features make the annual evolutions amenable to very simple modelling.

Table I. Monthly mean rainfall frequency (%): (a) observed from records for 1931–60 interval; (b) calculated using proposed model; (c) differences between calculated and observed values. Stepped lines indicate northern and southern validity limits

Location		J	F	M	A	M	J	J	A	S	O	N	D
Caldera	(a)	0.9	0.7	0.2	1.4	5.0	4.8	5.5	5.1	5.3	7.2	4.8	3.5
27°03′S	(b)	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
70°51′W	(c)	8.7	8.9	9.4	8.2	4.6	4.8	4.1	4.5	4.3	2.4	4.8	6.1
La Serena	(a)	1.3	1.2	1.8	3.1	8.0	8.3	9.4	8.9	8.2	5.6	3.7	1.6
29°54′S	(b)	0.0	0.0	0.0	4.8	11.1	10.8	11.1	10.8	9.3	2.9	2.9	1.9
71°15′W	(c)	−1.3	−1.2	−1.8	1.7	3.1	2.5	1.7	1.9	1.1	−2.7	−0.8	0.3
Coquimbo	(a)	0.2	0.3	0.7	1.4	6.7	8.2	8.9	8.0	4.9	3.9	1.4	1.0
29°57′S	(b)	0.0	0.0	0.0	4.8	11.1	10.8	11.1	10.8	9.3	2.9	2.9	1.9
71°22′W	(c)	−0.2	−0.3	−0.7	3.4	4.4	2.6	2.2	2.8	4.4	−1.0	1.5	0.9
Illapel	(a)	0.1	0.5	0.9	3.2	9.0	12.7	9.8	11.1	4.3	3.8	0.7	0.6
31°36′S	(b)	0.0	0.0	0.0	4.8	12.7	12.1	12.7	12.1	9.7	2.9	2.9	1.9
71°11′W	(c)	−0.1	−0.5	−0.9	1.6	3.7	−0.6	2.9	1.0	5.4	−0.9	2.2	1.3
Valparaíso	(a)	2.3	2.2	2.8	7.7	19.3	25.7	21.7	19.6	10.9	8.0	3.6	1.7
33°01′S	(b)	0.0	0.0	0.0	5.5	16.8	16.0	16.8	16.0	12.5	3.2	3.2	2.0
71°30′W	(c)	−2.3	−2.2	−2.8	−2.2	−2.5	−9.7	−4.9	−3.6	1.6	−4.8	−0.4	0.3
Querelena	(a)	2.2	2.2	2.6	9.2	23.7	33.7	25.4	25.1	14.7	9.9	4.7	2.3
34°37′S	(b)	0.0	0.0	1.8	9.3	24.6	23.4	24.6	23.4	18.7	6.1	6.1	4.6
71°56′W	(c)	−2.2	−2.2	−0.8	0.1	0.9	−10.3	−0.8	−1.7	4.0	−3.8	1.4	2.3
Tomé	(a)	5.6	3.7	10.3	18.1	37.5	46.3	40.7	34.8	23.9	14.8	10.1	5.8
36°37′S	(b)	0.4	0.4	8.7	18.5	38.8	37.2	38.8	37.2	31.0	14.4	14.4	12.3
72°57′W	(c)	−5.2	−3.29	−1.6	0.4	1.3	−9.1	−1.9	2.4	7.1	−0.4	4.3	6.5
Tumbes	(a)	5.2	6.6	13.1	21.8	39.9	49.0	44.7	39.6	28.3	19.3	12.1	7.2
36°37′S	(b)	0.4	0.4	8.7	18.5	38.8	37.2	38.8	37.2	31.0	14.4	14.4	12.3
73°06′W	(c)	−4.8	−6.2	−4.4	−3.3	−1.1	−11.8	−5.9	−2.4	2.7	−4.9	2.3	5.1

(*continued overleaf*)

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Table I. (*Continued*)

Location		J	F	M	A	M	J	J	A	S	O	N	D
Talcahuano	(a)	5.9	5.5	9.9	19.9	39.7	46.5	43.4	39.3	28.5	19.7	11.4	7.4
36°43′S	(b)	0.8	0.8	9.2	19.1	39.6	38.0	39.6	38.0	31.7	14.9	14.9	12.8
73°07′W	(c)	−5.1	−4.7	−0.7	−0.8	−0.1	−8.5	−3.8	−1.3	3.2	−4.8	3.5	5.4
Concepción	(a)	7.7	9.2	16.2	27.8	49.7	55.6	49.8	43.5	32.4	23.8	17.9	11.0
36°50′S	(b)	1.2	1.2	9.7	19.8	40.5	39.0	40.5	39.0	32.6	15.6	15.6	13.4
73°02′W	(c)	−6.5	−8.0	−6.5	−8.0	−9.2	−16.6	−9.3	−4.5	0.2	−8.2	−2.3	2.4
Pto Saavedra	(a)	15.2	16.3	21.3	30.3	50.5	58.5	51.6	46.9	35.7	25.4	21.6	20.0
38°47′S	(b)	13.3	13.3	22.9	34.4	57.9	56.1	57.9	56.1	48.8	29.5	29.5	27.1
73°22′W	(c)	−1.9	−3.0	1.6	4.1	7.4	−2.4	6.3	9.2	13.1	4.1	7.9	7.1
Valdivia	(a)	28.1	29.9	36.6	47.4	68.9	73.9	67.5	65.7	56.7	45.4	39.2	34.0
39°48′S	(b)	23.4	23.4	32.0	42.3	63.3	61.6	63.3	61.6	55.2	38.0	38.0	35.8
73°14′W	(c)	−4.7	−6.5	−4.6	−5.1	−5.6	−12.3	−4.2	−4.1	−1.5	−7.4	−1.2	1.8
Pta. Galera	(a)	26.6	27.5	37.8	45.8	64.8	69.3	65.7	62.5	51.6	42.3	34.2	33.9
40°02′S	(b)	25.5	25.5	33.9	43.9	64.3	62.7	64.3	62.7	56.4	39.7	39.7	37.6
73°44′W	(c)	−1.1	−2.0	−3.9	−1.9	−0.5	−6.6	−1.4	0.2	4.8	−2.6	5.5	3.7
Pto. Montt	(a)	35.2	36.5	43.8	52.2	67.8	69.0	66.2	63.3	56.0	49.8	46.4	41.5
41°28′S	(b)	37.2	37.2	44.1	52.4	69.2	67.9	69.2	67.9	62.7	48.9	48.9	47.2
72°56′W	(c)	2.0	0.7	0.3	0.2	1.4	−1.1	3.0	4.6	6.7	−0.9	2.5	5.7
Ancud	(a)	37.1	38.9	43.6	50.5	69.7	69.2	70.2	64.3	56.1	50.9	42.8	43.2
41°52′S	(b)	40.0	40.0	46.5	54.2	70.1	68.9	70.1	68.9	64.0	51.0	51.0	49.4
73°49′W	(c)	2.9	1.1	2.9	3.7	0.4	−0.3	−0.1	4.6	7.9	0.1	8.2	6.2
Is. Guafo	(a)	49.1	52.3	55.7	62.6	72.2	74.0	73.1	68.4	62.4	60.4	53.9	49.7
43°34′S	(b)	49.5	49.5	54.3	60.0	71.7	70.8	71.7	70.8	67.2	57.6	57.6	56.4
74°45′W	(c)	0.4	−2.8	−1.4	−2.6	−0.5	−3.2	−1.4	2.4	4.8	−2.8	3.7	6.7
Pto. Aysén	(a)	52.9	53.6	56.4	60.0	66.1	65.0	67.3	64.1	57.0	57.0	58.9	55.3
45°24′S	(b)	55.7	55.7	58.7	62.2	71.7	70.8	71.7	70.8	67.5	60.7	60.7	60.0
72°42′W	(c)	2.8	2.1	2.3	2.2	5.6	5.8	4.4	6.7	10.5	3.7	1.8	4.7
C. Raper	(a)	72.2	71.8	69.7	76.4	76.6	76.1	79.7	72.4	73.6	74.1	74.8	71.9
46°30′S	(b)	57.4	57.4	59.3	62.2	71.7	70.8	71.7	70.8	67.5	60.8	60.8	60.2
75°35′W	(c)	−14.8	−14.4	−10.4	−14.2	−4.9	−5.3	−8.0	−1.6	−6.1	−13.3	−14.0	−11.7

4. PROPOSED MODEL

Assuming that a linear relationship between monthly mean rainfall frequency (PP) for a given location and the location's latitude L relative to LMP's latitude L_i for each month i exists, the intercept A and slope B of best-fit regression lines

$$PP = A + B(L_i - L)$$

were first determined for each location listed in Table I. Values of L_i used are given in Table II. Figure 5 shows the results for Valparaíso (33°01′S; 71°30′W) and Isla Guafo (43°34′S; 74°45′W). The two locations were chosen as representative of locations situated north and south of a location that symmetrically divides the range for which the model applies, as will be discussed below. Then, the dependencies of both A and B on latitude were derived. A linear dependency of A on latitude is found to hold for the whole range. In the case of B, it is obvious that the observed values arrange themselves into two different branches, which to a approximation suggests a linear decrease with latitude for the northern part of the range and a linear increase with latitude for the southern part. The absolute values of the slopes of the two best-fit regression lines are found to be very similar, and a single value is adopted. In fact, the two slopes actually differ by less than

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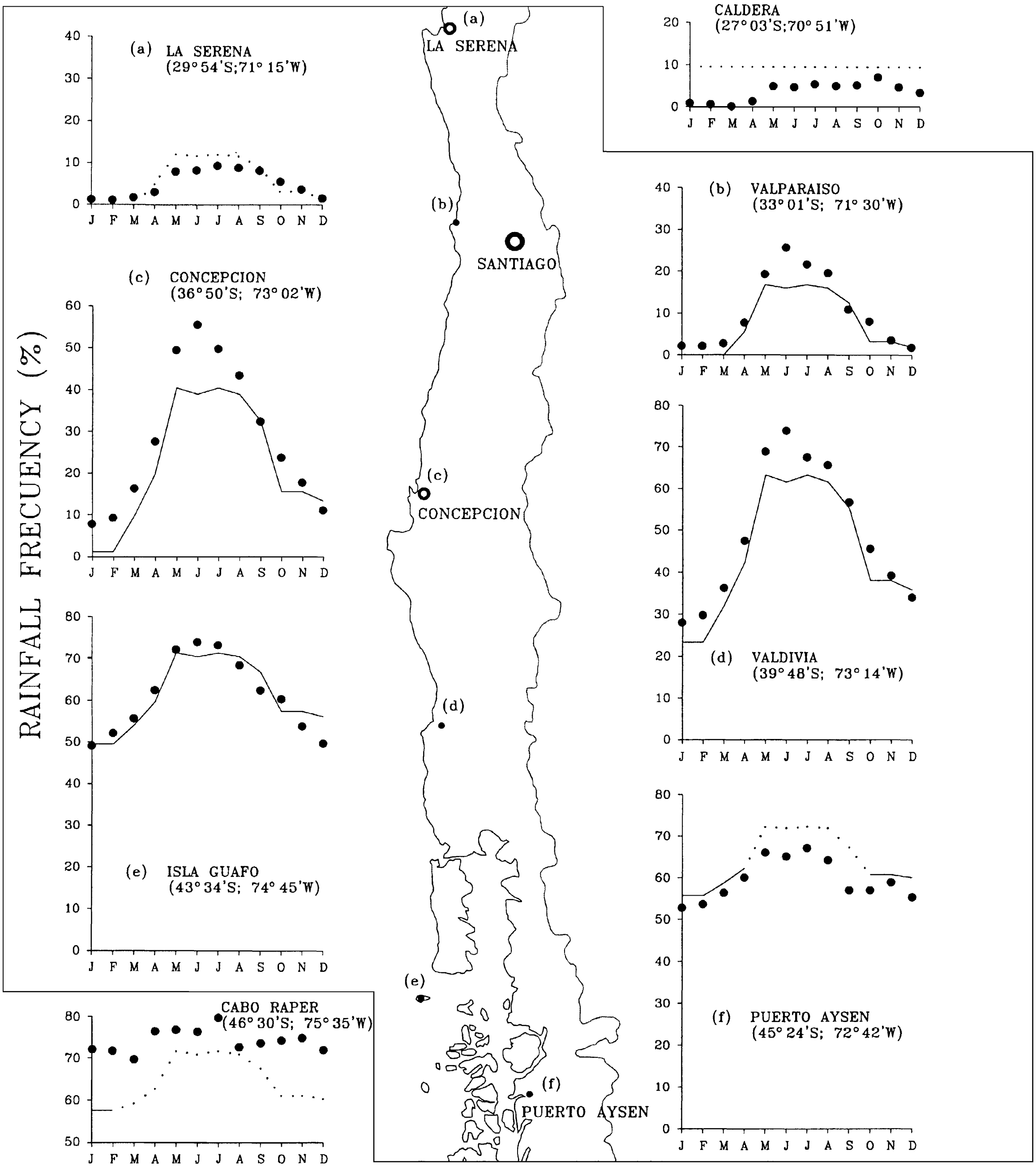

Figure 4. Sample annual evolutions of monthly mean rainfall frequency for locations along the Chilean coast. (●) Observed values corresponding to 1931–60 interval. (———) Proposed model. (- - - -) Proposed extension for rough climatic computations. Note that Caldera is beyond the latitude for which $B(L) = 0$ (see text)

2% from that adopted, and the dividing location changes by less than 0.2°, thus confirming the symmetry assumption. The adopted expressions for $A(L)$ and $B(L)$ are

$$A(L) = 34.8 + 2.22(L - 38.4)$$
$$B(L) = -6.29 \mp 0.633(L - 38.4)$$

Table II. Latitude (degrees S) of the location of maximum monthly mean pressure in Chile (LMP)

Month	J	F	M	A	M	J	J	A	S	O	N	D
Latitude	42.5	42.5	40.9	39.0	35.1	35.4	35.1	35.4	36.6	39.8	39.8	40.2

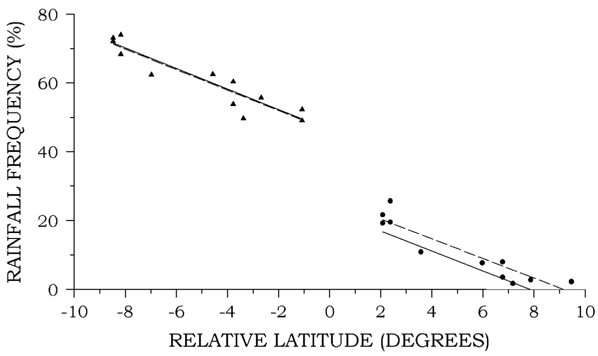

Figure 5. Monthly-mean rainfall frequency dependence, for a given location, on location latitude relative to LMP's latitude. Observed values for (●) Valparaíso (33°01′S; 71°30′W) and (▲) Isla Guafo (43°34′S; 74°45′W) corresponding to 1931–60 interval. (- - - -) Best-fit regression lines. (———) Linear relationship adopted after linear dependencies of individual intercepts and slopes with latitude were determined (see Figure 6)

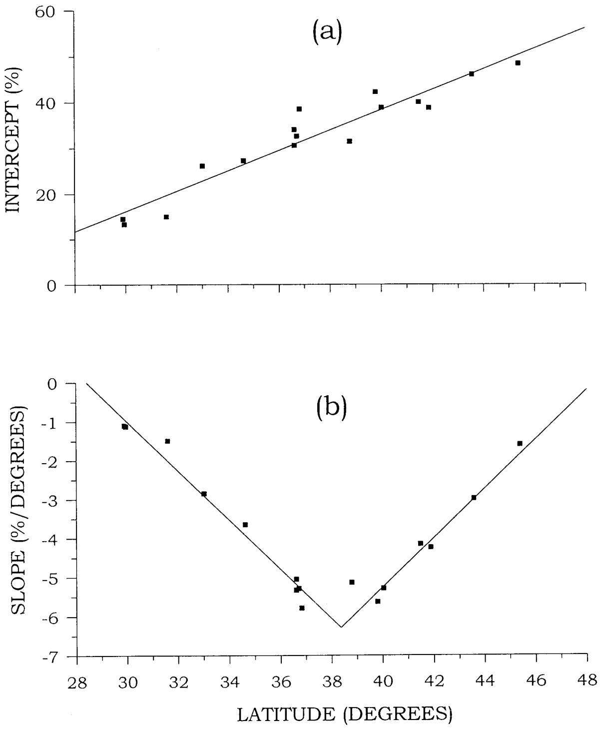

Figure 6. (a) Intercept and (b) slope of best-fit regression lines (see Figure 5) dependence on latitude. (■) Determined values for individual locations. (———) Adopted linear relationships

The − sign is used for locations north of 38.4 °S and the + sign for locations south of it. The goodness of fit to linear dependencies can be seen from Figure 6. The use of best-fit values of A and B back into the expression for PP corresponding to Valparaíso and Isla Guafo is illustrated in Figure 5.

The proposed model estimates of monthly mean rainfall frequency for all locations can then be calculated for any month as

$$\mathrm{PP} = A(L) + B(L)(L_i - L)$$

It can be easily shown that PP is a quadratic function of latitude and that it attains, for each month, a minimum value at the lower latitude end and a maximum value at the higher latitude end. The latitudes at which these values are reached (i.e. where $\partial \mathrm{PP}/\partial L = 0$) are considered here as the validity limits of the proposed model. However, for January and February (austral summer) the minimum value is negative, and hence there exists a somewhat higher latitude for which $\mathrm{PP} = 0$. These latter latitudes are taken as the validity limits. The climatic meaning of these validity limits is discussed in Section 6.

The proposed model could be extended to give rough climatic values beyond the validity limits, so as to apply to the original latitude range considered (Caldera to Cabo Raper) for all months. This can be achieved by assuming that, for latitudes north of the northern latitude of validity, PP is taken as the minimum value (or zero for January and February). For latitudes south of the southern latitude of validity, PP is taken as the maximum value.

5. RESULTS

Table I lists both the calculated values of PP using the above expressions and the differences between these and the observed values. The two stepped lines drawn across the table indicate the month-to-month northern and southern validity limits. Values outside the latitude range thus marked, correspond to those of the proposed extension. Figure 4 compares the calculated and observed values for sample locations.

To assess the proposed model goodness, distributions of differences between calculated and observed values for all locations and months within the limits of validity of the model were determined. These show that for 85% of all cases the differences were less than 7%. It should be noted that, as already mentioned, rainfall frequency is the ratio of number of days for a given location and month for which rainfall is greater than 0.1 mm to the total number of days of the month, expressed as a percentage. Thus, rainfall frequencies are actually expressed in 1 day units (i.e. about 3.3%), so that a difference between calculated and observed values of 7% corresponds to being wrong only 2 days out of 30. This model performance is considered good enough, particularly because the model is thought to be more valuable for its conceptual framework than for the numerical replication of observed values. The largest differences correspond to June (austral winter), when in four cases the differences amount to being wrong 3 days out of 30.

There is some evidence of an annual evolution of the mean/median/mode values of the distributions having significant semi-annual, and probably ter-annual components. However, no explanation of this effect is offered.

As regards the proposed extension for rough climatic computations, Table I and Figure 4 show that reasonable values are given for Coquimbo and La Serena. In fact, estimates can strictly be made up only to a location between La Serena and Caldera (28.4 °S). For Caldera proper, the extension assumptions no longer hold. Thus, a fixed value is given for all months. On the other hand, south of Raper the rough estimates could be made (not shown) up to 48.3 °S, where again a fixed value is given for all months.

6. DISCUSSION

6.1. A(L) and B(L)

Although the latitude functions $A(L)$ and $B(L)$ strictly relate only to linear fitting operations, and therefore are only valid for the range of corresponding observed values, it can be argued that they could be associated with two different features shown by the annual evolution of rainfall in Chile.

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As indicated before, $A(L)$ increases linearly with latitude. This is consistent with the observed increasing monthly mean rainfall frequencies all along the Chilean Pacific coast, as determined by Devynck (1971). Furthermore, for the much smaller LMP's latitude range (35.1 to 42.5 °S), $A(L)$ is the value of PP to be expected at the LMP's latitude each month. Thus, $A(L)$ is a sort of reference value and is always higher than PP for any month at locations north of the LMP's northernmost latitude, and lower for locations south of the southernmost latitude. Within the LMP's latitude range, it is a reference from which some amount has to be subtracted (or added) to get the proper PP for a given location and month. It should be noted that $A(L)$ is not the rainfall-frequency annual-evolution mean value, which also increases with latitude.

On the other hand, $B(L)$ is proportional to the amplitude of the annual evolution of rainfall frequency for any location; the proportionality constant is the inverse of the LMP's latitude range (7.4°). This amplitude is seen to increase with latitude up to a certain latitude and to decrease from there towards the south. The maximum absolute value of $B(L)$, and, consequently, the maximum annual evolution amplitude, is attained almost exactly in the middle of the LMP's range (38.4 °S). The extrapolated $B = 0$ value means the same PP all year round, as also approximately shown by the observed rainfall frequency annual evolution both in the north (almost nil every month) and the south (very large, but the same all months). It may be noted in passing that, for locations around the latitudes for which $B = 0$, a marked reduction of the correlation coefficients of the linear fitting operations is found. Furthermore, $B(L)$ can also be interpreted in terms of the annual evolution of the LMP's latitude. Assuming PP is a differentiable function of L_i, it can be easily shown that $B = \partial \mathrm{PP}/\partial L_i$. Thus, $B(L)$ gives, for a given location, the rate of change of PP with L_i. The significance of this feature will be considered in Section 7. Although a different $B(L)$ function fitting the observed rainfall frequencies better could easily be found (see Figure 6(b)), it is not considered justified because it would unnecessarily complicate the remarkable simplicity of the proposed model.

6.2. *Climatic zones defined by A(L) and B(L)*

The different ranges defined by $A(L)$ and $B(L)$ are illustrated in Figure 7. As will be seen, some Chilean climatic zones (e.g. Romero, 1985) can be directly associated with these ranges. In particular, a quantitative description of rainfall frequency can be made for those latitudes lying within the validity limits of the proposed model. Moreover, a qualitative statement can be made for those latitudes lying outside of them.

$A(L)$ can be considered by extrapolation as defining a large latitude range (22.7–67.8°) that generally coincides with what is known as the middle latitudes or temperate zone. It is interesting to note that $A(L) = 0\%$ near the Tropic of Capricorn (associated with the PA) and $A(L) = 100\%$ near the Antarctic Polar Circle (close to the sub-Antarctic trough mean latitude). Within this range, a much more restricted range can also be defined,

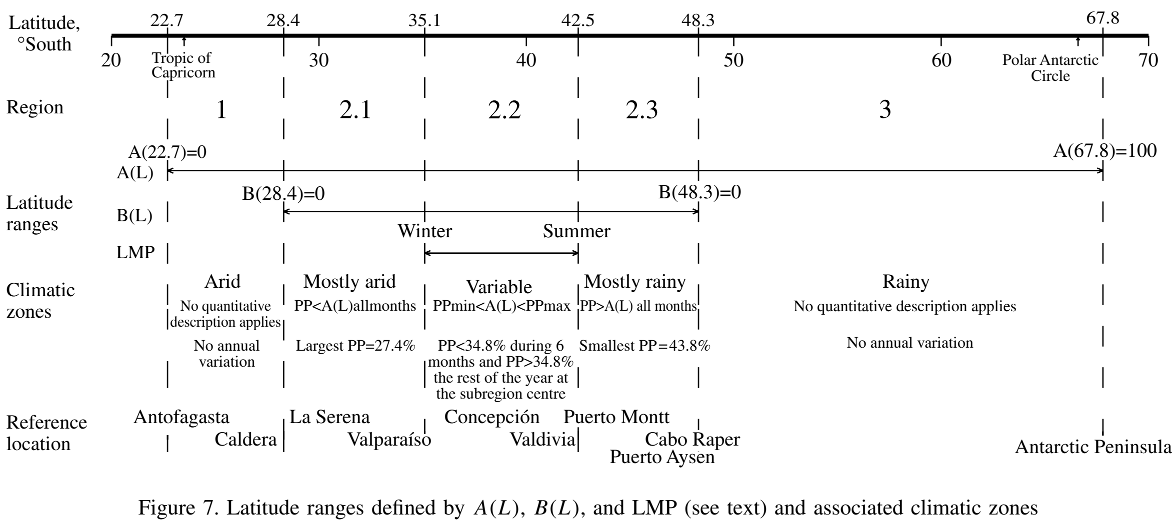

Figure 7. Latitude ranges defined by $A(L)$, $B(L)$, and LMP (see text) and associated climatic zones

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the limits of which are the latitudes for where $B(L)$ is zero (28.4° and 48.3°). This range could be thought of as the range in which the PA and the sub-polar frontal-wave cyclones disrupt the spatial domain.

North of the $B(L)$ range (region 1), the PA dominates without any significant PL perturbation. This region could be called an *arid* zone. No quantitative description applies. However, the extrapolation of the model would suggest that both no annual variation should be observed ($B = 0$) and PP should decrease with latitude in the same way every month up to a latitude where rainfall frequency is nil ($A = 0$). Although neither feature is actually observed, it should be noted that the assumed mechanisms are no longer applicable and that rainfall frequency is so small that any comparison between model and observed values is not meaningful. The region is one of the driest in the world.

South of the $B(L)$ range (region 3), the PLs dominate. This region could be called a *rainy* zone. Again, no quantitative description applies, and the extrapolation of the model would suggest that both no annual variation should be observed ($B = 0$) and PP should increase with latitude in the same way every month up to a latitude where it rains every day all year round ($A = 100$). Though once more the assumed mechanisms are no longer applicable, the observed values (Devynck, 1971) do indicate no annual variation as qualitatively expected. Moreover, rainfall frequency attains a maximum value of only about 72%, a feature interpreted in Section 7.

It is interesting to note that both these $A(L)$- and $B(L)$-defined ranges do not change from month to month. The region that lies between regions 1 and 3 can be considered as divided into three sub-regions. The central sub-region is the LMP's range (sub-region 2.2). Here, the PA and the PLs role is especially significant, since rainfall frequency exhibits the largest month-to-month change. It is a *variable* zone, where, for a given location, PP is equal to $A(L)$ those months when the LMP's latitude coincides with that of the given location. In the middle of this zone the rainfall frequency is less than 34.8% during 6 months and more than 34.8% the rest of the year. North of the LMP's range (sub-region 2.1), $\partial \mathrm{PP}/\partial L$ becomes zero in summer (33.7°) and winter (30.0°), thus determining the monthly dependent northern validity limit of the proposed model (note the restriction PP = 0 imposed for some months). In sub-region 2.1, a *semi-arid* or *mostly arid* zone, PP is less than $A(L)$ all year round; the largest value is 27.4%. Most of this region is covered by the northern validity limit of the model. The more southern that the location latitude is, then the larger the number of months for which the location is inside the validity limit, thus being inside the LMP's 'influence' and, therefore, having its particular character. Similarly, south of the LMP's range (sub-region 2.3), $\partial \mathrm{PP}/\partial L$ becomes zero in summer (47.2°) and winter (43.5°), determining the monthly dependent southern validity limit. Here, PP is more than $A(L)$ all months, a zone that could be denoted as *mostly rainy*, where the smallest PP is 43.8%. Sub-region 2.3 could be thought of as being symmetric with sub-region 2.1 (covered by the southern validity limit, the more northern the latitude is, then the larger the number of months for which the location is inside the validity limit). It is significant to note that the amplitude of the annual evolution of the validity limits is half that of the LMP. The shape of these evolutions is obviously that of the LMP.

7. SPECULATIVE MODEL IMPLICATIONS

7.1. Quantitative PA and PL dominance

As indicated in Section 2, it could be assumed that rainfall in Chile is of frontal origin, and, therefore, wherever and whenever it rains, an associated PL action is in course. Conversely, no rain should ever be associated with a PA action. This means that climatic mean rainfall frequency for any latitude could be taken as a climatic mean of PL actions. Thus, the rainfall frequency results presented in Section 6.2 could be interpreted as quantitatively indicating the PA and PL action dominance.

Since the observed maximum rainfall frequency is about 72%, it could be said that PA actions dominate all along the Chilean coast for at least 28% of the time. Obviously, no climatic map ever shows such a condition. However, even in region 3 the synoptic maps show from time to time anticyclonic action all along the coast all year round. Moreover, frontal-wave cyclones are observed to sweep the country from west to east as equatorward as region 2.2 in such a way that anticyclonic action dominates regions 2.3 and 3. These two features, and others of less significance, add to the 28%.

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Taking into account this 28%, say background PA dominance, it seems reasonable to interpret the model as indicating that the PA and PL actions disrupt the remaining 72% of the time in regions 2.1, 2.2 and 2.3. Thus, in region 2.1 the PL dominance is less than 27.4% all months, whereas in region 2.3 it is greater than 43.8% all year round. It is only in region 2.2 that the PL and PA can be 'equally' dominant, depending on the latitude or month. At the northern end of the LMP's range (35.1°) the PL dominates 27.4% of the time, and the PA 72.6% of the time for only 2 months (winter), with the PA's action being larger during the other 10 months. At the southern end of the LMP's range (42.5°) the PL dominates 43.8% of the time, and the PA 56.2% of the time for only 2 months (summer), with the PL's action being larger for the other 10 months. Only in the middle of the range, as indicated before, are the dominances the same (the number is actually 34.8% instead of exactly 36%).

Table I shows that when observed rainfall frequencies for all locations and months are used to specify PL and PA dominances instead of model frequencies, the numbers are somewhat different. However, the main results are kept, since, as indicated in Section 5, differences between calculated and observed values are small.

The numbers just quoted relate to monthly mean conditions, since no knowledge is available on the distribution of the LMP's latitude within a month. However, it is reasonable to argue that, outside of the LMP's range, the probability of finding a location where surface pressure along the coast is a maximum should be smaller than that within the LMP's range. This means that for months when the LMP is near the northern end of its range, the probability distribution should be skewed towards the south; conversely, it should be skewed towards the north when the LMP is near its southern end. A likely normal distribution is expected when the LMP is in the middle of its range. This is consistent with the fact that the annual evolution amplitude is a maximum at that latitude.

7.2. Climatic change

The LMP and the proposed rainfall frequency model relate to monthly mean conditions over many years. One could ask what would be the effect of taking into account the observed inter-annual variability. Inspection of monthly mean sea-surface pressure fields for a given year (i.e. 1997 associated with El Niño; Kousky, 1997) shows that for several months the estimated LMP's latitude derived from these fields can be systematically smaller (larger in the case of La Niña) than those given in Table II. This section presents the results of an exercise in which fixed latitude shifts of the LMP's latitude for every month are assumed. This exercise can be considered as the simplest attempt to quantify a climatic change of rainfall frequency. It preserves the LMP's role already mentioned and could be thought of as a perturbation approximation to the much more complex problem of long-term change in the interaction of the main meteorological centres of action in Chile.

In this exercise, PP is calculated using the proposed model equations assuming LMP latitude shifts of $\pm 1°$, $\pm 2°$, and $\pm 3°$. It is obvious that the 'new' latitudes for which the amplitude of the annual PP evolutions are maxima also shift the same amount. It can also be easily demonstrated that, for all months, latitude distributions of absolute PP change (not shown) reach maxima at latitudes lying between these, say, 'old' and 'new' latitudes. Furthermore, there are months for which the absolute change is largest for a given location. Figure 8 shows the annual evolutions of PP, with and without a shift of $+2°$ (i.e. towards the south), for three locations: (a) 38.4° (maximum absolute PP change in winter); (b) 39.4° (half way between 'old', 38.4°, and 'new', 40.4°, latitudes); and (c) 40.4° (maximum absolute PP change in summer). For all locations the effect of the shift is to reduce rainfall, but absolute reductions are clearly month dependent, except for the middle location, indicating drier winters for locations north of this middle location and drier summers south of it. Results for a latitude shift of $-2°$ (not shown) are opposite, i.e. wetter winters in the north and wetter summers in the south. The above results indicate that observational evidence of absolute PP changes is more likely to be found near the centre of the LMP's latitude range for all months.

When calculating relative PP changes (expressed as a percentage), several other features not easily apparent in the analysis of absolute PP changes become evident. Some of these are illustrated in Figure 9, which gives the latitude distributions of relative change of PP determined also assuming $+2°$ and $-2°$ shifts of the LMP's latitude. Though latitude distributions for summer months show very large relative rainfall changes at the lower latitudes, it should be noted that these changes are associated with very small PP values, and thus are

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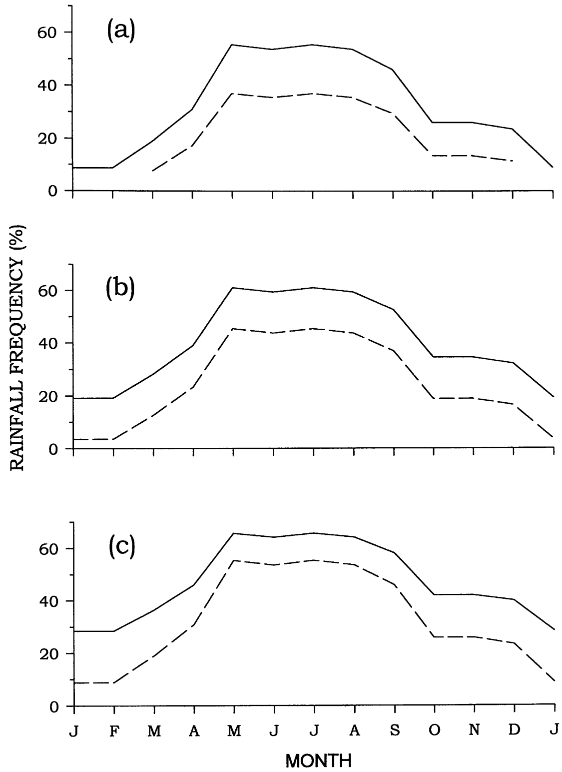

Figure 8. Annual evolutions of monthly mean rainfall frequency for locations along the Chilean coast assuming (———) no shift of the LMP's latitude and (- - - -) assuming a fixed 2° shift towards the south for all months (see text). (a) At 38.4° (maximum absolute PP change in winter). (b) At 39.4° (half way between 'old', 38.4°, and 'new', 40.4°, latitudes). (c) At 40.4° (maximum absolute PP change in summer)

hardly representative. Latitude distributions for all other months maximize at latitudes significantly lower than latitude distributions of absolute PP change, for both +2° and −2° shifts. Relative PP changes are much larger and the maxima are much sharper for the negative shift. This clearly means that, for most of the Chilean coast, drier conditions could be expected to be increased less and affect a wider area than wetter conditions, which increase more and over a narrower area. This is consistent with the fact that PP is larger south of the latitude of maxima annual evolution amplitude, and, consequently, these latitudes are less sensitive to the relative PP increases associated with the LMP's shifts towards the south.

Finally, the proposed rainfall frequency model has been shown to relate to PA and PL actions. Moreover, these actions have also been shown to relate to other climatic variables expressed in terms of frequency, such as wind direction and cloud cover (Saavedra, 1986; Saavedra and Foppiano, 1992a). Therefore, it is speculated here that the results given in this final section may be considered as one way of describing climatic change quantitatively.

8. CONCLUSIONS

The annual evolution of rainfall frequency is shown to share a common shape from La Serena to Puerto Aysen, the amplitude of the variation increasing with latitude up to a location between Concepción and Valdivia and then decreasing in a sort of symmetric fashion. The common shape resembles that of the LMP's latitude annual evolution.

Though the very simple model proposed permits estimates to be made of monthly mean rainfall frequency, which are considered good enough as climatological values, it is deemed particularly valuable because it

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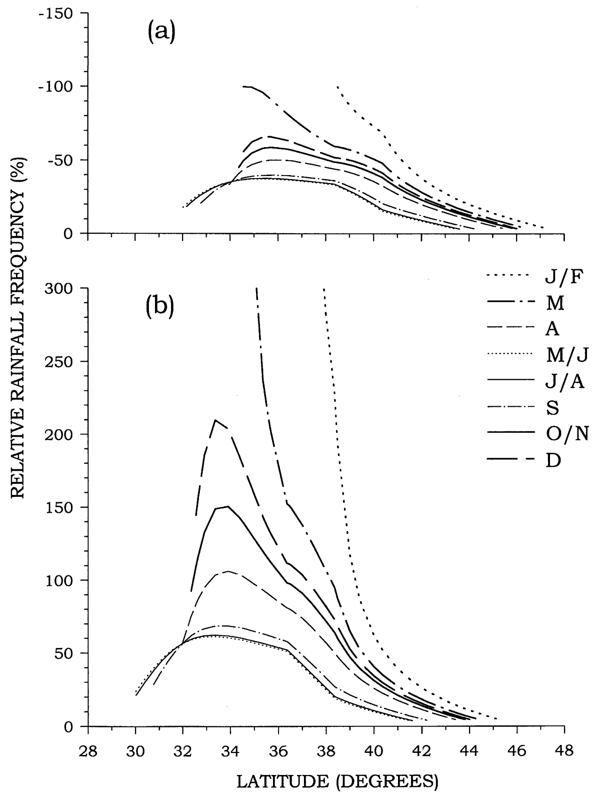

Figure 9. Latitude dependence of relative change of monthly mean rainfall frequency determined assuming a fixed LMP's latitude shift for all months: (a) 2° towards the south; (b) 2° towards the north

preserves the annual evolution features and is based on a conceptual framework. The largest differences from observed values amount to being wrong 3 days out of 30.

Some Chilean climatic zones can be directly associated with the regions defined by the proposed model in such a way that a quantitative description of rainfall frequency can be made for those zones lying within the validity limits of the model. Moreover, a qualitative statement can be made for those zones lying outside of these limits.

Climatic mean rainfall frequency for any latitude can be taken as a climatic mean of PL actions. Thus, the rainfall frequency results presented could be interpreted as quantitatively indicating the PA and PL action dominance.

It is speculated that the use of the simple model equations, as a perturbation approximation to the much more complex problem of long-term change in the interaction of the main meteorological centres of action in Chile, may be considered as one way of describing climatic change quantitatively.

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