On the climatology of surface wind direction frequencies for the central Chilean coast

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Abstract

A simple climatology giving the annual evolution of monthly-mean wind direction frequency along the central Chile coast is presented. An eight directions windrose is used. Particular attention is given to the combined monthly mean frequencies of North and North West and South and South West winds, since they are the largest frequencies for most locations. Moreover, they are conceptually the most directly related with the climatic scenario to be used. Simple relationships found between these frequencies and the latitude of the location of maximum monthly mean pressure in Chile are discussed. These confirms the validity of the climatic scenario used, which has already been found of value to develop simple empirical climatic models for coastal stations in Chile, such as a monthly-mean rainfall frequency model. The relationships found and the proposed empirical fitting allow estimations of wind frequencies where observed values are altered by local factors. Wind direction climatic zones are found to correspond to already known rainfall frequency climatic zones. Some preliminary implications regarding the ocean coastal circulation of the Chilean coast are offered.

Key words: Surface wind direction, Monthly-mean model, Chile

Introduction

The main synoptic meteorological centres of action in Chile are: (i) Pacific Anticyclone (PA), (ii) Coastal Low (CL), (iii) what has been called Enhancement of Coastal Low (ECL) - a nucleation of the CL frequently observed during summer in Central Chile, and (iv) Sub-tropical Lows (STL) and the Sub-polar (SPL). The SPL will not be considered a in the present paper. All four centres can be identified in a typical surface isobar pattern. 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 interaction between the four centres. Weather wise, "good weather" is to be found north of the wedge, while "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. 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 (Figure 2) on the basis of monthly-mean values of pressure published by Whittaker (1943), who used observations for the 1911-1940 interval (this interval includes 14 El Niño events: 4 strong, 6 moderate and 4 weak; Quinn et al., 1978). The LMP can be used as a pointer, which 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 be then considered as an index of the monthly mean spatial interaction of the meteorological centres.

The annual evolutions of the LMP’s latitude and pressure have been discussed by Saavedra and Foppiano (1992b) in terms of only two empirical Fourier components: annual and semi-annual. The semi-annual components give the observed LMP’s evolutions their characteristic shapes, i.e. a faster (slower) change of the LMP’s latitude (of pressure at the LMP) from summer to winter than from winter to summer. 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).

A strong confirmation of the validity of the climatic scenario sketched above comes from the work of Compagnucci and co-workers (e.g. Compagnucci and Salles, 1997). They conclude 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.

Obviously, there are perturbations that cause inter-annual and inter-monthly variability of meteorological variables as, for example, those related to El Niño/La Niña and to blocking conditions (mainly in southern Chile). Moreover, very occasionally cyclonic activity is observed in the north of Chile (so called cut-off lows). Also there is cyclonic activity associated with the ECL. All these perturbations do not significantly change the climatological scenario considered here. Furthermore, only coastal climatology is considered. Finally, it should be noted that the basic climatological scenario relates directly to climate defined as monthly mean values of frequency variables (expressed as percentage) rather intensity variables, which also basically depend on other mechanisms.

The purpose of this paper is to show that a simple interpretation of the annual evolutions of monthly-mean wind direction, for any location along the Chilean coast, is possible in terms of only the LMP's latitude permits. In particular, that of the evolutions of North and North West and South and South West winds. This is because they show the largest frequencies for most locations and are conceptually also the most directly related to the climatic scenario used. Furthermore, a simple empirical model for the annual evolutions is suggested. The goodness of fit of this model to measured values, as it was the case with the rainfall frequency model (Saavedra et al., 2002), confirms the main properties of the LMP as a descriptor of Chile’s climate. In Section 2, observed annual evolutions of wind direction frequency are presented, and the relationships of North and North West and South and South West winds with the LMP’s latitude are described in Section 3. This leads to an identification of the Chilean climatic zones as seen from wind direction frequencies. Finally, a brief discussion is given in Section 4 together with some preliminary implications on the ocean circulation off the Chilean coast.

Observed annual evolutions of wind direction frequencies

Annual evolutions of monthly-mean wind-direction frequencies were determined for 18 locations, covering most coastal central Chile. Table 1 gives location names, geographic co-ordinates, height of observation and length of time intervals used. For all but three locations, at least 18-year intervals are considered. All frequencies are computed from values recorded on the Anuarios published by the Dirección Meteorólogica de Chile (DMC). A monthly-mean wind-direction frequency is calculated for each of the eight standard directions (i.e. N, NE, E, SE, S, SW, W and NW). This is defined, as usual, as the ratio of number of occasions for a given location and month for which the corresponding wind direction is observed to the total number of occasions for which there are observations in the interval, expressed as percentage. A monthly-mean no-wind frequency is also calculated (referred to as calms). Thus, there are eight wind-direction frequencies for each location and month, which represents the whole interval used. No attempt is made to consider any type of inter-annual and inter-decadal variability (e.g. El Niño/La Niña cycles).

It could be argued that the intervals used for the different locations are not the same. Moreover, that they also differ from that used to derive the LMP. Unfortunately, the corresponding data sets were not readily available at the time the studies were performed. However, all intervals are long enough to be considered representative of a basic state of the concerned variables for climatic studies.

It is well known that the association between surface wind direction at a given location and the synoptic climatology for that location is not straightforward. The local surface wind directions depend on several factors. One of them is the geographic surrounding, which may lead to significant occurrence frequency departures for a given wind direction from what it would be expected. The changes in wind direction may be due to a direct mechanic action, as in the case of hills and valleys, or by means of more complex actions such as those related to thermal inversions (breezes and calms). Examples of these effects are given in Table 2. For instance, in many occasions SW wind is observed at Coquimbo (29°56'S; 71°22'W) while W wind prevails at La Serena (29°54'S; 71°12'W), two locations less than 20 km apart. This feature is related to the river Elqui valley. Here the Coquimbo wind occurrence frequency is considered to better represent the synoptic climatology. Further south, S wind at Isla Santa María (36°59'S; 73°32'W) is observed as SW wind in Concepción (36°46S; 73°04'W). This is most likely related to the sea breeze which is more significant in the morning during summer. Large calms frequencies of occurrence are observed at several nearby locations south of Valdivia (40°01'S; 73°44'W). Some of them are clearly due to orographic blocking, as in the case of Castro (42°29'S; 73°48'W). Data for several other locations between Castro and Cabo Raper (46°50'; 75°35'), that cannot be considered as coastal locations have also been considered in the next Section. Although this data can be objected because orographic effects contaminate them, they are use since there are no coastal stations in the corresponding latitude range. Specific comments will be made in each case. Moreover, a narrow but very significant climatic zone exits there, as it will be shown later.

Producing a wind climatology without the local effects mentioned above would have been ideal, for example, using the low level upper air observations as necessary to minimise or avoid altogether the above mentioned factors. However, only three upper air observing locations exist. Some of the local effects for a given wind direction could be minimised or avoided if only observations around local noon were to be included. Unfortunately, although standard observations are indeed made three times a day, no separate frequency calculations for a given time-of-day can be made because the observations are not reported separately in the DMC Anuarios.

Only the combined North and North West and South and South West monthly mean winds frequencies (NN and SS, respectively) are considered any further. Figure 3 shows the corresponding annual evolutions for the 18 locations already mentioned.

Relation of NN and SS with the LMP's latitude

Qualitative aspects

The following features are particularly significant. For fifteen locations the annual evolutions of NN exhibit a common shape, this being the shape of the LMP's latitude evolution shown in Figure 2 (note that the latitude increases downward). The SS exhibit a sort of complementary evolution. Furthermore, the NN and SS only have common values within the LMP's latitude range (from Constitución to Guafo). The

SS always dominate north of the northernmost latitude of the LMP (35.1°S). On the other hand, the NN always dominate south of the southernmost latitude of the LMP (42.5°S). A detailed analysis of Figure 3 also show that the amplitude of the annual evolutions of NN and SS increases with latitude up to a location between Concepción and Valdivia and then decreases in a sort of symmetric fashion (a quantitative description is given below). North of Coquimbo (not shown) and south of Puerto Aysen wind frequencies hardly show any change from month to month. These features closely resemble those already discussed for the annual evolution of rainfall frequency (Saavedra et al., 2002), suggesting a similar association with the LMP's latitude. The three Canal de Chacao locations (Maullín, Punta Corona and Ancud), for which at least two of these features are not observed, and which lie within a very small latitude range (0.28 degrees of latitude), are considered separately latter.

Quantitative aspects

Assuming that a linear relationship exist between both NN and SS, for a given location, with the location's latitude (L) relative to LMP's latitude (L_i) for each month (i), the correlation coefficients (R_n and R_s), the intercepts (A_n and A_s) and slopes (B_n and B_s) of best-fit regression lines

$$NN = A_n + B_n (L_i - L)$$

$$SS = A_s + B_s (L_i - L)$$

have been determined for each location. Values of L, NN and SS for fifteen locations shown in Figure 3 are given in Table 3, together with values of L_i. Values for the Canal de Chacao locations are also used but are not shown. Figures 4, 5 and 6 give R_n and R_s, A_n and A_s, and B_n and B_s, respectively. The straight lines shown in Figures 5 and 6 corresponds to the following equations which give wind direction frequency for a given location for any month

$$NN = A_n(L) + B_n(L)\,(L_i - L)$$

and

$$SS = A_s(L) + B_s(L)\,(L_i - L).$$

with $A_n(L)$ and $A_s(L)$ as

$$A_n(L) = 28.6 + 3.62(L - 35.1) \quad \text{for } 28.4 \le L < 35.1$$

$$A_n(L) = 28.6 \quad \text{for } 35.1 \le L < 42.5$$

$$A_n(L) = 28.6 - 10.0(L - 42.5) \quad \text{for } 42.5 \le L < 45.4$$

$$A_n(L) = 56.8 \quad \text{for } 45.4 \le L$$

$$A_s(L) = 43.7 + 5.60(L - 35.1) \quad \text{for } 28.4 \le L < 35.1$$

$$A_s(L) = 43.7 \quad \text{for } 35.1 \le L < 42.5$$

$$A_s(L) = 43.7 + 15.7(L - 42.5) \quad \text{for } 42.5 \le L < 45.4$$

$$A_s(L) = 18.3 \quad \text{for } 45.4 \le L$$

and $B_n(L)$ and $B_s(L)$ as

$$B_n(L) = -4.45 \mp 0.445(L - 38.4) \qquad \text{for } 28.4 \le L < 45.4$$

$$B_n(L) = 0 \qquad \text{for } 45.4 \le L$$

$$B_s(L) = 6.32 \pm 0.632(L - 38.4) \qquad \text{for } 28.4 \le L < 45.4$$

$$B_s(L) = 0 \qquad \text{for } 45.4 \le L$$

The – sign is used for locations North of 38.4 °S and the + sign for locations South of it. It can be easily shown that NN and SS are quadratic function of latitude and that they attain, for each month, minima values at the lower latitude end and maxima values at the higher latitude end.

The coefficients R_n and R_s are stable and are larger or equal ±0.9 from Constitución to Puerto Aysen, except for the Canal de Chacao locations. However, considering that even an $R \ge 0.8$ is good enough (see straight lines drawn for $R = \pm 0.8$ in Figure 4), the LMP's range (35.1 to 42.5 degrees S) could be extended to cover from Valparaíso to Puerto Aysen. Outside of this extended range the values of R sharply decrease, particularly R_n. Thus, the coefficients R permit an identification of the latitudinal ranges of the climatic centres of action whose interaction is described by the LMP. This is consistent with the relation previously found between rainfall frequency and the LMP's latitude (Saavedra et al., 2002). It should be noted that between Guafo and Puerto Aysen SS dominate, a feature that will be discussed later.

As discussed by Saavedra et al. (2002) in the case of rainfall frequency, the latitude functions A(L) and B(L) strictly relate only to linear fitting operations, therefore they are only valid for the range of corresponding observed values. However, it can be again argued that they could be associated with two different features shown by the annual evolution of NN and SS winds in Chile.

Although A_n and A_s show a large latitudinal variability, by inspection A_n and A_s can be considered constant to a good approximation within the LMP's range, as suggested by the straight lines drawn in Figure 4. Some of the variability in this range can be associated with local effects. For instance, the large difference between values for Constitución and Punta Carranza may result from orographic differences. This is because both locations are indeed coastal, their latitude and longitude differ only by 16' and 12', respectively, but Constitución is significantly blocked from de South. Thus, values for Punta Carranza are considered more representative. Similar arguments may be used for the Canal de Chacao locations. Values of A for a given location within the LMP's range correspond to the wind frequency for the location at the month when its latitude coincides with that of the LMP. Outside of the LMP's range, A corresponds only to values resulting from the fitting process.

In the case of B_n and B_s again there is a large latitudinal variability. However, for the extended LMP's range, values could be interpreted as defining two sub ranges for B, identical in latitude size, meeting at the middle of the LMP's range, as suggested by the straight lines drawn. One sub range for which B_s increases (B_n decreases) with latitude. The other being a mirrors image about the meeting latitude. This means that the largest changes of NN and SS associated with changes of the LMP's latitude are expected at Isla Mocha. The maximum attained by B_s is about one and a half times the minimum of B_n, in absolute terms. Thus, also larger changes of SS are expected for corresponding changes of the LMP's latitude. The latitudinal dependence of B_n is similar to that for the rainfall frequency model already referred to.

Climatic zones

The different ranges defined by A(L) and B(L) are pictured in Figure 7. As it will be seen Chilean climatic zones defined by Saavedra et al. (2002) can be directly associated with these ranges. In particular, a quantitative description of NN and SS wind frequency can be made for those latitudes lying within the validity limits of the proposed empirical fitting. Moreover, a qualitative statement can be made for those latitudes lying outside of them. Figure 7 gives the percentages as determined from the empirical formulae already mentioned. These percentages do not have the same significance than the corresponding ones to rainfall frequencies because wind directions are less reliable than rainfall values and winds are different than rainfall.

North of Coquimbo, not shown, NN wind frequency is less than 5% and this zone corresponds to the arid zone rainfall wise. From Coquimbo to Punta Carranza, SS dominates. This coincides with the mostly arid zone. Within the LMP range (Punta Carranza-Castro), NN and SS alternate dominances being consistent with a variable zone rainfall wise. The following zone does not coincide with the mostly rainy zone. It is narrower and, as already noted, do not relate to the LMP, as will be indicated below. The existence of this zone is mostly based in wind frequencies observed at Guafo. They are not disturbed by orographic features as it is the case for Aysen. Unfortunately, frequencies are not available for other locations in this zone. Further south there is a complete dominance of NN.

The remarkable correspondence between the rainfall climatic zones and the wind direction climatic zones indicates they relate to same climatic scenario in which the LMP plays a climatic descriptor role.

Discussion

A closer look at Figure 4 and Table 4 shows that for SS winds the assumption of constant R_s is good enough from Coquimbo to Aysen, except for the Canal de Chacao locations. The value for Raper and San Pedro are also somewhat lower than 0.8. Moreover, the value for Puerto Eden is negative indicating an anti-correlation. This is considered a singularity. For NN winds, the assumption of constant R_n is good from Valparaiso to Puerto Aysen, except for Ancud. Thus, on the northern latitude side, Coquimbo, is considered also as a singularity (almost no correlation) and so also are considered Cabo Raper, San Pedro and Puerto Eden (no correlation or anti-correlation) on the southern side.

The above features are discussed as follows for the SS and NN winds.

SS winds

For Guafo and Puerto Aysen SS frequency is larger than NN frequency all the year round although the LMP is located always north of Guafo. Particularly in winter when is located in the northern part of its latitude range. From October to April the difference between SS and NN frequencies for Guafo is considerable Since during this time the LMP is at the southern part of it range, the SS dominance may be associated with the LMP incursions south of it range in what can be considered an extension of its range. The same may be claimed for Puerto Aysen. However, the SS frequencies are up to 50% larger than the NN ones (October to March). This may be associated with orographic blocking since the calms frequency is very large. On the other hand, at Guafo, from May to September the SS frequency is about the same as the NN frequency, suggesting the existence of an unstable zone. The same may be claimed for Aysen. The suggestion is that cyclonic perturbation incursions to the north may statistically leave space for highs to develop south of the LMP latitude range, such as migratory anticyclones. These highs are not associated with the LMP. Thus, SS and NN exhibit a good correlation to the LMP latitude.

NN winds

As already indicated, there is no correlation between NN frequency and the LMP for Coquimbo in the northern side of the latitude range considered. On the other hand, for both winter and summer in the southern side NN dominates, as it would be expected since these locations are south of the LMP range. However, it should be stressed that the locations are outside of the range of the LMP validity.

NN+SS

As already mentioned, wind frequencies were determined for all 8 standard directions and frequencies for NN and SS were the largest. Now, the annual evolutions of NN and SS winds are complementary (see Figure 3), the sum being almost the same for all months. The anti-correlation coefficients are larger than 0.96 and the sum larger than 72% for locations where other factors such as orographic, blocking and calms are not significant. Moreover, NN and SS winds are the same all months for locations south of where they are complementary. These facts confirm that these winds result from the interaction between the PA and the STL, the pointer of which is the LMP.

As already mentioned, Figure 3 and Table 3 show that for locations within the LMP range, NN and SS wind frequencies are equal twice a year. This obviously requires assuming that observed monthly values are arbitrarily associated the 15^{th} day of each month, and that locations and times can be interpolated in between. From summer to winter the time at which the frequencies are equal almost coincide with the time when the LMP is over the location considered. By contrast, from winter to summer, the LMP is over the location one to two months after the NN and SS wind frequencies are the same. This is consistent with the fact that shape of the so called "high wedge" observed on the continent (see Figure 1) changes seasonally. It is narrow during winter and wider during summer, and the asymmetry relative the LMP changes systematically from month to month, being different from summer to winter than the other way round.

Ocean coastal circulation

Some preliminary implications of the present study are offered as follows. The coastal atmospheric circulation south of Cabo Raper is characterized by NN winds all the year round. This may suggest that winds, considered as an ocean coastal circulation forcing (Strub et al, 1998), have always the same sign, probably leading to the observed permanent ocean coastal circulation towards the south. By contrast, north of Cabo Raper, during summer the atmospheric circulation is characterized by SS winds. Thus, at Cabo Raper there is a kind of atmospheric circulation divergence which may contribute to the known west ocean coastal stagnation. During winter there is a wind direction alternancy, the number of months of NN dominance decreasing as latitude decreases. This alternancy may be associated with a large variability on the ocean coastal circulation. North of Punta Carranza, SS winds dominate and so the atmospheric circulation forcing always has a single but opposite sign.

Conclusions

The climatology of NN and SS winds over the Chilean coast, all along the LMP's range and its extensions, is mainly determined by the interaction of the PA and the

STLs. The LMP is a descriptor of this interaction. For northern locations SS winds dominate (there is no NN winds) while NN winds dominate for southern locations (there is no SS winds).

The kinematics of this interaction results from the continuous latitudinal movement of the CL and the STLs with the LMP from north to south (spring) and back (autumn). At the scale considered here (synoptic), these three move as a single unit implying that the STLs give way to the PA during the southward movement and erode the PA during the northward movement.

A quantitative description of NN and SS winds in terms of the LMP allows some estimations of their frequency for locations where observed winds are altered by local factors.

A correspondence is found between the climatic zones defined by the LMP and its extensions and those determined by rainfall and by wind frequencies leading to a unified view of the coastal Chilean climate.

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Figure captions

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

Figure 2. Annual evolution of the latitude of the location of maximum monthly mean pressure, along the Chilean coast (LMP). Values correspond to the 1911-1940 interval (adapted from Whittaker, 1943). (from Figure 2, Saavedra and Foppiano, 1992a).

Figure 3. Annual evolutions of monthly-mean frequency (%) of North and North West (NN) and South and South West (SS) winds for locations and time intervals in Table 1. Observed values: (●) NN and (○) SS. Empirical fitting: (—) NN and (---) SS.

Figure 4. Correlation coefficients for best-fit regression lines of assumed linear relationships between both North and North West (NN) and South and South West (SS) winds, for a given location, with the location’s latitude relative to LMP’s latitude. (●) NN and (○) SS.

Figure 5. Intercepts of best-fit regression lines of assumed linear relationships between both North and North West (NN) and South and South West (SS) winds, for a given location, with the location's latitude relative to LMP's latitude. Observed values: (●) NN and (○) SS. Empirical fitting: (—) NN and (---) SS.

Figure 6. Slopes of best-fit regression lines of assumed linear relationships between both North and North West (NN) and South and South West (SS) winds, for a given location, with the location's latitude relative to LMP's latitude. Observed values: (●) NN and (○) SS. Empirical fitting: (—) NN and (---) SS.

Figure 7. Latitude ranges defined by rainfall frequency, A(L) and B(L) (Saavedra et al., 2002), by wind direction frequency, $A_n(L)$, $A_s(L)$, $B_n(L)$, and $B_s(L)$, by the LMP (see text), and associated Chilean climatic zones.