

The climate of the coast and fog zone in the Tarapacá Region, Atacama Desert, Chile

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Abstract

In the Atacama Desert, the narrow littoral plain and the adjacent mountain range have a unique climate. This area is locally called the “coastal desert with abundant cloudiness”, and extends from the coastline up to an elevation of 1000 m. The climate is designated as being BWn according to Köppen’s Climate Classification as adapted for Chile. In the original classification the acronym (Bn) is used for foggy environments. Toward the east a “normal desert” climate (BW) is found. This is known as one of the most extreme deserts of the world. In the BWn areas there are meteorological differences between low and high elevation zones. The climate of the coastal plains and the mountains is described in this paper in order to show that there is an area where the climate differs from those classified as BWn and BW in the Chilean Climate Classification. This area is located between 650 and 1200 m a.s.l. and contains several fog oases or *lomas* vegetation, rich in biodiversity and endemism.

The weather is warmer near sea level, with an annual average temperature of 18 °C. At high elevation sites like Alto Patache, the temperature decreases at a rate of 0.7 °C for every 100-m increase in altitude. The average annual minimum temperature often approaches 1 °C in winter, while the mean annual temperature range is significant (8.3 °C in Los Cóncores). The mean monthly relative humidity in Alto Patache is over 80%, except during the summer months. During autumn, winter and spring high elevation fog is present in the study area at altitudes ranging from 650 m up to 1060 m, giving annual water yields of 0.8 to 7 L m⁻² day⁻¹. If vegetation is used as an indicator, the foggy zone lies between 650 m a.s.l. and 1200 m a.s.l. About 70% of the mountain range experiences the foggy climate, as opposed to the coastal plains that are characterized by a cloudy climate.

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1. Introduction

The general relief of the Tarapacá Region in the Atacama Desert of Chile exhibits four main features from west to east: a narrow littoral plain that ends in a

steep cliff, a coastal mountain range with 1500-m peaks called *Cordillera de la Costa*, an “Intermediate Depression” that is a longitudinal plain (*pampa*) located at about 1000 m of altitude, and the *Cordillera de los Andes* that ends in a high plateau with peaks over 6,000 m a.s.l. (Fig. 1).

The adaptation of the Köppen Climate Classification to the Chilean territory designates the climate of the coast from sea level up to 1000 m as BWn. Locally, this is called a “coastal desert with abundant cloudiness”. Immediately

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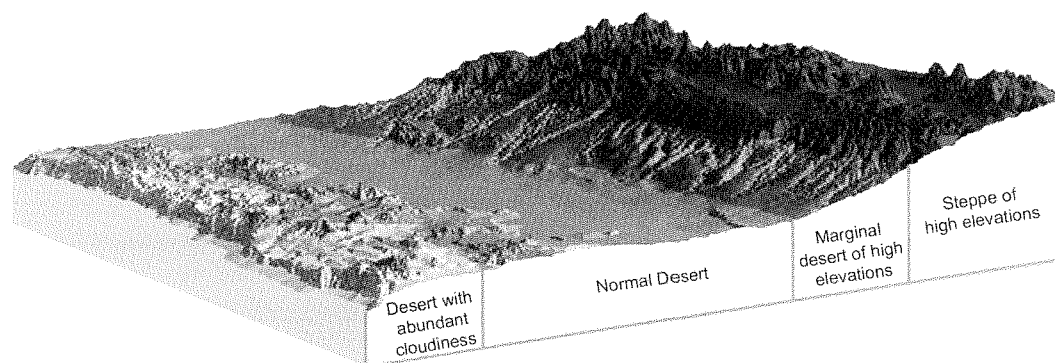


Fig. 1. Relief and climate of southern Tarapacá, Chile.

eastward of this is a zone with a BW climate known as the “normal desert”. Toward the Andes mountains two more climatic types are found, BWk and BWH (Errázuriz et al., 2000). In Tarapacá, the BWn and BW climates have a mean annual rainfall of 1 mm, while in the village of Putre in the high Andes the average annual precipitation is more than 250 mm (Novoa and Villaseca, 1989). In the coastal regions the mean annual temperature range is small, whereas inland it is very extreme. Average relative humidity is high at the coast (around 70%), and low 50 km inland (less than 50%) (Fig. 1). BWn climatic zone has been defined by Fuenzalida (1971) as extending from the coastline up to the 1000-m a.s.l. contour line, and BW zone, from that altitude to 1500 m a.s.l. However, in the Intermediate Depression there are low lands (salt flats and *pampas*) that still have the continental characteristics of the BW climate. The BWn zone has two sectors, one near the coast that is cloudy and another one in the mountain range that is foggy.

The importance of understanding the coastal foggy climates of South America is that in Perú and northern Chile there are important ecosystems of high biodiversity locally called *vegetación de lomas* or fog oases. They are ecologically endangered since the species are very fragile and depend mostly on fog, since annual precipitation is extremely low (Cereceda et al., 1999). Global climate change may be a significant issue for these ecosystems. They can also be good indicators of this planetary change (Rundel et al., 1997; Thompson et al., 2003).

In the past, the *Cordillera de la Costa* was inhabited by people living in small mining villages mainly associated with the exploitation of nitrate, but recently the population has migrated, especially to Iquique, the region’s capital. Over the last 15 years about 50,000 people have moved to Alto Hospicio, a new town located in the upper plateau of this mountain range at about 600 m a.s.l. The majority of the population work in Iquique and hence high traffic

volumes occur on a dangerous road that connects the two cities. This road, through a mega cliff where fog is present, especially during winter and spring, is causing hazardous conditions for traffic.

The objectives of this study were to investigate the climatic variability that occurs within the region as well as the differences in meteorological conditions that prevail at sea level and in the areas influenced directly by the almost permanent stratocumulus clouds of the eastern Pacific. The possibility of identifying and quantifying the spatial extent of the areas involved was also explored.

2. Background

Larrain et al. (2002) reviewed early studies of the coastal climates of the Atacama Desert and reported on fog water collection measured in northern Chile over the last 10 years. Fuenzalida (1971, p. 30) demarcated the extent of the BWn climatic zone as follows: “From the northern limit of the country until approximately the latitude of 30° S, along the littoral, there is a narrow fringe of territory with an altitude less than the height of the tradewinds inversion.” He refers to a stratocumulus (Sc) cloud cover, some hundreds of meters thick, that lies over the littoral during the night and dissipates in the morning, as causing cloudiness with a characteristic diurnal cycle. These clouds generate fog that is sporadic in some sites and frequent in others. Actually, this cycle and the Sc are being studied intensively because of their importance in the climates of the world (Garreaud and Muñoz, 2004).

In Koeppen’s (1948) original classification, the letter “n” is used for fog (*nebel*) with variations in the frequency of occurrence and temperature range denoted as n' , n'' , n''' , n'''' . The author refers mainly to the fog and drizzle events typical of Peru and the foggy areas of Morocco and California, USA.

One of the best descriptions of the climatic conditions of the Atacama – one of the most extreme deserts of the world – was made by Weischet (1975). He analysed the factors that are responsible for the arid climate of this coastal area and refers to it as a “climate of the desert of fog” which is greatly influenced by the inversion layer. He used the *Tillandsia* sp. *lomas* vegetation to locate “the zone of most frequent formation of high elevation fog, which is precisely at the lower limit of the inversion (...) [and defines] the upper limit of the climatic space corresponding to the coastal desert” (Weischet, 1975, p. 369). With reference to the climates of the coast and of the inland *pampas*, he stated the following: “There, where the inversion touches the coastal mountains, marks one of the few places on Earth where two basically different climates are separated from one another by a sharp and fine border line” (Weischet, 1975, p. 369). Both statements will be discussed in this paper, since the results of this research show the differences between the coastal climate of the lowlands and of the high elevation zones, with the former being cloudy and the latter, foggy.

Thompson et al. (2003) reported on meteorological data from five locations in the Pan de Azúcar National Park (25°53' to 26°15' S, 70°29' to 70°40' W), with altitudes of 210 m and 800 m, for the period June 1999 to March 2001. The authors discussed the general and seasonal climate of the park, as well as the spatial distribution of climatic zones and the relationship between climate and vegetation. They showed a clear difference between the climate of the low dry areas, the high fog zone, and inland sites. The park is located about 600 km south of the study area of Tarapacá, and according to Fuenzalida (1971), the entire area is classified as having a B_{Wn} climate. The above information is thus most relevant for the coastal Atacama Desert.

Cereceda and Schemenauer (1991) studied the presence of fog in Chile based on the records of the regular meteorological stations of the *Dirección Meteorológica de Chile*. Forty five stations with at least 10 years of data were analysed and a ranking of the presence of fog was made. The places with the highest frequency (50 or more days of the year) were found to be located in the Intermediate Depression and in the Andes of Central Chile. Only two of these meteorological stations were located in the country's foggy desert and semi-desert area (Los Cóndores and Huasco). Hence, the Chilean meteorological network could not be used to study the climate of areas of frequent fog. In addition, the traditional way of registering fog by visual observation using visibility at a 1 km distance does not reflect either the magnitude of the phenomenon or the potential for the collection of fog water or its benefit to the ecosystem. Consequently, in biogeographical, ecological

and botanical studies of fog ecosystems the lack of climatic information has always been a problem, and in cases where meteorological stations in low elevation zones are used, the results may have led to errors and wrong conclusions.

Schemenauer and Cereceda (1993) installed a Campbell Scientific Inc. portable meteorological station on Cerro Orara (11°49' S–77°09' W, 430 m a.s.l.) in the foggy area of Perú, 3.5 km from the sea. The data recorded from July to November 1990 showed that the mean monthly temperature increased from 13.1 °C in July to 15.5 °C in November. When including the climatological values from the Lima airport, at 11 m a.s.l. and 35 km from Orara, the lapse rate was found to be 0.5° C/100 m in the lower 400 m of the atmosphere. The mean relative humidity was near saturation from July to October, and only dropped slightly in November with the occurrence of drier conditions in late spring. The measured precipitation was 10.5 mm, an amount exceeding the long-term climatological value of 5.9 mm recorded for the same months at Lima airport.

Several geographic studies have been made since 1997 in the Tarapacá Region by the present scientific team. The main objectives were to learn about the spatial and temporal variability of the stratocumulus cloud and fog formation, to analyse the potential of fog water collection, and to identify its importance and role in the ecosystems of the steep cliffs and the coastal mountain range (Cereceda et al., 2007).

Since September 1997, fog water collection has been measured using Standard Fog Collectors (SFC) located at sites at the edge of the cliff near the coast and inland. Fog oases have been studied from a climatological, botanical, entomological, biogeographical and archaeological point of view (Cereceda et al., 1999; Pinto et al., 2001; Pinto and Marquet, 2002; Larrain et al., 2002; Sagredo et al., 2002; Egaña et al., 2004; Larrain et al., 2004; Cereceda et al., 2007). The studies highlight the importance of these relict ecosystems which are endangered due to natural and human factors, and point to the necessity of obtaining climatic information of the fog zone.

3. Methodology and study area

3.1. Methodology

This study was carried out in the Atacama Desert in the region of Tarapacá, northern Chile, in a narrow coastal plain, and in a mountainous area called *Cordillera de la Costa*.

Data were obtained from the *Dirección Meteorológica de Chile* (1899–2005) for three meteorological stations:

Table 1
 Meteorological stations in the Tarapacá Region, Chile

Station	Latitude and longitude	Altitude (m.a.s.l.)	Distance to Iquique (km)	Years of observations	No of years	No of months El Niño	El Niño (%)
Cavancha	20°12' S– 70°11' W	6	–	1963–1980	18	76	35
D. Aracena	20°32' S– 70°10' W	12	45 South	1980–2005	23	86	33
L. Cóndores	20°15' S– 70°07' W	515	5 East	1949– 1968	20	58	24
Alto Patache	20°49' S– 70°09' W	750	55 South	09-2001– 08-2003	2		

Los Cóndores in the mountain range, and Cavancha and Diego Aracena in the littoral plain. Since the stations have been moved over the years, it is not possible to have 30 years of continuous data for the same site. Dickson temperature and humidity sensors were installed at Alto Patache, and the data recorded on an hourly basis for the period September 2001 to August 2003. Fog characteristics were analysed using information obtained from two SFCs which were constructed according to specifications

by Schemenauer and Cereceda (1994a). Both SFCs are located in the mountainous areas of Alto Patache and Cerro Guatalaya, and the data reported on here correspond to that for the period August 1997 through to December 2005. Instantaneous wind direction and wind speed were measured using a vane and manual anemometers during the periodical field trips to measure the water collected at the SFC at Alto Patache. For each year there were more than 30 instant observations taken from the same site. The

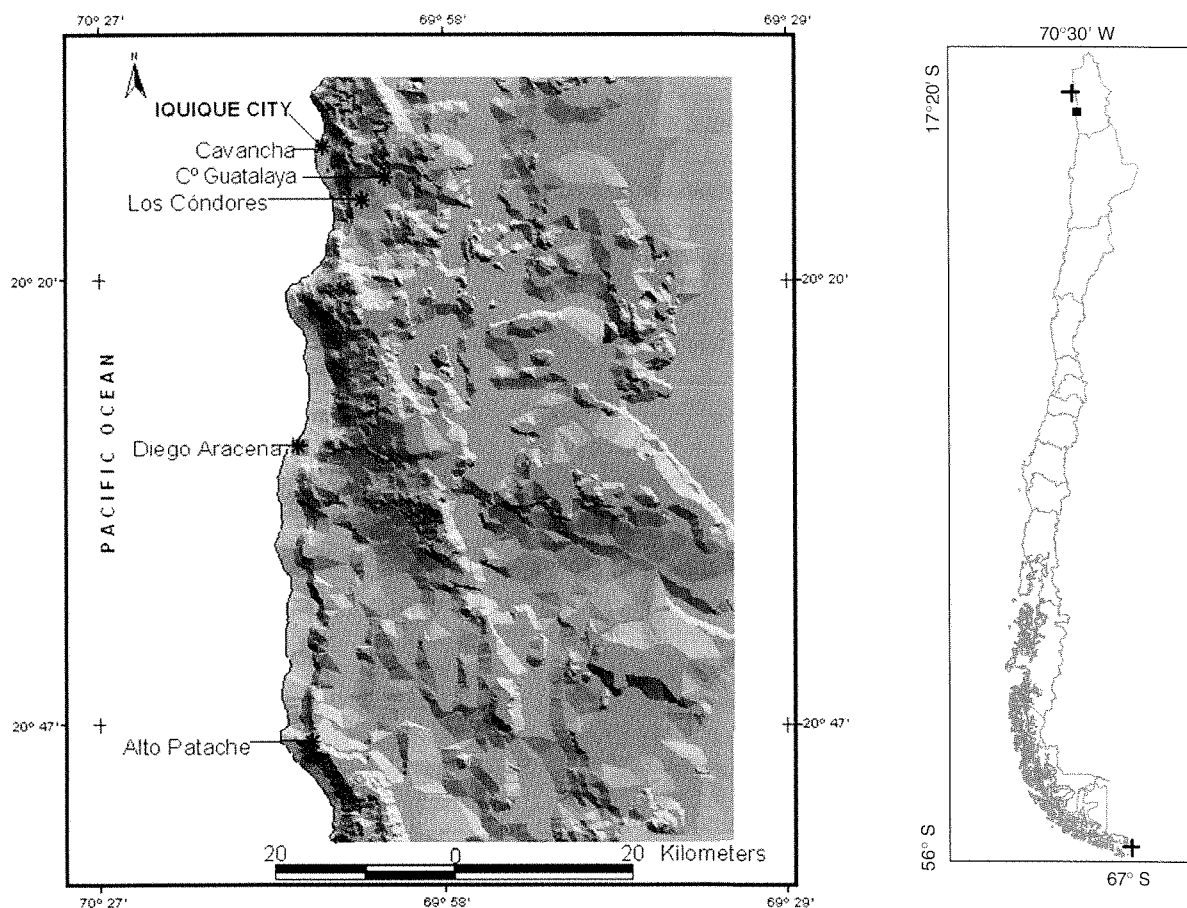


Fig. 2. The study area: littoral plains, coastal range and meteorological stations.

Table 2
El Niño occurrence in the second half of the 20th century (ENSO)

Period	Duration (months)	Period	Duration (months)	Period	Duration (months)	Period	Duration (months)
Aug 1951–Feb 1952	7	May 1965–Jun 1966	14	Jul 1977–Jan 1978	7	Mar 1991–Jul 1992	17
Mar 1953–Nov 1953	9	Sep 1968–Mar 1970	19	Oct 1979–Apr 1980	7	Feb 1993–Sep 1993	8
Apr 1957–Jan 1958	15	Apr 1972–Mar 1973	12	Apr 1982–Jul 1983	16	Jun 1994–Mar 1995	10
Jun 1963–Feb 1964	9	Aug 1976–Mar 1977	8	Aug 1986–Feb 1988	19	Mar 1997–Mar 1998	12

(Trenberth, 1997; Aceituno, 2005).

statistical analysis was simple, based mostly on averages and maximum and minimum values.

Mean annual precipitation data were obtained from historical references, reports of the Fuerza Aérea de Chile (1965) and annals of the *Dirección Meteorológica de Chile* (1949–2005) (Table 1).

The fact that the observation periods differ for the different stations is a limitation since it is not possible to compare meteorological situations. The data from Alto Patache cannot be used to characterize its climate because it consists of only 2 years of information, but the results are indicative of the climatic trends.

To calculate the surface area of the foggy zone, GIS was used in a wider zone that included the study area (19°40' S–21°30' S to 70°10' W–69°40' W). The variables selected included the continental surface covered by low clouds, as derived from GOES satellite images (10,047 km²) according to Farias et al. (2005), and altitudes of between 650 m a.s.l. and 1200 m a.s.l., based on data of the SFCs and the presence of *Tillandsia* sp. vegetation. The geomorphological description was done using 1:250,000 and 1:50,000 topographical maps, and the fog analysis was based on information given in Schemenauer and Cereceda (1994b).

3.2. Study area

Three important features are present in the study area: From west to east there is firstly a long narrow littoral plain with an average width of 3 km, then a steep mega cliff with summits between 500 m a.s.l. and 1000 m a.s.l., and thereafter a mountain range with peaks of more than 1500 m a.s.l. that ends in the Intermediate Depression, 50 km from the sea (Fig. 2).

The Cavancha station was located in the city of Iquique in the littoral plain, very close to the sea. The area is in a bay bordered by a small peninsula. In this sector the plain is 2.5 km from the cliff. The Diego Aracena station is located on the littoral plain at the Chucumata point, where the coastline and an abrupt 650-m high cliff are about 3 km apart. The station is only 2 km from the sea at an altitude of 12 m a.s.l. The Los Cóndores meteorological

station was located between two *pampas* or plains in the *Cordillera de la Costa*, at one end of a fog corridor which stretches for approximately 15 km from west to east and is surrounded by 1000-m high mountains that rise gradually from 500 to 800 m further inland. In a similar area but 7 km to the east, is the SFC of Cerro Guatalaya. It is situated at 1062 m a.s.l., at the summit of a hill, 12 km from the coastline in Iquique. The Alto Patache SFC is at 850 m a.s.l., 3.5 km from the coastline, on the edge of the cliff facing into the prevailing southerly winds. The Dickson instruments were placed nearby in a small *pampa* close to the edge of the upper part of the cliff, at an elevation of 750 m a.s.l. The cliff forms a crescent that faces south and rises from a plain that is 5 km long and 2–5 km wide.

The stations of the littoral plain represent low elevation sites whereas Patache, Los Cóndores and Guatalaya are denoted as high elevation sites.

At the low elevation stations, one third of the records reflect data recorded during El Niño years, while at Los Cóndores, El Niño was present during only 5 of the years. In the second half of the 20th century, El Niño occurred 16 times with the longest lasting ones (19 months) occurring from 1968 to 1970 and again from 1986 to 1988. The 1982–1983 El Niño was the strongest ever recorded (Trenberth, 1997 and Aceituno, 2005) (Table 2).

4. Results

4.1. Temperature

The temperature differs substantially between the stations located in the littoral plains and those in the mountains, which are much colder. The difference between the mean annual temperature averages for Diego Aracena and Los Cóndores is 4.0 °C — Diego Aracena being the warmer of the two. Diego Aracena's mean annual temperature is 6.0 °C warmer than that of Alto Patache (Table 3). The explanation for this difference in temperature is related to both altitude and the influence of the stratocumulus clouds.

The two stations located on the coastal plain differ from one another with respect to all the variables investigated.

However, the difference in data collection period should be taken into account in this analysis. Even though both stations experienced the El Niño phenomenon (for approximately 30% of the period), in 1982–1983 Diego Aracena measured the strongest El Niño of the century, and it was also present from 1986 to 1988 and from 1991 to 1992. The differences shown by the high elevation stations are normal (Alto Patache is 300 m higher than Los Cóndores).

The averages of the mean annual maximum temperatures are interesting. There is a difference of 2.3 °C between Cavancha in Iquique and Los Cóndores even though they are only 5 km apart and a difference of 4.9 °C between Diego Aracena and Alto Patache which are 10 km apart. The dominating factors are again elevation and fog (Sc).

Even though the highest recorded temperatures are similar at all the stations, this is not the case with the average of the mean annual minimum temperatures and the lowest recorded temperatures. It is interesting to note that a minimum temperature of 1 °C was recorded for several years at Los Cóndores. This is unexpected for an intertropical location so close to the ocean, since such a low temperature is more typical of continental deserts. According to the averages of both minimum and absolute annual data, Alto Patache experienced a maritime influence due to its proximity to the coastline and the frequency of fog.

Table 3
Temperature records for the meteorological stations

Temperature (°C)	Cavancha	Diego Aracena	Los Cóndores	Alto Patache (2 years)
Average of the mean annual temperatures	17.7	18.5	14.5	12.5
Average of the mean annual maximum temperature	21.1	22.0	18.8	16.9
Average of the mean annual minimum temperature	14.8	16.1	10.1	9.6
Highest recorded temperature	29.4	31.2	30.0	30.5
Lowest recorded temperature	3.9	7.6	1.0	4.5
Average of daily temperature range	5.6	6.5	8.3	7.7
Average of daily difference in the coldest month (8 and 14 h)	2.6	3.2	5.1	–
Average of daily difference in the warmest month (8 and 14 h)	3.4	3.2	4.0	–

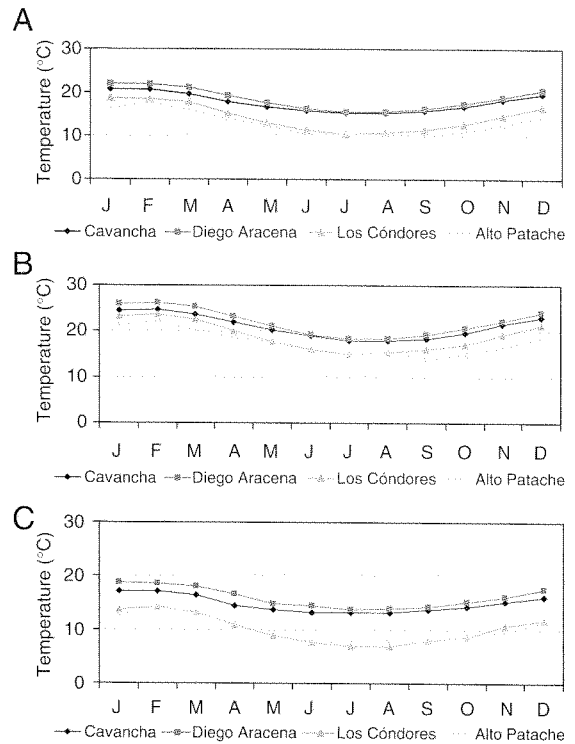


Fig. 3. A) mean monthly; B) mean monthly maximum and C) mean monthly minimum temperatures.

The temperature differences between 08:00 and 14:00 are small at all the stations in the coldest and warmest months. The temperature differences never exceed 5 °C, which is typical of climates with a marine influence. The summer months, from December to March, are warmer in the coastal plains than in the mountains. The coldest months are from June to September with Alto Patache experiencing the highest frequency of fog during September. March still maintains the conditions of the sunny summer days. The fluctuations in the average of the mean maximum and minimum temperatures for the other months of the year show the same trend. However, there is a bigger difference in the minimum values between the littoral plains stations than between those on the mountains (Fig. 3).

In Diego Aracena, the highest recorded monthly temperatures indicate that during 8 months of the year the temperature exceeded 28 °C, reflecting an intertropical coastal climate. In comparison, such high temperatures occurred during 4 months only at Los Cóndores and for 2 months only at Alto Patache (Appendix 1).

4.2. Relative humidity

The mean annual relative humidity for all stations is high and reflects the coastal climate BWn. It exceeds the

Table 4
Mean annual and hourly values for relative humidity (%)

Station	Annual	08:00	14:00	19:00
Cavancha	73	77	66	76
D. Aracena	68	71	61	73
L. Condores	76	81	68	79
A. Patache	80	86	73	81

value of 68%, with Alto Patache having the highest average (80%). The difference between the two low elevation sites is remarkable, probably due to the different periods in which the data were collected (Table 4).

The mean hourly relative humidity shows a drop at 14:00 in all the stations, which coincides with the warmer temperature. The frequency of the presence of low clouds shows a minimum expansion and continental penetration precisely at noon (Farias et al., 2005). This is more evident at Alto Patache, where the mean relative humidity at 08:00 is 86%; the highest mean value during the 2 years of measurement occurred at 08:00 with 86%. Such information is important when related to the presence of fog, when the air mass is at 100%, confirming that fog has its highest frequency at night and early morning in that area.

The mean monthly distribution of relative humidity shows a marked seasonal trend, and in some months it is very similar at all stations, with the exception of Alto Patache. It is interesting to note that the mean monthly relative humidity in September and October in Alto Patache is over 88% (Fig. 4).

4.3. Precipitation

Because the data were not obtained simultaneously, this parameter was not used in this study to analyse climatic differences between stations. However, it is important to examine precipitation for the characterization of the area’s climate.

The highest average precipitation occurred in Los Cóndores — less than 2 mm during 21 years of measurements. Rainfall was only registered during 4 of the years, and drizzle, with less than 1 mm precipitation, during 5 other years. It would have been expected that Los Cóndores would have more drizzle, since low clouds and fog are frequent at the altitude where the station is located (Table 5).

The highest annual precipitation in the area occurred during the El Niño years of 1957 and 1992. It is noteworthy that in 1992 almost all the water fell in 24 h (9.1 mm).

Because rainfall data are so important for climatological and biogeographical studies, the annual precipita-

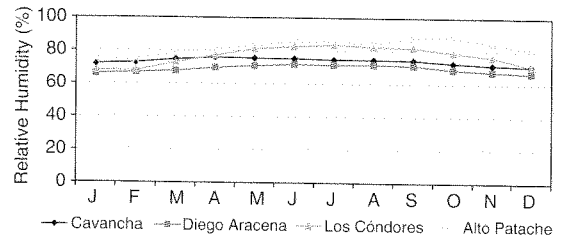


Fig. 4. Mean monthly relative humidity.

tion from 1899 to 2005 is analysed here. Precipitation occurred in only 41 of these years (38%), and the average for the entire period was 1.7 mm (Fig. 5). The statistical median and mode was 0.0 mm.

In the first half of the 20th century, rainfall was more frequent and abundant than in the second half; in 1940 there were 20 mm of rain and in 1905 there were 15 mm. There was a “rainy” period that extended from 1920 to 1940, with an average precipitation of 5.9 mm, while from 1946 to 1956 there were 10 years without rain. It is remarkable how rain has decreased over the years. If rainfall data for the last 30 years at Cavancha and Diego Aracena are analysed together, the average is less than 1 mm per year (0.8), and this average includes the 11 mm rain which fell in 1992, exceptional for the area.

There is a strong relationship between precipitation and El Niño years. Of the 15 years in which rain occurred in the second half of the 20th century, ten were during an El Niño year, with the highest volumes and intensities occurring during those years. It is interesting that in the strong El Niño that began in April 1982 and ended in July 1983, rain did not occur in the first year, but in 1983 7 mm fell and in 1984 3.6 mm recorded, significant amounts for the study area.

There are overlapping data in Cavancha and Los Cóndores from 1963 to 1968. At the former station it rained in only one year (7 mm in 1965), while in the

Table 5
Annual and maximum precipitation (mm) values for three stations

Station and years	Average of the annual precipitation amounts	Highest annual precipitation amounts	Highest daily precipitation amounts and year of occurrence
L. Condores (1949–1969)	1.6	16.2	9.0 — 1957
Cavancha (1970–1980)	0.3	1.5	1.1 — 1977
D. Aracena (1980–2005)	1.3	11.0	9.1 — 1992

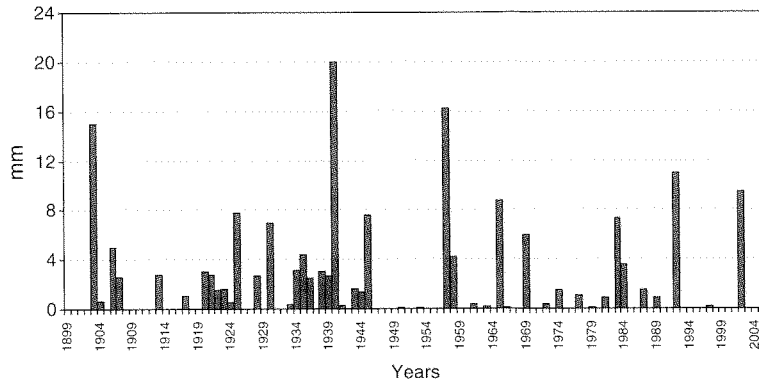


Fig. 5. Annual precipitation at Cavancha and Diego Aracena. (1899–2005). Data from 1899–1980 from Cavancha; 1981–2005 from D. Aracena.

mountain, rain and drizzle occurred in 4 years (8.7 mm in 1965). These data indicate the importance of topography, especially in relation to orographic rain, Sc and fog.

4.4. Wind

At the locations studied, wind is variable with respect to prevailing directions and changes during the day. At

Los Cóndores, calm conditions (no wind) are usual in the mornings, even though during some months light winds from the east (inland breeze) are present at 08:00. Rather similar conditions occur at Alto Patache, and in general the instantaneous observations recorded during field trips in the winter months indicate that at 08:00 windless or light breezes frequently prevail from the east and northeast.

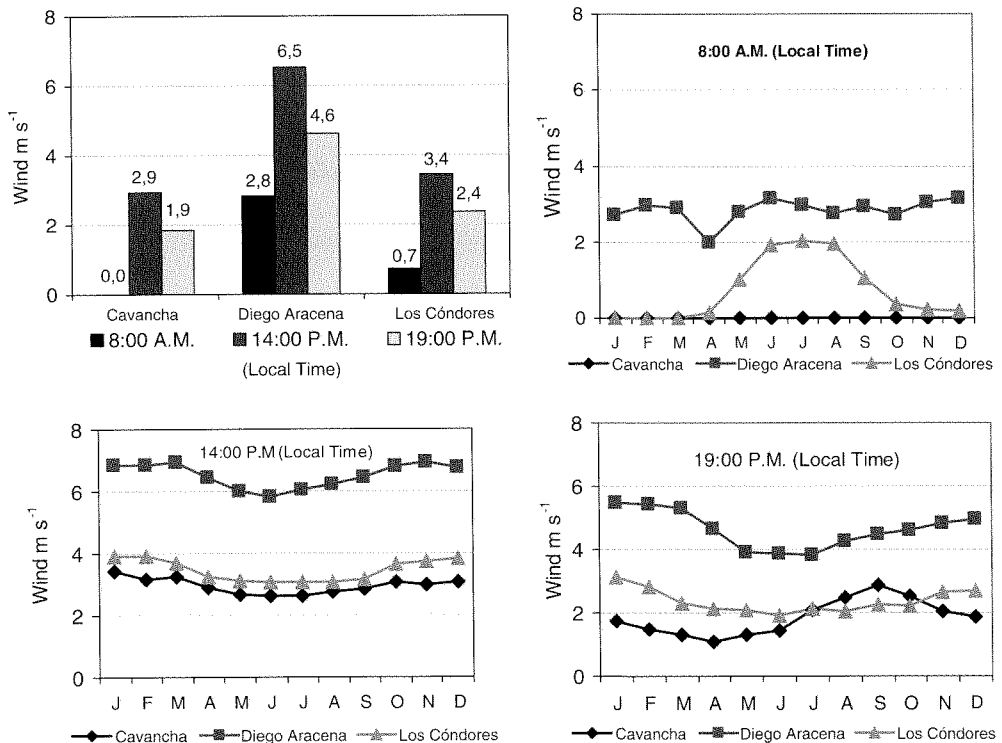


Fig. 6. Mean annual and monthly wind speed at 8:00, 14:00, 19:00.

At Los Cóndores, relief is decisive for wind direction, since the site is located in a very marked corridor between mountains. The data show the sea-breeze component, with winds from the west at 14:00 and 19:00, when the big inland *pampa* of the Intermediate Depression acts as a low pressure center that increases wind velocity at the time of maximum warming.

It is interesting to note that at 08:00 the wind at Diego Aracena comes from the south. At 14:00, both littoral plain stations experience south westerly winds which then changes direction to southerly at 19:00 at Diego Aracena. At Alto Patache, winds blow almost constantly from the south. Relief is an important factor in this meteorological aspect in controlling wind direction while the oceanic conditions influence some of these shifts (Appendix 1).

With regard to wind speed, there is a marked difference between Diego Aracena and the other two stations. It should be kept in mind that Diego Aracena is located at Chucumata point, a large flat tract of land that extends into the ocean and which is exposed to the winds coming from the sea. During every month, Diego Aracena has strong winds at 14:00, with mean speeds exceeding 5.6 m s^{-1} . Similar conditions occur at Alto Patache, where prevailing winds almost always come from the south and exceed 4.0 m s^{-1} after midday (except in winter). The geographical setting of Alto Patache in Patache point is similar to that of Diego Aracena (Fig. 6).

4.5. Fog

Traditionally, the presence of fog at a location is determined by counting the number of days in the year in which there is at least one period where the visibility is less than 1 km. For this research such information was only available for Los Cóndores, where over an 18 year period, the average annual fog day frequency was only 20 days (Cereceda and Schemenauer, 1991). This number is certainly far from accurate.

A survey of the spatial and temporal behavior of fog was conducted during the last 8 years in the study area, and its results are reported in Cereceda et al. (2007). Large differences in the spatial variability of fog were found between Alto Patache and the inland Cerro Guatalaya site. The annual average amount of fog water collected at the former was $7.0 \text{ L m}^{-2} \text{ day}^{-1}$ and at the latter, $0.8 \text{ L m}^{-2} \text{ day}^{-1}$. These amounts show the importance of elevation and distance from the ocean. The higher SFC is located near the top of the cloud, where the influence of the

inversion layer is apparent and/or the sun evaporates the droplets.

In a fog water collection study conducted at Alto Patache at intervals of 100 m between sites with altitudes between 350 m a.s.l. and 850 m a.s.l., the 750-m and 850-m altitudes showed the best fog water collection potential. From 650 m downslope, fog water collection was negligible during all months of the year.

5. Discussion

Differences were found between the climatic characteristics of the littoral plains and the mountain range in the Tarapacá Region between Iquique and Alto Patache. In Chile, these areas have been traditionally described as “coastal desert climate with abundant cloudiness”. Abundant cloudiness is indeed present in low elevation zones, but in high areas, fog is more frequently present. The factor that accounts for the differences between the high and low elevation climates is the presence of the almost permanent stratocumulus clouds, which in Alto Patache and Cerro Guatalaya are experienced as advective fog. At Los Cóndores the cloud base is near the surface, so sometimes the region is blanketed in fog and at other times it is below the Sc. In the cliffs and at certain altitudes in the mountain range, orographic fog is formed in high hill cap clouds.

If vegetation is used as an indicator of environments with frequent fog, the foggy zone should be limited to areas falling between the altitudes of 650 m a.s.l. and 1200 m a.s.l., since fog oases are typical of this altitudinal range. Fog measured in the regions of Tarapacá and Antofagasta shows that the best areas for fog water collection are in Cerro Moreno at 1150 m a.s.l. and Alto Patache, but good rates have also been found at 750 m a.s.l. and 600 m a.s.l. at other locations (Larrain et al., 2002).

The area located between the altitudes where fog is present in the *Cordillera de la Costa* was determined by means of a digital elevation model (DEM). In the coastal range from Iquique to 70 km south of Alto Patache, foggy weather it was found to occur in 75% of the 10,047-km² area (650–1200 m a.s.l.). In Tarapacá, the coastal range extends 300 km north–south and an average of 50 km west–east, covering an area of more than 15,000 km². If 75% of this area is different from the coastal plains, then it is important to make a distinction between both areas and classify them as different climates.

The calculations used to determine the areas occupied by a coastal desert with abundant cloudiness and that

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The spatial and temporal variability of fog and its relation to fog oases in the Atacama Desert, Chile

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Abstract

Fog has been studied in the Atacama Desert of Chile for the past ten years. This paper analyzes its temporal and spatial variability, relying in part on satellite images (GOES) to analyze the frequent orographic fog and the low cloud deck (stratocumulus, Sc) that generates advective fog in the area. Fog water fluxes were measured with Standard Fog Collectors (SFC). Field trips and observers provided information on cloud top and base and the presence of fog. Vegetation in fog oases were used to confirm the results of these surveys.

The Sc moves onshore into the continent with different intensities depending on season and time of day. The maximum spatial extent occurs during winter and at night. Fog is frequent in the coastal cliffs, where fog water fluxes of $7.0 \text{ L m}^{-2} \text{ day}^{-1}$ were measured using a SFC. It is less frequent 12 km inland, where the collection rates were less than $1 \text{ L m}^{-2} \text{ day}^{-1}$. The height of the fog collector above the ground affected the collection rate. The highest fog water fluxes were recorded at Alto Patache at altitudes of between 750 and 850 m a.s.l. The growth or thickness of the cloud is important in the collection of fog water. The information that GOES provides on the altitude of the top of low clouds is used to analyze this factor. Fog oases are described and analyzed in relation to how the geographical location of fog influences the growth of vegetation.

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1. Introduction

Since 1997, geographical studies about fog and ecosystems have been carried out in the *Cordillera de la*

Costa, a coastal range of the Atacama Desert, Chile. Fog has been investigated with respect to its origin, factors that define its variability, its potential for water collection, and the importance of low clouds (stratocumulus, Sc) in its formation (Cereceda et al., 2002; Larrain et al., 2002; Osses et al., 2005a,b). Fog oases have been surveyed in terms of geographic location, geomorphology, substrate and vegetation (Cereceda et al., 1999; Pinto et al., 2001; Larrain et al., 2002; Egaña et al., 2004), and systematic studies of insects have also been conducted (Sagredo et al., 2002). In addition,

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