The Occurrence of Fog in Chile

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ABSTRACT

The topography in Chile is extremely complex and many types of fog are found; both factors complicate the presentation of the data. Despite this, measurements from standard meteorological stations suggest a latitudinal maximum in fog frequency between 35° and 40°S for coastal stations. This is supported by data from inland stations in Chile and the available observations from Argentina on the Atlantic coast of South America. Along the Chilean coast the average number of days with fog ranges from 3 to 59 per year. The variation in fog frequencies is related to persistent synoptic-scale circulation patterns and to ocean currents.

Specialized fog observations were made at three remote locations in northern Chile to determine fog frequencies on the coastal mountains. The sites were in a very arid region (26°–28°S) near a large-scale fog-water collection project. Fog frequencies as high as 189 days per year with another 84 days of patchy fog were reported at an altitude of 860 m. These are 3–15 times higher than at low-elevation coastal locations at similar latitudes. Clearly, observations from standard meteorological stations are not suitable for estimating higher-elevation fog frequencies.

1. Introduction

In a country with a topography as diverse as Chile, it is very difficult to discern patterns in fog frequency. Advection fog occurs in some sections along the coast, radiation fog can occur in interior valleys, and both the coastal mountains and the Andes experience fog when they are cloud covered. As a result, fog can occur practically anywhere in the country, but the local topography and sources of water vapor play a very large role in determining the fog frequency at any point.

Chile's vast, arid, northern regions lead to two very different reasons for examining fog frequencies. The first is the more traditional one of risks to air and road transport; to this air pollution problems can now be added. The second is decidedly nontraditional. A serious effort is being made to use high elevation coastal fogs as a water resource for Chilean desert villages (Schemenauer 1988; Schemenauer et al. 1988). For the first purpose, the normal observations at city airports can prove acceptable. But the latter needs specialized observations that are incompatible with standard urban measurements. In a sense, all published fog datasets (e.g., Stone 1936; Court and Gerston 1966; Peace 1969) are biased in that they mainly represent highly populated, generally lower elevation areas. Information on fog in remote areas comes from specialized studies, such as those on acidic fog (Saxeena et al. 1989), the capture of fog by vegetation (Kerfoot 1968), or studies of fog collection by man-made collectors (Cereceda-Troncoso et al. 1988; Schemenauer et al. 1987; Schemenauer and Cereceda 1988). This paper presents the currently available data on fog occurrence in Chile and discusses the compatibility of the different datasets.

2. The observations

a. Meteorological stations

Cereceda-Troncoso (1989) presented a first look at the distribution of fog in Chile at standard meteorological stations, which report fog when the visibility is 1 km or less. The Chilean Meteorological Annuals, which have only been published for the period 1940–1978, are the source for the data. During most of this period observations were made three times a day. A fog day was defined as a day where there were one or more observations of fog. The fog frequency calculated for each site is the number of fog days divided by the number of days of observation.

More than 200 stations have fog observations, but only 42 have at least 10 years of acceptable and com-

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parable data. These stations span a tremendous range of latitudes from Iquique (20°15′S) in the north to Base Antártica (63°19′S) in the south. Isopleths of fog frequency with so few stations would be unrealistic, and a map showing ranges of fog frequency will not be presented here.

b. Special coastal fog observations

In order to determine the fog frequency on coastal mountain ranges extending up to 2000 m in altitude, a number of special observation programs were undertaken. These consisted of a paid observer taking (within a few minutes of 0800 LST) daily observations of a particular point on the mountain ridge and noting whether it was in fog, clear of fog, or whether there was some patchy cloud touching the mountain. In practice this means that a point above cloud base was considered to be covered in fog. The relatively consistent cloud-base heights near 400 m (Fuenzalida et al. 1989a) along this part of the coast, and the cloud thicknesses of approximately 400 m justify this assumption. The use of paid observers is the only low-cost option available for high elevation fog observations along the remote northern coast of Chile. Even if fog-water detection instrumentation could be purchased, past experience has demonstrated that site security is impossible to maintain without a permanent caretaker.

In these coastal locations, fog on the hills is produced either by onshore movement of marine stratocumulus decks or by orographic effects associated with the late afternoon sea breeze. The periods of observation are not extensive but they do generate numbers that will prove useful for the extension of the results (Fuenzalida et al. 1989b) from a fog collection experiment, which has operated for 3 yr near La Serena in the north of Chile. The El Tofo field site in Chile uses 50 polypropylene mesh fog collectors, each 4 m high × 12 m long, to produce an average of about 7200 l of water per day throughout the year. This has been accomplished during a 3-yr drought period when the average annual rainfall has dropped from the normal of 70 mm to values of 10, 50, and 10 mm. The site is at an altitude of 780 m and is 5 km from the coast. A 6.5-km pipeline to a 100 000-l storage tank in a coastal village of 330 people will be completed in mid-March 1991.

3. Results

a. Standard meteorological stations

The number of standard meteorological stations that had acceptable fog observations varied from region to region. Santiago and the lake region had multiple stations; in contrast, the regions of Tarapacá, Antofagasta, La Araucanía, and Magallanes had only a single station each. Of the 42 usable stations, 24 were on the coast and 18 in the interior (Figs. 1 and 2).

Table 1 lists the 24 coastal stations from north to south with the average number of days with fog each year, the number of years of record, the latitude and longitude, and the altitude. Table 2 lists similar data for the 18 stations in the interior. Clearly the database is heavily weighted towards stations along the coast and in the great Intermediate Depression. The Andes, for example, has barely any representation at all. In the Andes, especially in summer (December—March), one might expect high frequencies of orographically produced fogs that are not reported due to a lack of stations.

The coastal station data extend from 20° to 63°S. The three stations with the highest fog frequencies are in a narrow latitude range around 38°S: Punta Tumbes (36°37′S) with 59 days per year, Santa María (36°59′S) with 54 days, and Valdivia (39°48′S) with 53 days. Fog frequencies generally decrease both north and south of these latitudes but some sites are exceptions. Figure 3 is a plot of the coastal data from Table 1 averaged into 5° latitude segments. Sites 23 and 24 are omitted because they have the only observations in their latitude range. The maximum frequency is clearly between 35° and 40°S and averages 36.4 fog days per year. The inland data from Table 2 are also plotted on Fig. 3 and show higher values in the 35°–40°S range than in the 30°–35°S range, supporting the trend in the coastal data. Sites 1 to 3 in Table 2 were omitted because these inland stations receive fog as a result of low cloud, which pushes up the transverse valleys from the coast and are atypical of inland stations. Sites 16 and 18 were the only ones in their latitude range and were also not plotted.

It is informative to look at what happens at comparable latitudes on the Atlantic coast of South America. Of the five coastal stations in Argentina (Table 3), by far the highest fog frequency is 61 days per year at Mar del Plata (37°56′S). The frequencies drop dramatically to the north and south. The situation is remarkably similar to that on the coast of Chile with even the maximum values (59 in Punta Tumbes, Chile, 36°37′S; and 61 in Mar del Plata, Argentina, 37°56′S) being almost identical.

At inland stations in Chile, maximum fog frequencies are at Panimávida (35°45′S) with 89 days and Lonquimay (38°26′S) with 73 days. Vallenar (28°35′S) with 76 days also has a high fog frequency but, as was noted previously, it is unusual in that it is influenced by low cloud pushing up the transverse valleys from the sea. If one includes Vallenar, the latitude range is more spread out than for coastal stations, reflecting the varying physiography, but still two of the three stations are near 38°S (the approximate midpoint of the 35°–40°S latitude interval).

In Argentina (Table 4), maximum frequencies for inland stations are at Azul (36°45′S) and Rosario (32°55′S), each with 44.1 days, and Paraná (31°47′S) with 27.4 days. Again the latitude range is spread out

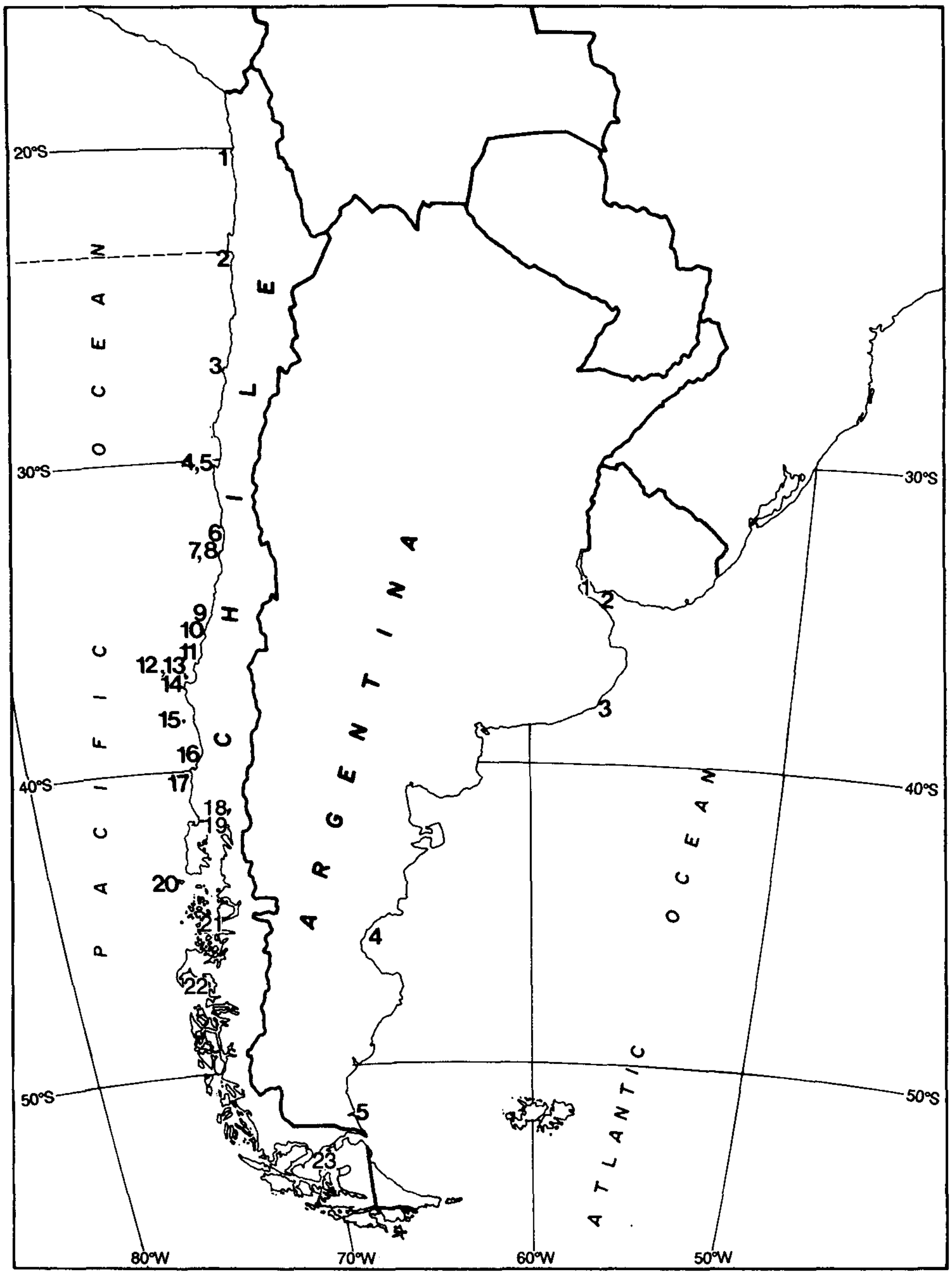

FIG. 1. A map of Chile and Argentina showing the coastal meteorological stations discussed in the text (Tables 1 and 3).

but the highest values are found at 33° and 37°S. It is not possible to say if these represent a maximum frequency since data are not available for higher latitude inland stations in Argentina.

The general pattern to the fog frequencies in Chile is for a maximum in coastal and perhaps inland values at about 38°S. This basic pattern seems to appear in the Argentinian data to the east of the Andes as well. Possible reasons for this latitudinal maximum will be discussed in the following.

b. *Specialized fog observations*

In a study of the suitability of fog-water collection at coastal locations in the north of Chile, observers noted, at approximately 0800 LST each morning, whether the crest of the ridge at the site was in thick fog, was clear of fog, or was in thin or patchy fog. Interpretations of the data are of necessity limited because of the short periods of record and the discontinuities in the records. However, these are the only high ele-

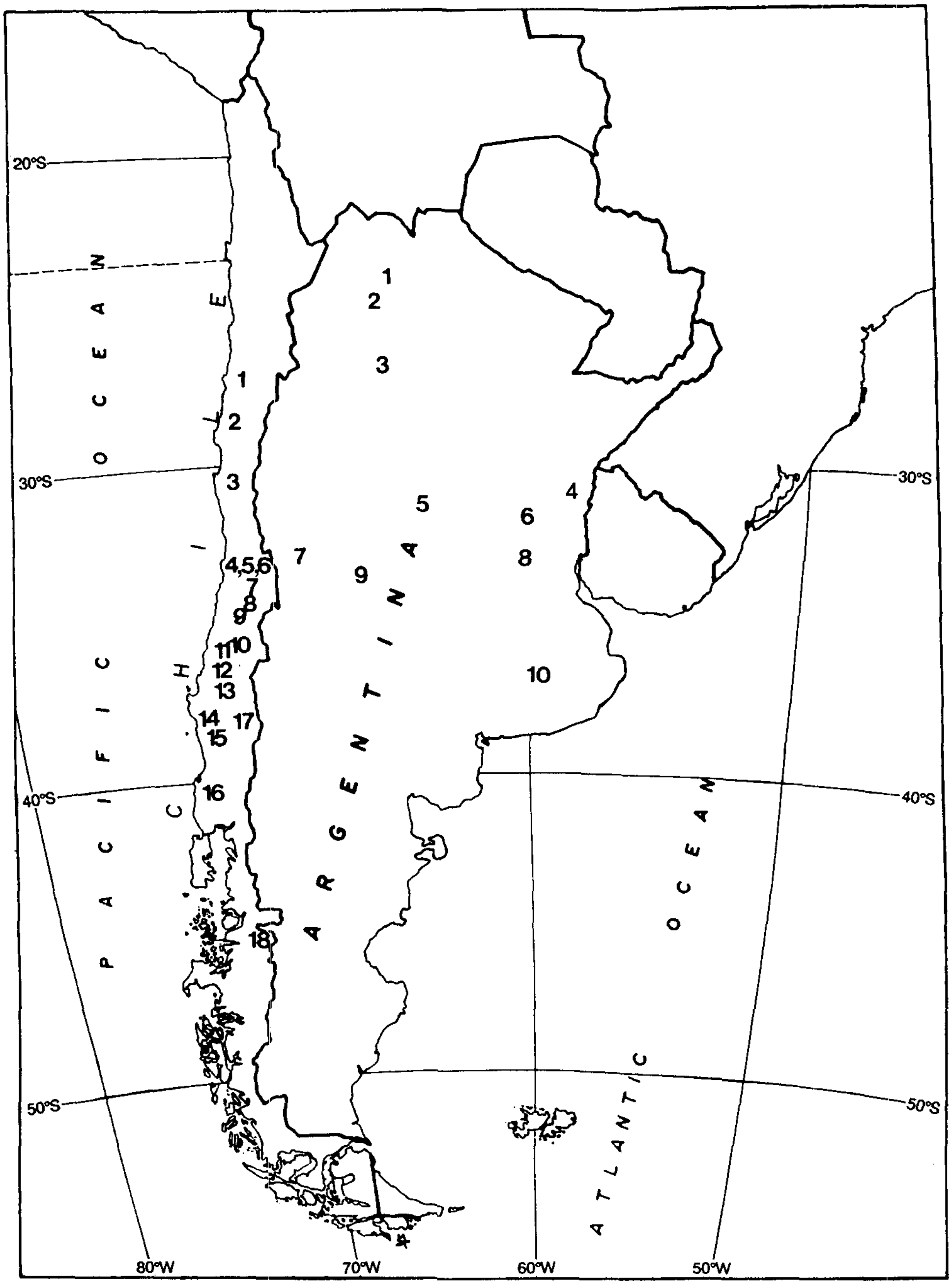

FIG. 2. A map of Chile and Argentina showing the inland meteorological stations discussed in the text (Tables 2 and 4).

vation fog frequency records that exist for remote coastal sites in Chile, and they deserve examination. The discontinuities in the data occurred when the site operator was unavailable. The sites were remote fishing villages and the operators worked on a part-time basis. When family reasons or the demands of work caused them to leave the site, the data were lost for a period of time. The sites were without power, telephones, and regular mail service making direction from Santiago (800 km away) very difficult. Because the observations are from a fixed time of day, the actual average number of days with fog per month or per year will exceed the values presented here by some unknown amount; i.e., fog may not occur at 0800 LST but at some other time of the day and not be recorded. This is not peculiar to only this dataset; the same situation applies whenever observations at fixed times are used; e.g., the standard meteorological observations or other fog observations from research stations such as the Gobabeb site (Schulze 1969) in Namibia. The lack of complete years

TABLE 1. Average number of days per year with fog at coastal stations in Chile. Los Cóndores is included because it is in the coastal mountains and is strongly influenced by maritime air.

Number	Site name	Fog days	Years	Lat (S)	Long (W)	Alt (m)
1	Los Cóndores	20	18	20°15′	70°07′	515
2	Antofagasta	3	26	23°26′	70°28′	119
3	Caldera	12	16	27°03′	70°58′	14
4	La Serena	38	15	29°54′	71°15′	32
5	Pta. Tortuga	20	19	29°56′	71°22′	25
6	Quintero	16	16	32°47′	71°32′	07
7	Punta Angeles	36	29	33°01′	71°39′	41
8	El Belloto	39	15	33°03′	71°24′	121
9	Constitución	16	17	35°20′	72°25′	06
10	Cabo Carranza	30	10	35°32′	72°32′	30
11	Punta Tumbes	59	21	36°37′	73°06′	100
12	Talcahuano	35	10	36°43′	73°07′	84
13	Concepción	25	11	36°46′	73°03′	08
14	Santa María	54	14	36°59′	73°32′	79
15	Isla Mocha	19	16	38°22′	73°54′	30
16	Valdivia	53	18	39°48′	73°14′	13
17	Punta Galera	28	10	40°01′	73°44′	40
18	El Tepual (Puerto Montt)	42	17	41°26′	73°06′	84
19	La Chamiza (Puerto Montt)	12	11	41°29′	72°40′	15
20	Isla Guafo	47	12	43°32′	74°45′	140
21	Puerto Aisén	12	23	45°24′	72°42′	11
22	Cabo Raper	9	18	46°50′	75°36′	40
23	Punta Arenas	7	12	53°00′	70°58′	37
24	Base Antártica	37	10	63°19′	57°54′	10

TABLE 2. Fog frequencies at inland stations in Chile.

Number	Site name	Fog days	Years	Lat (S)	Long (W)	Alt (m)
Transverse valleys of the Norte Chico						
1	Copiapó	35	19	27°21′	70°20′	370
2	Vallenar	76	18	28°35′	70°46′	469
3	Ovalle	41	18	30°24′	70°11′	371
Intermediate depression of the central zone						
4	Pudahuel (Santiago)	70	11	33°23′	70°47′	475
5	Quinta Normal (Sant)	36	18	33°26′	70°04′	520
6	Los Cerrillos (Sant)	38	12	33°30′	70°42′	506
7	Rancagua	33	11	34°10′	70°45′	482
8	San Fernando	37	11	34°35′	71°00′	350
9	Curicó	58	19	34°59′	71°13′	211
10	Panimávida	89	19	35°45′	71°24′	175
11	Linares	46	15	35°51′	71°35′	157
12	Chillán	43	20	36°36′	72°02′	118
13	Los Angeles	17	17	37°28′	72°21′	120
14	Traiguén	50	12	38°15′	72°40′	170
15	Temuco	54	14	38°45′	72°35′	114
16	Osorno	55	10	40°32′	73°11′	24
In the Andean Cordillera						
17	Lonquimay	73	12	38°26′	71°15′	900
Austral transandean zone						
18	Balmaceda	16	18	45°54′	71°43′	524

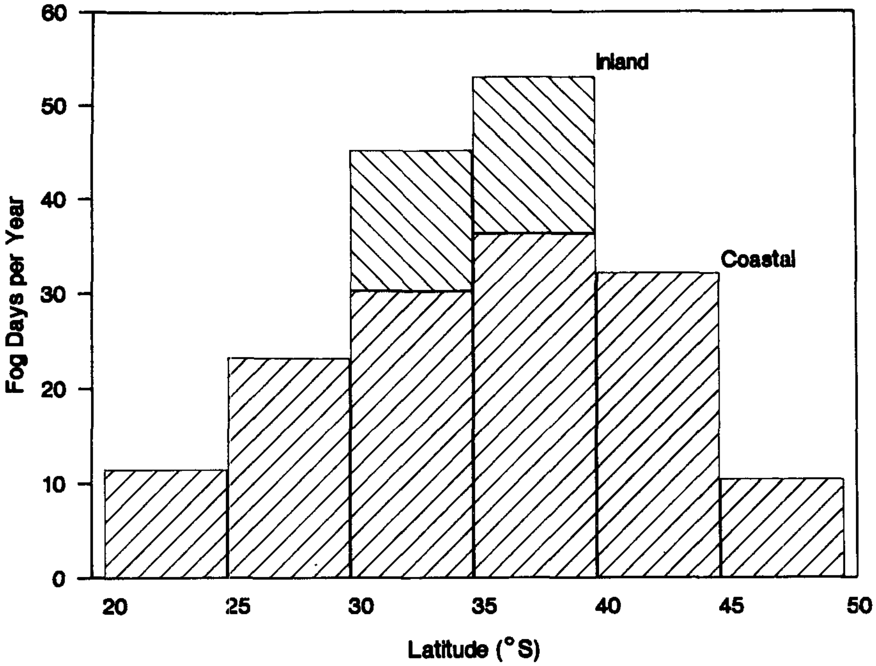

FIG. 3. The average number of fog days per year as a function of latitude for coastal (Table 1) and inland (Table 2) stations in Chile.

of data makes the extrapolation to annual fog percentages approximate. However, the data are considered sufficient to demonstrate that they are markedly different from those for the standard low elevation stations.

Tables 5–8 present monthly observations from two coastal sites and one site under the influence of coastal fogs. There were 241 days of observations at Carrizal Bajo (28°08′S) between January 1988 and February 1989. The ridgeline at 700 m was in fog 42.3% of the time, in the clear 28.6% of the time and in patchy fog 29.1% of the days. On an annual basis this would lead to 154 days with fog plus another 106 days with patchy fog. The other coastal site, Obispo (26°38′S), also has high percentages of fog: on 362 observation days from June 1987 to January 1989, 51.7% had fog, 25.4% were clear, and 22.9% had patchy fog. This would result in 189 fog days per year, 93 clear days, and 84 days of patchy fog.

The Las Bombas site (26°04′S) is different in that it is 25 km east of the ocean at the inland end of a shallow valley. At 600 m, the ridge was in fog 23.4% of the time, in the clear 67.5% and in patchy fog 9.1%. The corresponding percentages at 700 m were very similar 18.8%, 72.1%, and 9.1%. The latter dataset would yield annual numbers of days with fog of 69, clear 263, and patchy fog 33. Las Bombas is somewhat similar to sites 1, 2, and 3 in Table 2, which are in transverse valleys connected to the sea.

The projected number of fog days per year at the two sites, 160 km apart on the coast, Carrizal Bajo and Obispo, are 154 and 189 days, respectively, with a further 106 and 84 days, respectively, with patchy fog.

TABLE 3. Average number of days per year with fog at coastal meteorological stations in Argentina, 1961–1970. Adapted from Boletin Informativo No. 20, Servicio Meteorologico Nacional de Argentina, 1984.

Number	Site name	Fog days	Lat (S)	Long (W)	Alt (m)
1	Federal Capital	20.1	34°45′	58°29′	24
2	La Plata	35.2	34°58′	57°54′	21
3	Mar del Plata	61.0	37°56′	57°35′	18
4	Comodoro Rivadavia	5.0	45°47′	67°30′	58
5	Rio Gallegos	14.2	51°37′	69°17′	20

TABLE 4. As for Table 3, but for inland stations in Argentina.

Number	Site name	Fog days	Lat (S)	Long (W)	Alt (m)
1	Jujuy	4.7	24°23′	65°05′	921
2	Salta	10.0	24°51′	65°29′	1238
3	Tucumán	7.1	26°51′	65°06′	440
4	Concordia	20.7	31°18′	58°01′	35
5	Córdoba	21.5	31°19′	64°13′	484
6	Paraná	27.4	31°47′	60°29′	74
7	Mendoza	1.3	32°50′	68°47′	705
8	Rosario	44.1	32°55′	60°47′	25
9	San Luis	11.0	33°16′	66°21′	710
10	Azul	44.1	36°45′	59°50′	132

TABLE 5. Days per month with fog, no fog, or patchy fog on the cliff at Carrizal Bajo (28°08'S, 71°15'W; 700 m) on the coast of northern Chile. The observed percentage is used to calculate an approximate number of fog days per year.

Month	Fog	No fog	Patchy fog	Number of days observed
January 1988	4	2	1	7
February 1988	18	5	6	29
March 1988	14	8	9	31
April 1988	0	0	4	4
May 1988	6	4	6	16
June 1988	17	5	8	30
July 1988	2	7	6	15
November 1988	16	12	2	30
December 1988	13	8	10	31
January 1989	8	10	13	31
February 1989	4	8	5	17
Total	102	69	70	241
Percentage	42.3	28.6	29.1	100
Days per year	154	104	106	

The sum of days with thick plus patchy fog is very similar at both sites, 260 and 273 days, respectively. These values for the coastal mountains at an altitude of about 700 m far exceed the values (section 3a) for the standard meteorological stations. The inland Las Bombas site, on the other hand, has a projected number of 69 fog days per year with an additional 33 days of patchy fog; these are very similar frequencies to those for the foggier inland meteorological stations. The period of record is considered too short at these three sites to say anything about the consistency of the monthly fog frequencies from year to year.

Table 9 combines the data from Tables 5 and 6 into expected numbers of days per month with fog. The total number of observation days is 583, but the number per month is highly variable. Partial data for April and May have been omitted. No strong annual trend is apparent in the fog frequencies, only a tendency for the winter (June–August) to be somewhat foggier (59.7% of the days) than the spring (55.9%), which in turn is foggier than the summer (40.5%). Spring is the season with maximum fog-water collection at the more southerly (29°26'S) El Tofo field site (Fuenzalida et al. 1989b).

TABLE 6. As for Table 5, for Obispo (26°38'S, 70°40'W; 860 m) on the northern coast of Chile.

Month	Fog	No fog	Patchy fog	Number of days observed
June 1987	12	4	2	18
July 1987	17	10	4	31
August 1987	24	5	2	31
September 1987	13	7	10	30
October 1987	22	5	4	31
November 1987	16	7	7	30
December 1987	10	8	13	31
January 1988	16	9	6	31
February 1988	10	11	8	29
March 1988	6	2	1	9
November 1988	16	7	7	30
December 1988	10	8	12	30
January 1989	15	9	7	31
Total	187	92	83	362
Percentage	51.7	25.4	22.9	100
Days per year	189	93	84	

TABLE 7. As for Table 5, for the ridge at Las Bombas, Chile (26°04'S, 71°26'W; 600 m), 25 km from the coast.

Month	Fog	No fog	Patchy fog	Number of days observed
November 1987	11	9	3	23
December 1987	7	24	0	31
January 1988	0	19	4	23
Total	18	52	7	77
Percentage	23.4	67.5	9.1	100
Days per year	85	246	33	

4. Discussion

The data from the standard meteorological stations at both coastal and to a lesser degree inland sites (Tables 1 and 2) suggest a maximum fog frequency at a latitude near 38°S (35°–40°S) in Chile. There is support for this latitudinal maximum in the data from Argentina as well (Tables 3 and 4). One might reasonably expect the fog frequencies to decrease to the north of latitude 38°S, as is documented here, due to the strong subsidence associated with the South Pacific anticyclone at latitudes less than 30°S (Romero-Aravena 1985; Schemenauer et al. 1988). Indeed, this is one of the principal reasons for the extremely arid conditions and good visibility in northern Chile and southern Peru. Similar observations of a latitudinal maximum have been re-

TABLE 8. As for Table 5 for the higher elevation on the ridge at Las Bombas, Chile (26°04'S,71°26'W; 700 m), 25 km from the coast.

Month	Fog	No fog	Patchy fog	Number of days observed
November 1987	6	10	7	23
December 1987	3	28	0	31
January 1988	2	21	0	23
November 1988	11	9	3	23
December 1988	7	24	0	31
January 1989	0	19	4	23
Total	29	111	14	154
Percentage	18.8	72.1	9.1	100
Days per year	69	263	33	

TABLE 9. Monthly fog frequencies (number of days) calculated from the data in Tables 5 and 6 for Carrizal Bajo and Obispo. Data for April and May have been omitted because less than a full month is available.

Month	Fog (days)	Fog (%)	No fog (days)	Patchy (days)	Total (days)
January	43	43.0	40	27	100
February	32	42.7	24	19	75
March	20	50.0	10	10	40
April	—	—	—	—	—
May	—	—	—	—	—
June	29	60.4	9	10	48
July	19	41.3	17	10	46
August	24	77.4	5	2	31
September	13	43.3	7	10	30
October	22	71.0	5	4	31
November	48	53.3	26	16	90
December	33	35.8	24	35	92
Total	283		157	143	583
Percentage	48.6		26.9	24.5	100
Days per year	177		98	90	365

ported for the west coast of the United States by Peace (1969). He found maximum heavy fog frequencies (up to 100 days per year) between 34° and 37°N. The east coast maximum was at somewhat higher latitudes, 41°–45°N.

South of 40°S in Chile, the westerlies bring considerable rain associated with progressively cooler temperatures. One might expect this to generate higher fog frequencies but this is not the case. The reason for this may be associated with sea surface temperatures along the coast. Romero-Aravena (1985), for example, in a discussion of the climate of Chile, maps an extensive area of cold water off the coast at latitudes of about 40°S. This corresponds to the approximate latitude where the cold eastward moving Humboldt current turns to flow northward along the coast. Relatively warm, moist westerly winds on the south side of the Pacific anticyclone will be cooled and humidified as they pass over this region of cold water. This may well be the cause of the increased fog frequencies both along the coast and inland between 35° and 40°S. Farther to the south, between latitudes 40° and 55°S, the cold water lies off the coast, and the cloud bases over the continent may be somewhat higher resulting in lower fog frequencies. On the Atlantic coast of Argentina, 40°S marks the approximate latitude where the cold northward flowing Malvinas current meets the warmer southward flowing Brazil current. The cold current then turns eastward away from the coast. It is therefore not unreasonable to expect that fog frequencies might again decrease north of 40°S in agreement with the observations. To the south of 40°S, subsidence of the westerly winds in the lee of the Andes may play an important role in decreasing fog frequencies as the cordillera is closer to the coast at these latitudes. In addition, the surface winds in this region will be off the land rather than the ocean, reducing the possibilities for fog formation. However, the almost complete lack of data for Argentina at these latitudes makes this discussion speculative.

The specialized fog observations along the northern coast of Chile are distinct from the standard meteorological observations. The resultant fog frequencies are much higher because the remote sites are in locations where the coastal mountains are expected to intercept the marine cloud decks. Carrizal Bajo (Table 5) and Obispo (Table 6) have fog frequencies 3–15 times higher than low elevation coastal locations such as Caldera and La Serena (Table 1) at the same latitudes.

Peace (1969) also found that stations in California located high in the mountains had fog frequencies up to three times as high (251 days per year) as the maximum coastal values. This was termed "high fog" by Stone (1936), who gave an interesting discussion of the types of fogs and fog regimes. The physical properties of the fogs will vary depending on how and where they are formed and, thus, the mechanisms for collecting fog water will also of necessity be different (Schemenauer and Joe 1989).

The direct use of fog water as a village water supply in Chile is discussed in Schemenauer and Cereceda (1991a). Due to the high fog frequencies in California, some interest has also been shown there in carrying out fog collection experiments along the coast. Goodman (1977) looked at the microphysical structure of the coastal fog and stratus and (Goodman 1985) reported on experiments with small collectors in the San Francisco Bay area indicating that significant amounts of fog water can be collected. An extensive review of fog collection experiments around the world can be found in Schemenauer and Cereceda (1991b).

5. Conclusions

Fog frequency data for Chile are not extensive but do indicate that the maximum number of fog days per year is found between latitudes 35° and 40°S. The maximum is probably associated with the offshore region of cold water generated by the Humboldt current and is maintained by relative decreases in fog frequency to the north and south due to synoptic-scale circulations and the pattern of ocean currents.

This study has demonstrated that data from standard meteorological stations are not suitable for identifying coastal locations where fog-water collection programs may be undertaken. These programs, such as the Camanchaca Project (1987–89) in Chile, will produce large quantities of water at low cost only if the site is in fog perhaps one-third or more days per year. To find such sites, a preliminary topographical and meteorological analysis of potential sites has to be followed up by a specialized observing program at the site or actual in situ measurements with small inexpensive fog-water collectors. These measurements may produce fog frequencies as much as 15 times greater than the standard, low elevation, coastal observations at the same latitude.

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