

## The Quality of Fog Water Collected for Domestic and Agricultural Use in Chile

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### ABSTRACT

One exciting new application of meteorology is the prospect of using high-elevation fogs as an arid land's water resource. This has now become reality in northern Chile where a pilot project has used 50 fog collectors to generate an average of 7200 l of water per day during three drought years. The chemical composition of the fog water is of primary importance and is examined in this paper.

A small, carefully cleaned fog-water collector was used at the site (elevation 780 m) to study the incoming fog (cloud). The ion and trace-element concentrations met Chilean and the World Health Organization's (WHO) drinking-water standards. The pH values, however, were at times extremely low. Samples from 1987 and 1988 were consistent with those from the larger dataset in 1989. The lowest observed pH was 3.46. The acidity was associated with high concentrations (89%) of excess sulfate in the 15 fog-water samples (based on  $\text{Cl}^-$  as the seawater tracer element). The  $\text{NO}_3^-/\text{SO}_4^{2-}$  equivalents ratio for the fog samples was 0.18, showing the dominance of  $\text{SO}_4^{2-}$  in determining the acidity of the fog samples. The relative abundances of ions and trace elements in the dry deposition are very similar to those in the fog water, suggesting that the aerosols originate primarily from evaporated cloud droplets over the ocean. Based on enrichment-factor calculations (with  $\text{Cl}^-$  as the indicator element for seawater and Al for the earth's crust), sea salts were the main source of  $\text{Na}^+$ ,  $\text{Mg}^{++}$ , and  $\text{Cl}^-$  in the fog water; soil dust was the main source of Fe, Al and Ti; and other sources provided  $\text{Ca}^{++}$ ,  $\text{K}^+$ ,  $\text{NH}_4^+$ ,  $\text{Br}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$ , As, Cd, Pb, V, Mn, Ni, Cu, Sr, Sb, and Ba in the fog water. The use of enrichment factors based on the relative abundances in soil extracts suggests that As, V, Cu, and Sr may be available from wetted soil dust.

The output from the large (48 m<sup>2</sup>) fog collectors was also acceptable, except for several of the 24 trace elements, which exceeded the maximum allowable values in the first flush of water after a dry period of a few days. The pH values were again near 4 and would have to undergo a simple treatment to raise them to a value of 6 or more to meet the drinking-water standard. The output from a 2000-l fog-water storage tank was completely acceptable and that from a 25 000-l storage tank completely acceptable, except for a low pH. In contrast, both the water presently being used in a nearby village and local spring water were unacceptable. It is concluded that fog water is an attractive alternative as a water supply even after collection on the large meshes at this site.

### 1. Introduction

There is presently an effort underway to develop the collection of high-elevation fog into a water resource for certain arid lands (Schemenauer and Cereceda 1991). A major research program and pilot project has been underway since 1987 (Schemenauer 1988; Schemenauer et al. 1988) in Chile where 50 large (48 m<sup>2</sup>) polypropylene mesh collectors have been installed at a coastal field site. The Camanchaca Project (1987–89) has demonstrated that there are diurnal and annual cycles to the collection of fog water as well as a day-to-day variability (Schemenauer and Cereceda 1988; Fuenzalida et al. 1989a,b). The role of terrain orientation and wind flow over the terrain in determining

the amount of water collected has been studied with small (0.25 m<sup>2</sup>) collectors (Schemenauer et al. 1987; Cereceda-Troncoso et al. 1988). Because the only purposes of these experiments were to measure the relative water collection at different locations and to optimize the collection process, the chemical composition of the water collected was of no concern. But now that the average year around water collection has been demonstrated to be large enough to provide a viable water supply for a nearby village of 330 people (Cereceda et al. 1989), the ability of the collectors to produce water meeting Chilean and international drinking-water standards is important. The collector array has averaged 7200 l day<sup>-1</sup> during three drought years when the annual precipitation totaled 10, 50, and 10 mm as opposed to the normal value of 70 mm.

The collectors (Schemenauer and Joe 1989) are located on a ridgeline at 780 m near the coastal village of Chungungo. The fog is produced when marine stra-

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tocumulus cloud decks are blown over the ridge by the prevailing winds and daytime sea breeze. The fog droplets impact on the fibers of the collectors and form large drops, which drip off the collectors into troughs. The water from several prototype collectors has been used since 1984 by two caretakers on the ridge and for a 3-ha tree plantation. Recently a 100 000-l storage tank has been constructed in Chungungo, and a 6.5-km pipeline has been completed from the ridge to the village where the high-elevation fog will provide the permanent water supply.

The quality of water from the fog-water collection system will depend on several factors: first, the composition of the incoming fog water; second, the material of the collectors; and third, the amount and chemical composition of the dry deposition on the collectors, which will increase with the length of time between fog episodes. Fog-water quality is discussed in this paper based on a set of water samples collected at the El Tofo, Chile, site (29°26'S, 71°15'W) from 1987 to 1989.

Previous studies of fog-water collection with small collectors in arid lands (summarized in Schemenauer and Cereceda 1991) have ignored the question of water quality. Even more general reviews of fog-water collection (Kerfoot 1968; Stadtmüller 1987) have not dealt with the issue. Much literature exists dealing with acidic deposition due to fogs in temperate climates (e.g., Mohnen and Kadlec 1989), but the literature is not directly relevant to arid coastal climates nor is it dealt with in a manner that allows potability to be addressed. Rainwater chemistry has also been extensively studied, but it is not comparable in any simple manner with the fog-water chemistry in this essentially precipitation-free region. The data presented here represent the first published evaluation of the quality of water being produced by a large-scale fog-water collection program. The data have immediate application in decisions relating to the implementation of operational programs not only in Chile but in other arid coastal locations with similar meteorological and topographical conditions.

## 2. Analysis

The fog-water ion analysis (except for  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$ ) was performed at the Environment Canada laboratory at the Atmospheric Environment Service in Toronto by high-pressure liquid chromatography. The laboratory specializes in the analysis of precipitation. The analysis for  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  using flame atomic absorption spectroscopy (FAAS) was done by Laboratoire Savoie-Dufresne in Montreal, which has done extensive work in the analysis of fog water for the Chemistry of High Elevation Fog program in Canada (Schemenauer 1986). The trace-metal analysis was performed using inductively coupled plasma-mass spectroscopy (ICP-MS) by the Ontario Ministry of the Environment laboratory in Toronto. The laboratory

does the bulk of the domestic water analysis for the province of Ontario. The soil samples were finely ground and digested before being analyzed by ICP-MS. The analysis was then confirmed in some cases by optical ICP and FAAS. The three laboratories routinely participate in national and international laboratory intercomparisons such as the Canada Centre for Inland Waters LRTAP Inter-Comparability Study (60 laboratories) for major ions.

The samples were collected in clean polyethylene bottles that had been triple rinsed in distilled water. The bottles were filled completely, sealed, and kept for 5 days at approximately 20°C, followed by continuous storage and transportation at 4°C. The initial period at 20°C may have resulted in some loss of  $\text{NH}_4^+$  and possibly of  $\text{NO}_3^-$  from the samples but was unavoidable. Ramundo and Seastedt (1990) report a reduction in  $\text{NH}_4^+$  concentrations of 29% in unpreserved, unrefrigerated samples but no reduction in  $\text{NO}_3^-$  concentrations. Though, because of the relatively low pH values for the samples described here, the reductions in  $\text{NH}_4^+$  concentrations could be even less (Vesely 1990). The precision in ion analysis was very high. On 10 November 1988, four water samples were collected that were expected to have similar analyses. Fog water was flowing at a rate of  $1 \text{ l s}^{-1}$  into the 25 000-l tank on the ridge. A duplicate pair of samples was taken from the input to the flowmeter, another from the flowmeter output, and one from the tank outlet. The laboratory pH values were 3.81, 3.81, 3.81, and 3.85;  $\text{SO}_4^-$  values were 20.6, 20.7, 21.0, and 19.6 ppm. The other ions showed similar excellent agreement.

Ideally, acid-washed polyethylene bottles and ultra-pure acids (to lower the pH) should have been available in the field to store the samples for the subsequent trace-element analysis. However, they were not, since the samples were to be used for both ion and trace-element analysis. It is also unlikely that these precautions have been taken routinely in developing countries in the past for the analysis of drinking water. The aliquots for trace-element analysis were not filtered but were removed from the tops of the sample bottles after allowing the bottles to settle, prior to ICP-MS analysis.

It does not appear that the polyethylene bottles were a significant source of trace elements since tests of bottle blanks produced by soaking bottles with distilled deionized water for more than 48 h produced concentrations below the detection limits (BDL) for all 23 trace elements. Soaking in a very acidic solution of 1% nitric acid also produced concentrations BDL for most elements; though, Al, Cu, Zn, and Pb typically were present in concentrations of 1 ppb or less, and, on one occasion each, a concentration as high as 10 ppb of Al, Cu, or Zn was seen. Ross (1986) reported higher concentrations of Cu, Zn, and Pb in rinsed polyethylene bottles as compared to those that had been acid washed and it is clear that the bottle walls can be a source. Given that the normal sample pH in the study

ranged from 4 to 6, and that the primary purpose was to assess the potability of the water, where the maximum allowable limits are unstated for Al, 1000 ppb for Cu, 5000 ppb for Zn, and 50 ppb for Pb, it is felt that the walls did not present a major contamination problem.

It is also possible that the polyethylene bottles may have been a sink for trace elements, but soaking the bottles in 1% nitric acid after emptying and rinsing with distilled deionized water failed to leach concentrations of 18 of the trace elements in excess of the detection limits. Measurable concentrations of the other five elements were sometimes present. The most notable were lead, which was in all cases above background, though always less than 2 ppb, and the Al concentrations that ranged from 8 to 88 ppb. Therefore, though the uncertainties in the absolute concentrations of some of the elements measured in very low concentrations may be large, the data are considered quite acceptable for addressing the question of whether the water samples meet Chilean (or WHO) standards for drinking water. Where drinking-water standards exist for an element, they are listed at the bottom of the first appropriate table.

A calculation of the excess sulfate (i.e., subtracting the seawater correction from the measured concentration using  $\text{Cl}^-$  as the sea-salt tracer element) was done for the 15 fog samples in 1987, 1988, and 1989, and excess sulfate values averaging 89% of the measured values were obtained. Using  $\text{Na}^+$  as the sea-salt tracer element the average excess sulfate value was 88%. Therefore, since the samples contain largely excess sulfate, the original noncorrected values are reported. This has the advantage of showing the true composition of the water available at the site.

The ion balances in microequivalents per liter ( $\mu\text{eq l}^{-1}$ ) for the fog-water samples showed an average absolute difference of 3% for samples with a total ion concentration  $>650 \mu\text{eq l}^{-1}$  and 6.5% for samples with a total ion concentration  $<300 \mu\text{eq l}^{-1}$ . This indicates that all of the major ions are being sampled; however, since most of the samples showed a small surplus of cations, there may be an additional anion present such as bicarbonate or one of the organic acid anions. In the presentation of the ion analyses, mass ratios (ppm) will normally be used and termed ion concentrations.

### 3. Results

The first kind of collector was built at the Atmospheric Environment Service (AES) and is especially designed for studies of acidic fogs (Schemenauer 1986). The collecting surface is composed of vertical Teflon fibers and the droplets contact only Teflon, polyethylene, and polypropylene surfaces. It can be very carefully cleaned and is a modified version of the design of Falconer and Falconer (1980). The second kind of collector is designed to collect very large volumes of

fog water. What are indicated in the tables as flowmeter samples in fact originate on the  $48\text{-m}^2$  collectors. The collecting mesh is polypropylene supported by plastic-coated, galvanized metal wires. The water drips into PVC or fiberglass troughs and runs through PVC pipes to a Perspex and aluminum flowmeter from which it flows into a galvanized metal pan and out into the polyethylene collecting bottle. This should approximate the quality of water ultimately available for use in the village of Chungungo. Absolutely no cleaning was done of the water collection system prior to collecting the samples.

Figure 1 shows the location of the field site at El Tofo in relation to the coastal village of Chungungo. It also shows Chungungo's location in the IV region of Chile, which in turn is shown in relation to the country as a whole.

#### a. Rinses, dry deposition, and soils

Tables 1, 2a, and 2b give the results from distilled water rinses (samples 1, 3) of the AES fog-water collector after cleaning. The ion concentrations in Table 1 are, with one exception, under 1 ppm, and in many cases are under 0.1 ppm. The concentrations of the 23 trace elements in Tables 2a and 2b are low, with the exception of boron (B). For 15 of the elements, the concentrations are below the method detection limits (BDL). For Al, Ti, and Zn, the concentrations range from 10 to 20 ppb and result from both the composition of distilled water and the material on the collector surface. The rinses are sufficiently clean to allow the collectors to be used to study the composition of the incoming fog. The high concentration of B is probably due to the distilled water purchased in Chile for the rinsing. Even though it was purchased and stored in plastic containers, it may have previously been kept in glass containers, resulting in the leaching of B from the glass. Because of this possibility, the B concentrations are not reported below.

On 5 November, the AES fog collector was mounted 1.5 m above the ground and left exposed for 25 h during a period of sunny, dry weather. On 6 November, the collector was rinsed with distilled water and the first 60 ml of rinse water was collected as sample 2. The ion concentrations in this dry deposition sample are shown in Table 1. The pH of the sample (5.03) is somewhat lower than for the rinses in Table 1 and the concentrations of the ions are an order of magnitude higher. Presumably, the aerosols deposited on the collector originate in the ocean and the soil, and some of the aerosols may be of anthropogenic origin. The origins of the aerosols can be examined through the use of enrichment factors ( $\text{EF}_{\text{Cl}}$ ) in the manner of Ahmed et al. (1990). The

$$\text{EF}_{\text{Cl}}(X) = \frac{(X/\text{Cl})_{\text{fog}}}{(X/\text{Cl})_{\text{sea}}}$$

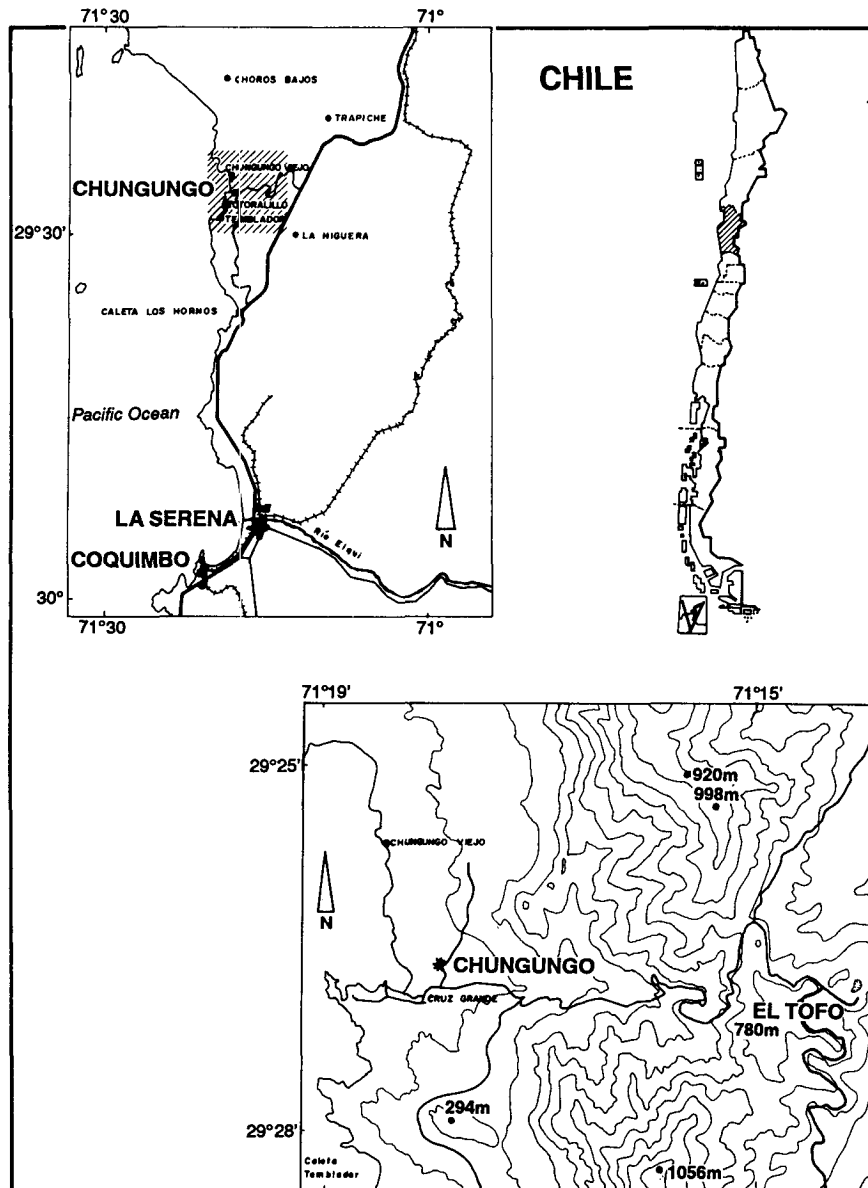


FIG. 1. The topography (lower right) near the field site at El Tofo, Chile, the position of the field site (upper left) with respect to the city of La Serena in region IV, and the location of region IV within Chile (hatched area, upper right).

ratio of the ion ( $X$ ) to chlorine concentrations in the aerosol rinse is divided by the comparable mass ratio for seawater to obtain  $EF_{Cl}$ . Values obtained were  $Ca^{++}$  0.31,  $Na^+$  1.16,  $Mg^{++}$  0.97,  $K^+$  1.52, and  $SO_4^-$  2.93. The ions  $Na^+$ ,  $Mg^{++}$ , and  $Cl^-$  (by definition) clearly originate from salt spray. The aerosol is deficient in  $Ca^{++}$  and somewhat enriched in  $K^+$  and  $SO_4^-$ . Enrichment factors cannot absolutely apportion sources for constituents of aerosols, precipitation, or fog for a number of reasons related to processes that can take place after spray leaves the ocean surface or dust leaves the soil surface. They are, however, extremely useful

and point in this case, for example, to a strong additional source for the  $SO_4^-$  aerosol.

Table 3 shows the major ion concentrations in two soil samples (1 and 2) collected on the ridge at El Tofo, Chile, and in the solutions made by soaking the finer part of the soils ( $<0.5$  mm) in distilled deionized water (1 part to 10 by weight) for 1 h. The 1-h period approximates the contact time of fog water for any dust on the collector and in the troughs. The dominant cation in the soils was  $Ca^{++}$ , and it was the water-soluble cation with the highest concentration as well. The major water-soluble anion was  $SO_4^-$ . Other ions were also

TABLE 1. The concentrations of major ions in two distilled water rinses (1 and 3) of a cleaned AES fog-water collector, and in a distilled water rinse (number 2) after 25 h of dry deposition onto the AES collector are listed. The detection limits are also given. Values below detection limits are shown with a < sign.

Sample number	pH	SO <sub>4</sub>	NO <sub>3</sub>	Br	Cl	Na	NH <sub>4</sub>	K	Ca	Mg	Date
(ppm)											
1	5.18	0.33	0.048	<0.015	0.58	0.26	0.040	0.085	0.17	0.03	5 November 1989
3	5.66	0.51	0.25	0.018	1.61	0.94	0.18	0.29	0.02	0.05	6 November 1989
2	5.03	17.5	5.90	0.053	42.9	27.4	1.67	1.37	2.84	2.80	6 November 1989
Detection limits		0.045	0.045	0.015	0.02	0.01	0.04	0.03	0.02	0.002	

present in appreciable concentrations, indicating their availability when soils or soil dust are wetted.

The trace-element analysis of the dry deposition sample (Tables 2a and 2b) also shows elemental concentrations higher than those for the rinse of the clean collector. The highest concentrations are for Zn, Al, Fe, Mn, Sr, Cu, As, and Ni, in that order. The fact that the site was above an abandoned iron mine did not result in high iron concentrations. It is possible that this results in part from the fact that the diurnal cycle of wind speeds does not normally result in values above 7 m s<sup>-1</sup> and the largest surface dust particles will not become airborne. Other possible explanations are that the site is on the upwind side (for higher wind speeds) of the area of mine tailings, or that the particles containing iron were not readily water soluble.

The trace-element analysis for the soils and the water-soluble components of the soils are given in Tables 4a and 4b. The primary components of the soils were Fe and Al and, to a lesser extent, Ti and Mn. The five most abundant water-soluble elements in the soil were Cu, Al, Fe, Sr, and Ti, with some significant differences between the two samples from the ridge. Moderate to high concentrations of these elements as well as As and V will be available if the fog water is in contact with the soil dust. Enrichment factors were calculated in the manner of Galloway et al. (1982) and Ahmed et al. (1990), but in this case the mass ratio of the element concentration to the Al concentration in air (dry deposition) was divided by the element to Al concentration in the soil samples to obtain EF<sub>Als</sub> and by the element to Al ratio in the soil extracts (solutions) to obtain EF<sub>w</sub>.

Here

$$EF_{Als}(X) = \frac{(X/Al)_{fog}}{(X/Al)_{soil}}$$

$$EF_w(X) = \frac{(X/Al)_{fog}}{(X/Al)_{soln}}$$

For the major elements, the EF<sub>Als</sub> calculation yields: Cu 69, Fe 0.29, Sr 129, Ti 2.0, and Zn 159. The elements Zn, Sr, and Cu are highly enriched in the aerosol; Ti is also enriched, but Fe is not. It should be remembered that these EF were calculated using elemental concentrations for the soils at the site, not average crustal values. The EF<sub>Als</sub> value of <1 for Fe reflects the high Fe concentrations in the soil, which is not surprising given that the site was the largest iron mine in Chile for 50 years. The EF<sub>Als</sub> values for the more minor constituents are: V 5.5, Co 15.3, Ba 19, Cr 28, Mn 30, Pb 32, Be 73, Mo 179, Ni 360, and Cd 735. All the minor constituents in the aerosol are highly enriched. In fact, of the 15 elements for which EF<sub>Als</sub> values are available, only Fe is not enriched, that is, there is more than sufficient Fe in the soil to explain the concentrations in the aerosol. The situation is slightly different if one calculates EF<sub>w</sub> values. For the major constituents in the dry deposition rinse they are: Cu 0.027, Fe 0.99, Sr 0.52, Ti 0.63, and Zn 28.5. Thus, based on the elemental ratios in the soil extracts, only Zn is enriched. The remaining EF<sub>w</sub> values are: V 0.17, Co 0.56, Cr 0.92, As 1.6, Be 9.5, Mn 11.5, Cd 15.6, Pb 37.1, and Ni 56.9. The soluble component of the soils clearly explains the presence of a larger percentage of the soluble constituents of the aerosols.

TABLE 2a. The concentrations of trace elements in two distilled water rinses (1 and 3) of the cleaned AES fog-water collector, and in a distilled water rinse (number 2) after 25 h of dry deposition onto the AES collector are listed. Dates are as in Table 1. Parentheses indicate questionable data.

Sample number	Fe	As	Cd	Pb	Be	B	Al	Ti	V	Cr	Mn	Ni
(ppb)												
1	<50	<1	<0.5	<0.5	<0.5	(1711)	15.5	11.0	<0.5	<1.0	3.2	<2.0
3	<50	<1	<0.5	<0.5	<0.5	(2110)	18.8	9.6	<0.5	<1.0	5.0	<2.0
2	52	16.9	1.3	3.3	<0.5	—	52.7	12.7	2.4	2.5	49.7	13.5
Detection limits		50	1.0	0.5	0.5	20	1.0	2.0	0.5	1.0	0.5	2.0

TABLE 2b. As in Table 2a.

Sample number	Co	Cu	Zn	Se	Sr	Mo	Ag	Sb	Ba	Tl	U
						(ppb)					
1	<1.0	<1.0	17.3	<5.0	0.6	<0.5	<0.5	<0.5	0.9	<0.5	<0.5
3	<1.0	2.3	18.3	<5.0	1.3	<0.5	<0.5	<0.5	0.8	<0.5	<0.5
2	1.2	19.7	100.8	<5.0	25.8	0.9	<0.5	8.2	<0.5	<0.5	<0.5
Detection limits	1.0	1.0	2.0	5.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5

### b. The incoming fog

#### 1) ION CONCENTRATIONS

A series of 8 consecutive samples were collected with the AES fog collector during an extended fog event lasting from 6 to 7 November 1989. The sample periods, in relation to the output of one of the 48-m<sup>2</sup> collectors (atrapanieblas in Spanish), are shown in Fig. 2. These samples provide a look at the chemical composition of the incoming fog water before it impacts on the large collectors and before it passes through the collection system. The ion concentrations for the eight samples are given in Table 5a. The first episode began with a very low pH (4.01) and the highest ion concentrations observed in the 19.5-h event. The pH increased and the ion concentrations decreased markedly during the first 7-h episode, and they then stayed fairly constant during four minor fog episodes over the remaining 12 h. The major ions throughout the event were Cl<sup>-</sup>, SO<sub>4</sub><sup>=</sup>, and Na<sup>+</sup>, with moderate amounts of NO<sub>3</sub><sup>-</sup> also present. The concentrations of all the ions were well within the allowable limits (bottom line Table 5a). However, it should be noted that pH values under 6 are unacceptable for drinking water due mainly to the possibility of corrosion in pipes and plumbing systems. To give one an idea of the magnitude of this event, at 15 cm<sup>3</sup> s<sup>-1</sup>, from one collector, the 50 collectors were producing 2700 l of fog water per hour. The winds during the event were from the west except for a few hours (0100–0300 and 0400–0500) on 7 November.

The initial ion concentrations were about 50 times higher than those observed in the clean collector rinses and clearly result from the fog and not the collector surface. The fact that the major ions in the fog water

are the same as those in the dry deposition sample suggests that there is a common origin for the aerosol particles and the fog (cloud), and perhaps that as the cloud deck moves onshore, it scavenges the aerosol in the coastal boundary layer, resulting in high initial concentrations. As the aerosols are depleted, the ion concentrations are reduced in the fog water until a point is reached where the fog water contains only the background concentration of marine-derived constituents. It is interesting in this regard to look at the excess sulfate concentrations in the samples. From the beginning to the end of the event, the excess sulfate values were from 80% to 92% of the measured values. Thus, the SO<sub>4</sub><sup>=</sup> is present in much higher values than in seawater. The source may still be oceanic though, since the contribution from airborne soil dust during the fog event would not be expected to be large and the anthropogenic sources in the region are negligible. One possible source for the excess SO<sub>4</sub><sup>=</sup>, which is generating a lot of interest, is dimethyl sulfide (DMS) emissions from the ocean (Andreae and Raemdonck 1983; Luria and Meagher 1986), however, there is no evidence for or against it being the productive mechanism here.

The pH and ion concentrations for two samples collected with the AES collector in 1987 and for five collected in 1988 are given in Table 5b. The pH of the samples ranged from a low of 3.46 for the sample (number 14) on 11 November 1988 to a high of 5.84 for the overnight sample on 12/13 November 1987. The major ions were again SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, and Na<sup>+</sup> with high concentrations of SO<sub>4</sub><sup>=</sup> in the two most acidic samples (14 and 15). The results are similar to those presented above for 1989, and the concentrations are certainly well within what is acceptable for drinking-water purposes in Chile.

TABLE 3. Major ion concentrations in soils from the ridge at El Tofo, Chile, (1 and 2) and the concentrations of water-soluble constituents (3 and 4) of the soils. Soil samples collected 13 March 1990. A dash indicates no data.

Sample number	pH	SO <sub>4</sub>	NO <sub>3</sub>	Br	Cl	Na	NH <sub>4</sub>	K	Ca	Mg
						(ppm)				
1	—	—	—	—	—	—	—	—	14 200	2 900
2	—	—	—	—	—	—	—	—	7 600	3 250
3	7.31	9.51	3.85	—	12.5	15.0	0.84	22.7	31	19
4	7.28	10.7	10.0	—	19.5	22.7	0.67	16.9	46	35

TABLE 4a. Trace-element concentrations in soils from the ridge at El Tofo, Chile, (1 and 2) and the concentrations of water-soluble constituents (3 and 4) in the soils.

Sample number	Fe	As	Cd	Pb	Be	B	Al	Ti	V	Cr	Mn	Ni
(ppm)												
1	28 000	—	0.36	31	1.0	—	8 400	892	68	13.2	295	7.2
2	33 500	—	0.24	5.2	1.4	—	9 500	1 250	80	17.1	262	5.5
(ppb)												
3	38.9	15.6	0.12	0.12	0.06	—	73.4	25.3	25.2	4.5	4.0	3.1
4	113.1	14.5	0.12	0.14	0.10	—	79.2	32.3	15.5	3.3	8.5	3.8

Lazrus et al. (1970) collected eight fog-water samples from an uncleaned aluminum mesh collector on Pico del Oeste in Puerto Rico at an altitude of 1020 m. They observed an increase in sea salt, as measured by the  $\text{Cl}^-$  concentrations in the samples, during periods of rough seas (15.0–70.0 ppm), as opposed to during calmer periods (5.4–8.2 ppm). Comparable  $\text{Cl}^-$  values were found for the 1987, 1988, and 1989 fog-water samples in this study (0.7–27.9 ppm; Tables 5a and 5b). A calculation of the excess  $\text{Mg}^{++}$  in the samples (using  $\text{Cl}^-$  as the sea-salt tracer), in the manner of Lazrus et al., yields an average of only 0.09 ppm (15%) of the  $\text{Mg}^{++}$  not originating from seawater. Two possible sources of the additional  $\text{Mg}^{++}$  are chemical fractionation during aerosol formation or nonmarine production. On the other hand, an average of 0.76 ppm (79%) of the observed  $\text{Ca}^{++}$  values had a source unrelated to sea salt. The excess  $\text{SO}_4^-$  values noted above averaged 8.0 ppm (89%) of the measured values in the samples compared to 2.1 ppm and 60.5% in the Puerto Rican samples of Lazrus et al. The average excess  $\text{SO}_4^-$  concentrations of  $167 \mu\text{eq l}^{-1}$  (8.0 ppm) are much higher than those ( $4.1 \mu\text{eq l}^{-1}$ ) reported by Galloway et al. (1989) for precipitation in remote marine areas and higher than their measured values ( $14.1 \mu\text{eq l}^{-1}$ ) in Bermuda. This may be due in part to different source regions for the air masses and in part to different formation and deposition mechanisms in fog and rain.

The  $\text{Na}^+/\text{Cl}^-$  ratio for the 15 fog-water samples was

between 0.55 and 0.70; the average was  $0.64 \pm 0.04$  (or 0.99 as an equivalents ratio). This is higher than the ratio (0.53) observed by Lazrus et al. (1970) in Puerto Rico and higher than the ratio for seawater (0.55). It is also higher than the typical sea-salt equivalents ratio for  $\text{Na}^+/\text{Cl}^-$  of 0.86 (Wagner and Steele 1989). Wagner and Steele discuss mechanisms by which the  $\text{Na}^+/\text{Cl}^-$  ratio in rain can be increased by the addition of  $\text{Na}^+$ -rich mineral aerosols from land sources or through the loss of  $\text{Cl}^-$ , particularly at coastal sites, due to the reaction of  $\text{NaCl}$  aerosols with atmospheric acids and ozone. The mechanism active at the El Tofo site in Chile is not known, but given the semiarid and arid nature of the terrain, the augmentation of the  $\text{Na}^+$  concentrations in the fog water due to the incorporation of some terrestrial aerosols would be reasonable. The value for the rain  $\text{Na}^+/\text{Cl}^-$  ratio divided by the seawater  $\text{Na}^+/\text{Cl}^-$  ratio (in equivalents) for coastal areas in the United States was found to be  $1.00 \pm 0.02$  by Wagner and Steele. The value for fog in Chile was 1.15 (0.99/0.86), which is more characteristic of the central United States downwind of the semiarid western states (Texas 0.96–1.65; Oklahoma 1.08–1.22; Kansas 1.04–1.17; Nebraska 0.97–1.23).

Enrichment factors ( $\text{EF}_{\text{Cl}^-}$ ) for the ions in the 15 fog-water samples were calculated using  $\text{Cl}^-$  as the tracer element for seawater (Table 5c). All of the ions, except possibly  $\text{Mg}^{++}$  and  $\text{Na}^+$ , show some enrichment ( $\text{Cl}^-$  is 1.0 by definition):  $\text{Ca}^{++}$  8.6;  $\text{Mg}^{++}$  1.2;  $\text{Na}^+$  1.2;  $\text{K}^+$

TABLE 4b. As in Table 4a.

Sample number	Co	Cu	Zn	Se	Sr	Mo	Ag	Sb	Ba	Tl	U
(ppm)											
1	15.2	43	190	—	31	1.0	—	—	130	—	—
2	11.2	52	23	—	37	0.70	—	—	17	—	—
(ppb)											
3	4.0	54.4	6.1	<1.0	44.7	—	—	—	—	—	—
4	2.3	151.6	4.1	<1.0	100.9	—	—	—	—	—	—



TABLE 5b. Concentrations of major ions in samples from the AES fog collector at the El Tofo ridge site in 1987 and 1988.

Sample number	pH	SO <sub>4</sub>	NO <sub>3</sub>	Br	Cl	Na	NH <sub>4</sub>	K	Ca	Mg	Date	Time
(ppm)												
5	5.84	5.16	1.11	—	3.19	2.03	0.94	0.19	0.92	0.36	12/13 November 1987	1830–1008
6	4.98	7.86	0.71	—	6.81	3.73	0.58	0.38	1.83	0.54	12 November 1987	1700–1809
5	5.64	1.66	0.45	—	1.01	0.66	0.32	BDL	0.38	0.10	9 November 1988	1200–1225
6	4.62	3.50	0.48	—	1.52	1.07	0.59	BDL	0.19	0.14	9 November 1988	1507–1528
8	4.11	10.1	1.79	—	4.85	2.87	1.37	0.25	0.55	0.39	9/10 November 1988	1830–0920
14	3.46	36.4	6.24	—	20.5	13.4	2.84	0.71	1.33	1.79	11 November 1988	0958–1519
15	3.88	21.7	0.54	—	23.1	13.8	2.06	0.82	1.60	1.79	12 November 1988	1210–1254

pronounced decrease during the first 7 h (as for the ions) and then relatively constant values for the remaining 12 h. As, Pb, Al, Mn, Cu, and Zn values are all substantial at the beginning of the event, but they are well within allowable drinking-water limits. It is also worth noting that the Fe concentrations are low despite this being the site of a former iron mine. Once the fog-water event is well underway, the concentrations of the trace elements of concern are one to three orders of magnitude less than the maximum allowable values (bottom lines Tables 6a and 6b). This means that the fog provides a water supply that meets the Chilean drinking-water criteria both from the major ion and the trace-element points of view. There are no trace-element analyses for the 1987 and 1988 samples to be used for comparison.

A comparison of the trace-element concentrations in the first two fog-water samples (4 and 5, Tables 6a and 6b) with that in the dry-deposition rinse (Tables 2a and 2b) shows almost identical relative abundances. The similar relative abundances argue for a common source. Since the daytime is characterized by a strong sea breeze, and the early morning hours by calm winds or a light offshore wind, the aerosols at 780 m most likely originate over the ocean from evaporated cloud droplets. The aerosols are then reincorporated into the leading edge of new cloud decks as they push onshore. To some extent they will also be deposited on the

ground (Barrie and Schemenauer 1986; Barrie and Schemenauer 1989) to form part of the water-soluble trace-element composition of the soils.

The enrichment factors for the trace elements in the fog-water samples are given in Table 6c. The  $EF_{Cl}$  values show the fog has much higher relative concentrations of trace elements than would be expected if seawater were the source. The  $EF_{Al}$  values are also high for almost all of the elements. These values were calculated using the analysis for the soils at the site to define the  $X/Al$  values for the soil. Values of  $EF_{Al}$  were also calculated for Fe (1.5) and Ti (0.9) using standard crustal values. These are the only two elements for which the enrichment factors are near 1. The sea-salt fraction (SSF) for the fog water is near 0 as is the crustal fraction (CRF) for all elements except Fe, Ti, and Al (by definition). This leaves a large unexplained residual fraction (NSSCRF) for As, Cd, Pb, V, Mn, Ni, Cu, Zn, Sr, Sb, and Ba. However, if one calculates enrichment factors  $EF_w$  based on the relative abundances of the elements  $X/Al_{soln}$  in the solutions made from the soil samples, then the enrichment factors are much lower for all elements except Pb (250). The corresponding residual fractions (NSSCRF<sub>w</sub>) lead to the conclusion that it is primarily Cd, Pb, Mn, and Zn that appear not to be available from the soils near the site. About one-half the Ni is locally available. The fact that some  $CRF_w$  values are greater than 100% implies that

TABLE 5c. Mean enrichment factors for high-elevation coastal fog in Chile based on seawater  $Cl^-$  ( $EF_{Cl}$ ) and crustal Al ( $EF_{Al}$ ,  $EF_w$ ) values. Sea-salt (SSF), crustal (CRF), and residual fractions (NSSCRF) of the ions in the fog water are also given.

Element	$X/Cl^*$ Sea	$X/Cl$ Fog	$EF_{Cl}$	$X/Al^{**}$ Crust	$X/Al$ Solution	$X/Al$ Fog	$EF_{Al}$	$EF_w$	SSF (%)	CRF (%)	NSSCRF (%)
Ca <sup>++</sup>	0.021	0.18	8.6	0.50	500	39	79	0.08	12	1	87
Mg <sup>++</sup>	0.067	0.081	1.2	0.28	350	18	64	0.05	83	2	16
Na <sup>+</sup>	0.55	0.64	1.2	0.28	250	160	570	0.65	87	0.2	13
K <sup>+</sup>	0.021	0.059	2.8	0.25	260	15	61	0.06	35	2	63
NH <sub>4</sub> <sup>+</sup>	—	0.28	—	—	10	75	—	7.5	—	—	—
Cl <sup>-</sup>	1.00	1.00	1.0	0.0016	210	250	156 000	1.2	100	0	0
Br <sup>-</sup>	0.003	0.01	3.4	0.00003	—	2	74 000	—	30	0	70
SO <sub>4</sub> <sup>-</sup>	0.14	1.44	10	—	130	300	—	2.3	10	—	90
NO <sub>3</sub> <sup>-</sup>	—	0.32	—	—	89	91	—	1.0	0	—	—

\* Kennish (1989).

\*\* CRC Handbook (1990).

TABLE 6a. Concentrations of trace elements in sequential fog-water samples from the AES fog collector. Dates and times as in Table 5a.

Sample number	Fe	As	Cd	Pb	Be	B	Al	Ti	V	Cr	Mn	Ni
(ppb)												
4	70	20.3	1.2	36.1	<0.5	—	65.1	3.8	7.9	<1.0	35.4	5.1
5	54	15.3	0.6	16.1	<0.5	—	54.5	<2.0	4.2	<1.0	27.4	6.0
6	<50	7.4	<0.5	5.6	<0.5	—	29.5	<2.0	1.5	<1.0	12.7	2.7
7	<50	2.8	<0.5	0.5	<0.5	—	15.8	<2.0	0.7	<1.0	6.1	<2.0
8	<50	3.2	<0.5	1.1	<0.5	—	9.1	<2.0	0.8	<1.0	5.4	<2.0
9	<50	1.8	<0.5	0.5	<0.5	—	4.3	<2.0	0.5	<1.0	3.0	<2.0
10	<50	3.1	<0.5	0.6	<0.5	—	6.7	<2.0	0.5	<1.0	3.5	<2.0
11	<50	3.4	<0.5	<0.5	<0.5	—	4.5	<2.0	0.59	<1.0	3.6	<2.0
Maximum allowed	300	50	10	50						50	100	

TABLE 6b. As in Table 6a.

Sample number	Co	Cu	Zn	Se	Sr	Mo	Ag	Sb	Ba	Tl	U
(ppb)											
4	<1.0	44.4	78.2	<5.0	18.3	<0.5	<0.5	0.8	8.1	<0.5	<0.5
5	<1.0	30.4	34.6	<5.0	11.1	<0.5	<0.5	0.6	4.3	<0.5	<0.5
6	<1.0	16.3	16.1	<5.0	4.4	<0.5	<0.5	<0.5	2.1	<0.5	<0.5
7	<1.0	4.9	9.9	<5.0	2.4	<0.5	<0.5	<0.5	1.0	<0.5	<0.5
8	<1.0	6.5	13.1	<5.0	1.9	<0.5	<0.5	<0.5	1.0	<0.5	<0.5
9	<1.0	2.2	5.4	<5.0	0.7	<0.5	<0.5	<0.5	0.6	<0.5	<0.5
10	<1.0	2.1	4.5	<5.0	0.8	<0.5	<0.5	<0.5	1.0	<0.5	<0.5
11	<1.0	<1.0	4.1	<5.0	1.1	<0.5	<0.5	<0.5	0.7	<0.5	<0.5
Maximum allowed		1000	5000	10					1000		

TABLE 6c. Mean enrichment factors for trace elements in high-elevation coastal fog in Chile based on seawater Cl<sup>-</sup>(EF<sub>Cl</sub>) and crustal Al(EF<sub>Al</sub>, EF<sub>w</sub>) values. Sea-salt (SSF), crustal (CRF), and residual fractions (NSSCRF) of the ions in the fog water are also given as are crustal fractions (CRF<sub>w</sub>) and residual fractions (NSSCRF<sub>w</sub>) based on the soluble-soil mass ratios (X/Al)<sub>soln</sub>. A dash signifies that the value is not available.

Element	X/Cl* Sea (10 <sup>-6</sup> )	X/Cl Fog (10 <sup>-3</sup> )	EF <sub>Cl</sub>	X/Al Soil	X/Al Solution	X/Al Fog	EF <sub>Al</sub>	EF <sub>w</sub>	SSF (%)	CRF (%)	NSSCRF (%)	CRF <sub>w</sub> (%)	NSSCRF <sub>w</sub> (%)
Fe	0.2	2.9	14 500	3.44 (0.68)**	1.00	1.04	0.3 (1.5)**	1.0	0	344 (65)**	0	96	4
As	0.1	0.8	8 000	0.00022**	0.20	0.30	13 600	1.5	0	0**	100	67	23
Cd	0.006	0.04	7 000	0.000034	0.0016	0.015	440	9.4	0	0	100	11	89
Pb	0.003	1.2	400 000	0.0020	0.0017	0.43	220	250	0	1	99	0	100
Be	0.00003	—	—	0.00013	0.0010	—	—	—	—	—	—	—	—
Al	0.1	2.8	28 000	1.0	1.0	1.0	1.0	1.0	0	100	0	100	0
Ti	0.05	0.2	4 000	0.12 (0.069)**	0.38	0.064	0.5 (0.9)**	0.2	0	188 (108)**	0	590	0
V	0.1	0.3	3 000	0.0083	0.27	0.099	12	0.4	0	8	92	270	0
Cr	0.009	—	—	0.0017	0.051	—	—	—	—	—	—	—	—
Mn	0.06	1.5	25 000	0.031	0.082	0.52	17	6.3	0	6	94	16	84
Ni	0.2	0.3	1 500	0.00071	0.045	0.094	130	2.1	0	1	99	48	52
Co	0.008	—	—	0.0015	0.041	—	—	—	—	—	—	—	—
Cu	0.07	1.7	24 300	0.0054	1.35	0.62	110	0.5	0	1	99	220	0
Zn	0.4	2.6	6 500	0.012	0.067	0.92	77	14	0	1	99	7	93
Se	0.01	—	—	—	—	—	—	—	—	—	—	—	—
Sr	—	0.7	—	0.0038	0.95	0.24	63	0.3	—	2	98	400	0
Mo	0.3	—	—	0.000095	—	—	—	—	—	—	—	—	—
Ag	0.009	—	—	—	—	—	—	—	—	—	—	—	—
Sb	0.02	0.03	1 500	0.00002**	—	0.012	6 000	—	0	0**	100	—	—
Ba	1.0	0.3	300	0.0083	—	0.10	12	—	0	8	92	—	—
Tl	—	—	—	—	—	—	—	—	—	—	—	—	—
U	0.2	—	—	—	—	—	—	—	—	—	—	—	—

\* Kennish (1989).

\*\* CRC Handbook (1990).

TABLE 7a. Concentrations of major ions in samples from the flowmeter (large fog collectors) on the lower ridge at El Tofo, Chile.

Sample number	pH	SO <sub>4</sub>	NO <sub>3</sub>	Br	Cl	Na	NH <sub>4</sub>	K	Ca	Mg	Date	Time
		(ppm)										
F	3.71	129.9	59.4*	0.54	312.0*	200.0	8.75	6.84	19.1	21.0	6 November 1989	1940
G	4.01	26.0	7.56	0.11	41.0	28.0	1.67	1.52	2.45	2.40	6 November 1989	2010
H	4.56	3.62	0.82	0.028	4.19	2.67	0.45	0.31	0.30	0.30	7 November 1989	0012
I	4.88	1.81	0.33	0.018	0.80	0.63	0.30	0.16	0.11	0.10	7 November 1989	0953
J	4.65	3.37	0.68	0.026	2.24	1.35	0.68	0.25	0.27	0.22	7 November 1989	1200

\* Exceeds Chilean or WHO maximum allowable concentration.

certain elements are available in solution in relative abundances, which are more than sufficient to explain their presence in the fog water.

Rojas et al. (1990) examined the aerosols in Santiago, Chile, for the presence and sources of 17 elements. Santiago is approximately 500 km south of our study site and is 100 km inland at an altitude of 600 m. They found that sea spray had been transported into Santiago, suffering several transformations and a sulfur enrichment in the process. Secondary SO<sub>4</sub><sup>-</sup> was responsible for 49% of the fine-mode aerosol mass fraction and soil dust for 74% of the coarse-mode mass fraction. In the fine mode, they ascribed Al, Si, and Fe to soil dust, and Mn, Cu, Zn, Br, Pb, V, and K to other non-sea-salt, nonsoil dust sources. These results are in excellent agreement with the results reported here for the coastal fog samples. In the coarse aerosol fraction, Rojas et al. ascribed Mg, Al, Si, K, Ca, Ti, and Fe to soil dust. The size distribution of the aerosols at the fog collection site is not known so a detailed compar-

ison of the datasets is not in order, but it is interesting to see that soil dust origins are given for Fe, Ti, and Al in both datasets.

### c. The output from the large collectors

#### 1) ION CONCENTRATIONS

A series of samples was collected from the flowmeters, which receive water from the large 48-m<sup>2</sup> fog-water collectors. The system had never been cleaned in the 2-yr period since its construction. The concentrations of the major ions in the samples from November 1989 are given in Table 7a. The timing of the samples in relation to the flow from the flowmeter is shown in Fig. 3. Again, one sees decreases in concentrations until about midnight on the 6 November and then relatively constant values. In the first sample (F) taken at 1940 LST 6 November after about 30 h without fog, the NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> values exceed the maximum allowable

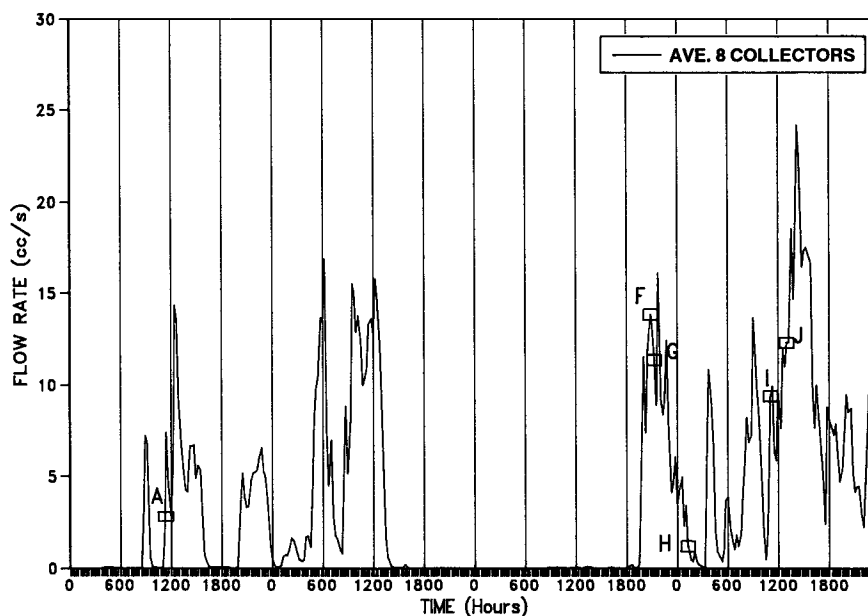


FIG. 3. The average flow rate from eight fog collectors as a function of time on 6 and 7 November 1989. The sample periods corresponding to flowmeter sample numbers in Tables 7a, 8a, and 8b are indicated on the figure.



TABLE 8a. Concentrations of trace elements in samples from the flowmeter (large fog collectors) on the lower ridge at El Tofo, Chile.

Sample number	Fe	As	Cd	Pb	Be	B	Al	Ti	V	Cr	Mn	Ni
	(ppb)											
F	209	72.8*	6.3	181.4*	<0.5	—	(1441)	7.6	10.7	2.6	283*	11.7
G	152	49.5	0.7	21.2	<0.5	—	(388)	10.6	5.0	<1.0	40.2	<2.0
H	63	25.2	<0.5	2.4	<0.5	—	(148)	5.3	1.9	<1.0	6.0	<2.0
I	<50	13.0	<0.5	1.0	<0.5	—	(92.1)	4.7	1.3	<1.0	2.3	<2.0
J	<50	12.0	<0.5	1.6	<0.5	—	(163)	8.7	1.7	<1.0	6.7	<2.0

\*Exceeds Chilean or WHO maximum allowable concentration. Dates and times as per Table 7a.

much higher in the sample from the flowmeter. This is understandable, since the flowmeter has a perforated aluminum front plate through which the water exits. Therefore, the aluminum value is not reliable in this set of samples. This means that  $EF_{Al}$  and  $EF_w$  values cannot be calculated for samples taken from the flowmeter. As was true for the major ion concentrations, a blend of the water produced during the event would meet the drinking-water standards for trace-element concentrations.

#### 4. Discussion

The water analysis was done for pH, 9 ions, and 23 trace elements. No bacterial analyses were done. The incoming clouds off the Pacific Ocean, which produce the fog on the coastal mountains, should have negligible bacterial concentrations. The large fog-water collectors, the pipes, and the storage tanks should have no problems from fecal coliform in this isolated environment, but there may be contamination from birds, insects, and plant matter. It is expected that this can be taken care of by the small chlorination plant, which will be built in 1992, when the fog water is piped 6.5 km down the mountain to the village of Chungungo. There may also be potential problems with algae in the storage tanks, but the combination of a continuous flow of water through them and chlorination should minimize problems.

A specialized small fog-water collector was used to study the composition of the incoming fog. At all times the ion and trace-element concentrations were well within allowable drinking-water limits. The only concern is with pH. Fourteen of the 15 samples had pH values below 6, which is the Chilean minimum stan-

dard. It is felt that this can be modified with a simple treatment in the field when it comes to providing water to the nearby village.

The very low pH values in the incoming fog water are of considerable interest. They fall in the range of acidic fogs in eastern North America. Sulfate was the major ion contributing to the acidity of the samples. In all cases excess sulfate contributed 80%–94% of the sulfate measured. A dry-deposition test showed that considerable  $SO_4^{2-}$  was present as an aerosol on a clear day, but whether the  $SO_4^{2-}$  resulted from an oceanic production source is not known for certain. The most likely source is thought to be related to oceanic emissions of dimethyl sulfide and possibly other sulfur species in the organically rich cold waters off the coast of Chile. The excess  $SO_4^{2-}$  concentrations in the Chilean fog water are considerably higher than for comparable high-elevation fog samples in Puerto Rico (Lazrus et al. 1970) and for precipitation in remote marine areas (Galloway et al. 1989).

The relative abundances of the ions and trace elements in solutions made from the soil at the field site, from aerosols as measured in a dry-deposition sample, as well as in the fog (samples 4 and 5, 1989), are summarized in Table 9. The order of importance of the ion concentrations in the fog water is clearly much more like that for the aerosol than for the soil. Five of the nine ions are in the same order, and the other four are displaced only one rank. The ranking of the most important trace elements in the fog water is also closer to that for the aerosols than for the soils. This suggests that the aerosols on clear days largely result from evaporated cloud droplets over the ocean and that the soil dust component is of less importance. In addition, one

TABLE 8b. As in Table 8a.

Sample number	Co	Cu	Zn	Se	Sr	Mo	Ag	Sb	Ba	Tl	U
	(ppb)										
F	6.3	218	228	16.3*	200	0.5	<0.5	5.2	47.1	<0.5	<0.5
G	<1.0	46.2	33.7	<5.0	24.0	<0.5	<0.5	3.7	7.0	<0.5	<0.5
H	<1.0	7.3	7.0	<5.0	2.9	0.5	<0.5	2.6	1.2	<0.5	<0.5
I	<1.0	2.7	2.5	<5.0	1.0	0.6	<0.5	1.3	0.7	<0.5	<0.5
J	<1.0	5.1	5.2	<5.0	2.8	<0.5	<0.5	1.7	2.3	<0.5	<0.5

TABLE 9. The relative abundances of ions and trace elements in solutions made from soils at the site, in aerosols deposited on a dry collector, and in the fog-water sample 4. The pH range is for all 15 fog samples.

Order	Ions (ppm)			Trace elements (ppb)		
	Soil	Aerosol	Fog	Soil	Aerosol	Fog
1	Ca	Cl	Cl	Cu	Zn	Zn
2	Mg	Na	SO <sub>4</sub>	Al	Al	Fe
3	Na	SO <sub>4</sub>	Na	Fe	Fe	Al
4	Cl	NO <sub>3</sub>	NO <sub>3</sub>	Sr	Mn	Cu
5	K	Ca	Ca	Ti	Sr	Pb
6	SO <sub>4</sub>	Mg	NH <sub>4</sub>	V	Cu	Mn
7	NO <sub>3</sub>	NH <sub>4</sub>	Mg	As	As	As
8	NH <sub>4</sub>	K	K	Mn	Ni	Sr
9		Br	Br	Zn	Ti	Ba
10				Cr	Ba	V
pH	7.3	5.0	3.5-6.7			

would expect some of the marine aerosols, and the fog droplets themselves, to be deposited onto the ground and, therefore, to contribute to the water-soluble components of the surface soils. Enrichment-factor calculations indicate that Mg<sup>++</sup>, Na<sup>+</sup>, and Cl<sup>-</sup> in the fog originate from sea salts, and that Fe, Al, and Ti are soil dust derived. Other sources dominate for Ca<sup>++</sup>, K<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, Br<sup>-</sup>, SO<sub>4</sub><sup>=</sup>, NO<sub>3</sub><sup>-</sup>, As, Cd, Pb, V, Mn, Ni, Cu, Zn, Sr, Sb, and Ba. If one considers the soluble components of the soil at the site, then As, V, Cu, and Sr may also be soil derived.

In 1989, five water samples were taken from the output of eight 48-m<sup>2</sup> fog collectors on the lower ridge at El Tofo. The first sample (F) was collected after a dry 24-h period and had both a very low pH and concentrations of NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> above the maximum acceptable limits. Four of the 24 trace elements (As, Pb, Mn, Se) were also found in unacceptable concentrations in this sample. In the subsequent four samples, everything but H<sup>+</sup> (pH) was present in acceptable amounts. Comparing the first flowmeter sample (F) to a fog sample from the cleaned Teflon collector taken at the same time (number 5), one sees that the fog itself was clean and that, therefore, the water quality problem with the first flow of water from the collectors is due to dry deposition on the collectors. Once this first flow of water is mixed with the subsequent collection, the water is of acceptable quality. This is confirmed by water samples taken from the two fog-water storage tanks on the mountain, which were of completely acceptable quality, except for a low pH in one tank. The seven water samples collected from the large collectors in 1987 and 1988 also had acceptable ion concentrations except for pH (H<sup>+</sup>), which ranged from 3.88 to 5.19.

The question of the quality of the water always has to be discussed within the context of the conditions in the area. The fog-water collection site is on the southern

edge of the driest region on earth. Precipitation at the site averages about 70 mm yr<sup>-1</sup>, and sometimes no rain falls for several years. Further north in Chile the average rainfall drops to <1 mm yr<sup>-1</sup>. The current water supply for villages such as Chungungo is of questionable quality and the delivery by truck is at times unreliable. Two water sources in the area were examined for comparison with the two fog-water reservoirs. The sample of the existing trucked water supply in the village had unacceptably high concentrations of SO<sub>4</sub><sup>=</sup> and Se. Spring water on the mountain side, which the villagers sometimes mix with the trucked water, had completely unacceptable concentrations of SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, Ca<sup>++</sup>, and Mg<sup>++</sup>. A trace-element analysis was not possible because of the extreme sample composition (Cl<sup>-</sup> 3028 ppm, SO<sub>4</sub><sup>=</sup> 593 ppm). Fog water from the 25 000-l storage tank was acceptable except for a low pH. Finally, the fog water passing through iron pipes, an old iron tank, and a 50-yr-old plumbing system to the water taps in the caretaker's house on the ridge at El Tofo was found to be acceptable in all respects.

The fact that the fog water meets the existing Chilean drinking-water standards in all respects but pH is critical to the development of this resource in northern Chile. The pH values, of about 4, pose no problems for agricultural use of the water in the desert, nor do they for washing clothes or other household uses. The water is also almost certainly acceptable for drinking and cooking as well. The concern is with protecting the various parts of the transmission system. The use of polyethylene or polyvinyl chloride pipes and fittings will go a long way toward solving this problem, since these materials have excellent resistance to weak acids. The most direct solution however is to treat the water on the upper part of the mountain near the collectors in order to raise the pH. This can be done by the addition of a buffering agent such as sodium bicarbonate or perhaps by percolating the water through a bed of

crushed limestone. The water would then be piped the 6 or 7 km to the village at an acceptably high pH.

## 5. Conclusions

An analysis of 21 water samples from early November 1989 and 14 samples from 1987 and 1988 has produced an initial assessment of the quality of the fog water present at a high-elevation coastal site in northern Chile, the water being produced by an array of large fog collectors, and the present local water supplies. Clearly, samples need to be acquired on an ongoing basis to ensure that the water quality stays within acceptable limits. However, this is the first published data in the world on the use of fog water for domestic consumption and, as such, demonstrates both the potential of the technology and the sources of possible future problems. There are contributions to the composition of the fog water from both the marine aerosols and the soils near the site. This might be expected to vary somewhat from site to site depending on the remoteness of the sites, the local topography, and the surface wind speeds.

The persistent decks of low cloud along the northern coast of Chile have been observed to produce high elevation fogs on the coastal mountains up to 189 days per year (Cereceda and Schemenauer 1991) with another 89 days of patchy fog. In a region almost devoid of rain, potable spring water, or rivers, these fogs represent an enticing new water resource. This study has shown that, even at a site above an extensive area of mine tailings, the quality of the fog water is such as to justify the use of the water for a nearby village. One might expect that at other less disturbed sites, the water quality might be even better. However, if the observed low pH values are associated with the oceanic production of sulfur compounds, then the water will likely be acidic at all sites along the coast. This is a factor in the use of the water that will have to be dealt with in a manner that is acceptable to the local water authorities.

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## REFERENCES

- Ahmed, A. F. M., R. P. Singh, and A. H. Elmubarak, 1990: Chemistry of atmospheric precipitation at the western Arabian gulf coast. *Atmos. Environ.*, **24A**, 2927–2934.
- Andreae, M. O., and H. Raemdonck, 1983: Dimethyl sulfide in the surface ocean and the marine atmosphere: A global view. *Science*, **221**, 744–747.
- Barrie, L. A., and R. S. Schemenauer, 1986: Pollutant wet deposition mechanisms in precipitation and fog water. *Water, Air, Soil Poll.*, **30**, 91–104.
- , and —, 1989: Wet deposition of heavy metals. *Control and Fate of Atmospheric Trace Metals*. J. M. Pacyna and B. Ottar, Eds., Kluwer Academic Publishers, 203–231.
- Cereceda, P., and R. S. Schemenauer, 1991: The occurrence of fog in Chile. *J. Appl. Meteor.*, **30**, 1097–1105.
- Cereceda-Troncoso, P., R. S. Schemenauer, and N. Carvajal-Rojas, 1988: Factores topográficos que determinan la distribución de las neblinas costeras en El Tofo (IV Region de Coquimbo—Chile). X Congreso Nacional de Geografía, Santiago, Chile, B1–B6.
- Cereceda-Troncoso, P., R. S. Schemenauer, and N. Carvajal-Rojas, 1988: Factores topográficos que determinan la distribución de las neblinas costeras en El Tofo (IV Region de Coquimbo—Chile). X Congreso Nacional de Geografía, Santiago, Chile, B1–B6.
- Cereceda, P., and M. Suit, 1992: An alternative water supply for Chilean coastal villages. *Intl. J. Water Resources Development*, (in press).
- Falconer, R. E., and P. D. Falconer, 1980: Determination of cloud water acidity at a mountain observatory in the Adirondack Mountains of New York state. *J. Geophys. Res.*, **85**, 7465–7470.
- Fuenzalida, H. A., R. S. Schemenauer, and P. Cereceda, 1989a: Sub-tropical stratocumuli as a water resource. *Third International Conf. on Meteorology and Oceanography in the Southern Hemisphere*, Buenos Aires, Amer. Meteor. Soc., 199–200.
- , J. Rutllant, and J. Vergara, 1989b: Meteorological aspects of water collection from stratocumuli in northern Chile. *Third International Conf. on Meteorology and Oceanography in the Southern Hemisphere*, Buenos Aires, Amer. Meteor. Soc., 156–161.
- Galloway, J. N., J. D. Thornton, S. A. Norton, H. L. Volchok, and R. A. N. McLean, 1982: Trace metals in atmospheric deposition: A review and assessment. *Atmos. Environ.*, **16**, 1677–1700.
- , W. C. Keene, R. S. Artz, J. M. Miller, T. M. Church, and A. H. Knap, 1989: Processes controlling the concentrations of  $\text{SO}_4^-$ ,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{H}^+$ ,  $\text{HCOO}^-$  and  $\text{CH}_3\text{COO}^-$  in precipitation in Bermuda. *Tellus*, **41B**, 427–443.
- Kennish, M. J., 1989: Section 2: chemical oceanography. *Practical Handbook of Marine Science*. CRC Press, 55–62.
- Kerfoot, O., 1968: Mist precipitation on vegetation. *For. Abstr.*, **29**, 8–20.
- Lazrus, A. L., H. W. Baynton, and J. P. Lodge, 1970: Trace constituents in oceanic cloud water and their origin. *Tellus*, **22**, 106–113.
- Lide, D. R., Ed., 1990: *CRC Handbook of Chemistry and Physics*. CRC Press, 14–7.

- Luria, M., and J. F. Meagher, 1986: Computer simulation of the oxidation and removal of natural sulfur compounds in the marine atmosphere. *Seventh World Clean Air Congress*, Sydney, International Union of Air Pollution Prevention Associations, 295-301.
- Mohnen, V. A., and J. A. Kadlecek, 1989: Cloud chemistry research at Whiteface Mountain. *Tellus*, **41B**, 79-91.
- Ramundo, R. A., and T. R. Seastedt, 1990: Site-specific underestimation of wetfall  $\text{NH}_4^+$  using NADP data. *Atmos. Environ.*, **24A**, 3093-3095.
- Rojas, C. M., P. Artaxo, and R. Van Grieken, 1990: Aerosols in Santiago de Chile: A study using receptor modeling with X-ray fluorescence and single particle analysis. *Atmos. Environ.*, **24B**, 227-241.
- Ross, H. B., 1986: The importance of reducing sample contamination in routine monitoring of trace metals in atmospheric precipitation. *Atmos. Environ.*, **20**, 401-405.
- Schemenauer, R. S., 1986: Acidic deposition to forests: The 1985 Chemistry of High Elevation Fog (CHEF) project. *Atmos.-Ocean*, **24**, 303-328.
- , 1988: Fog water to quench a desert's thirst. *WMO Bull.*, **37**, 281-286.
- , and P. Cereceda, 1988: The collection of fog water in Chile for use in coastal villages. *Proc., VIth IWRA World Congress on Water Resources*, Vol. II, Ottawa, International Water Resources Association, 660-669.
- , and P. I. Joe, 1989: The collection efficiency of a massive fog collector. *Atmos. Res.*, **24**, 53-69.
- , and P. Cereceda, 1991: Fog water collection in arid coastal locations. *Ambio*, **20**, 303-308.
- , P. Cereceda, and N. Carvajal, 1987: Measurements of fog water deposition and their relationships to terrain features. *J. Climate Appl. Meteor.*, **26**, 1285-1291.
- , H. Fuenzalida, and P. Cereceda, 1988: A neglected water resource: The camanchaca of South America. *Bull. Amer. Meteor. Soc.*, **69**, 138-147.
- Stadtmüller, T., 1987: Cloud forests in the humid tropics. The United Nations University, NRTS-33/UNUP-670, pp. 81.
- Vesely, J., 1990: Stability of the pH and the contents of ammonium and nitrate in precipitation samples. *Atmos. Environ.*, **24A**, 3085-3089.
- Wagner, G. H., and K. F. Steele, 1989:  $\text{Na}^+/\text{Cl}^-$  ratios in rain across the USA, 1982-1986. *Tellus*, **41B**, 444-451.