A Neglected Water Resource: The Camanchaca of South America

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Abstract

Many parts of the world are currently suffering water shortages. Few areas, however, have as little precipitation and groundwater available to alleviate the problem as does the northern coast of Chile. The historical background of the attempts to collect water directly from the coastal stratocumulus decks is reviewed in this paper as are the meteorological and geographical considerations important to the collection of the cloud water. Calculations of water availability and cost indicate that this may well be an important source of water for some coastal regions. A combined research and applied project to study the properties of high-elevation fogs and their use as a water supply will be conducted by Chilean and Canadian agencies from late 1987 to the end of 1988.

1. Introduction

The lack of fresh water for human consumption, agricultural purposes, and a variety of industrial uses increasingly is becoming a problem throughout the world. Shortages arise in highly developed areas (e.g., the southwestern United States) as well as in areas lacking the resources to attempt costly remedies for the lack of water (e.g., north central Africa). Shortages arise because of over utilization of existing groundwater or because of a lack of replenishment of the groundwater due to short-term or long-term decreases in precipitation. Traditional solutions to the problem have been to better utilize surface runoff with dams and altered cropping practices, to consider limiting or moving populations, and to initiate rainfall-augmentation or snowpack-augmentation programs. There are many reasons why these solutions may not be practical in a particular location, and new ideas tailored to a particular locale should be pursued.

Chile is a country of geographical and climatological extremes. With an average width of only 175 km, its 4200-km length is "sandwiched" between the Andean Cordillera and the Pacific Ocean. The northern part is probably the driest region on the globe while the southern region is the wettest extratropical region in the world (Miller, 1976). A sketch of the different precipitation zones in the northern third of Chile is shown in Fig. 1. The amount of precipitation (1911–1949) measured at two stations, Arica and La Serena, in this region is given in Table 1. Precipitation is almost nonexistent at Arica where the mean annual total is 0.7 mm! The annual total of 133.3 mm at La Serena is considerably more but the area is still very arid. There is also a lack of good groundwater, and few rivers that can be used for irrigation and thus, though the region is blessed with warm weather throughout, the year there is little potential for agriculture. This shortage of water for drinking, sanitary, and agricultural purposes is a contributing factor to the movement of people from the coastal fishing villages to the larger cities.

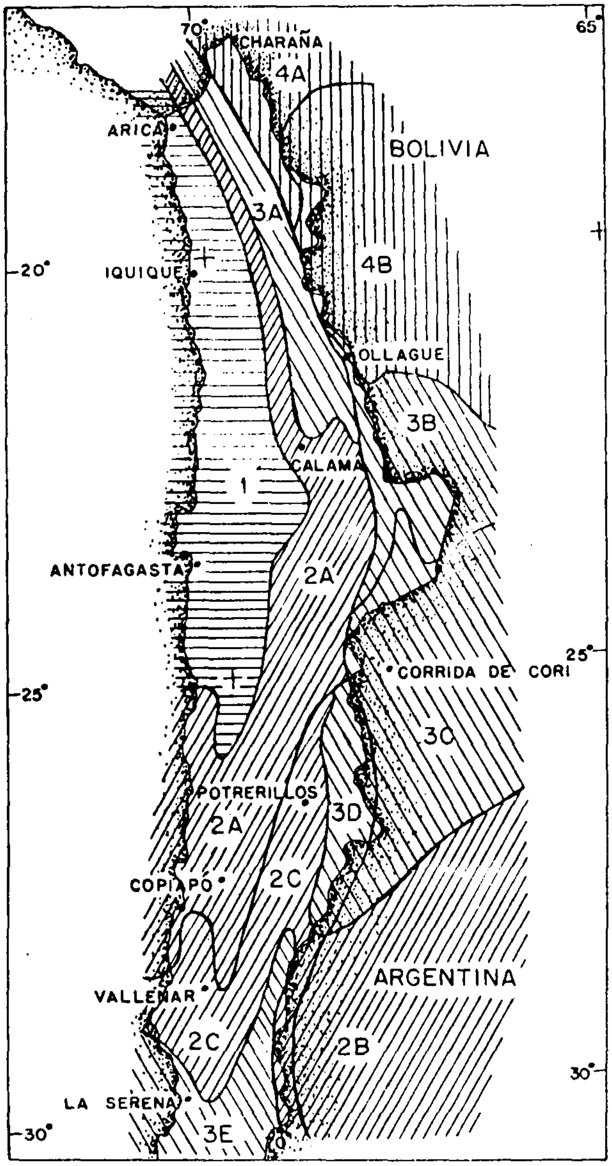

FIG. 1. Precipitation characteristics of northern Chile. (1) extremely arid; (2A) arid, very rare winter rain; (2B) arid, rare summer rain; (2C) arid, occasional light winter rain; (3A) semi-arid, occasional summer showers; (3B) semi-arid, summer rain showers, occasional winter snow and rain (Altiplano); (3C) semi-arid to arid, light summer rain, occasional winter snow; (3D) semi-arid, light winter rain or snow; (3E) semi-arid, becoming sub-humid extreme south, winter rain; (4A) sub-humid, summer rain, occasional winter rain or snow (Altiplano). (From Miller [1976]).

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TABLE 1. Monthly mean and 24-hour maximum precipitation values for two stations in northern Chile. The record period is 1911 to 1949. Adapted from Miller (1976).

ARICA
latitude 18°28′S,
longitude 70°22′W,
elevation 29 m

Month	Precipitation (mm) Mean	Max. in 24 h
Jan	0.3	10.0
Feb	tr.	0.4
Mar	tr.	tr.
Apr	0.0	0.0
May	tr.	tr.
June	0.1	1.0
July	0.1	0.6
Aug	0.1	2.0
Sept	tr.	0.4
Oct	tr.	0.1
Nov	0.0	0.0
Dec	0.1	1.7
Annual	0.7	10.0

LA SERENA
latitude 29°54′S,
longitude 71°15′W,
elevation 35 m

Month	Precipitation (mm) Mean	Max. in 25 h
Jan	0.1	1.1
Feb	0.8	54.3
Mar	0.6	3.5
Apr	2.6	28.0
May	21.9	89.2
June	43.7	80.9
July	29.7	57.0
Aug	23.2	39.9
Sept	6.0	19.2
Oct	3.7	33.3
Nov	0.7	9.0
Dec	0.3	17.2
Annual	133.3	89.2

FIG. 2. Photograph of the landscape in the vicinity of El Tofo looking south to the Cordon Sarcos. The tree plantation referred to in the text is at the center of the photograph.

In the northern third of Chile and in Peru, the weather is dominated by the Pacific anticyclone throughout the year. It produces a light southerly flow or southwesterly flow in the lower kilometer of the atmosphere and a stratus or stratocumulus deck that extends a few-hundred kilometers out over the ocean. The anticyclone also can produce a few periods of fog, primarily in the winter, in the coastal villages. Fog events are much-more frequent at altitudes between 500 m and 1000 m in the coastal mountains where the terrain intercepts the low clouds. These high-altitude fog events are called camanchacas. Camanchacas can occur almost every day during the winter and on perhaps one-half of the days during the summer. Vegetation in the "fog" zone can intercept some fog water and the fog drip can sustain the plant. The importance of fogs as sources of water in certain locations has been recognized for a considerable time. Kerfoot (1968) and more recently Schemenauer (1986) have reviewed the literature pertaining to deposition rates of water from fogs. The rates can be substantial, equalling or exceeding the amounts of rainfall in areas with rain and providing the only significant and reliable sources of water in some desert areas.

The landscape at El Tofo (immediately north of La Serena, Fig. 1), the main field site to be discussed here, is arid and rocky with a sparse coverage of cacti and shrubs (see Fig. 2). On the summit (not shown) is an anomalous grouping of eucalyptus trees that reach heights of 10 m. Until very recently the mountain was the location of Chile's largest iron mine and it is to the miners that we owe the trees. Lacking any shade near their homes on the upper mountain, the miners planted some eucalyptus seedlings about 50 years ago. The trees were watered until they reached heights of about 2 m. From that point on they relied on their natural "fog-collecting" abilities and have existed on water from the camanchacas ever since. The area under the trees has moss-covered rocks and lichen-covered cacti all existing on fog drip from the trees. The El Tofo site is a focus for several Chilean research groups using a variety of small collectors and large collectors. Currently one 40-m^2 collector and one 90-m^2 collector provide drinking, cooking, and sanitary water for two men, "plus" irrigation water for a small garden and a three-hectare plantation of native and introduced tree seedlings.

Follmann (1963) discusses the "cloud oases" in northern Chile that consist of small forests at Fray Jorge and Talinay (Fig. 3) that receive water for subsistence through fog interception. The existence of these forests has intrigued Chilean scientists for some time. Interest in removing water from the camanchacas has existed for 30 years or more in Chile. Most of the work has been done in small projects that are described in institutional or university reports. Major projects have not been undertaken due to both insufficient funding and a lack of continuity in funding. Bowen (1966) discusses the "Chilean fog broom" that was developed in an attempt to collect water from fogs in the Atacama desert in northern Chile. Vogelmann (1973) in a discussion of fog precipitation in the cloud forests of eastern Mexico mentions that the coast of Chile is another location where the conditions would be suitable for the collection of fog moisture. There has been, however, no extensive discussion in the English literature of the meteorological and topographical factors relevant to the formation of camanchacas and the collection of water from them. In this paper we will deal with these areas, will present some recent data from field experiments in Chile, and will look at the potential for removing useful amounts of water from the camanchacas.

2. Meteorological considerations

The subtropical arid coast of northern Chile, between 18°S and 33°S, is under the influence of the east-Pacific subtropical anticyclone. Its persistence can be inferred from the fact that at Quintero (near La Serena), in the southern end of the region, the trade wind inversion is present 77 percent of the time, and at Antofagasta at 24°S it is present about 97 percent of the time. The associated stratocumulus "shield" is almost always present in satellite pictures and its occurrence is related to the cold surface water in the ocean. However, along a coastal strip about 200-km wide the cloud layer shows weaker persistence, frequently breaking around noon and reforming in the late evening or early morning.

The stratocumulus layer is topped by the trade-wind inversion and its base corresponds to the condensation level of a fairly well-mixed atmospheric boundary layer (Fuenzalida, 1985). Annual mean values for the inversion-base height at Antofagasta (24°S) and Quintero (33°S) are 1016 m and 760 m above sea level with standard deviations of 274 m and 469 m, respectively (Rutllant, 1981). The cloud base at Antofagasta is reported at an altitude of about 700 m and it is some 200 m lower at La Serena (30°S). Along the northern Chilean coast the terrain rises quite abruptly and summits emerging above the cloud deck are common (see Fig. 3). Along the mountain slopes there are places where the stratocumuli come into contact with the ground.

The high stability and intensity of the temperature inversion keep the evaporated sea water from defusing upwards into the dry and warm subsiding air. The moist air under the inversion is in contact with a cool ocean and therefore the mean temperature is 4° to 6°C cooler than the air above. The moist air also is mixed well due to the radiative cooling operating on top of the cloud deck (Deardorff, 1976 and Randall, 1980). Over the open sea the depth of the moist boundary layer results from a delicate balance between subsident motion, and turbulent and radiative fluxes via processes so far not fully understood (Randall et al., 1984). Near the coast there also must be advective fluxes involved.

The site chosen for the study is an old iron mine, El Tofo (29°26′S, 71°15′W) at 780 m above sea level and 5-km away from the coast (see Fig. 4). At this place the National Forestry Corporation (CONAF) has been operating an experimental station for about three years with the partial support of the Regional Planning and Coordination Office (SERPLAC) and UNESCO.

The meteorological data available at El Tofo have been obtained in two separate periods since September 1982. The first period covers 11 months when an automatic station was in operation giving hourly values of atmospheric pressure, air temperature, relative humidity, solar radiation, and wind speed and direction. This period extending from September 1982 until July 1983, which has been analyzed by Fuenzalida et al. (1984), is a most interesting one since it emcompasses the last strong El Niño but for the same reason is highly anomalous. The second period started in January 1984 when a climatological station was set up. The instruments for temperature, relative humidity, wind, solar radiation, rainfall, and evaporation were read three times a day. The observations of the first 13 months have been reported by CONAF (CONAF, 1984; Soto and Elicer, 1985) and will be summarized here. Therefore what follows is based on one "normal-year" record and an atypical one.

El Tofo is located at the summit of a short mountain range separating the coast from a sedimentary basin. Annual regional rainfall resulting from a few frontal passages during the cold season scarcely amounts to 100 mm. It has a very-peculiar climate with its cycles and variations controlled by the height of the trade-wind inversion. When the inversion base is over 780 m the site is within the atmospheric boundary layer, the temperature is comparatively low, the relative humidity exceeds 70 percent, and the skies are frequently overcast. On the other hand if the inversion base is below the level of El Tofo the subsiding air is clear, warm, and dry, with relative humidities under 40 percent.

The amplitudes of the daily temperature and humidity cycles at El Tofo are very small; the most-important variations are

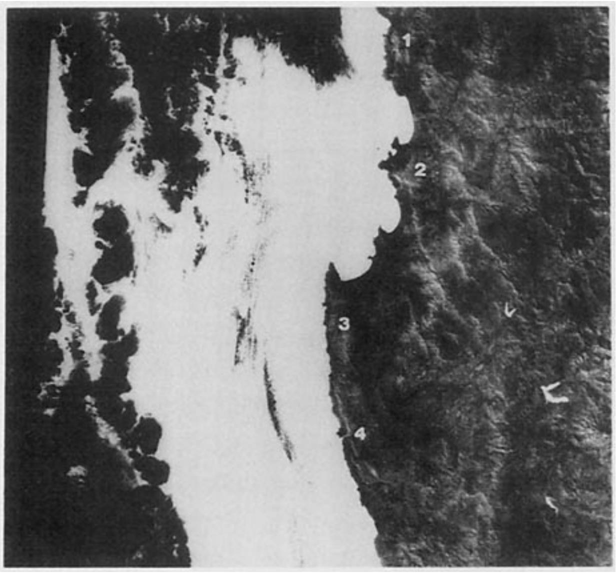


FIG. 3. Satellite photograph of the coast of Chile south of El Tofo (29°26′S). North is at the top; the vertical photo dimension is approximately 200 km. The numerals indicate the following small mountain ranges: (1) Juan Soldado; (2) Totoralillo; (3) Fray Jorge; (4) Talinay. The white area is ocean; the dark area on the left is cloud.

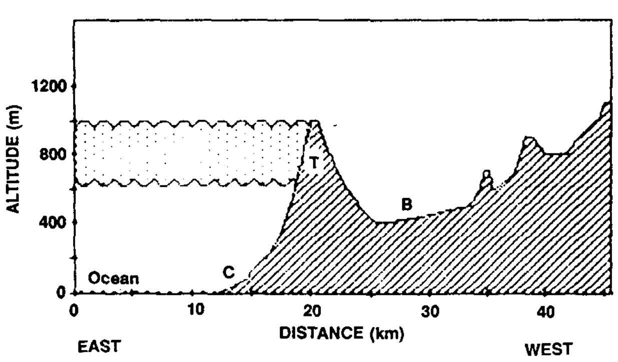


FIG. 4. Idealized terrain cross section through the highest peak near El Tofo (T). The locations of the village of Chungungo (C) and the interior basin (B) are also shown.

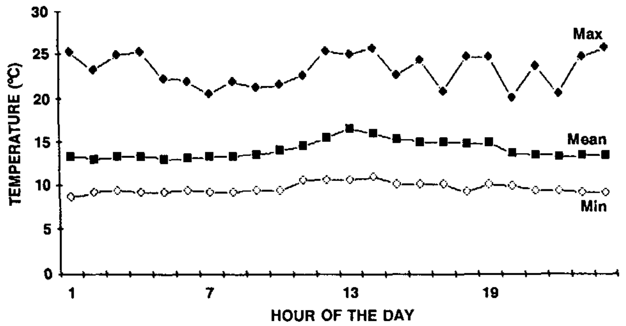


FIG. 5. The daily variation of mean and extreme temperatures at El Tofo during September 1982.

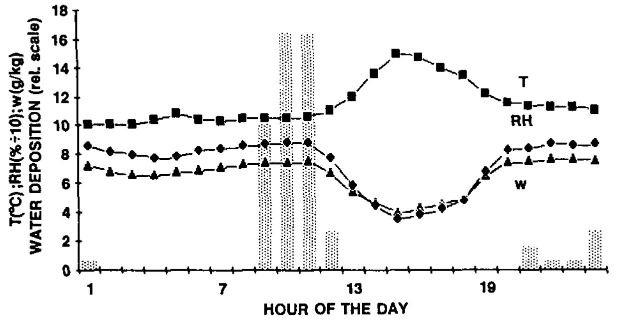


FIG. 6. Instantaneous hourly temperature, relative humidity, and water-vapor mixing-ratio values for 15 October 1982 at El Tofo. The vertical bars give the liquid water collected by the 90-m² collector in relative units.

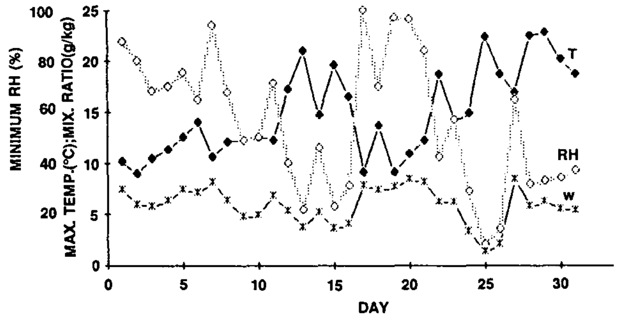


FIG. 7. Daily mean values of hourly maximum temperature, hourly minimum relative humidity, and hourly water-vapor mixing ratio during August 1984 at El Tofo.

represent the liquid water collected by the 90-m² collector in arbitrary units. It can be appreciated that between 14 hours and 18 hours the station was in the subsiding air, while for the rest of the day it was immersed in the cold, moist air of the marine boundary layer. Since the maximum temperature is normally associated with the lowest humidity, Fig. 7 containing the daily extreme values of temperature and humidity shows that at least on eight days in August 1984 the subsiding air mass reached the station; these are 13, 15, 16, 24, 25, 26, 28, and 29. Using this technique it is possible to identify the source of the air for a particular day.

The station altitude is such that during 1984 most of the time the site was in a transition from one air mass to the other. Only a few winter days were completely in the subsiding air mass but daily minimum relative humidities under 40 percent due to the alternating presence of boundary-layer air and subsiding air. The height of the inversion is controlled by some factors with irregular variations such as large-scale subsidence, upper-level cloudiness and middle-level cloudiness and sea-surface temperature. These perturb the regularity that other "participating" factors could impose, with the result that changes in the inversion level over the time scale of a few days dominate any possible daily variation. To illustrate the point, Fig. 5 shows the monthly mean daily variation of mean and extreme temperatures at El Tofo during September 1982. Opposite changes in temperature and relative humidity, (not shown) are so dramatic that they allow one to determine whether the air mass present is the upper or the lower one. Fig. 6 is a graph portraying temperature, relative humidity and water-vapor mixing ratio for a particular day, Oct. 15, 1982. Vertical bars were observed. In summer, daily minimum relative humidities were never under 40 percent (see Table 2). Such behavior is consistent with a lower inversion level in winter as a consequence of colder sea water or stronger subsiding motion. The annual course of the absolute extreme temperatures, which is shown in Fig. 8, must reflect the annual sea-temperature variation because maximum temperatures probably belong to the subsiding air and the lowest values come from the marine air within the boundary layer.

The dependence of the inversion height on the subsidence or sea-surface temperature had an additional test during the El Niño of 1982–3. On this occasion, hourly observations at El Tofo indicate that the inversion base went so high that the cloud base remained almost continuously above the station for 60 days, from mid-December to mid-February.

TABLE 2. Meteorological data for the El Tofo field site during 1984.

Month	Sunshine hours % of max.	Number of days with: $RH_{min} < 40$	$RH_{max} < 80$	Wind speed at 14-h local time ($m \cdot s^{-1}$)
January	47	—	—	7.4
February	42	—	—	6.5
March	34	—	—	5.0
April	51	7	1	5.1
May	65	10	1	3.0
June	38	11	3	3.1
July	37	9	2	3.4
August	49	10	1	2.7
September	47	12	2	4.0
October	44	1	—	5.8
November	51	3	—	6.1
December	28	—	—	6.1

Sunshine hours (see Table 2) measured as a fraction of the theoretical maximum during 1984 show no seasonal cycle, probably because the greater middle and upper cloudiness in winter is balanced by more-abundant lower clouds in summer. But the actual number of sunshine hours varies between 6.5 hours in January and 3.8 hours in June and July. In agreement with this variation the wind speed measured at 5 m above the ground shows a well-defined annual cycle with summer mean values (3.3 m · s^{-1}) about 50 percent larger than the winter one (2.1 m · s^{-1}). The largest wind speeds, registered in the afternoon, only rarely exceed 10 m · s^{-1} in January. Wind directions are mainly from the west but east winds are not unusual early in the morning in winter.

In summary, El Tofo enjoys a peculiar location at the level of the trade-wind inversion and its climate depends almost completely on the level of the base of the inversion. The possibility of collecting the liquid water available in the stratocumuli is also clearly associated with its position so that a climatology of the inversion height is essential for determining the optimum collector altitude.

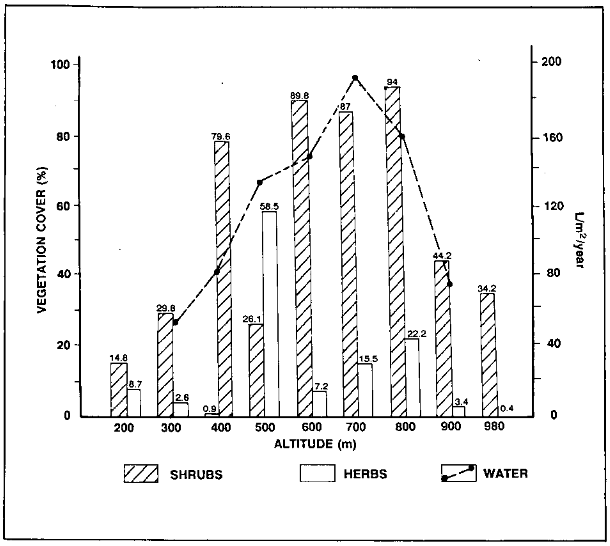


FIG. 9. Water collected per m² per year on Cordon Sarcos (see Fig. 11) near El Tofo as a function of altitude. Percentage of ground covered by shrubs and herbs is also shown.

3. Topographical influences on fog-water collection

In order to determine whether the camanchacas are a suitable water resource for the arid regions of Chile, it is necessary to understand their spatial variations and the reasons for these variations. This problem has been examined in the Coquimbo region (29°17′S to 32°14′S) since 1980. Some conclusions have been presented in Carvajal (1982), Larrain and Cereceda (1982, 1983) and Cereceda (1983).

Although the presence of the camanchaca is a general phenomenon along the northern coast of Chile, its behavior is controlled by the physiography of the coast. The geographical analysis of the spatial variation of the fog was done on both regional and local scales. The following procedures were used: analysis of topographic maps, scale 1 : 50,000; analysis of aerial photographs, scale 1 : 70,000; measurements with passive fog-water collectors; phytogeographical analyses; and questionnaires to local inhabitants.

The macrotopography is a factor that is highly influential in the site-selection process. It determines the path the air takes as it moves from the ocean to the continent and at the same time provides the barrier to "intercept" the cloud. On the regional scale there are four aspects of relief that are important. First, there must be a mountain range with an average altitude of 500 m or more. This will be high enough to control the boundary-layer flow and to intercept the camanchacas. Second, the principal axis of the range should be perpendicular to the predominant wind direction (southwest) at the altitude of the camanchacas. The satellite photo, in Fig. 3 (north at top), shows the coastal terrain immediately south of El Tofo and Cordon Sarcos for 200 km. The mountain ranges Juan Soldado, Totoralillo, Fray Jorge, and Talinay have their axes parallel to the coastline and approximately perpendicular to the prevailing wind. They have all been studied and found to have their summits almost constantly in cloud. Third, the preferred site location is on a mountain range close to the coast. This minimizes the loss of cloud water due to evaporation before the clouds reach the site. In some cases there are mountains that are relatively far from the sea (more than 10 km) that have a significant fraction of days with their summits covered by fog; but in general they are connected to the coast by broad valleys that provide passage for the fog. Fourth, to the east of the mountain range, is found a broad basin that produces an ascending region of warm air due to high daytime heating. This serves to suck the oceanic air through the mountains, see Fig. 4.

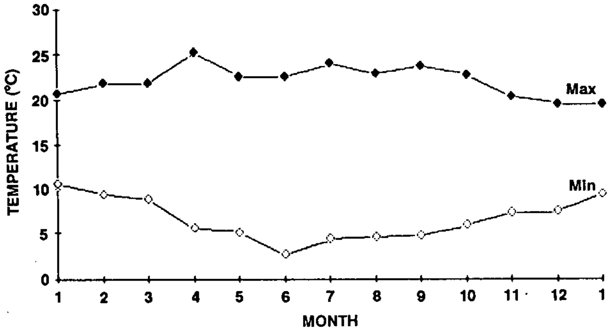


FIG. 8. Monthly mean values of hourly maximum and minimum temperatures from January 1984 to January 1985 at El Tofo.

Once a mountain range is selected as an appropriate place for the presence of fog, and hence of potential value for the capture of fog water, there are some features of relief that should be considered for the location of the collectors. The altitude range where maximum amounts of water are collected is between 600 m and 900 m (e.g., Figs. 9 and 10). Fig. 9 shows the amount of water collected (1981, 1982) by passive fog collectors at seven altitudes on Cordon Sarcos (near El Tofo). Maximum collection was at 700 m. The percentage of ground covered by shrubs also shows a broad peak at mid-levels as do the shrub densities (not shown) and the percent of organic matter in the soil (not shown). The relationship between water availability and herbs is not as clear.

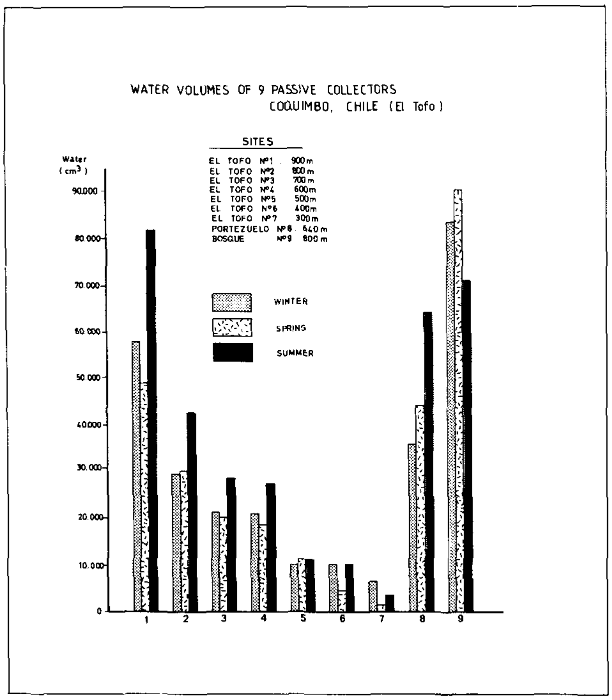


FIG. 10. Amounts of water collected at nine locations (see Fig. 11) on and near El Tofo from June 1982 to March 1983. The data are divided into amounts by season. (From Schemenauer et al. [1987].)

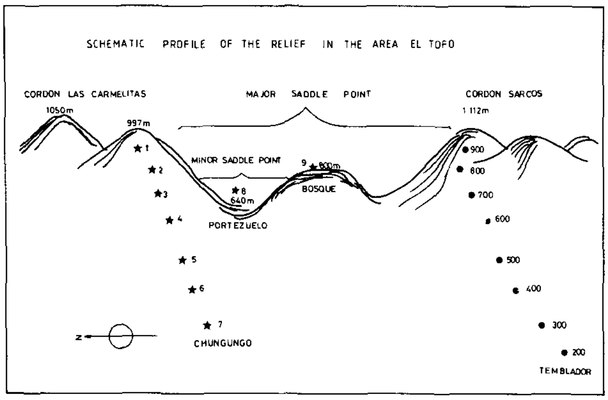


FIG. 11. Schematic profile of the relief in the area of El Tofo (an old iron mine) which is located at the small Bosque summit. The locations of the sampling sites in Figs. 9 and 10 are indicated. (From Schemenauer et al. [1987].)

A careful orientation of the collectors to the prevailing wind bringing the fog increases the amount of water collected. Generally the fog moves in from the southwest and west but the features of the local relief are highly influential in the amount of water collected. In the area of El Tofo and Cordon Sarcos the southwest hillside is the best collection area whereas in Totoralillo 50 km to the south the best orientation for fog-water collection is the north to east quadrant. The presence of a saddle point along the summit line is important. The wind speed at the mountain surface varies with the geomorphological features. At a cliff face or abrupt slope the wind speed is reduced. But if there is a saddle point at the right altitude the air is accelerated toward the basin behind the range. The importance of a saddle point is illustrated by the case of the summit (called El Bosque, the forest) of El Tofo (the name of the iron mine) where the present (Section 4) project will be held. Fig. 10 shows the results of a one year survey (1982–1983) in the mountain range where a set of 9 passive collectors was installed and read weekly (Schemenauer et al. [1987]). Collectors 1 to 7 were located on an adjacent hillside and collectors 8 and 9 in two different saddle points; the first one in a minor saddle point, and the second in a major saddle point. The volume of water collected by instrument #8 on the minor saddle point, Portezuelo, at 640 m above sea level is larger than the total of the water collected by both instruments placed at 600 m and 700 m on the hillside. The passive collector on the small summit in the major saddle point, Bosque, registered more than twice the water collected by the instrument installed at the same altitude (800 m) on the hillside. Fig. 11 shows a schematic profile of the relief in the area El Tofo.

In addition to the larger-scale features, the microtopography may play an important role, but up to now there are no measurements that can prove its influence on the water collection. Perhaps the slope, the form of the hillside (concave–convex), the lithology, runoff features, or even the natural vegetation are variables that should be analyzed in the future.

The geomorphology determines the flow of the air mass that is generated over the ocean and advances inland. The coastal terrain with its particular topography is the natural interceptor of fog, and different forms of the relief influence in a direct way the speed and direction of the flow and the potential capacity for water collection. An intensive field program that will allow for the testing of some of these guidelines is necessary before a comprehensive search of the Chilean coastlines for other collection areas is undertaken.

4. Proposed field program

A cooperative field program began in spring 1987 (October–December). The program was financed by the International Development Research Centre (a Canadian government agency) and the participating research groups in Chile. There are five organizations involved in the planning and field activities of this project. They are the Departmento de Geologia y Geofísica of the Universidad de Chile, the Instituto de Geografia of the Pontificia Universidad Católica de Chile, the Corporation Nacional Forestal (CONAF), the Secretaria Regional de Planificacion y Coordinacion (SERPLAC), and the Atmospheric Environment Service (AES) of Environment Canada.

The general scientific objectives and practical objectives of the project are to provide a better understanding of the behavior and the microphysics of the stratocumulus along the coast of Chile and to alleviate the shortage of drinking water in one isolated small community. The work begins with a two-year program centered at the El Tofo site. This choice is a consequence of the better knowledge available for this location and its proximity to the village of Chungungo where about 450 people suffer a serious shortage of drinking water. The core of this program is a 15-day field experiment to be run during the springtime, when observations indicate that best conditions for water collection occur. A continuous recording of collected water and meteorological variables (temperature, humidity, radiation, wind speed and direction) will be maintained at El Tofo

FIG. 12. Photograph of the 90-m² collector at El Tofo.

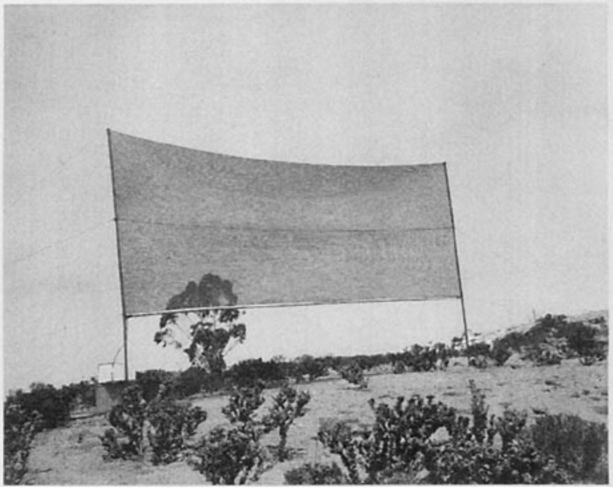


FIG. 13. Photograph of the 40-m² collector at El Tofo.

(780 m) and the saddle point (680 m) with two automatic weather stations for a period of two years.

5. Fog-water collectors

El Tofo has been used as a test site for a series of different designs of small collectors. This resulted in the construction of a large, 90-m² collector made from a nylon material which is locally available under the brand name of Rashell (see Fig. 12). It is a triangular weave of a flat fiber about 1 mm wide into a mesh with a pore size of about 1 cm. The material covers approximately 47 percent of the cross-sectional area of the mesh. Water is taken off at four levels by horizontal troughs. This collector has now been superseded by a 40-m² collector of the same material shown in Fig. 13. Two panels cover the 4-m–by–10-m collector and the water is taken off with one trough. Volumes of collected water for the 90-m² collector are included in Table 3 together with some figures for the 40-m² collector. The latter has been producing more water per unit area than the larger one. A surprising result, probably due to a more-favorable exposure rather than a better design. The mean values, which include days with no collection at all, are comparable with results of other authors reporting volumes obtained near Antofagasta using small collector prototypes (see Table 4).

Forty 40-m² collectors will be installed at the summit and 20 more at the saddle point on the ridge line. Groups of collectors will be connected to one outlet pipe in which a flowmeter with a recordable output will be placed. This arrangement will be employed for a period of years allowing a determination to be made of the relative amounts of collection at different locations.

Additionally, 40 small collectors (0.5 m by 0.5 m) with a recordable output (Schemenauer et al. 1987) will be installed on the west slope of El Tofo and on a higher nearby summit. This will give a more-detailed look at the availability of fog water in the near vicinity of the two main installations. If a location with substantially more available fog water is found after two years of measurements, then the 60 large collectors could be relocated to maximize their output.

6. Potential water availability

a. The Camanchaca Project

In estimating the amount of fog water likely to be collected during the project, it seems reasonable to make use of actual measured values from Tables 3 and 4, which range from 1 to 11 $\mathrm{L \cdot m^{-2} \cdot d^{-1}}$ for the larger collectors and 0.2 to 12 $\mathrm{L \cdot m^{-2} \cdot d^{-1}}$ for the smaller collectors. Since collector configuration and location are important factors it is probably not unreasonable to take the values for the 40-m² collector in Table 3 and hope one can do as well over an extended collection period.

If one applies the daily mean collection rate for the 40-m² collectors, 10 $\mathrm{L \cdot m^{-2} \cdot d^{-1}}$, to 60 collectors that are in clouds almost daily for six months of the year and about one-half of the time for the other six months (Miller, 1976), the total amount of water collected would be $6.6 \times 10^6\ \mathrm{L \cdot y^{-1}}$. Using a small reservoir this water could be spread out over 365 days giving $1.8 \times 10^4\ \mathrm{L \cdot d^{-1}}$, or 40 $\mathrm{L \cdot d^{-1}}$ for each of the 450 people in the village of Chungungo. This is a substantial amount of water for people who presently use about 7 $\mathrm{L \cdot d^{-1}}$ per person of poor-quality water that is trucked in at a considerable expense on an irregular basis.

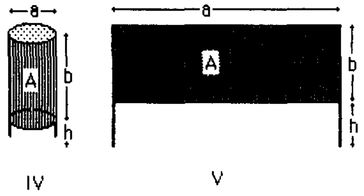
Presumably the 40 $\mathrm{L \cdot d^{-1}}$ per-person figure would be reduced if the cloud availabililty was less than the values experienced by the 40-m² collector during the two months of Table 3. More conservatively one might expect one-half this value or 20 $\mathrm{L \cdot d^{-1}}$ per person. On the other hand the amount of water could be increased by improving the collection efficiency of the collectors or even more simply by increasing the number of collectors.

The cost of each 40-m² collector is approximately US $285 in Chile. The 60-collector array costs approximately $17,000 with about another $10,000 required for reservoirs, pressure-relief stations, and pipes to take the water to Chungungo. This implies a cost of $8.30 $\mathrm{m^{-3}}$ (based on 20 $\mathrm{L \cdot d^{-1}}$ per person; $3.3 \times 10^6\ \mathrm{L \cdot y^{-1}}$) if operated for one year or $1.70 $\mathrm{m^{-3}}$ ($0.0017 $\mathrm{L^{-1}}$) amortized over the minimum five-year estimated life of the Rashell material. Additional water would be available at about two-thirds of this cost, $1.10 $\mathrm{m^{-3}}$, by adding more collectors since the pipes could carry a greater supply. The

TABLE 3. Amounts of water collected during previous experiments at the El Tofo field site (780 m).

Shape (1)	Dimensions a [m]	b [m]	h [m]	Area [m^2]	Year	Month	Collected Vol. Max. [L · m^{-2} · d^{-1}]	Mean
IV(2)	0.3	0.5	?	0.14	1980	Aug–Sep		0.8
						Oct–Dec		0.8
					1981	Jan–Feb		0.2
						Mar–May		0.4
						Jun–Jul		0.4
V(3)	30	3	2	90	1984	Jan	18.8	2.4
						Feb	10.3	2.0
						Mar	19.2	3.1
						Apr	18.3	2.7
						May	7.3	1.1
						Jun	6.7	1.2
						Jul	12.1	2.1
						Aug	13.6	3.1
						Sep	27.6	4.3
						Oct	25.7	3.6
						Nov	9.7	1.9
						Dec	19.8	3.6
					1985	Jan	12.2	1.1
V(4)						Sep	24.7	5.6
						Oct*	13.6	3.9
V(4)	10	4	2	40	1985	Sep	46.8	11.2
						Oct*	35.0	9.1

(1): According to the following schemes



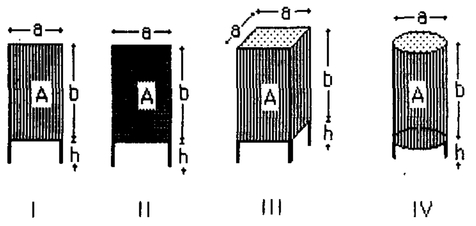
(2): Experiments at 700 m very near El Tofo (Temblador), from Carvajal (1982)
(3): From CONAF (1984)
(4): From Soto and Elicer (1985)
(*): 18 days only

TABLE 4. Amounts of water collected during previous experiments near the city of Antofagasta (24°S). From Tapia and Zuleta (1980), Veinte Anos de Camanchacas y Dos del Proyecto Mejillones. Informe Personal, Antofagasta, Chile, 105 pp.

Shape (1)	Dimensions a [m]	b [m]	h [m]	Mesh	Area A [m^2]	Altitude	Date	Collected Vol. Max. [L · m^{-2} · d^{-1}]	Mean
I	.3	1.2	?	VNS*	0.38	1050	Sep–Oct '62		3.0
I	.3	.6	?	VNS	0.21	1050	Sep '63–Dec '64	34.2	6.2
II	.7	2.0	0.9	VNS	1.4	850	Dec '61–Dec '63		<4.5
III	?	?	?	MM#	?	850	1965		<4.5
I	.3	.6	?	VNS	0.21	850	Aug '63–Aug '64		
							Sep '64–Oct '65		
							Aug '67–Feb '68	7.6	0.7
IV	.4	1.5	0.9	VNS	0.7	Sev.	Sep '68–Aug '72	12.3	3.0
I	1.0	1.0	?	MM	1.0	3 hts.	Aug '70–Feb '71		2.7
									5.5
									13.4
?	?	?	?	?	0.02	950	Sep '70–May '72		9.0

(1): According to the following schemes

(*): Vertical nylon strings
(#): Mosquito mesh



present cost of water to the people of Chungungo is \$8.00 m^{-3} (partially subsidized by the government). It is of poor quality and available only in small quantities since it must come nearly 60 km by truck over the mountains. The camanchaca water would be available at one-fifth or less of the cost. In fact it would be free to the people of Chungungo since they would not participate in the capital cost of the project. If the Camanchaca Project is successful it is anticipated that the regional or national governments would pay the costs of future installations.

The water collected previously at El Tofo has been analyzed and found to be potable, free from detrimental concentrations of minerals or bacteria. The iron concentration is high though; it is not clear if this is due to dust that is deposited on the collector or whether the iron is actually in the cloud water. This will be examined during the field project. The mechanisms by which pollutants can enter fog water are discussed by Barrie and Schemenauer (1986). The outflow water from the collectors will also be analyzed routinely during the project for bacteria and elemental composition.

b. Weather modification

Weather modification has been and is being used in some parts of the world for drought relief. Most goals or guarded claims of success speak of increasing rainfall by perhaps 10 percent. In the arid north of Chile with annual rainfall of 0 to 100 mm this will obviously do little good even if at all achievable given the existing clouds. The difficulty is compounded by the fact that the rain would fall on parched terrain and be totally unavailable for managed use.

An alternative approach is discussed by Erickson and Badilla (1982). They describe a snowpack-augmentation program on the west slopes of the Andes in Chile. The goal was to increase runoff into existing rivers and reservoirs so that the water would be available for irrigation purposes. The project used a meteorological radar and a cloud seeding aircraft with silver iodide pyrotechnics. If successful, more water would be available in several small river systems for irrigation but could never be piped to the numerous distant small towns due to high costs. At present only larger cities such as Santiago and Antofagasta can afford to pipe their water large distances from the Andes.

No project costs are given by Erickson and Badilla (1982) and no evaluation of the work was done so it is difficult to know what the increased water, if any, would have cost. But let's assume a cost of US \$1,000,000 for a 12-month operation with summer and winter project areas averaging 20 000 km^2. The mean annual rainfall in their project areas is approximately 70 mm. Thus a 10 percent increase would yield 7 mm per year. Perhaps 1 percent of this might be usable or storable runoff in these areas. This set of assumptions gives a net annual water increment of 1.4×10^9 L at a cost of \$0.80 m^{-3}. This is somewhat cheaper but of the same order of magnitude as the cost of the water from the Camanchaca Project. As we have seen numerous times in the past, however, proving that cloud seeding actually produces an increase in rainfall is an extremely difficult and expensive task. Capturing and piping the water to villages would be even more so. The costs of delivering the additional water to the villages across the project area would easily increase the water cost several fold. The final cost over a period of years might be \$2.00 m^{-3} or more.

The advantages of collecting fog water are that one knows for certain that additional water has been obtained, the exact amount of water obtained is measurable, and it can be delivered directly to towns in the near vicinity. On the other hand, in inland areas with no fog (or fog in inaccessible areas) one obviously cannot expect to generate a water supply. The two techniques of producing arid-zone water increases are therefore in some senses complementary.

7. Discussion

The stratus and stratocumulus decks that form over the eastern Pacific and move over the western coast of Chile and Peru result in high-elevation fogs known as camanchacas. Based on past work in Chile and on calculations of water availability it appears that the camanchacas may provide a significant new source of water for the arid north of Chile. A large number of 40-m^2–mesh collectors can be located on the coastal mountains near small villages and potentially increase the current meager water supply fivefold. This has important implications not only for improving the quality of village life and beginning agricultural production in the desert but also for reversing the migration to the cities and for the reforestation of the hillsides. Once a careful site-selection study has been completed, the installation of the collectors is relatively low cost and straightforward. Maintenance is minimal and could be handled by local populations. The water itself is clean and the system free of possible contamination.

The Camanchaca Project is relatively modest in terms of resources but by coupling a study of the microphysics of the clouds and the dynamics of the boundary layer with a practical demonstration of water collection it should place future proposals on a firmer footing. The first "core-observation" period was held for 15 days in late 1987. A second intensive study will be conducted in late 1988. Meteorological measurements and water collection will take place continuously from late 1987.

An important part of the Camanchaca Project will be the subsequent utilization of the meteorological and topographical relationships that are found to influence fog-water collection. Initially the northern coast of Chile, and then eventually the southern coast of Peru, will be examined for locations where the conditions are such that water could be provided to isolated villages. In principle, water could be provided to any size of town or city given sufficient space for the collectors and sufficient funds. In fact this has been discussed in past years for Antofagasta, a city of 100 000 people. In practice it is likely to be unworkable and too costly for a city of this size unless collector efficiencies can be significantly improved.

There are of course no reasons why fog water can be used as a water supply only on the west coast of South America. There is a modest body of literature to suggest that other continental margins and some island locations with little rainfall could benefit in a major way from the application of this technology.

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References

Barrie, L. A. and R. S. Schemenauer, 1986: Pollutant wet deposition mechanisms in precipitation and fog water. *Water, Air, Soil Pollut.*, **30,** 91–104.

Bowen, D., 1966: A new way of clearing fog. *New Scientist,* 8 December, 583.

Carvajal, N. H., 1982: Antecedents Generales, Observación y Cuantificación de las Neblinas, Sector Temblador, IV Región, Chile. Memoria para optar al Título de Geógrafo, Pontificia Universidad Católica de Chile, Instituto de Geografia, 78 pp.

Cereceda, P., 1983: Factores Geográficos que Determinan el Comportamiento Espacial y Temporal de la Camanchaca, Informe Final. Dirección de Investigación de la Pontificia Universidad Católica de Chile, Santiago, Chile, 121 pp.

CONAF, 1984: Evaluación de las Neblinas Costeras (Camanchacas) en el Sector El Tofo. Informe Final de CONAF a SERPLAC IV Region, 76 pp.

Deardorff, J. W., 1976: On the entrainment rate of a stratocumulus topped mixed layer. *Quart. J. Roy. Meteor. Soc.*, **102,** 563–582.

Erickson, D. and O. Badilla, 1982: Cloud seeding in Chile. *J. Wea. Mod.*, **14,** 47–51.

Follmann, G., 1963: Nordchilenische Nebeloasen. *UMSCHAU, Heft 4,* 101–104.

Fuenzalida, H., 1985: Estructura y Comportamiento Invernal de la Capa Límite Atmosférica sobre Antofagasta. *Rev. TRALKA,* 2, 4, 405–418.

——, J. Rutllant and B. Rosenbluth, 1984: Estudio de las Capa Límite Atmosférica en el Litoral Arido de Chile. Informe Final Proyecto No. 1156 a Fondo Nacional de Ciencia, Comisión Nacional de Investigación Científica y Tecnológica, Santiago, Chile, 19 pp.

Kerfoot, O., 1968: Mist precipitation on vegetation. *For. Abstr.*, **29,** 8–20.

Larrain, H. and P. Cerceda, 1982: Camanchaca, Recurso Hídrico Postergado. *Revista Universitaria,* No. 7, Pontificia Universidad Católica de Chile, Santiago, Chile, 115–127.

—— and ——, 1983: Aprovechamiento de la Camanchaca, IV Región, Chile, Informe Final para la Intendencia Regional de Coquimbo, Chile, 155 pp.

Miller, A., 1976: The climate of Chile. Chapter 3 in, *World Survey of Climatology, Vol. 12, Climates of Central and South America,* ed. Werner Schwerdtfeger, Elsevier Sci. Publ. Co.

Randall, D. A., 1980: Entrainment into a stratocumulus layer with distributed radiative cooling. *J. Atmos. Sci.*, **37,** 148–159.

——, J. A. Coakley, C. W. Fairall, R. A. Kropfli and D. H. Lenschow, 1984: Outlook for research on subtropical marine stratiform clouds. *Bull. Amer. Meteor. Soc.*, **65,** 1290–1301.

Rutllant, J., 1981: Subsidencia Forzada sobre Ladera Andina Occidental y su Relación con un Episodio de Contaminación Atmosférica en Santiago, *Rev. TRALKA,* 2, 1, 57–76.

Schemenauer, R. S., 1986: Acidic deposition to forests: the 1985 Chemistry of High Elevation Fog (CHEF) project. *Atmosphere-Ocean,* **24,** 303–328.

——, P. Cereceda and N. Carvajal, 1987: Surface-based measurements of cloud liquid water contents and their relationship to terrain features. *J. Climate Appl. Meteor,* **26,** 1285–1291.

Soto, G. and L. R. Elicer, 1985: Proyecto Abastecimiento de Agua de Camanchaca a Caleta Chungungo. CONAF IV Region, Informe Interno, La Serena, 5 pp.

Vogelmann, H. W., 1973: Fog precipitation in the cloud forests of eastern Mexico. *BioScience,* **23,** 96–100. ●