Coastal fog and its relation to groundwater in the IV region of northern Chile

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Abstract

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Environmental isotopes have been used as tracers to study the water cycle of coastal ecosystems in northern Chile. Coastal fog (mean δ of $-1.86‰$ for ^{18}O and $-3.2‰$ for ^{2}H) and rainwater (mean δ of $-5.6‰$ for ^{18}O and $-40‰$ for ^{2}H) have distinct isotopic compositions which reflect the different histories of the air masses that provide moisture to these waters. Groundwaters from the two study areas have an isotopic composition similar to rainwater, suggesting that coastal fog does not play a significant role as a source of recharge for the coastal aquifers. However, the isotopic evolution of leaf water from coastal trees substantiated the importance of the interrelationship between the coastal fog and the vegetation in these coastal ecosystems.

1. Introduction

One of the particular features of the Pacific coast between 8°S and 32°S is the almost permanent presence of cumulostratus-type clouds named by the ancient indians "Camanchaca, the kingdom of the mist". This area is part of the arid region of the Southern American continent and the high moisture content of the Camanchaca represents the main water resource available to the coastal ecosystems. The mean precipitation rate in this area is ~50 mm yr.$^{-1}$.

This climatic pattern is controlled by the presence of the Pacific anticyclone and the cold Humboldt current that circulates parallel to the coast in this region. The Alisios wind generated by the activity of the anticyclone carries moisture from the ocean toward the continent and when these air masses come in contact with cold water close to the coast, advective clouds are formed. The coastal mountains, which rise to altitudes between 600 and 1000 m above sea level (a.s.l.), act as a barrier and the clouds are compelled to ascend. The relative humidity increases due to decreasing temperature; however, the clouds cannot reach higher altitudes and a higher level of condensation due to the presence of an inversion layer. This barrier represents the top of the Camanchaca clouds and is formed as a result of the descent of the counter-Alisios wind in this region.

The coastal area where the Camanchaca frequently exists is relatively rich in economic resources such as mining and fishing. However, the lack of water and energy resources has been an obstacle to greater development of economic activity and, consequently, a better standard of life for the small communities in these areas.

The need for new water resources for the coastal ecosystems has led numerous Chilean

and Peruvian researchers to evaluate the potential of the Camanchaca as an alternative resource. Many studies have focused on the development of structures called fog-traps that can efficiently collect water from the Camanchaca, and on the evaluation of its hydric potential (Valdivia, 1972; Espinosa, 1978; Tapia and Zuleta, 1980; Larrain and Cereceda, 1983). Other studies on the use of the Camanchaca as a resource for reforestation programs have yielded very promising results. Moreover, the influence of geographic parameters on the spatial and temporal behavior of the fogs has also been assessed (Cereceda, 1983).

Another aspect that has been addressed in these studies is the role of the Camanchaca as a possible source of recharge to coastal springs. This idea was postulated based on archeological evidence that shows the existence of greater population in the past, associated with the development of coastal springs that no longer exist today (Nuñez and Valera, 1968). The intervention of man in coastal ecosystems, i.e. deforestation for mining activities, may have eliminated the natural fog-traps, thereby interrupting the system Camanchaca–vegetation–soil–aquifers. An example of the interrelationship between vegetation and the Camanchaca is the Fray Jorge forest, located near to La Serena in the IV region of Chile. Today, this relict forest only exists in the southern part of Chile, where precipitation is >1000 mm yr.$^{-1}$. The mean annual precipitation in Fray Jorge is only ~ 150 mm and the water provided by the Camanchaca is ~ 900 mm yr.$^{-1}$ (Kummerov, 1966). The idea of a link between the Camanchaca and the coastal springs is also supported by ^{18}O data from coastal springs in areas totally without rain (Gischler, 1977). $\delta^{18}O$-values of some of these springs were similar to the $\delta^{18}O$-value of the Camanchaca water but, unfortunately, no deuterium analyses were performed. These analyses could have been used to evaluate the possibility that these spring waters are not fog water, but rainwater modified isotopically due to evaporation processes.

The potential for groundwater recharge from Camanchaca-type clouds has been demonstrated recently in the south of the Sultanate of Oman (Clark et al., 1987). This study, based on isotope data, showed that most of the groundwater found in the Salalah area and the Dhofar Mountains has been recharged by water from monsoon clouds.

The present article intends to contribute to the discussion of the role of the Camanchaca as a source for groundwater recharge in the coastal aquifers of northern Chile. Environmental isotopes techniques have been used as a tool to identify and evaluate the role of the different components of the water cycle in these ecosystems.

2. Study areas

Two areas, El Tofo and the Parque Nacional Fray Jorge, localized between 29°S21′ and 30°S42′, in the IV region, northern Chile, were selected for this study (Fig. 1). These areas have coastal springs and coastal fog occurs during most of the year. Abundant vegetation exists today at Fray Jorge and rich organic soil hori-
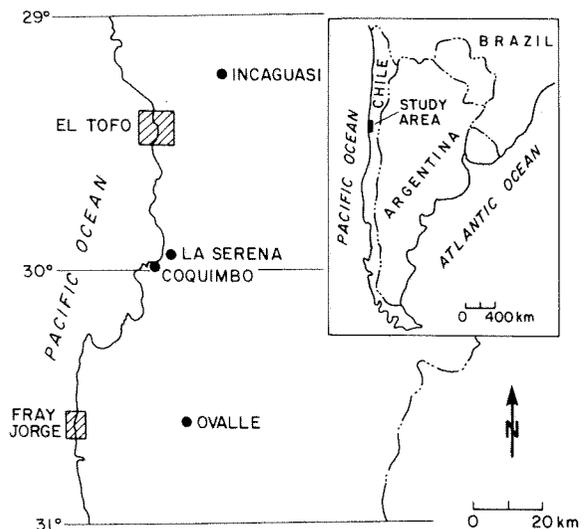

Fig. 1. Study area.

zons indicate the presence of abundant vegetation in the recent past at El Tofo. Both areas have coastal mountains with altitudes between 500 and 900 m a.s.l., with a north–south orientation and with a mean distance of ~ 2 km to the coast line. The mountains are mainly composed of metamorphic and granitic rocks of Paleozoic age. The coastal aquifers of very poor development are part of the abrasion terraces that exist at different elevations in these areas (Bohnhorst, 1967).

3. Materials and methods

Water samples for environmental isotope analysis (^{18}O, ^2H and ^3H) were collected from springs, wells, rain and fog. The dates of collec-

TABLE I

Isotopic content of rain and fog, IV region, Chile

Location	Sampling date	$\delta^{18}O$ (‰ vs. SMOW)	δ^2H (‰ vs. SMOW)
Fog:			
Cuesta Buenos Aires	Sep. 14, 1981	−1.2	−1
Caleta Temblador	Dec. 3, 1980	−1.8	−1
	Dec. 3, 1980	−1.5	−3
El Tofo Portezuelo	May 12, 1982	−1.2	−4
	May 12, 1982	−2.5	−5
	Apr. 10, 1983	−1.8	−1
	Apr. 10, 1983	−2.5	−1
	Apr. 11, 1983	−1	−1
El Tofo Hill	Apr. 10, 1983	−1.2	−2
Fray Jorge	Apr. 14, 1983	−2.2	−4
	Apr. 14, 1983	−2.5	−4
	May 19, 1985	−2.7	−10
Puntilla Viento F.R.	Apr. 14, 1983	−2.2	−4
Rain:			
Fray Jorge	May 12, 1981	−6.4	−40
Cruz Grande	Jun. 19, 1982	−5.1	−44
	Jun. 24, 1982	−4.8	−34
La Serena	Jun. 19, 1982	−5.9	−40

tion are reported in Tables I–III. Leaves from *Eucalyptus* sp. trees from a small forest on top of the El Tofo hill were also collected at different times of the day. The leaf water was extracted for isotope analyses under vacuum at $\sim 80 °C$. The springs and wells used in this study are listed in Tables II and III.

One type of fog-trap used to collect water from the Camanchaca is shown in Fig. 2. This apparatus having a surface area of ~ 90 m^2 is rectangular in shape. Water collection is achieved by a vertical array of fine Nylon® wires that intercept the small droplets of water in the fog. Accumulating drops eventually grow in size and then flow by gravity to a grooved tube, whereby the water is transported to a suitable container.

The ^{18}O and ^2H analyses were done at the Environmental Isotope Laboratory, Comisión Chilena de Energía Nuclear and the ^3H analysis at the Institut für Hydrologie, GSF, F.R. Germany. The analytical reproducibility is $\pm 0.1‰$ for ^{18}O, $\pm 2‰$ for deuterium and ± 0.7 TU for tritium. Further details of the analytical procedures are available from Pollastri et al. (1983).

4. Results and discussion

4.1. Rain and fog

Table I shows the environmental isotope data for the rain- and fog water of the two areas under study.

The rain is characterized by δ-values between −6.8 to −4.8‰ for ^{18}O and −44 to −34‰ for ^2H. Isotope data for precipitation from the central and southern coastal areas show a similar isotope range (I.A.E.A., 1970; A. Pollastri, unpublished data, 1983).

The isotope content of the fog water ranges between −2.7 to −1.0‰ for the ^{18}O and −10 to −1.0‰ for ^2H. These values are similar to others reported in the literature for this type of water (Gischler, 1977).

Fig. 3 shows the isotope data of these waters for both areas in a $\delta^{18}O$ vs. δ^2H plot. Their iso-

TABLE II

Isotopic content of groundwater, El Tofo, IV region, Chile

No.	Location	Sampling date	$\delta^{18}O$ (‰ vs. SMOW)	δ^2H (‰ vs. SMOW)	^3H (TU)
1	El Trigo (s)	Apr. 9, 1982	−4.6	−25	
		Jul. 17, 1982	−4.7	−31	
	Mean		−4.7	−28	
2	Yerbas Buenas (s)	Jul. 17, 1982	−4.9	−30	
		Apr. 9, 1983	−5.1	−31	
	Mean		−5.0	−31	
3	El Cono (s)	Jul. 17, 1982	−5.9	−37	
		Apr. 9, 1983	−5.7	−32	
	Mean		−5.8	−34	
4	El Olivo (s)	Sep. 24, 1981	−5.6	−31	
		Jul. 18, 1982	−5.5	−31	
		Apr. 9, 1983	−5.5	−33	
	Mean		−5.5	−33	
		May 10, 1984			<1.1
5	Los Corajes (s)	Sep. 24, 1981	−5	−33	
		Apr. 10, 1982	−5	−29	
		Jul. 18, 1982	−4.9	−32	
	Mean		−5	−32	
6	Aguada Sra Ines (s)	Apr. 9, 1983	−5.5	−31	
7	Caleta Temblador (w)	Jul. 18, 1982	−3.3	−22	
		Apr. 9, 1983	−2.8	−17	
	Mean		−3.1	−20	
8	Cataplum (d)	Apr. 9, 1983	−4.3	−28	
9	Plantilla (s)	Apr. 9, 1983	−5.1	−29	
10	Quebrada Chungungo Peralito (p)	Jul. 18, 1982	−4.1	−24	
		Apr. 10, 1983	−4.4	−29	
	Mean		−4.2	−27	
11	Quebrada Chungungo (s)	Apr. 10, 1983	−5.2	−32	
		May 10, 1984			<1.1
12	La Verita (w)	Jul. 18, 1982	−5.9	−34	
		Apr. 10, 1983	−5.4	−31	
	Mean		−5.7	−32	
13	Chungungo Viejo (s)	Jul. 17, 1982	−5.5	−34	
		Apr. 10, 1983	−5.6	−34	<1.2
	Mean		−5.5	−34	
14	El Cabrero (s)	Apr. 11, 1983	−5.8	−37	

s = spring; w = well; p = small pond; d = dug well.

topic ranges are also plotted in Fig. 4 for the interpretation of the isotope data of the Fray Jorge groundwater. The global meteoric water line (GMWL) (Craig, 1961) is used in these plots because the local meteoric water line is not defined; however, significant differences are not expected: Isotopic studies done in Chile in different areas show that rain- and groundwa-

TABLE III

Isotopic content of groundwater, Fray Jorge, IV region, Chile

No.	Location	Sampling date	$\delta^{18}O$ (‰ vs. SMOW)	δ^2H (‰ vs. SMOW)	^3H (TU)
1	Quebrada Queseria (s)	May 19, 1985	−4.9	−26	
2	Quebrada Los Puentes (s)	May 19, 1985	−4.8	−27	
3	Quebrada Honda (s)	May 19, 1985	−5	−30	
4	Quebrada El Zapallo (s)	May 19, 1985	−5	−28	
5	El Corcovado	May 19, 1985	−5.4	−31	
6	Quebrada Ramaditas (s)	May 19, 1985	−4.6	−25	
7	El Mineral (s)	Apr. 1983	−5.2	−32	
		May 1984	−5.3	−28	
	Mean		−5.3	−30	
8	La Escondida (p)	Apr. 1983	−4.3	−33	<1.5
		May 1984	−4.3	−30	
	Mean		−4.3	−31	
9	Picnic (p)	Apr. 1983	−4.5	−33	
		May 1984	−4.6	−31	
	Mean		−4.6	−32	
10	Administración (w)	Apr. 1983	−4.5	−35	<1.3
		May 1984	−4.7	−29	
	Mean		−4.6	−32	
11	Quebrada Las Vacas (c)	Apr. 1983	−4	−31	
		May 1984	−4.2	−25	
	Mean		−4.1	−28	

s = spring; p = small pond; w = well; c = creek.

ter are all located on a line similar to the GMWL (A. Pollastri, unpublished data, 1983; Suzuki and Aravena, 1984; Aravena et al., 1987). Rain- and fog water are also located on the GMWL corroborating the latter statement, although there exists a significant isotopic difference between these two types of water. The rain has a mean δ-value of −5.6‰ for ^{18}O and −40‰ for ^2H, while for the fog, it is −1.8‰ for ^{18}O and −3.2‰ for ^2H.

The isotopic signal of the fog likely reflects a single-stage evaporation–condensation cycle near the coast. In general, when evaporation occurs from the ocean, kinetic and equilibrium isotope effects combine to yield a vapor that is depleted by ∼12–13‰ for ^{18}O with respect to the seawater. A fog (such as the Camanchaca)

condensed from this vapor will be subject only to equilibrium isotope effects and the resulting isotopic composition should plot on the GMWL and depleted in ^{18}O by only 1–3‰ from the seawater value (Majoube, 1971), precisely as suggested by Fig. 3.

The pronounced offset of rainwater samples from the fog waters reflects a multi-stage rainout effect, whereby progressive isotopic depletion of the air-borne vapor (and the precipitation derived from it) occurs along the air mass trajectory.

The consistent isotopic difference between rain- and fog water allows the use of stable-isotope data in the groundwater to assess whether the fog water could be a source of recharge for the groundwater.
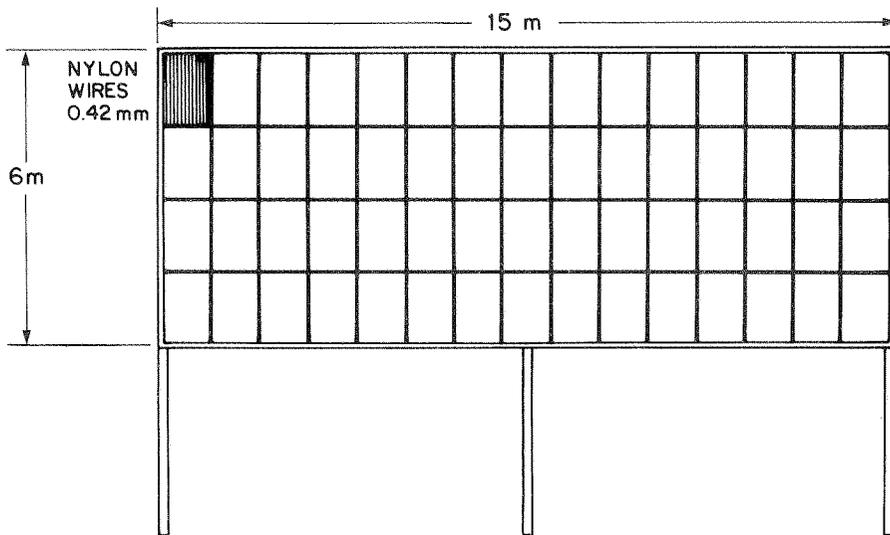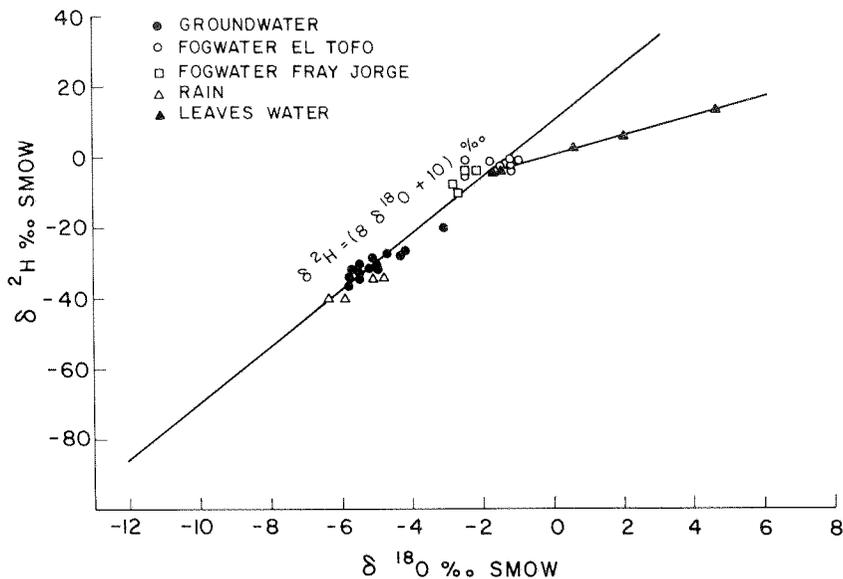
Fig. 2. Type of apparatus used for fog collection.

Fig. 3. $\delta^{18}O$ vs. δ^2H plot for fog, rain, El Tofo groundwaters and leaf water.

4.2. Groundwater

Environmental isotope data for the groundwater in the two areas under study are reported in Tables II and III.

No significant isotope difference is observed in the groundwater from both areas. Its isotope content varies between -5.9 to -4.0% for ^{18}O

and from -35 to -26% for ^2H. These values are typical for groundwater in coastal aquifers in the central part of the country (Suzuki and Aravena, 1984).

Figs. 3 and 4 show the isotope data of the groundwater in a $\delta^{18}O$ vs. δ^2H plot for El Tofo and Fray Jorge, respectively. These waters are mainly located on the GMWL, indicating that
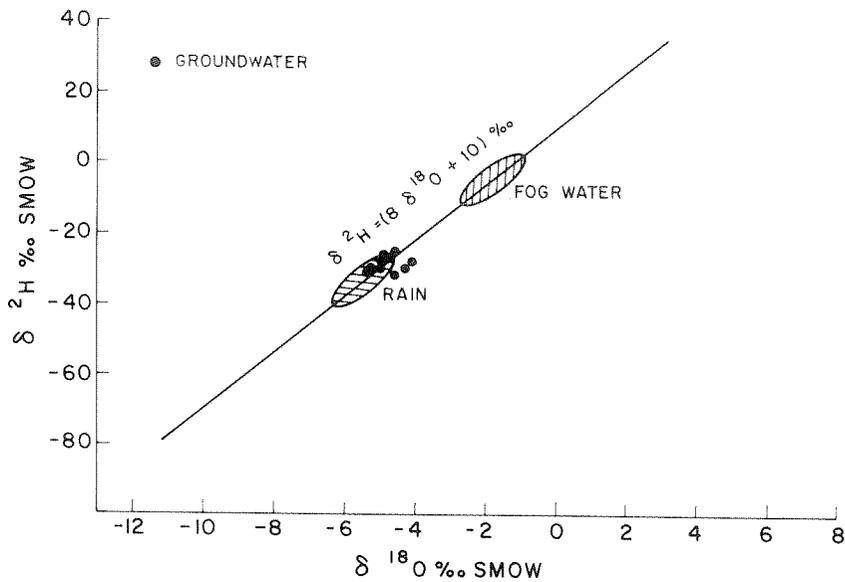
Fig. 4. $\delta^{18}O$ vs. δ^2H plot for Fray Jorge groundwaters.

they were not affected by evaporation during infiltration in the recharge areas.

Fig. 4 also shows that most of the groundwater samples plot in the precipitation isotopic field, with the notable exception of one enriched sample that shows a trend toward the fog water. This sample is from a well located close to the sea coast with a water level ~9 m below the sea surface. This well is probably tapping water from the fresh water–seawater interface, which could explain its isotopic composition as seawater is characterized by isotopic values close to 0‰ and plot below the GMWL. Minor evaporation effects may be responsible for the somewhat heavy isotopic composition of two samples collected from pools at the springs outcrop.

The isotopic composition of the groundwater in the El Tofo area indicates that the coastal aquifers are being recharged by precipitation. The low tritium contents of these waters (< 1.1 TU) suggest the absence of thermonuclear tritium, implying that they have a residence time in the aquifer of at least 35 yr.

A similar situation as to the El Tofo groundwater can be observed in Fray Jorge (Fig. 4).

The groundwater from both sides of the mountain range including springs and wells located along the Fray Jorge valley do not show any significant contribution from fog water. These aquifers are recharged by rain and, again, the residence time of the groundwater should be > 35 yr., based on their low tritium contents (< 1.5 TU).

4.3. Vegetation

The isotopic data for leaf water (Fig. 3) attest to the importance of the Camanchaca for vegetation of these coastal ecosystems. The $\delta^{18}O$- and δ^2H-values of this water plot to the right of the GMWL along a typical evaporation line. This shift reflects the isotopic enrichment of plant waters occurring in the leaves during evapotranspiration. The degree of leaf water isotopic enrichment is controlled mainly by temperature and relative humidity of the environment (Dongmann et al., 1974; Förstel, 1978; Aravena and Acevedo, 1984). A trend to more depleted isotopic contents reaching values close to that of the fog water is observed during the day and early morning (Table IV). This trend

TABLE IV

Isotopic content of leaf water

Sampling date	Time	$\delta^{18}O$ (‰ vs. SMOW)	δ^2H (‰ vs. SMOW)
Apr. 10, 1983	10:25 a.m.	+4.6	+14
Apr. 10, 1983	12:25 p.m.	+2	+6
Apr. 10, 1983	16:45 p.m.	+0.6	+3
Apr. 10, 1983	19:20 p.m.	−1.5	+4
Apr. 1, 1983	8:30 a.m.	−1.8	+4

is associated with an increase in relative humidity.

As isotopic modification does not occur during the uptake of water by the roots and transport to different parts of the tree (Zimmermann et al., 1967; Förstel, 1978), the evaporation line defined by the leaf water data could be used to estimate the isotopic composition of the soil water used by the trees. This is valid for the particular case when the source water is in isotopic equilibrium with the atmospheric moisture (Allison et al., 1985). Back extrapolation along the leaf water line clearly indicated that fog water is the moisture source for these trees in this dry environment. Indeed, this is consistent with the empirical observation made by the senior author during days with dense fogs. The wetness inside the forest is similar to a light rain; the tree leaves are covered by water drops and the soil is clearly wet.

5. Summary and conclusions

Rain- and fog water show distinct isotopic compositions which reflect the different history of the air masses that provide the moisture for these waters. The groundwaters from both study areas are characterized by an isotopic composition similar to that of the rain. This isotopic pattern suggests that fog water does not play a significant role as a source of recharge for the coastal aquifers. These aquifers are recharged by precipitation and the very low tritium content of the groundwater suggests that these waters were presumably recharged at some

time in the past under conditions that must have been moister than those of the present. Carbon isotope analyses (^{14}C, ^{13}C) of the groundwater could provide additional information.

The analysis of the isotopic evolution of the leaf water substantiated the importance of the interrelationship between the Camanchaca and the vegetation in these coastal ecosystems.

Further detailed studies which should cover the entire water cycle in these ecosystems are warranted to investigate the importance of the fog to the local hydrologic balance. The Fray Jorge area is the most suitable for these studies. Furthermore, isotope analyses of the northern coastal springs where no rain exists, which should include the ones analyzed by Gischler (1977), will provide additional information about the role of the fog water as a source of recharge for the coastal aquifers.

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