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A field comparison of cloud water collectors in a mountainous region under low wind speed conditions in Eastern Mexico

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RESUMEN

Se colectó simultáneamente agua de nube en un sitio montañoso localizado en el poblado de Teziutlán, Sierra Madre Oriental, en el Estado de Puebla, México, para hacer la comparación entre tres colectores de agua de nube co-localizados. Dos de los colectores fueron pasivos; el primero fue un colector omnidireccional conocido como ASRC (Colector de Cuerdas del Centro de Investigación de Ciencias Atmosféricas), el segundo fue un colector de malla metálica con alambres de acero inoxidable entretejidos con un diámetro de 0.041 cm en una estructura de polietileno. El tercer colector fue un activo, en el cual el aire es aspirado a través de un ducto a una velocidad de 3.5 m s^{-1} . Las gotas del agua de nube son colectadas en alambres estirados verticalmente y colocados en una estructura de teflón.

El contenido de agua líquida y la capacidad de los colectores fueron evaluados a través de las ecuaciones correspondientes. Los resultados indicaron que entre los colectores pasivos no hubo diferencias en las concentraciones de la composición química, sin embargo, se encontraron diferencias estadísticas entre el colector activo y los colectores pasivos.

Finalmente, la capacidad de colección fue más alta en el colector activo que en la de los colectores pasivos, debido a las diferencias inherentes en el diseño entre los colectores activo y pasivos.

ABSTRACT

Cloud water was simultaneously collected in Teziutlan town, located in a mountainous region in the Sierra Madre Oriental, State of Puebla, Mexico, to compare three co-located cloud water collectors. Two of the collectors were passive; the first one was an omnidirectional collector known as ASRC (Atmospheric Science Research Center String Collector). The second was a metallic mesh collector with 0.041-cm diameter stainless steel wires woven on a polyethylene frame. The third one was an active collector in which air is aspirated through a duct at a rate of 3.5 m s^{-1}. Cloud droplets are collected on vertically strung wires on a teflon frame.

Liquid water content and collector capacity were evaluated by the corresponding equations. The results indicated that there were not differences in chemical composition concentrations between the passive collectors, however, statistical differences were found between the active and passive collectors.

Finally, the collection capacity was higher in the active collector than in passive collectors, due to the inherent differences in design between the active and passive collectors.

1. Introduction

The chemistry of cloud water has arisen significant interest because of its potential effects on the environment, mainly in elevated forests. Typically, soluble particles in 1 m^3 of air may be condensed in 1 mL or less of cloud water during the formation stages of an orographic cloud (De Felice and Saxena, 1990). The study of the cloud water chemistry provides an opportunity for investigating the origen of air masses (Saxena and Yeh, 1988) since it represents the end product of natural processes leading to the condensation of air pollutants in small amounts of aqueous samples (De Felice and Saxena, 1990).

Cloud water effects on forest ecosystems had not been realized until recently. The research work of Comtois and Schemenauer (1991) suggests that polluted cloud water affects tree pollen viability in Quebec, Canada. This study is the first attempt to establish a cloud water sampling procedure adequate to tropical environments. The first study related to cloud water in Mexico was that of Vogelmann (1973), who estimated the amount of water that vegetation intercepts upon clouds impactations in the Sierra Madre Oriental (Eastern Mexico).

Knowledge of both cloud liquid water content and cloud water chemical composition, is necessary to calculate pollutants deposition rates to forests due to clouds.

In this study, three different cloud water collectors were used for cloud water chemistry, a field comparison of cloud water collection and the evaluation of systematic differences, if any, among samples. The parameters that were examined include: a) cloud water acidity, b) ionic species concentration, c) liquid water content and d) collection capacity.

2. Experimental

Sampling sites

The cloud water sampling and comparisons were made at Teziutlan; a town located in the Sierra Madre Oriental, State of Puebla, Mexico, at 1990 m.a.s.l. Figure 1 shows the location of the sampling site.

Teziutlan is located in the windward side of the Sierra Madre Oriental in Puebla State, Mexico, in a region where the mountain slopes face to the NNE approximately. This makes Teziutlan a suitable cloud water sampling site since it is directly exposed to moist air and clouds coming from the Gulf of Mexico. Fog episodes can occur throughout the year. However, they are much more frequent from November to January, due to the complex interaction between topography and the "nortes" (a term used to name the outbreaks of cold air in the Gulf of Mexico). Also, fog formation is enhanced in winter because dominant winds come from the North, perpendicularly striking mountain slopes. Finally, Teziutlan has also the facilities required to install confortably and safely a cloud water monitoring station.

According to García (1981) the modified Köppen classification of Teziutlan climate is C(fm) w"b(i')g. Briefly, this nomenclature means that in Teziutlan winter rains account for less than 18% of the annual total rainfall (around 1600 mm). It has two rainy seasons separated by a short dry period during summer and by a long dry period in the cold half of the year. The mean monthly temperature oscillation lies between 5 and 7 °C, with a long fresh summer. The maximum temperature occurs before the summer solstice and the mean annual temperature is about 16 °C.

Sampling procedures

The collectors were set up on the roof of a 6-store building, located on the top of a hill, facing

the prairies down to the Gulf of Mexico. The experimental design included: a) three co-located samplers and b) the simultaneous operation of the samplers during the cloud events.

The samplings were performed during intensive campaigns. Cloud water collection design was such that each cloud water sample corresponded to each fog event during short fog event episodes. During long fog episodes (several hours or even days) subsamples or fractions were collected instead of a single sample.

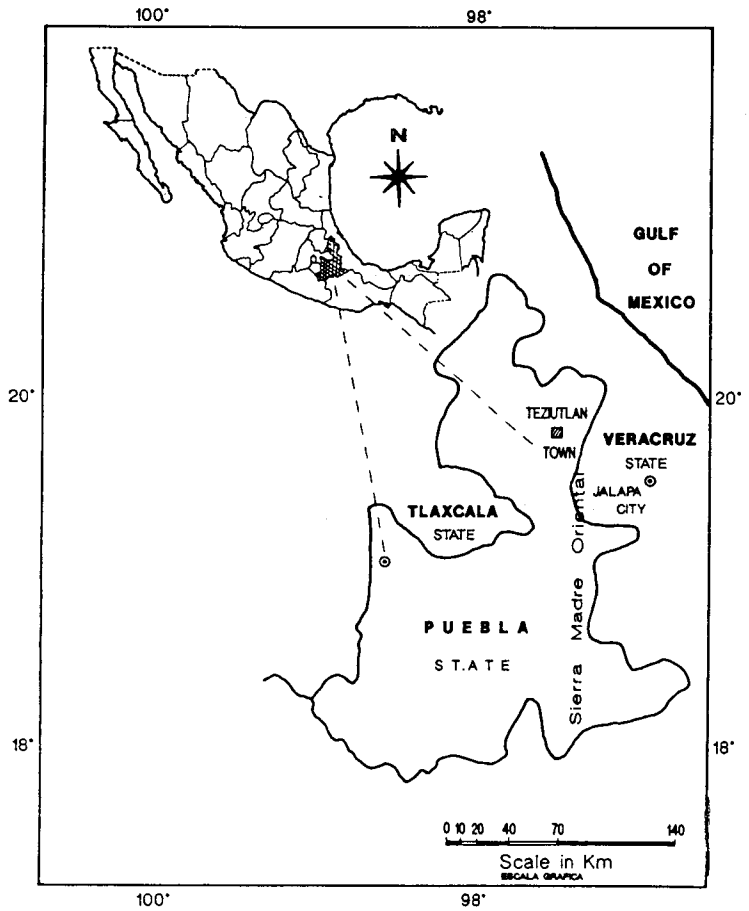

Fig. 1. Map showing the location of cloud water sampling at Teziutlan, Puebla State, Mexico, in the Sierra Madre Oriental.

Due to inherent differences in samplers design and collection rates, the required time varied until enough cloud water was collected for chemical analyses. During sampling, meteorological parameters such as wind speed, wind direction and temperature were monitored with a Davis Portable Weather Monitor II Station. However, in this study, only wind speed and temperature were used in the equations.

Description of the cloud water collectors

Two types of collectors were used, two passive and one active. The passive collectors were designed with different collecting surfaces in order to test the performance of the materials used in their construction and geometric design.

The first one was an omnidirectional collector (OC). It was constructed based on the passive collector most used in other countries, commonly known as ASRC (Atmospheric Science Research Center String Collector). Schemenauer (1986) fully described this collector, but briefly, it consisted of a double screen of wires lying out in a cylindrical arrangement. The wires are identical to those used in the active collector. Their total length and effective area are 258.367 m and 0.0646 m^2 respectively (Fig. 2).

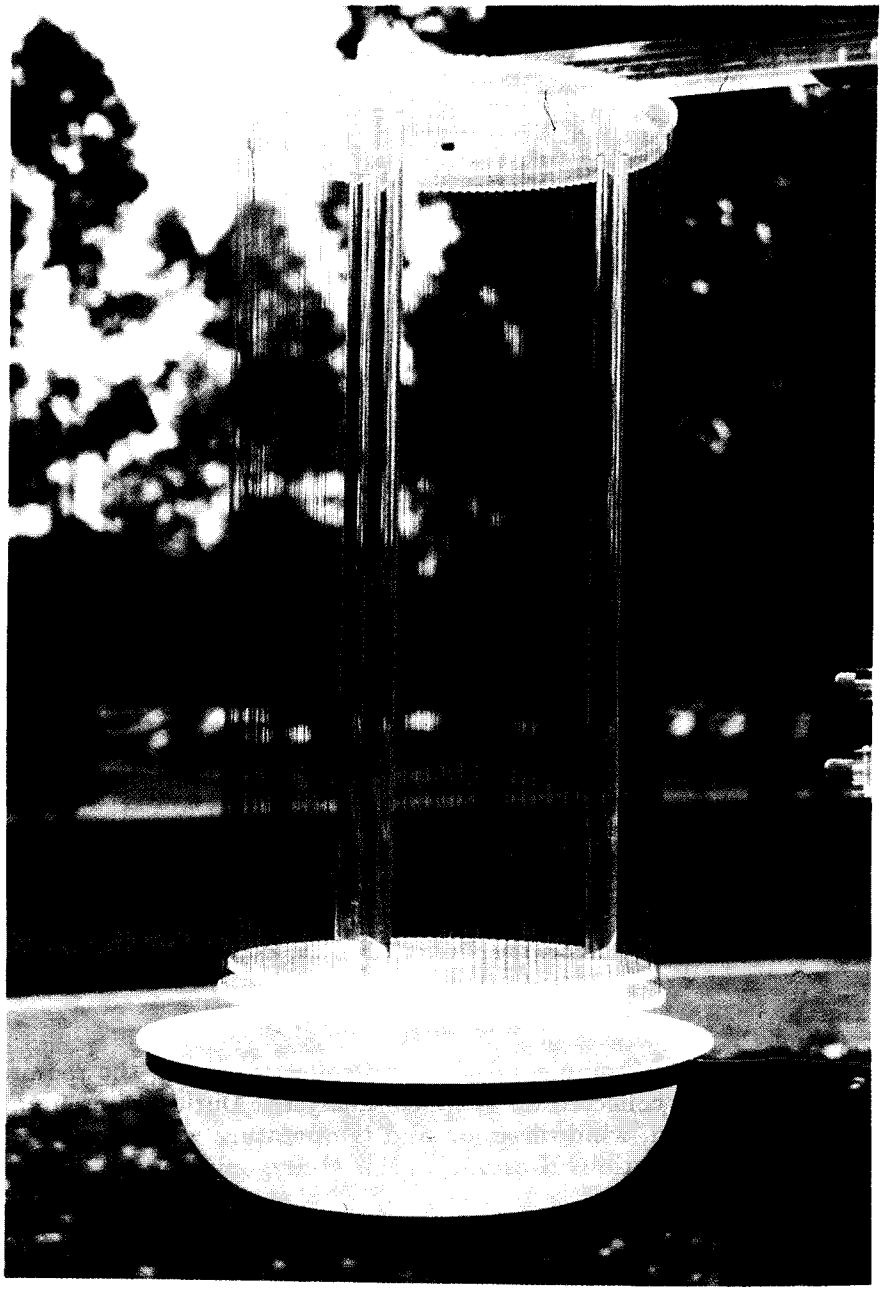

Fig. 2. Photography of the passive omnidirectional cloud water collector (ASRC).

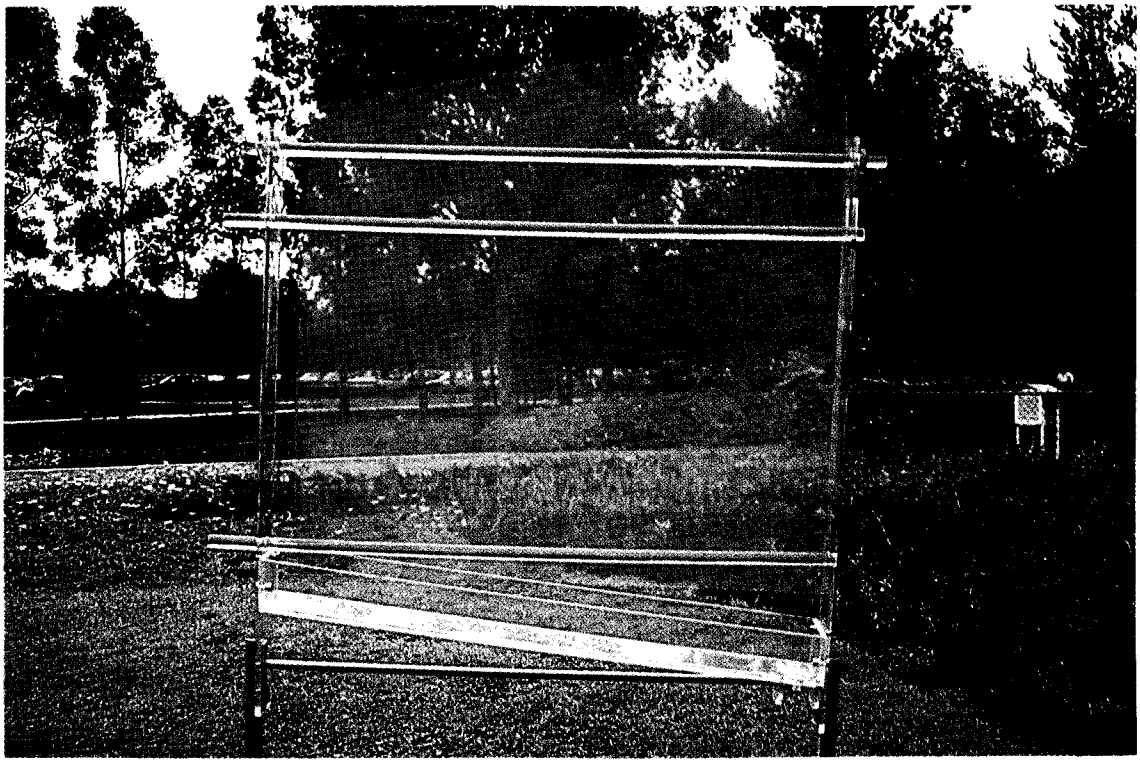

Fig. 3. Photography of the metallic mesh cloud water collector.

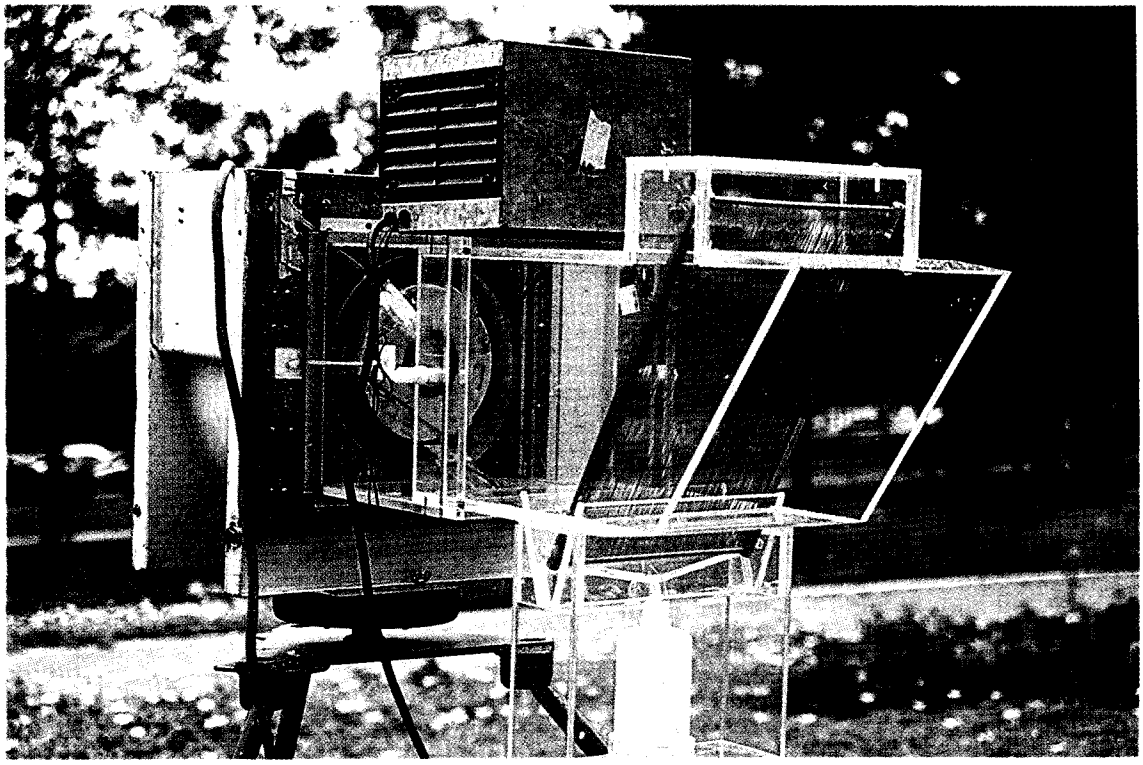

Fig. 4. Photography of the active cloud water collector (After Jacob *et al.*, 1985).

The other passive collector is the Metallic Mesh Collector (MMC). It consisted of a flat surface made out of 0.041-cm diameter wires woven on a polyethylene frame in a racquet style, in a similar way to that described by Hindman *et al.* (1992). The total wire length is 815.50 m and its effective area is 0.3344 m^2 (Fig. 3).

The active collector was constructed according to Jacob's *et al.* (1985) design which briefly is described as follows: Air is aspirated through a square duct at a rate of 3.5 m s^{-1}. Fog droplets impact on the stainless steel 0.025-cm diameter wires vertically strung on a teflon frame between two threaded polyethylene rods. Cloud water collected on the strings flows down to a polyethylene canal connected directly to a polyethylene bottle. The total length of the wires is 88.692 m giving an effective collection area of 0.0222 m^2 (Fig. 4).

Chemical analysis

Upon the arrival of samples to the laboratory, Ca^{2+}, Mg^{2+}, K^+ and Na^+ were analyzed by Atomic Absorption Spectrophotometry; NH_4^+, Cl^-, NO_3^- and SO_4^{2-} by Ion Chromatography; HCO_3^- by Gran titration and pH by a digital pH meter with a combination glass electrode.

Expressions for the calculation of Cloud Liquid Water Content (LWC) and Collection Capacity of the collectors

To calculate cloud liquid water content (LWC) it is necessary first to compute cutoff diameters (d_{50}) (Hindman *et al.*, 1992) using the following expressions:

$$d_{50} = [0.9(\gamma\rho U/18\eta d_c)^{-1/2}] \times 10^4 \tag{1}$$

Where:

d_{50} = cutoff diameter in μm

γ = slip corrector factor nearly 1.0 for cloud droplets

ρ = cloud droplet density $\approx$ 1.0 g cm^{-3}

U = wind speed in cm s^{-1}

η = air dynamic viscosity = $2.48 \times 10^{-6} \times T^{0.754}$ in g cm^{-1} (T in °K)

d_c = wire diameter in cm

For droplets larger than the cutoff diameter, the LWC is calculated from the collectors design parameters (Hindman *et al.*, 1992) in the form:

$$LWC = v/UAt \tag{2}$$

Where:

LWC = cloud liquid water content for droplets $\geq d_{50}$, in g cm^{-3}

v = cloud water sample volume in cm^3

U = wind speed in m s^{-1}

A = collector effective area in m^2

t = sampling time in seconds

For the active collector

$U = \hat{U} + 3.5$

Where:

$\hat{U}$ = vectorial wind speed average obtained from the meteorological portable station data

3.5 = velocity in m s^{-1} at which air is drawn into the collector at the collecting surface

In low wind speed environments if no wind speed data are available, U can be approximated to 3.5 m s^{-1}, since this speed is much greater than $\hat{U}$.

For the passive collectors U is simply $\hat{U}$.

As it will be dealt with in the discussion, when using passive collectors in environments with wind speeds lower than the sensor threshold. Equation (2) presents a serious shortcoming in calculating the LWC since it gives unreal high values. To avoid this, a new parameter will be introduced which we shall denominate as the cloud water collecting capacity of the collector (CC). To calculate it we simply eliminate U from equation (2) giving:

$$CC = v/At \tag{3}$$

Where:

CC is the collecting capacity in g m^{-2} h^{-1}

v and A have the same meaning as in equation (2)

t sampling time in hours (h)

It is important to state that the collecting capacity should not be considered as a synonymous of collecting efficiency. Collecting efficiency is the ratio of collected cloud water droplets to total cloud droplets or liquid water content. Since no cloud droplets spectra were measured, cloud water collector efficiencies were not calculated.

3. Results and Discussion

To know whether differences in chemical cloud water composition exist among samples collected by the active and passive collectors; the Wilcoxon-Mann-Whitney test was applied to 1993 data and the Kruskal Wallis test to 1995 data. Tables 1 and 2 show the results. To further compare in detail the chemical data between each pair of cloud water collectors, the Wilcoxon-Mann-Whitney test (Table 3) was also used for the 1995 sampling campaign, when it was possible to operate the three cloud water collectors simultaneously.

In November 1993 (Table 1), no difference was observed in cloud water samples composition between the active and omnidirectional collector, except for potassium.

In January 1995 (Table 3), more statistical differences in cloud water samples composition were observed between the active and both passive collectors. This may be due simply to

greater sample numbers, suggesting that if large sample numbers had been collected, statistical differences would probably have been observed more consistently. Unfortunately, fog events are not frequent and do not last long enough in Mexico as in some midlatitude regions, so sample numbers are low.

Table 1. Cloud water ionic composition comparison between active and passive collectors using the Wilcoxon-Mann-Whitney (U-test) in Teziutlan, November 1993.

	U-TEST								
Collectors	SO_4^{2-}	Cl^-	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	H^+
ASRC[a]-ACTIVE	17	6	11	7.5	1[b]	14	12	6	10

[a] Omnidirectional collector.
[b] The null hypothesis (Ho: equal means) is rejected at the 5% significance level; two-tail test.

Table 2. Cloud water ionic composition comparison between active and passive collectors using the Kruskal-Willis test in Teziutlan, January 1995.

	Test statistic (H)								
Collectors	SO_4^{2-}	Cl^-	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	H^+
ASRC[a]-METALLIC MESH-ACTIVE	5.991	5.811	4.600	7.258[b]	8.782[b]	4.843	2.761	8.253[b]	2.055

[a] Omnidirectional collector.
[b] The null hypothesis (Ho: equal means) is rejected at the 5% significance level; two-tail test

Table 3. Cloud water ionic composition comparison between active and passive collectors using the Wilcoxon-Mann-Whitney (U-test) in Teziutlan, January.

	U-Test								
Collectors	SO_4^{2-}	Cl^-	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	NH_4^+	H^+
ASRC[a]-ACTIVE	31	28[b]	34	25[b]	19.5[b]	39	59	18[b]	47
ASRC[a]-METALLIC MESH	56.5	60	55.5	52.5	55	43.5	37	52.5	48
METALLIC MESH-ACTIVE	37	30[b]	31.5	30[b]	31.5	40.5	40.5	29.5[b]	41

[a] Omnidirectional collector.
[b] The null hypothesis (Ho: equal means) is rejected at the 5% significance level; two-tail test

On the contrary, no differences were observed in any case between passive collectors (omnidirectional and metallic mesh); this was indeed expected.

The Kruskal-Wallis test (Table 2), indicates statistical differences for sodium, potassium and ammonium ions. Again, the small sample numbers may explain this apparent inconsistency. Ammonium ion concentrations seem to present more systematic differences between the active and passive collectors.

Tables 4 and 5 show the cutoff, LWC, CC, sample volumes and some meteorological variables for Teziutlan, November 1993 and January 1995.

In general, the active collector gave the highest CC, this is not surprising since the air extractor aids cloud droplets collection because air is drawn at a considerable higher speed than natural mean wind speed, what it is interesting is the comparison between passive collectors.

Table 4. Speed and wind direction, cutoff diameter, cloud liquid water content, and collecting capacity of the cloud water collectors at Teziutlan, November 1993.

DAY	TIME	COLLECTOR type	VOLUME (mL)	Wind direction	$\bar{U}$ m s^{-1}	U m s^{-1}	TEMP (°C)	Cutoff diameter (μm)	LWC[a] (g m^{-3})	C C[b] (g m^{-2} h^{-1})
27	11:00-13:00	ASRC[c]	77.4	1.00	0.48	0.48	11.44	11.58	0.35	599.07
27	15:45-18:15	ASRC	118.9	1.00	0.38	0.38	9.78	12.92	0.54	736.22
28	10:00-13:55	ASRC	224.7	1.01	0.61	0.61	10.18	10.21	0.40	888.08
28	14:00-16:35	ASRC	114.4	1.17	0.22	0.22	9.45	17.09	0.87	685.51
28	16:35-18:25	ASRC	66	1.50	0.09	0.09	8.60	26.74	1.74	557.28
28	10:00-13:55	Active	203.6	1.01	0.61	4.11	10.18	3.94	0.16	2341.58
28	13:55-16:30	Active	201.5	1.12	0.27	3.77	9.45	4.11	0.25	3403.72
28	16:30-18:18	Active	127	1.50	0.10	3.60	8.66	4.20	0.25	3178.18

[a] Liquid water content
[b] Collecting capacity
[c] Omnidirectional collector

Table 5. Speed and wind direction, cutoff diamenter, cloud liquid water content, and collecting capacity of the cloud water collectors at Teziutlan, January 1995.

DAY	TIME	COLLECTOR type	VOLUME (mL)	Wind direction	$\bar{U}$ m s^{-1}	U m s^{-1}	TEMP (°C)	Cutoff diameter (μm)	LWC[a] (g m^{-3})	C C[b] (g m^{-2} h^{-1})
18-19	22:55-00:25	Active	39	14.83	1.32	4.82	11.63	3.64	0.07	1171.17
19	00:25-01:35	Active	69.5	10.01	1.29	4.79	11.30	3.66	0.16	2683.40
19	01:35-06:55	Active	487	0.00	1.10	4.6	8.98	3.72	0.25	4113.18
19	07:00-07:50	Active	36.5	0.67	0.90	4.4	7.80	3.80	0.12	1972.97
19	07:50-08:35	Active	45	0.50	0.90	4.4	7.85	3.80	0.17	2702.70
19	08:35-09:10	Active	59.9	0.00	1.10	4.6	7.80	3.71	0.28	4625.48
19	10:00-11:00	Active	62.5	0.00	1.30	4.8	7.57	3.63	0.16	2815.32
19	11:52-13:15	Active	24.4	0.33	0.90	4.4	7.77	3.80	0.05	794.53
19	13:15-15:00	Active	136.9	0.66	1.06	4.56	7.74	3.73	0.21	3523.81
19	15:00-18:42	Active	103	0.56	1.01	4.51	6.84	3.74	0.08	1253.96
18-19	22:30-00:35	ASRC[c]	238.00	14.71	1.24	1.24	11.88	7.19	0.40	1768.42
19	00:35-01:35	ASRC	207.8	10.01	1.29	1.29	11.30	7.04	0.69	3216.72
19	01:35-07:00	ASRC	981.8	0.00	1.10	1.10	8.98	7.61	0.71	2805.81
19	07:00-07:50	ASRC	83.2	0.67	0.90	0.90	7.80	8.39	0.48	1545.51
19	07:50-08:35	ASRC	163.4	0.50	0.90	0.90	7.85	8.40	1.04	3372.55
19	08:35-10:00	ASRC	385.2	0.00	1.33	1.33	7.70	6.92	0.88	4209.07
19	10:00-11:00	ASRC	181.4	0.55	1.30	1.30	7.57	6.98	0.60	2808.05
19	11:52-13:23	ASRC	73.9	0.00	0.77	0.77	7.78	9.05	0.27	754.26
19	13:23-15:00	ASRC	174.7	0.66	1.06	1.06	7.74	7.74	0.44	1672.78
19	15:00-16:55	ASRC	196.2	0.33	1.08	1.08	7.08	7.66	0.41	1584.60
18-19	22:30-00:40	Metallic mesh	525.40	14.71	1.24	1.24	11.88	9.21	0.16	725.16
19	00:40-01:40	Metallic mesh	516.7	10.01	1.29	1.29	11.30	9.02	0.33	1545.16
19	01:40-07:10	Metallic mesh	2216.9	0.00	1.10	1.10	8.98	9.74	0.30	1205.36
19	07:15-07:55	Metallic mesh	106.7	0.67	0.90	0.90	7.80	10.75	0.15	478.62
19	07:55-08:40	Metallic mesh	248.4	0.50	0.90	0.90	7.85	10.75	0.31	990.43
19	08:40-10:05	Metallic mesh	575.8	0.00	1.33	1.33	7.70	8.86	0.25	1215.45
19	10:05-11:00	Metallic mesh	234.7	0.00	1.30	1.30	7.57	8.94	0.16	765.66
19	11:52-13:23	Metallic mesh	40.8	0.55	0.77	0.77	7.78	11.59	0.03	80.45
19	13:23-15:05	Metallic mesh	190.1	0.66	1.06	1.06	7.74	9.91	0.09	334.40
19	15:05-16:55	Metallic mesh	219.1	0.33	1.08	1.08	7.08	9.80	0.09	357.38

[a] Liquid water content
[b] Collecting capacity
[c] Omnidirectional collector

The MMC capacity was less than that of the OC due mainly to the geometric designs. The MMC has 0.041 cm diameter wires spaced approximately by 0.09-cm, whereas the OC has 0.025-cm wires spaced 0.3-cm, allowing a more unrestricted air flow through the collector surface. In other words, the metallic mesh deflects more the air flow so cloud droplets that otherwise could be intercepted by the wires, follow air currents around the collector and thus decreasing the CC. Another factor is that the wires diameter is 0.041-cm instead of 0.025-cm of those of the omnidirectional collector. Collection efficiency increases as wire diameter decreases (Mohnen and Kadlecek 1989). The theory and procedure to calculate collection efficiency as a function of wire or string diameter is shown elsewhere (Langmuir and Blodgett, 1961; Stallabrass, 1978).

Another additional factor that could be important is that if the metallic mesh (which is a flat surface) is no perpendicular to wind due to shifts in wind direction, the CC decreases, reaching a minimum, when the surface is parallel to wind flow. On the contrary, no matter how much wind direction change, the omnidirectional collector will always be perpendicular to wind.

Regarding CC (equation 3), the best passive collector was the omnidirectional. However, if we want to calculate LWC (equation 2) for cloud droplets $\geq d_{50}$, both passive collectors were not suitable at all, due to low wind speeds.

This is the reason why Tables 4 and 5 show that the LWC, calculated from passive collector design characteristics, are much higher than those calculated from the active collector characteristics.

As it can also be seen, in many cases wind speeds ($\hat{U}$) are very low because some wind speeds lay below wind speed sensor threshold. Consequently, if these wind speeds were read as zero, the $\hat{U}$ values reported in Tables 4 and 5 could yield LWC values higher than they really are. In fact, the lower wind speeds the higher LWC values.

Another disadvantage of both the omnidirectional and metallic mesh passive collectors are the larger cutoff diameters, compared to the ones obtained with the active collector. Upon substituting wind speed in equation 1, a similar problem arises, the lower wind speeds, the larger the cutoff diameters. In other words, if wind speed is low, the diameter interval of the collected cloud droplets is shrunk.

4. Conclusions

The chemical composition results of cloud water samples collected with three cloud water collectors, indicated after comparison that no differences were found between the passive collectors. However, statistical differences in chemical composition were observed between the active and passive collectors in samples obtained on January 1995; it was probably due to the greater number of samples collected. On the other hand the small number of samples may explain the apparent inconsistency of ammonium and potassium ions concentration.

In general, the active collector showed the highest collector capacity because the air is drawn at speed considerable higher than natural mean wind speed. The omnidirectional passive collector showed a higher collector capacity than the metallic mesh passive collector.

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