Atmósfera (1991), **4**, pp. 53–64

Warm fog in eastern Mexico: A case study*

F. GARCIA-GARCIA and R. A. MONTAÑEZ

Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, 04510, México, D. F., MEXICO

(Manuscript received June 11, 1990; accepted in final form Aug. 27, 1990)

RESUMEN

Se llevaron a cabo mediciones de parámetros microfísicos de niebla orográfica en una zona rural de la Sierra Madre Oriental de México. Distribuciones por tamaños de gotitas de niebla fueron determinadas haciendo uso de un espectrómetro de gotas de dispersión frontal (FSSP) montado en una camioneta instrumentada. Se colectaron datos durante una semana en invierno, presentándose aquí los resultados de un día de mediciones. Las concentraciones totales de gotitas y los contenidos de agua líquida obtenidos presentaron valores promedio de 150 cm^{-3} y 0.44 g/m^3, respectivamente, con diámetros de la masa media de entre 14 y 19 μm. Los contenidos de agua líquida encontrados, de hasta 0.85 g/m^3 y con diámetros modales en sus distribuciones por tamaños de aproximadamente 30 μm, son evidencia de que este tipo de niebla presenta características ideales para la extracción de agua para consumo humano. Se discute brevemente la posibilidad de captar agua de niebla y utilizarla como recurso hidráulico en regiones viento abajo de la Sierra, donde la precipitación promedio es menor y predominan condiciones semiáridas.

ABSTRACT

Measurements of microphysical characteristics of up-slope fog were carried out on a rural, mountain site in the Sierra Madre Oriental of eastern Mexico. Fog droplet-size distributions were obtained with a Forward Scattering Spectrometer Probe (FSSP) mounted on an instrumented ground-based vehicle. Data were gathered during one week in winter, but only the results for one day are presented here. Measured total droplet concentrations and liquid water contents (LWC) had average values of 150 cm^{-3} and 0.44 g/m^3, respectively, with mean volume diameters between 14 and 19 μm. Liquid water contents as high as 0.85 g/m^3, with LWC peak diameters close to 30 μm, indicate that these fogs could have ideal characteristics for artificial water removal for human consumption. The potential for fog-water to be collected and used as a water supply in areas downwind of the study site, where average rainfall diminishes and semi-arid conditions prevail, is briefly discussed.

1. Introduction

Fog represents a serious hazard to navigation in the air, on land and at sea. For this reason, much of the early interest in fog research focused on fog dissipation. On the other hand, fog can be considered a potential, non-conventional source of water in parts of the world where water shortages are critical. The importance of fogs as sources of water, in particular for agricultural and afforestation purposes, has been recognized for a considerable time. However, it has been only until recently that serious efforts and major projects have been undertaken in order to remove useful amounts of water from fogs for human consumption (see, for example, Schemenauer *et al.*, 1988).

---

* The substance of this paper was presented at the 1990 Conference on Cloud Physics of the American Meteorological Society, July 22-27, San Francisco, CA., U. S. A.

Mexico is a country with a great variety of climatic regimes which reflect the uneven distribution of water resources throughout its territory. In particular, at the mountainous eastern coast along the Gulf of Mexico, the topography is such that the landscape changes from that of a dry desert to that of a cloud forest and then to that of a semidesert within a distance of 100 km or less. Fog occurrence is common at the higher sites and a strong gradient of annual rainfall is characteristic of the region. In spite of this, the impact of fogs on the water budget has not been assessed. In fact, the only related study known to the present authors is that of Vogelmann (1973), who showed the significance of fog precipitation as a factor regulating the limits of the cloud forests in eastern Mexico.

The present study constitutes a first attempt to estimate the potential for fog-water removal in a region of the Sierra Madre Oriental of Mexico. Data gathered during one week in a mountain site have been used to characterize fog from a microphysical point of view. In the following, a case study is presented which includes the results obtained during one day of measurements. Measured parameters included fog droplet-size distributions and concentrations obtained with a Forward Scattering Spectrometer Probe (FSSP) mounted on an instrumented van. It is worth mentioning that the field site is included within the limits of the region considered by Vogelmann (1973) in his study.

2. The study region: geographical and climatological background

The Sierra Madre Oriental of eastern Mexico extends in a chain from the northern State of Nuevo Leon to the State of Oaxaca in the south. Through the States of Puebla and Veracruz, the Sierra runs at a distance of 100 km or less from the coast of the Gulf of Mexico (Figure 1) and almost parallel to it. The Sierra Madre Oriental includes the highest elevation in the country (the Pico de Orizaba Volcano, 5747 m ASL) and most cities and towns in the area are located between 1300 and 2000 m ASL. East of the mountains lies the coastal plain of the Gulf of Mexico, while to the west a high dry plateau forms the interior of Mexico.

The average meteorological conditions are as follows. In summer, the coastal region lies in the influence of the trade easterlies along the southwestern end of the Bermuda high. In winter it lies closer to the subtropical high, with the passage of *nortes* being a common disruption of the normal conditions. (A "norte" or norther is a northeasterly wind which blows in Mexico and in the shores of the Gulf of Mexico, and results from an outbreak of cold air from the north.) In any case, the prevailing northeasterly winds gather moisture as they sweep over the Gulf of Mexico. After passing over the coastal plain the air flows up the eastern slopes of the mountains, bringing frequent fogs to the upper elevations throughout the year. This constitutes a typical case of warm, up-slope fog (Byers, 1974), very commonly accompanied by drizzle and rain during the summer and early fall months. The formation of stratus decks in the late morning over the coastal plain is a common occurrence during winter. These stratus decks are observed to be advected later in the day toward the slopes, thus intersecting the mountain range at an altitude between 1000 and 2000 m ASL. Often, both the mountain fog and the stratus decks are advected onto the dry plateau lands above. However, beyond the mountains toward the interior plateau, the climate rapidly becomes dryer and the vegetation changes to that of a semidesert.

Meteorological records (DGSMN, 1982) show that some locations in the Sierra, such as Teziutlan

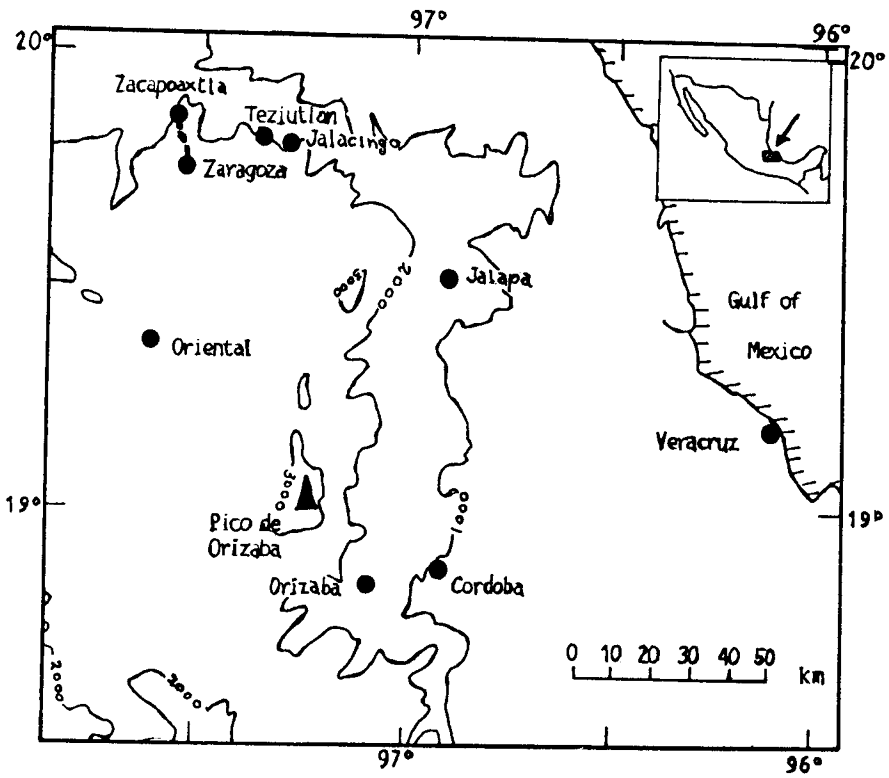

Fig. 1. Location of the study region, including the field site. The dashed line indicates Puebla State Highway #1. Elevations are indicated in meters ASL.

and Jalacingo, have average precipitation amounts of 1600 mm/yr and about 150 fog-days per year. [A fog-day is defined as a 24-hour observation period during which fog is reported by at least one surface observer in a meteorological station.] In contrast, sites located in the high plateau such as Oriental (about 50 km downwind) have only one third those amounts of both precipitation and fog-days. About 80% of the precipitation occurs during the summer and early fall months, while fog occurrence is more evenly distributed throughout the year, presenting a small peak in the winter months. Minimum and maximum annual average temperatures are 8 and 22°C, respectively.

3. Instrumentation and methodology

A mobile ground-based vehicle was equipped with an FSSP[1, 3] (Knollenberg, 1976) for the measurement of cloud-droplet concentrations. The probe was mounted on the front of the van for

---

[1] Forward Scattering Spectrometer Probe, Model FSSP-100, Serial # 16.

[3] Manufactured by Particle Measuring Systems, Inc. (PMS), Boulder, CO., USA.

operation in a horizontal orientation, as on an aircraft (Figure 2). Care was taken to place the probe sampling tube above and ahead of the front of the van in an attempt to minimize airflow distortion caused by the moving vehicle. A data acquisition system [2, 3] (DAS) along with a tape recorder[4] and a CRT display were mounted on a rack located in the cargo compartment. A power generator[5] was used to drive the electronic and recording systems, thus allowing continuous data collection.

Fig. 2. Photograph of the ground-based vehicle at the field site, with FSSP mounted on its front.

Laboratory performance tests and calibrations were conducted on the FSSP prior to the field data collection, in accordance with the guidelines suggested by Dye and Baumgardner (1984). These results have been reported elsewhere (García and Montañez, 1989). Estimations on coincidence and dead-time losses of the measured concentrations were made applying the correction algorithms developed by Baumgardner *et al.* (1985). It should be mentioned that the gains at the output of both the annulus and the signal photodetectors of the probe were set up too high. This modified the nominal channel detection thresholds, thus resulting in larger measured droplet diameters (up to 3 μm in some channels) as compared to those reported by both the manufacturer and other investigators.

---

[2] Model DAS-2D-32, Serial # 15.

[3] Manufactured by Particle Measuring Systems, Inc. (PMS), Boulder, CO., USA.

[4] Formatted Tape Transport, Model FT-7640-9F-25/U2. Manufactured by Pertec Computer Corporation, Chatsworth, CA., USA.

[5] Mac Power-Pac Generator, Model 1500E, manufactured by McCulloch Corporation.

The site chosen for the present study is a 6 km-long stretch of Puebla State Highway #1. The road runs roughly in a south-north direction, between the towns of Zaragoza and Zacapoaxtla, through a sparsely populated rural area and at a mean height of 2050 m ASL (see Figure 1). This field site was selected because it is considered to be representative of the study region, since it is located barely in the limits between the Sierra and the high plateau. Furthermore, the highway has very sparse vehicular traffic and it is safe to drive through it at speeds necessary for proper operation of the FSSP. During sampling, the van was driven at a constant speed of 18 m/s, thus performing continuous penetrations through the cloud. Though the FSSP was mounted horizontally, irregularities of the highway may have caused that samplings were at times carried out at some "angle of attack" relative to the horizontal, thus causing a vertical component of the air/droplet motion as the droplets entered the probe inlet. This effect would cause, in general, an underestimation of the total droplet concentration, especially if it is considered that some of the larger droplets could impact on the upper walls of the FSSP sampling tube. It should be mentioned that no attempt was made to correct any of the measurements due to this effect.

Normally, droplet sizes and concentrations were recorded each second and the probe operated with a nominal channel width of 3 μm. Occasionally, with the purpose of examining the droplet spectra in more detail, recordings were carried out every two seconds and the probe range was changed to nominal channel width of 2 μm. Liquid water contents were derived from the measured concentrations.

The fog measurements were carried out the last week of January 1990. During this period, there were three fog-days (25, 26 and 29 January) with similar characteristics. Due to a malfunction in the DAS, part of the data on two of the three fog-days was not properly recorded. However, data on 29 January were satisfactory recorded and allowed detailed documentation of that fog event. In what follows, the results obtained on that day are presented.

4. Results and discussion

On 29 January 1990, a cold front approached from the north (Figure 3) bringing humid, relatively colder air to the study region. At about 1200 LST (1800 GMT), fog with a visibility less than 400 m started to form over a 20 km diameter area centered in Teziutlan. [All values of visibility stated here correspond to estimations made by eye.] Although it is possible that scattered fog patches were present at this time over a much larger area (perhaps as far south as Orizaba, about 130 km away from Teziutlan) there are no direct reports available to these authors to confirm it. However, satellite images (Figure 4) show low-cloud, overcast conditions all over the Sierra along the coast, with generally clear skies over the high plateau. By 1400 LST, visibilities were reduced to less than 100 m and fog was well established. This episode lasted for more than 15 hours, with fog dissipation taking place in the early hours of 30 January and coinciding with the passage of the *norte* associated to the front.

Microphysical measurements are summarized in Figures 5 to 8. For the sake of brevity only typical, representative data are shown. The spatial variability of fog is shown in Figure 5, which presents total droplet concentrations, averaged over 126 m-long stretches, as functions of the position along the highway for cloud penetrations at different times. The afternoon data indicate that fog was fairly uniform, with an average droplet concentration of 197 cm^{-3} (standard deviation of 50 cm^{-3}) and a visibility less than 100 m. The night data show that fog tends to dissipate

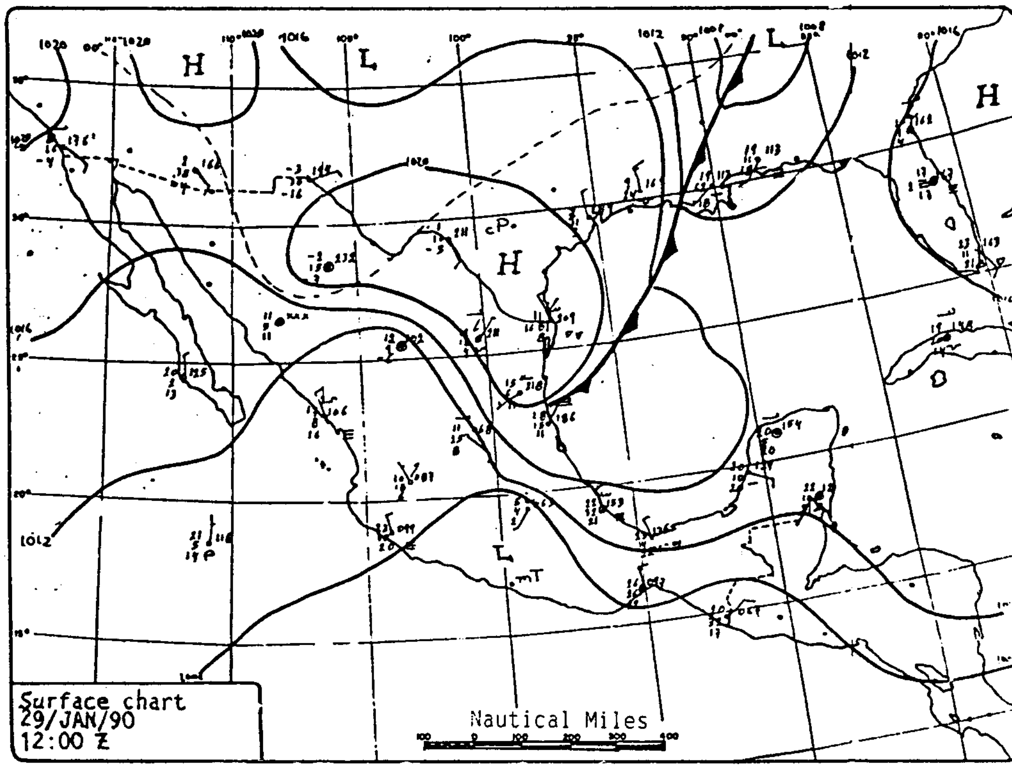

Fig. 3. Surface chart depicting the synoptic situation on 29 January 1990 at 0600 LST (1200 GMT). Fog started to form six hours later over the study region.

towards the end-points of the sampling trajectory, and that droplet concentrations are slightly smaller than earlier in the day. This latter behavior was observed for several hours, with maxima in the total concentration moving back and forth within the sampling path. The fact that all individual averages over 126 m-long stretches had standard deviation values smaller than 10%, along with the results from averages made over 1 and 2 km-long stretches (see below), indicate that these data can be considered as representative "point" values. Maximum observed total droplet concentrations and liquid water contents were 250 cm^{-3} and 0.85 g/m^3, respectively.

Data were also analyzed by taking averages over 1 and 2 km-long stretches. Relative concentrations always showed similar trends (Figure 6), with average droplet concentrations of 150 cm^{-3} (standard deviation of 24 cm^{-3}). The size distributions almost always had a single peak with a mode in the 2 to 5 μm range, with a second, less pronounced peak occurring at times in the 10 to 13 μm range. Although there is a possibility that the probe's channel two could be reading too low, a more detailed examination of the data available in the 2 μm width probe-range revealed that the second peak showed up either in the 8 to 10 or in the 10 to 12 μm ranges. Plots of droplet concentration per bin width (Figure 7) also reinforce these observations.

The predominance of the first peak in the spectra is associated with the presence of a large number of droplets with diameters below about 4 μm, the so-called "haze mode". This has been observed by several authors in different types of inland fog [Garland *et al.* (1973) in a polluted environment; Roach *et al.* (1976) in radiation fogs; Pilié *et al.* (1975) in valley fogs]. The presence

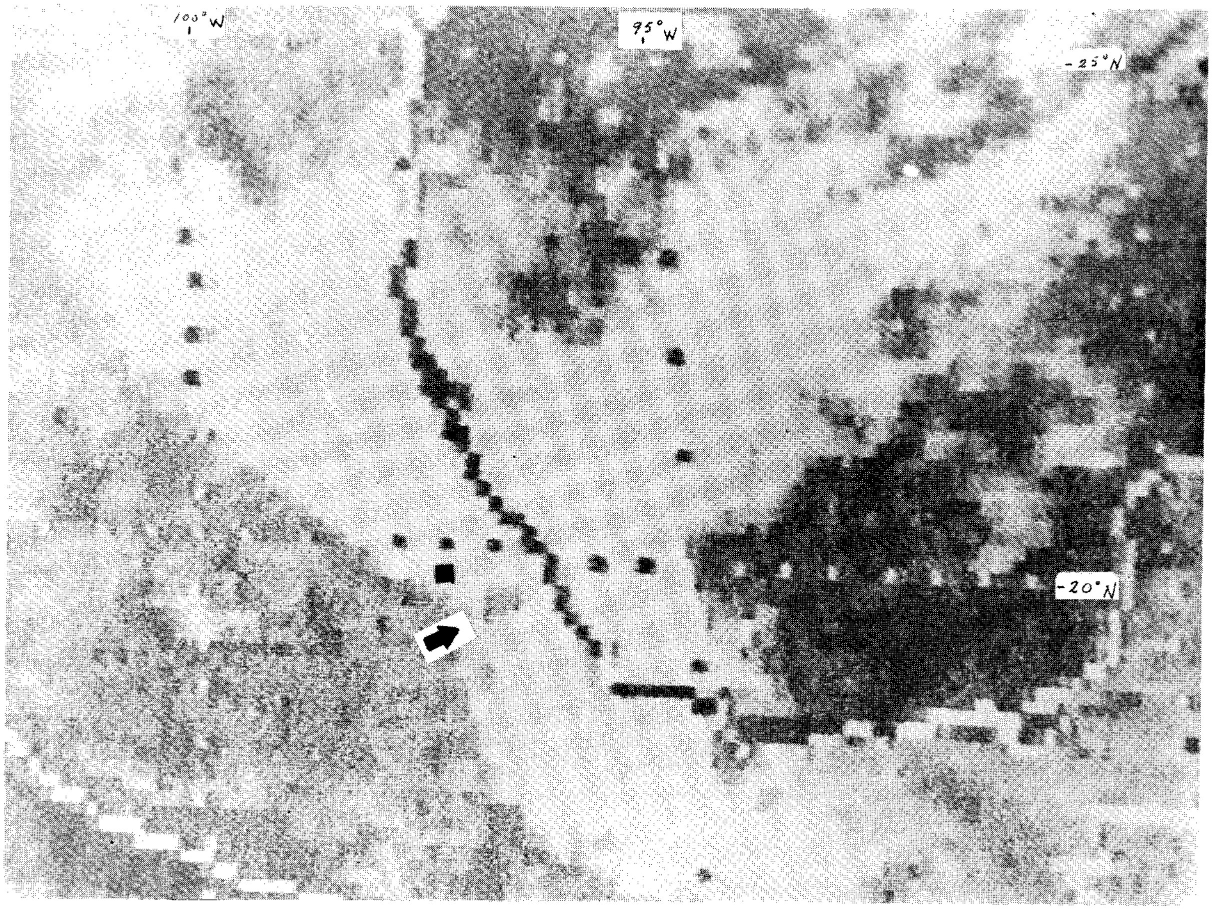

Fig. 4. Visible satellite image on 29 January 1990 at 1200 LST, showing low-cloud, overcast conditions over the Sierra Madre Oriental. The cloudy area roughly delimits the Sierra from the high plateau. The arrow points to the cloud-free summit of the Pico de Orizaba Volcano, and the black square indicates the approximate location of the field site.

of the haze mode in the present results is consistent with observations that haze particles make a substantial contribution towards light extinction, thus playing an important role in visibility impairment (see Eldridge, 1966). It may also be an indication of possible local effects on fog evolution.

Maximum droplet diameters larger than 35 μm were common but they did not contribute significantly to the total droplet concentration. However, very few droplets larger than 47 μm contributed to the fog liquid water content (LWC) as much as all droplets smaller than 13 μm (Figure 8). Measured LWC were as high as 0.85 g/m^3, with an average value of 0.44 g/m^3. Mean volume diameters (MVD) ranged between 14 and 19 μm, with a LWC peak diameter of 30 μm. These values are very high for the case of surface generated fogs and are mainly due to the presence of the larger drops in the distribution. Although it can not be conclusively stated whether drizzle was or not present in the fog, visual observations indicate that this was not the case.

Values of droplet diameter range and MVD found here are in agreement with what Jiusto (1981) reports as valley fogs, but with higher LWC's. The latter are more similar to reports by

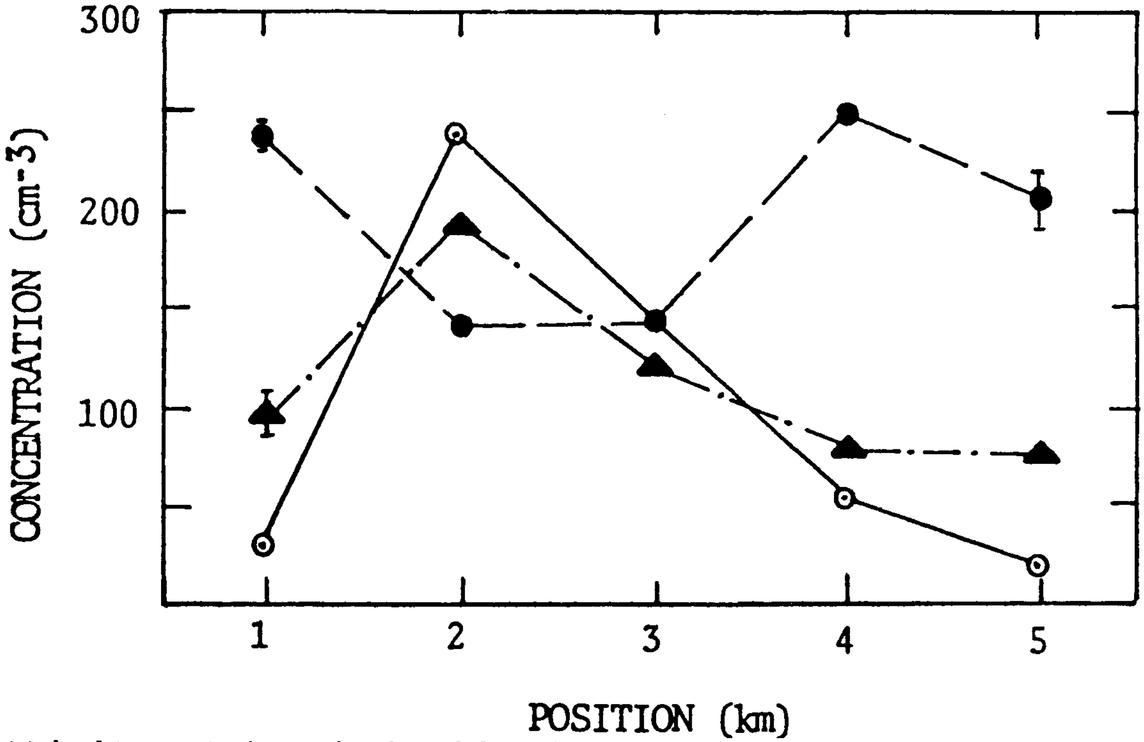

Fig. 5. Total droplet concentrations as functions of the position along the sampling trajectory for three different cloud penetrations: at 1412 LST (solid circles); at 2019 LST (triangles); and at 2035 LST (dotted circles). Each experimental point represents an average over 126 m. Error bars, corresponding to one standard deviation, are shown. Each penetration lasted 6 minutes.

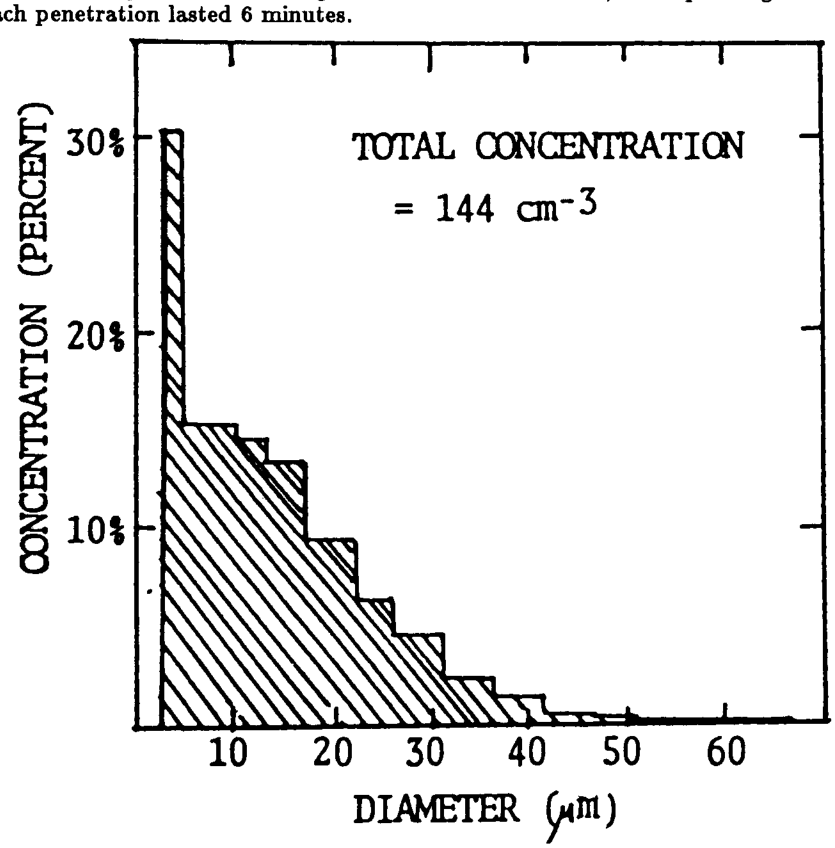

Fig. 6. Fog droplet-size distribution in percent at 2021 LST, averaged over 2 km. Total concentration was 144 cm^{-3} in this case.

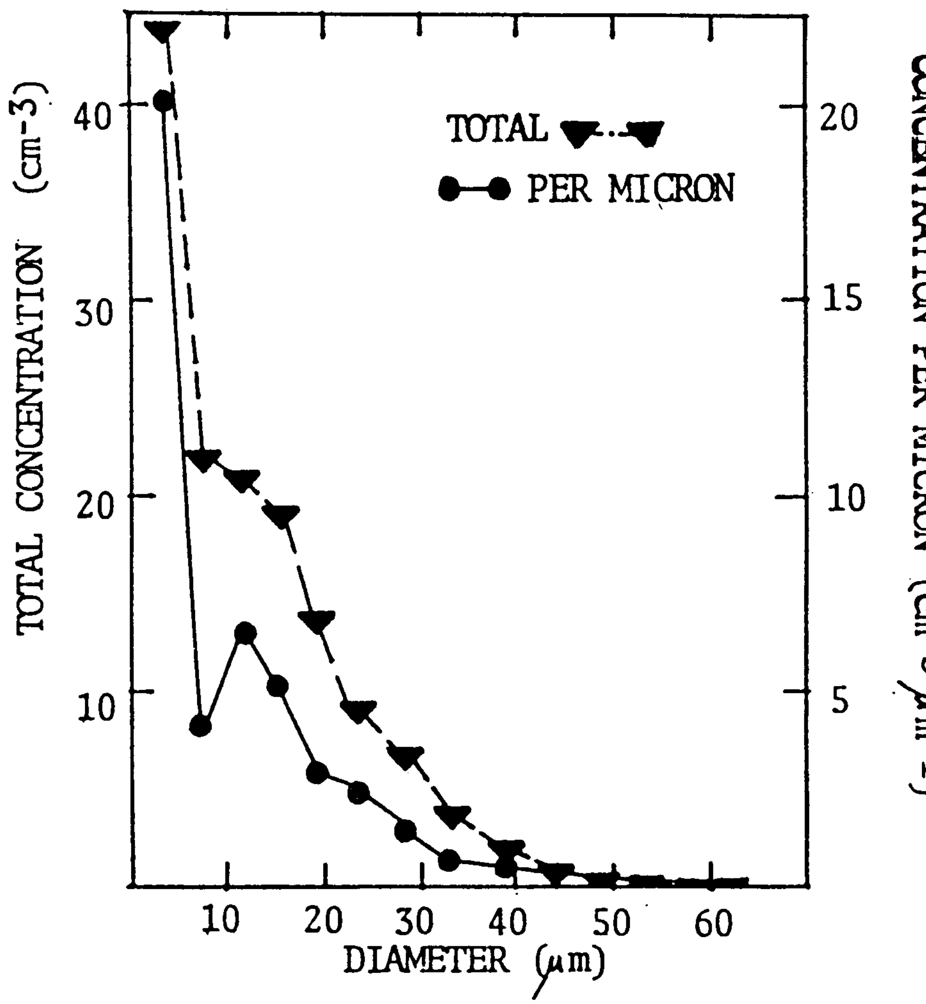

Fig. 7. Distribution of fog droplet-sizes in terms of total and per bin width concentrations, for the same case shown in Figure 6.

Schemenauer and Joe (1989) regarding "camanchacas" in Chile. Droplet concentrations are also larger and more in line with those of advection fogs of continental trajectories along the coast of California (Goodman, 1977). The fact that the microphysical parameters do not seem to fully agree with any of the "typical" fog types indicate that different effects may play a role in fog evolution in the Sierra, pointing to the fact that fog formation was mainly due to the advection of stratus decks towards the mountains. Unfortunately, no radiosonde or similar sources of data (for calculating adiabatic LWC values) are available to confirm this conclusion.

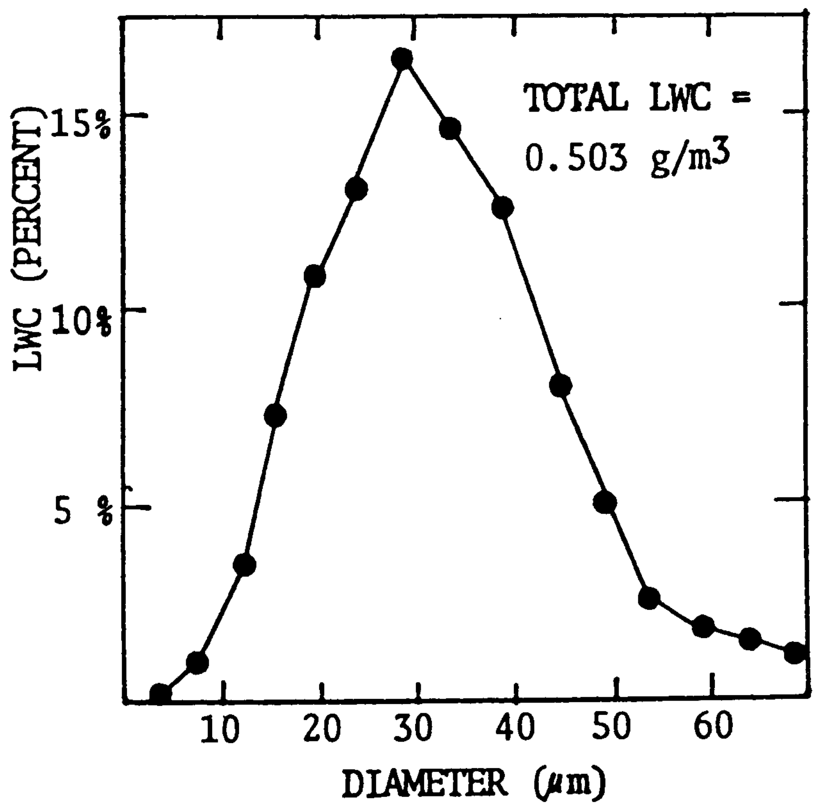

Fig. 8. Distribution of fog liquid water content in percent, for the same case shown in Figures 6 and 7. The total LWC and the MVD were 0.503 g/m^3 and 18.9 μm, respectively.

5. Concluding remarks

In this paper, characteristics of the microstructure of fog in eastern Mexico have been presented. If the case study discussed here is representative of fog formation in the region, at least in the winter season, then the following conclusions may be drawn.

It is apparent that up-slope motion and adiabatic cooling, accompanied by moisture flow from the Gulf of Mexico, are common mechanisms of fog formation in the region. The characterization of other sites in the region and the correlation between fog and precipitation during the rainy season, as well as detailed microphysical fog evolution with time, should give further clues to better understand the problem.

The relatively large values of liquid water content found here are not commonly reported. The fact that liquid water contents can be as high as 0.85 g/m^3 is of great importance if any efforts on removing water from fogs are to be pursued. If small fog collectors of 0.5 m by 0.5 m with an assumed collection efficiency of 50% were deployed in the area of interest, and assuming a wind speed of 3 m/s and an average LWC value of 0.44 g/m^3, each of them would remove about 6 liters of water in a single fog event ten hours long. If a much larger 40-m^2 collector (see Schemenauer *et al.*, 1988) were used, it would be able to catch about 1000 liters of water per day assuming the same conditions as above. In this scenario, the collected water would be enough to fulfill the necessities of a typical four-member family in an urban area of Mexico during one day. These estimates are in agreement with measurements made in the region by Vogelmann (1973), which show that collected fog-water amounts during the dry season (winter and spring) can be as large as those of total rainfall in the same period. Fog-water could be of particular importance in areas downwind towards the interior plateau where, as mentioned before, average rainfall diminishes and semi-arid conditions prevail.

A more comprehensive research program, including data collection at different field sites throughout the year and detailed meteorological information, will be required in order to confirm the conclusions stated above. Further equipping of the mobile laboratory, with instrumentation that will include microphysical and meteorological probes, will be of great help and is already in progress. Future studies will comprise measurements on the amount of available cloud condensation nuclei and their sources. Understanding the meteorological and topographical relationships that may influence fog-water collection will be very important: the fog zone may penetrate as much as 50 km into the dry plateau, and fog-water may also play an important role in the reforestation of the mountains. In summary, the formation of dense, frequent fogs is expected to have considerable local influence in the water budget of the study region, and this is a topic which should be the subject of further research.

Acknowledgements

The authors want to thank Messrs. P. Mosiño and F. Villicaña for supplying the synoptic and meteorological data, and A. Báez for the loan of the power generator used in the mobile laboratory. Technical support by Messrs. V. Zarraluqui, J. Escalante and A. Rodríguez is also appreciated. Part of this study was sponsored by the Instituto Mexicano de Tecnología del Agua (IMTA) of the Comisión Nacional del Agua, and by Consejo Nacional de Ciencia y Tecnología (CONACyT), México.

REFERENCES

Baumgardner, D., W. Strapp and J. E. Dye, 1985. Evaluation of the Forward Scattering Spectrometer Probe. Part II: Corrections for coincidence and dead-time losses. *J. Atmos. Oceanic Technol.*, **2**, 626-632.

Byers, H. R., 1974. General Meteorology, Fourth Edition. McGraw-Hill Book Co., 461 pp.

DGSMN (Dirección General del Servicio Meteorológico Nacional), 1982. Normales Climatológicas: Período 1941-1970. Secretaría de Agricultura y Recursos Hidráulicos, México, 799 pp.

Dye, J. E., and D. Baumgardner, 1984. Evaluation of the Forward Scattering Spectrometer Probe. Part I: Electronic and optical studies. *J. Atmos. Oceanic Technol.,* **1,** 329-344.

Eldridge, R. G., 1966. Haze and fog aerosol distributions. *J. Atmos. Sci.*, **23**, 605-613.

García-García, F., and R. A. Montañez, 1989. Evaluación de un espectrómetro de gotas para estudios de microfísica de nubes. *Geos (Boletín Unión Geofísica Mexicana)* Epoca II. **9**, 25-31.

Garland, J. A., J. R. Branson and L. C. Cox, 1973. A study of the contribution of pollution to visibility in a radiation fog. *Atmos. Environ.*, **7**, 1079-1092.

Goodman, J., 1977. The microstructure of California coastal fog and stratus. *J. Appl. Meteor.*, **16**, 1056-1067.

Jiusto, J. E., 1981. Fog structure. In: Clouds: Their formation, optical properties, and effects, P.V. Hobbs and A. Deepak (Eds.), Academic Press, 187-239.

Knollenberg, R. G., 1976. Three new instruments for cloud physics measurements: The 2-D Spectrometer, the Forward Scattering Spectrometer Probe, and the Active Scattering Aerosol Spectrometer. *Prepr. Int. Cloud Phys. Conf., July 26-30, Boulder, Colo.* Amer. Meteor. Soc., 554-561.

Pilié, R. J., E. J. Mack, W. C. Kocmond, W. J. Eadie and C. W. Rogers, 1975. The life cycle of valley fog. Part II: Fog microphysics. *J. Appl. Meteor.*, **14**, 364-374.

Roach, W. T., R. Brown, S. J. Caughey, J. A. Garland and C. J. Readings, 1976. The physics of radiation fog: I - a field study. *Quart. J. Roy. Meteor. Soc.*, **102**, 313-333.

Schemenauer, R. S., and P. I. Joe, 1989. The collection efficiency of a massive fog collector. *Atmos. Res.*, **24**, 53-69.

Schemenauer, R. S., H. Fuenzalida and P. Cereceda, 1988. A neglected water resource: the camanchaca of South America. *Bull. Amer. Meteor. Soc.*, **69**, 138-147.

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