The IMADA-AVER Boundary Layer Experiment in the Mexico City Area

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ABSTRACT

A boundary layer field experiment in the Mexico City basin during the period 24 February–22 March 1997 is described. A total of six sites were instrumented. At four of the sites, 915-MHz radar wind profilers were deployed and radiosondes were released five times per day. Two of these sites also had sodars collocated with the profilers. Radiosondes were released twice per day at a fifth site to the south of the basin, and rawinsondes were flown from another location to the northeast of the city three times per day. Mixed layers grew to depths of 2500–3500 m, with a rapid period of growth beginning shortly before noon and lasting for several hours. Significant differences between the mixed-layer temperatures in the basin and outside the basin were observed. Three thermally and topographically driven flow patterns were observed that are consistent with previously hypothesized topographical and thermal forcing mechanisms. Despite these features, the circulation patterns in the basin important for the transport and diffusion of air pollutants show less day-to-day regularity than had been anticipated on the basis of Mexico City's tropical location, high altitude and strong insolation, and topographical setting.

1. Introduction

Air pollution is a major concern in Mexico City, where high population density (approximately 19 million people in 1000 km^2), generally light synoptic winds, sheltering by nearby mountains, multiple pollution sources, and strong insolation (which leads to the photochemical formation of ozone) combine to produce frequent episodes of poor air quality (Collins and Scott 1993). As part of an ongoing series of projects to investigate the causes and characteristics of the pollution problem and to develop mitigation methods for it, a field experiment was carried out in the Mexico City area from 24 February through 22 March 1997. The experiment was part of a research program entitled Investigacion sobre Materia Particulada y Deterioro Atmosferico-Aerosol and Visibility Research (IMADA-AVER) and was jointly sponsored by Petróleos Mexicanos (PEMEX) through the Instituto Mexicano del Petróleo (IMP) and the U.S. Department of Energy's (DOE) Office of Biological and Environmental Research. The objective of the program was to identify the nature and causes of high $PM_{2.5}$ and PM_{10} concentrations (particles with aerodynamic diameters less than 2.5 and 10 μm, respectively), visibility impairment, and high ozone levels

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in the Mexico City region. The experiment also provided an opportunity to obtain a database for air quality studies in an urban setting in complex terrain, and such opportunities are relatively rare. Principal participants included DOE's Argonne National Laboratory, Los Alamos National Laboratory, and Pacific Northwest National Laboratory, the National Oceanic and Atmospheric Administration's Environmental Technology Laboratory, IMP's Gerencia de Ciencias del Ambiente, the Comision Metropolitana para la Prevención y Control de la Contaminación Ambiental en el Valle de México, the Instituto Politecnico Nacional: Vocacional 10, and the Desert Research Institute for the University and Community College System of Nevada.

Because of the importance of meteorological conditions in determining the transport, diffusion, transformation, and removal of air pollutants, an extensive meteorological measurement and analysis program was conducted as one component of this study. A set of meteorological measurements was designed to investigate the occurrence and properties of local flow patterns, examine the structure and evolution of the mixed layer over the basin, provide data for the testing and evaluation of numerical models to be used to describe the meteorology in the region, and provide information that could be used to identify and describe significant transport and diffusion patterns for airborne pollutants in the Mexico City area. Numerical modeling was used to help in the design of the experiment, assist in the interpretation of the data, and help explain the observed wind, temperature, and pollution patterns. The purpose of this paper is to describe the meteorological field program, give an initial look at some of the boundary layer features of the Mexico City region that are relevant to air quality, and serve as an introduction to more detailed analyses of the data presented in other publications. Some additional information on the air chemistry measurements and ozone patterns will also be given.

Few boundary layer studies have been conducted in Mexico City, and those studies that have been carried out have relied primarily on near-surface observations. Jauregui (1973, 1988, 1993, 1997) has examined local circulations related to Mexico City's urban heat island and their effects on pollutant transport, and Oke et al. (1992) carried out measurements of the surface energy balance in the city. Some upper-air measurements were obtained from tethered balloons, rawinsondes, and a lidar during the Mexico City Air Quality Research Initiative (MARI) (Streit and Guzmán 1996) during the winter of 1991. In addition, an airplane collected meteorological and air chemistry data during approximately 40 h of flights (Nickerson et al. 1992). Williams et al. (1995) conducted mesoscale modeling studies for several selected days of the MARI experiment. Although they were able to reproduce some features of the wind patterns determined from a network of surface stations and from radiosondes released from the Mexico City airport, their modeling domain was limited to Mexico City and the surrounding mountains and could not accommodate possible interactions between regional and local flows. Using a considerably larger outer domain in a nested model configuration, Bossert (1997) concluded that regional and synoptic flows could combine with locally induced circulations and significantly affect the resultant pollutant patterns found over the area. He suggested that a regional flow of air from the north that develops in response to the daytime heating of the central Mexican plateau might be particularly important. More recent computer modeling studies also identified likely temperature and wind patterns over the Mexico City area (Zhong et al. 1997; Fast et al. 1997) and the movement of atmospheric pollutants in response to those patterns.

2. Topographical setting and related circulation patterns

Mexico City lies in an elevated basin at an altitude of approximately 2250 m above mean sea level (MSL). Mountains border the basin to the east, south, and west, rising 1000 m or more above the basin, with several peaks attaining elevations of nearly 4000 m MSL and two major volcanoes to the southeast reaching over 5000 m MSL. South of the mountains the terrain falls away rapidly, and there is a low-lying gap or channel through the mountains in the southeastern corner of the basin. To the north of the city lies a collection of hills extending to 3000-m elevation but with lower terrain on either side and farther to the north. Figure 1 shows a topographical map of the area, including the locations of some meteorological instrumentation and air chemistry sites that will be discussed later. The main urban area is located on the west side of the basin and is shown as the shaded region in the figure.

Mexico City has a network of air quality and meteorological stations operated by the Dirección General de Prevención y Control de la Contaminación de la

Ciudad de México. Nineteen of these Red Automática de Monitoreo Atmosférico (RAMA) stations measure, among other pollutants, ozone concentrations on an hourly basis. An examination of the ozone concentration patterns shows that peak values can differ dramatically in both magnitude and location from day to day. Figure 2 shows examples of this variation measured during the 1997 experiment. Hourly ozone values are given for four of the RAMA sites shown in Fig. 1: Pedregal (PED), Xalostoc (XAL), ENEP Acatlan (EAC), and Tlahuac (TAH). Analyses with numerical models (Bossert 1997; Zhong et al. 1997; Fast et al. 1997) showed that important aspects of these concentration patterns could be understood only with careful consideration of the factors affecting the local circulations and that these are sensitive to the interaction of synoptic, regional, and local influences. Particulate concentration patterns were also expected to be similarly affected, although the existence of several important point, area, and mobile sources would lead to different behavior than that found for the more widely dispersed ozone precursor sources (Collins and Scott 1993; Edgerton et al. 1998).

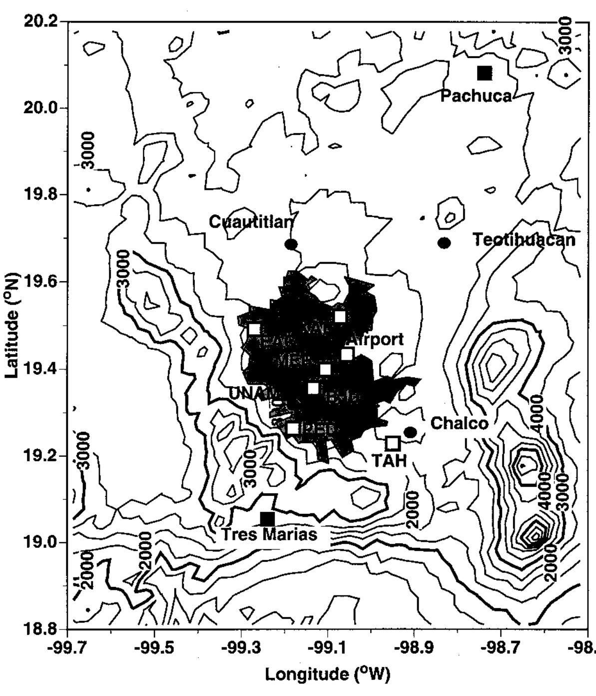

FIG. 1. Topographic map of Mexico City and its surroundings showing locations of the four 915-MHz radar wind profiler sites (filled circles), the Tres Marias radiosonde and Pachuca rawinsonde sites (filled squares), and the airport and six air chemistry monitoring sites (open squares). The gray area marks the approximate bounds of the main Mexico City urban area. Elevations are in meters.

Because of the topographic setting of the city, the moderately strong insolation associated with its tropical latitude (19°N) and high elevation, and the weak prevailing synoptic winds, it was anticipated that the Mexico City area would be strongly affected by thermally and topographically induced circulations. Based on previous observations and conceptual and numerical modeling, three principal daytime wind patterns were expected to be identifiable. The first was the development of local upslope flows driven by the heating of the sidewalls of the mountains. In particular, the slopes to the south and west were expected to produce readily discernible flows in the nearby sections of the city. It had been suggested by Mexican scientists that upslope flows of this kind are a major factor responsible for the tendency for ozone concentrations to be

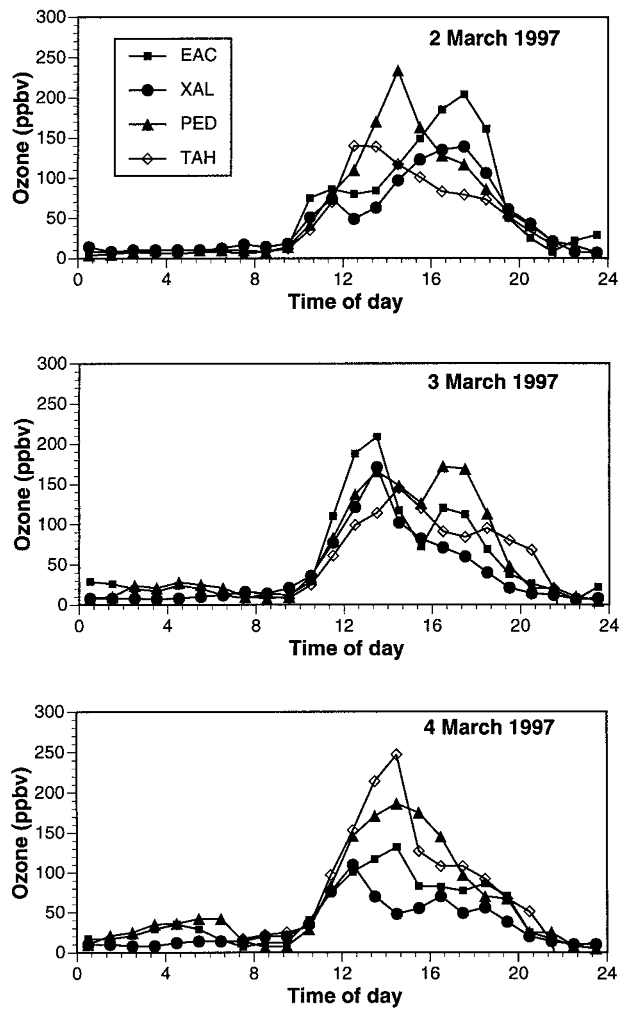

FIG. 2. Time series of ozone concentrations at four RAMA network sites in Mexico City during a three-day portion of the field campaign. The stations are Pedregal (PED), Xalostoc (XAL), ENEP Acatlan (EAC), and Tlahuac (TLA).

highest in the southwestern portions of the city, but the depth and strength of the flows were unknown. The second pattern was a local valley-to-basin flow in which southerly winds would develop and propagate through the gap in the mountains to the southeast and over the ridge forming the southern boundary of the Mexico City basin. Such winds were expected because the boundary layer over the basin was likely to be warmer than that outside the basin over the moister and more vegetated areas to the south. No data were available, however, to indicate how significant those temperature differences were likely to be. Numerical simulations carried out to help identify locations for deploying instruments for the IMADA-AVER field campaign also indicated that such flows should be common, although we found no evidence that such a flow regime had ever been identified from previous measurements. The third pattern was a regional plain-to-plateau flow of air from the lower-lying areas to the north and east into the basin from the north in the late afternoon, driven by the heating of the elevated terrain in central Mexico. This pattern was simulated by Bossert (1997) in his study, but he also emphasized the need for additional observations to confirm its occurrence and measure its properties. The flow was expected to have some similarities to regional circulations found in the Rockies (Bossert and Cotton 1994) and the Cascade Range (Doran and Zhong 1994). Figure 3 is a schematic diagram illustrating these hypothesized contributions to the flow fields in the Mexico City area.

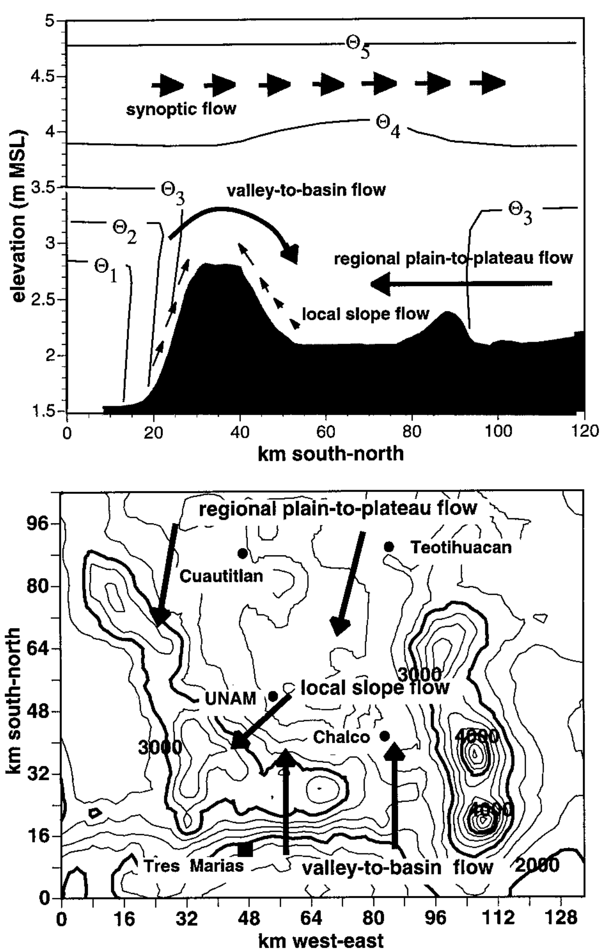

FIG. 3. Schematic diagram showing hypothesized daytime flow patterns affecting the Mexico City basin. (top) Vertical cross section, representative potential temperature contours are shown; (bottom) horizontal cross section, elevations are in meters.

3. Instrumentation

a. Aerosol and chemistry measurements

A wide variety of chemistry, aerosol, and visibility data was acquired during the course of the experiment. Edgerton et al. (1998) provide a description of the objectives and initial findings of the chemistry and aerosol components of the IMADA-AVER program, so only a brief listing of some of the important aspects of this component is given here.

Ten RAMA sites recorded PM_{10} concentrations on an hourly basis. At three base monitoring sites, supplementary measurements were made to acquire PM_{10} and $PM_{2.5}$ data for mass, light absorption, and elemental concentrations (for elements from sodium to uranium), and ion (sulfate, nitrate, ammonium, soluble sodium, and soluble potassium), and carbon (organic and elemental) concentrations four times per day (0000–0600, 0600–1200, 1200–1800, and 1800–2400 LST). At three other base sites similar data were acquired for 24-h periods. At one core site (MER, cf. Fig. 1), additional measurements were obtained for nitric acid and ammonia, heavy hydrocarbon gases (C_8-C_{20}), and polycyclic aromatic hydrocarbons (PAHs) at 6-h intervals. Canister samples for light hydrocarbon C_2-C_{10}) gases were also collected, as were high-volume total suspended particulate samples to measure nitro-PAH. Twenty-five satellite sites measured daily PM_{10} mass, light absorption, elemental, and ammonia concentrations, and half of the sites acquired additional samples for carbon and ion analyses. Measurements of peroxyacetyl nitrate (PAN) were taken at a site north of the downtown area of the city at 30-min intervals.

Data from the six base monitoring sites will be used to establish spatial and temporal distributions of particle size and chemical composition; provide input and evaluation data for particulate dispersion, receptor, and visibility models; quantify measuring limitations of the long-term monitoring network; and apportion ambient $PM_{2.5}$ and PM_{10} concentrations to their sources. The satellite sites were chosen to provide information on source zones of influence, receptor zones of representation, PM gradients between fixed sites, and transport into and out of the urban area.

b. Meteorological measurements

Twice-daily rawsinsonde soundings are regularly made at the Benito Juarez International Airport, and the RAMA network has 10 surface stations that record hourly values of wind speed and direction, temperature, and humidity. There are some questions regarding the representativeness of the data from some of the RAMA stations because of possible blocking or channeling of flow in the urban environment and the light winds that characterize the area. Moreover, the RAMA stations only provide information on flows near the surface while pollutant patterns depend on winds throughout the depth of the boundary layer. Thus, the emphasis for this experiment was on determining the flows in the lowest few kilometers of the atmosphere.

Four main sites for upper-air monitoring were chosen (Fig. 1): Chalco, UNAM (Universidad Nacional Autónoma de México), Teotihuacan, and Cuautitlan. The UNAM site was a campus location in the southwest part of the city, and the Teotihuacan site was in a semiarid region to the northeast of Mexico City, while the land surrounding Cuautitlan and Chalco was primarily agricultural. A 915-MHz radar wind profiler was installed at each of these sites to collect hourly averaged wind profiles during the experiment. Vertical resolution was 60 m to heights exceeding 1 km and 100 m to heights on the order of 3 km or more. The base elevation (MSL) of each profiler was within 30 m of the other profilers (cf. Table 1), making comparisons of wind profiles among the sites straightforward. Sodars at Cuautitlan and Teotihuacan provided supplemental wind data in the lowest few hundred meters of the atmosphere at 15-min intervals, which were then averaged over 1-h periods. In addition, radiosondes that measured pressure and dry- and wet-bulb temperatures were released five times per day (0800, 1100, 1330, 1630, and 1930 LST) Monday through Saturday during each week of the campaign. To supplement these measurements, additional radiosondes were released at 1330 and 1630 LST at Tres Marias, situated on the southern flank of the mountains forming the southern boundary of the basin (Fig. 1). Finally, a sixth site was established at Pachuca, which lies approximately 70 km northeast of the city. Rawinsondes equipped with Global Positioning System receivers were released here at 1330, 1630, and 1930 LST.

The wind, temperature, and humidity data from the four main sites gave a picture of the boundary layer structure and development over the Mexico City area. The temperature data from the Tres Marias and Pachuca sondes provided information on temperature differences between the basin atmosphere and its surrounding environment, while wind, temperature, and

TABLE 1. Sites and instruments deployed during the experimental campaign. The averaging time for radar profilers is 1 h and for sodars is 15 min. The averaging times for surface station data are 1 min for Teotihuacan and UNAM sites and 15 min for Chalco.

Site	Lat °N	Long °W	Elev (m MSL)	915-MHz profiler	Radiosondes (T, q)	Rawinsondes (T, q, V)	Sodar	Surface station
Chalco	19.25	98.91	2248	x	x		x	
Cuautitlan	19.69	99.19	2252	x	x		x	
Pachuca	20.08	98.74	2425			x		
Teotihuacan	19.68	98.85	2275	x	x		x	x
Tres Marias	19.05	99.25	2810		x			
UNAM	19.32	99.19	2274	x	x			x

humidity data from the Pachuca sondes provided a measure of the "upstream" conditions for flow into the basin from the north.

Surface stations recorded wind speed and direction, temperature, humidity, and solar or net radiation at Chalco and UNAM at a height of 10 m, and at Teotihuacan at 2 m. The averaging time for the UNAM and Teotihuacan sites was 1 min while for Chalco it was 15 min. Table 1 provides a summary of the instruments and data collected at the various sites.

4. Weather conditions

Early in the experiment the 500-hPa analysis showed a deep trough over New Mexico and Texas whose influence extended southward to north and central Mexico, producing strong southwesterly winds aloft (26 February pattern in Fig. 4). This pattern gradually gave way to one with high pressure over central Mexico with weak upper-level winds (7 March pattern in Fig. 4). The high weakened briefly on 13 and 14 March, allowing somewhat stronger westerly winds aloft to develop. On 19 March a cutoff low formed off the east coast of central Mexico, producing even stronger (on the order of 20 m s^{-1}) winds from the southwest at 500 hPa. At the surface the first 10 days of the experiment were generally warm and showed a slow drying trend. After 6 March temperatures became noticeably cooler and the relative humidity increased but with a drier period on 14–15 March (Fig. 5). There was also significantly more cloudiness after 6 March as can be seen in Fig. 6, which shows the solar radiation measured over the experimental period.

An analysis of 10 years of RAMA data also showed that the ozone patterns found during February and March of that time were similar to those found in 1997, although the peak concentration values in 1997 were lower than the average. Diurnal cycles of wind speed, temperature, and humidity were compared for the two periods and indicate that the upper-level wind conditions in 1997 were generally representative of conditions found in previous years (Bian and Whiteman 1998).

5. Observations

The expected strong influence of topographic and thermal forcing suggested that the boundary layer development on each day would be similar and the three wind patterns described in section 2 would be seen on a regular basis. In fact, the growth of the mixed layer was often comparable from one day to the next and an examination of one or two representative days is sufficient to indicate the general features. There is also evidence for the occurrence of the various wind patterns on many days of the field campaign, but there were also a number of occasions when only some or none of these patterns was observed. Moreover, the relative prominence of each pattern differed significantly from day to day, making it more difficult to describe the winds on a "typical" day by looking at a

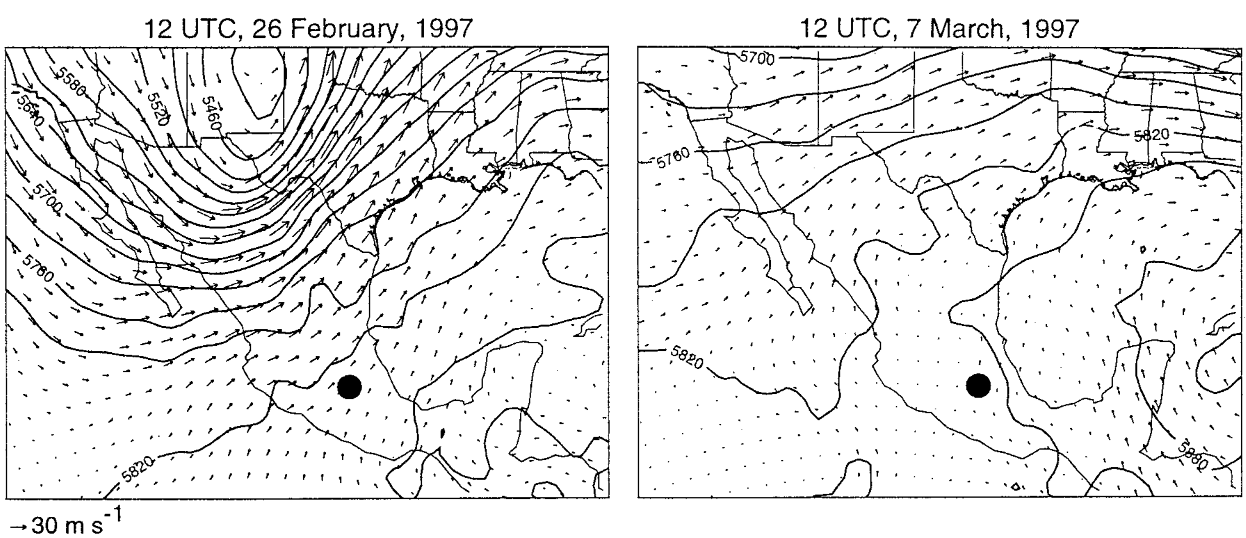

FIG. 4. Maps of the 500-hPa height (m) and wind patterns during two days of the 1997 experiment. The filled circle marks the location of Mexico City.

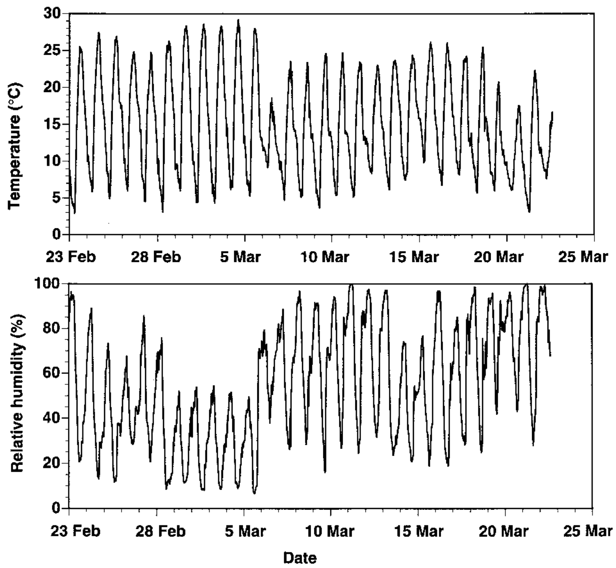

FIG. 5. Near-surface (2 m AGL) temperature and relative humidity time series measured at Teotihuacan during the 1997 experimental period.

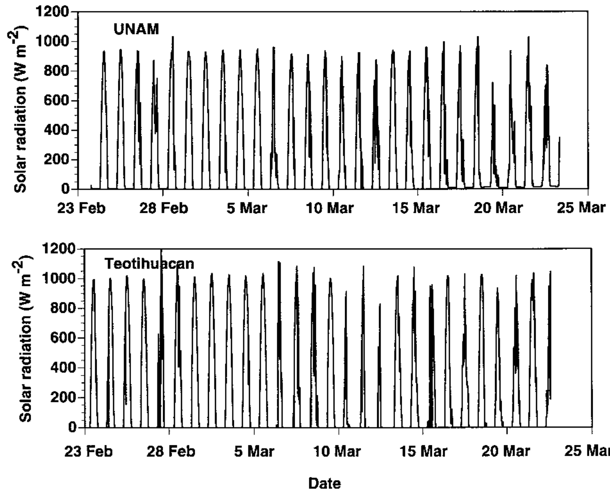

FIG. 6. Solar radiation measured at the Teotihuacan and UNAM sites during the 1997 experiment.

single case. It is useful to keep this in mind when wind and temperature patterns are described below.

a. Potential temperature evolution

Figure 7 shows potential temperature profiles measured at the four radar profiler sites for four times on 7 March 1997. This day was chosen because the profiles clearly show a number of features that were observed on a regular basis. A well-developed surface-based inversion formed overnight and by late morning was only partially eliminated. The mixed layer was less than 1 km deep an hour before noon but in the next few hours grew rapidly. Further development between the 1330 and 1630 LST soundings was considerably slower. Typical late afternoon mixed layer depths ranged between approximately 2500 and 3500 m; on this day the depths reached nearly 3000 m. These values agree well with previous findings from lidar and rawinsonde measurements reported by Williams et al. (1995). Although on this day the Cuautitlan sounding was the coolest at 1630 LST, there was a tendency for the potential temperatures in the mixed layer at Chalco to be around 1 K cooler

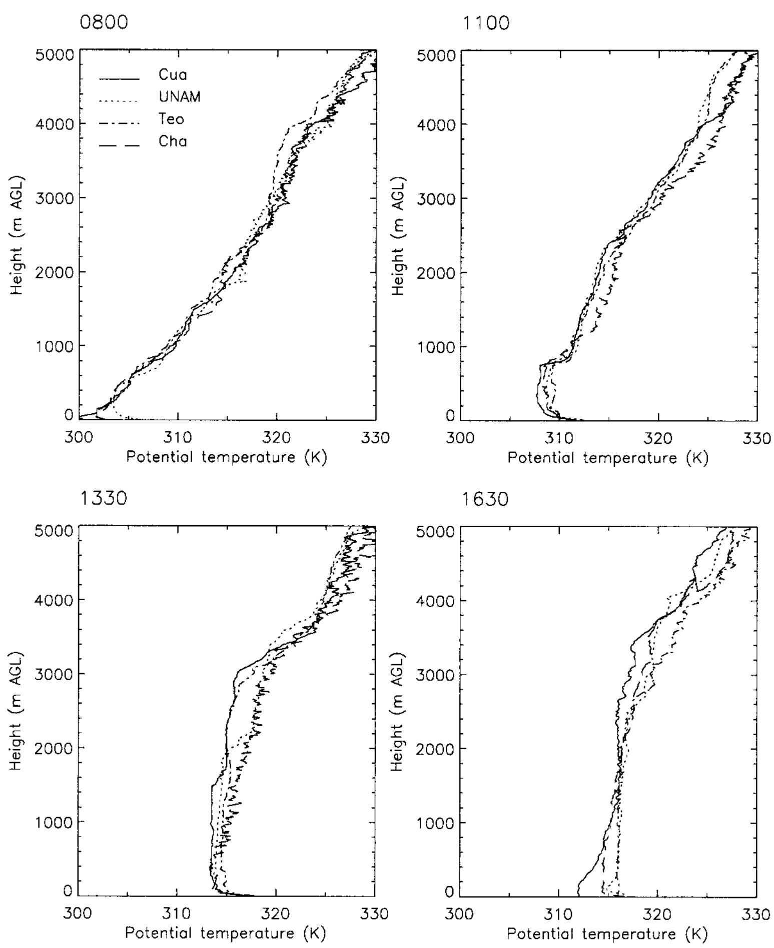

FIG. 7. Potential temperature profiles at the four radar profiling sites at 0800, 1100, 1330, and 1630 LST on 7 March 1997.

than those at the other profiler sites at this time. The difference may be associated with an influx of cooler air from outside the valley, which is discussed later, or the greater amount of vegetation in the region. The 1930 LST soundings (not shown) at all of the profiler sites often exhibited a cool layer near the surface and a residual layer with nearly constant potential temperatures aloft. Efforts are now under way to estimate energy budgets in the Mexico City basin from the time evolution of the potential temperature profiles and to explain the mechanisms contributing to those budgets (Whiteman et al. 1998).

As expected, differences were also found between the mixed layer temperatures inside and outside the Mexico City basin. An example is given in Fig. 8, which shows the 1630 LST potential temperature soundings obtained from the Teotihuacan, Tres Marias, and Pachuca sites on 11 March 1997. The Tres Marias soundings often showed potential temperatures in the boundary layer between 1.5 and 3 K cooler than those found at UNAM, Cuautitlan, and Teotihuacan in the late afternoon; on this day the difference between Tres Marias and Teotihuacan is nearly 4 K. Such differences between the Tres Marias and Mexico City basin temperatures are consistent with the development of a thermally driven southerly flow through the gap in the mountains. The temperature differences between the profiler sites and Pachuca were somewhat smaller, but the Pachuca basin temperature differences are also consistent with the development of winds with northerly or easterly components found at the Teotihuacan and Cuautitlan sites. Analysis of the temperature soundings at Pachuca, Teotihuacan, and Cuautitlan show that these latter winds were sometimes associated with the arrival of slightly cooler and moister air masses that moved into the Pachuca area and the northern part of the basin in the late afternoon. A more complete discussion of the various flow patterns is given in the following section. While other differences could be found among the potential temperature soundings at the four profiler sites, the differences were typically small and varied from day to day so that no consistent pattern was discerned.

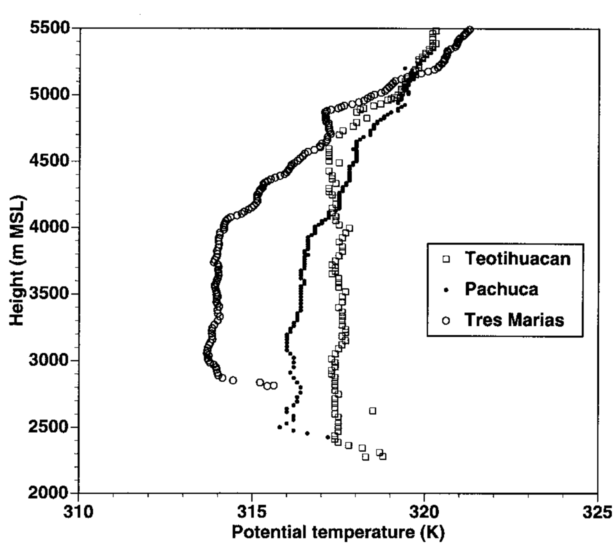

FIG. 8. Potential temperature profiles at approximately 1630 LST at Teotihuacan, Tres Marias, and Pachuca on 11 March 1997.

b. Wind patterns from profilers

The boundary layer winds in the Mexico City basin were typically light and thus easily influenced by small differences in synoptic conditions from day to day. Rather than show examples for one or two individual days, therefore, we have averaged the winds at each profiler site for all days during the experiment when synoptic influences were weak, as evidenced by the general absence of moderate to strong boundary layer winds (> 8 m s^{-1}) over the experimental domain. Because not all of the profilers began operation on the same day and because of data recovery problems on a few days, the number of days used for this average ranged from 14 to 18 for the different sites. Figure 9 shows the results for an "average" day with weak synoptic forcing.

At Cuautitlan, there is a transition in the lowest kilometer in the late afternoon and evening from northeasterly winds to northerly winds and then back to northeasterly winds; the latter transition is marked by a substantial increase in wind speeds. At Teotihuacan, there is also a transition in wind directions in the lowest few hundred meters than begins around sunset, with afternoon winds from the west giving way to evening winds from the east, but any increase in wind speed is rather small. The transitions at the two sites may be evidence for the regional type of wind pattern described earlier, in which the heated plateau of central Mexico draws air in from the north and east and eventually into the Mexico City area. The resultant winds do not appear to be sufficiently strong to propagate along the full length of the valley. It is not clear at this time why the winds during the transition period at Cuautitlan are significantly stronger than the corresponding winds in the lowest kilometer at Teotihuacan.

To the southeast at Chalco, a layer of southeasterly winds up to 1 km deep develops in midafternoon and continues past sunset. This pattern was the most

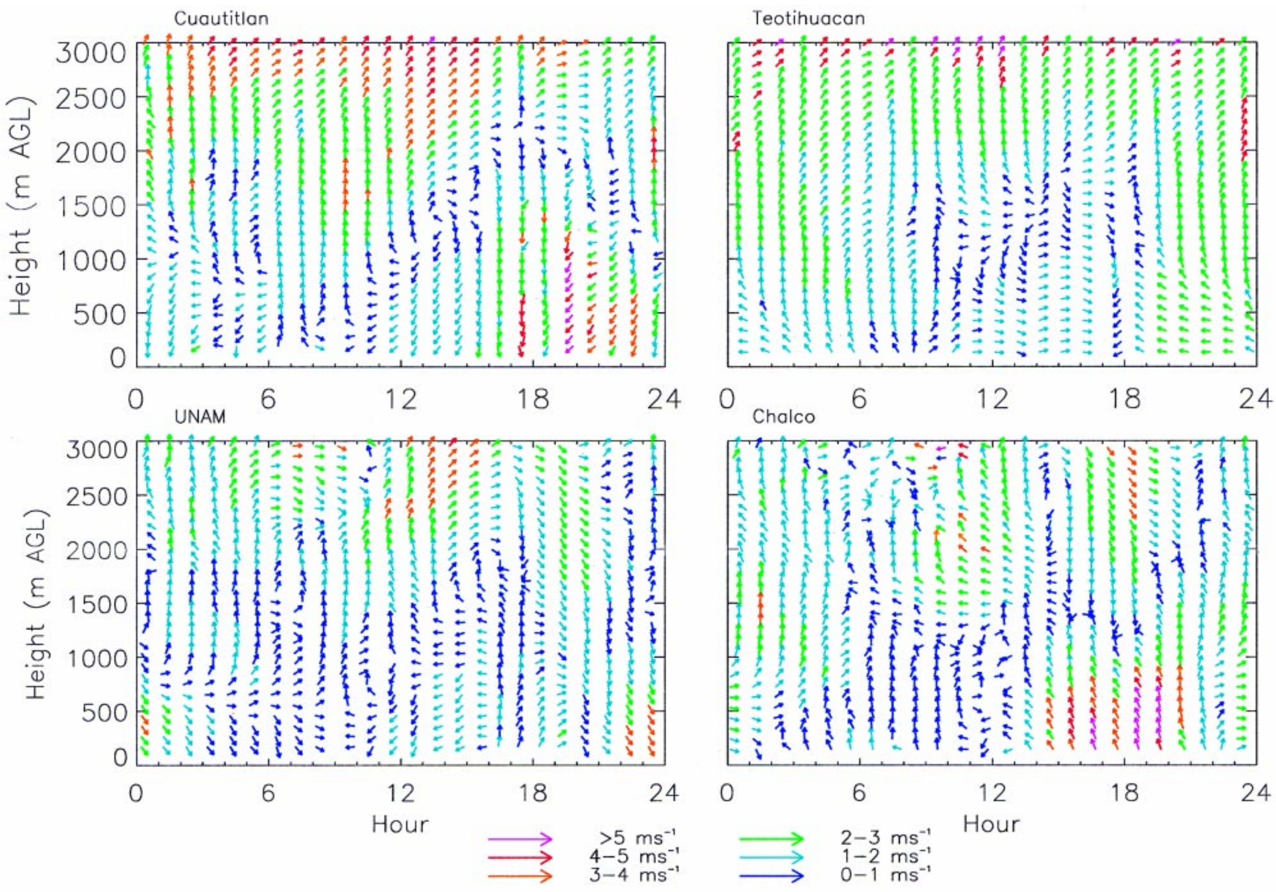

FIG. 9. Radar wind profiles at Cuautitlan, Teotihuacan, UNAM, and Chalco averaged over days with weak synoptic forcing during the IMADA-AVER experiment.

consistent boundary layer flow feature measured during the experimental period and it is remarkable that its existence appears not to have been fully appreciated prior to this study. Winds in excess of 10 m s^{-1} were sometimes found a few hundred meters above the surface, and southeasterly winds occurred even in the presence of moderate (8–9 m s^{-1}) northerly winds 1500 to 2000 m above the surface, although in those circumstances the depth of the southeasterly wind layer was several hundred meters less. This pattern is almost certainly the valley-to-basin flow described earlier. Interestingly, a deep layer of surface winds having a strong southerly component was not found at UNAM. Instead, Fig. 9 shows a period of a few hours in the late afternoon when only very weak southerly winds develop at the surface. This indicates that thermal forcing was sufficient to bring a deep layer of air through the gap in the mountains to the southeast but did not result in correspondingly strong flows over the ridge forming the southern end of the valley.

It was expected that upslope flows driven by heating of the basin sidewalls would be readily apparent at UNAM because of its proximity to the mountains. Around midmorning, a layer of northeasterly winds develops and then strengthens and deepens until midafternoon, reaching a height of about 1 km by 1600 LST. Northerly and northeasterly winds are consistent with a general upslope pattern in this part of the valley. The highest ozone concentrations tend to occur in midafternoon in the southwestern part of the basin, and—as noted earlier—this tendency has been attributed to the prevalence of this flow feature.

Later in the afternoon, the layer of northeasterly winds in the lower levels at UNAM gives way to a deeper, somewhat stronger flow from the east, followed by a weaker flow from the south and southwest. The timing of this transition seems to be associated with the rapid deepening of the mixed layer. Note, however, that the depth of the mixed layer, as indicated by temperature soundings, was substantially larger than the heights at which significant directional shear can be seen at UNAM and the other profiler sites.

Under the light wind conditions experienced during the measurement period, it was sometimes difficult to identify a particular flow pattern on any individual day. On a day-to-day basis there were often indications of large-scale (tens of kilometers) eddies in the profiler data, but characterizing these patterns in detail from observations alone would require a considerably denser observation network than was available. Determining prevailing wind patterns from surface observations in Mexico City is likely to be even more problematic because of the difficulty of finding sites with adequate exposure and no obstructions. Whiteman et al. (1998) have analyzed the persistence of the various wind regimes and find periods of light and variable winds at all of the sites, especially during midday and between heights of 500 and 2000 m. They also present a more complete analysis of the wind patterns and their relationship to the thermal driving forces over the region. For example, in the late afternoon and early evening the average wind profiles at Cuautitlan and Chalco show convergence at low levels and divergence farther aloft. These patterns can be related to a rapid cooling of the atmosphere during this period.

As shown in Fig. 2, pollutant patterns can shift significantly from day to day, and reproducing the wind patterns in numerical models with sufficient accuracy to predict the movement of pollutants is a major challenge. Fortunately, initial attempts to model these shifts using four-dimensional data assimilation (4DDA) techniques have been quite encouraging (Fast and Zhong 1998; Zhong et al. 1998; Fast 1998) and considerable insight into the processes responsible for pollutant transport and dispersion has been gained. Fast and Zhong (1998) report results from seven pairs of days selected from the IMADA-AVER experiment. The results have been less satisfactory when the models are not constrained by 4DDA techniques. For example, simulated late afternoon and early evening downslope flows over the mountains to the south are typically stronger than indicated by the profiler measurements at UNAM. The reasons for these difficulties are being investigated.

c. Near-surface winds

The exposures for the surface meteorological stations at the profiler sites were reasonably good, and it was often easier to discern regular patterns from these data than from the profiler data. This is probably due to a combination of stronger thermal forcing near the surface and perhaps some terrain channeling, which leads to wind direction distributions that tend to be bimodal. Figure 10 shows the distribution of wind directions as a function of time of day at Teotihuacan and UNAM. At Teotihuacan, the bimodal nature of the wind directions is evident when the data are displayed in this fashion; note in Fig. 9 that the profiler winds in the lowest levels exhibit more complicated behavior. Near the surface, northeasterly winds prevail except for a period of approximately 9 h in the late morning and afternoon. The northeasterly winds may arise either from regional plain-to-plateau flows or drainage flows from higher terrain to the northeast. The southwesterly winds in the afternoon may be an indication of local upslope flows toward the same higher terrain. At UNAM, the thermally driven flows toward the slopes to the southwest that develop after sunrise and persist until early afternoon are apparent, and a possible drainage flow from the southwest in the late evening and early morning hours can also be seen. This latter feature is not seen in the low-level profiler winds (height range ≥ 144 m AGL), which show flows from the northwest instead. The origin of the northwest flows is not understood at this time.

There was no meteorological tower at Cuautitlan but a minisodar provided wind data at a vertical resolution of 5 m to depths of 200 m. The near-surface winds measured by this sodar show some interesting differences from the behavior at Teotihuacan and from the profiler wind patterns shown in Fig. 9. For example, Cuautitlan data at 25 m above ground level (AGL) often showed northeasterly winds during the daylight hours and southwesterly winds during the late night and early morning hours (Fig. 11). The distribution in directions is again more bimodal than might have been anticipated from a consideration of the low-level profiler winds. The significant differences between the properties of the near-surface winds and the winds a few hundred to a thousand or more meters above the surface illustrate the hazard of relying on near-surface wind observations to understand air pollution patterns in this region.

6. Summary

The measurements described in this paper represent the first detailed examination of the planetary boundary layer in the Mexico City basin. Radar wind profilers, radiosondes, sodars, and surface stations were used to obtain a picture of the structure and evolution of the boundary layer over the Mexico City area under typical late winter conditions. The combination of thermal and topographical forcing and the interac-

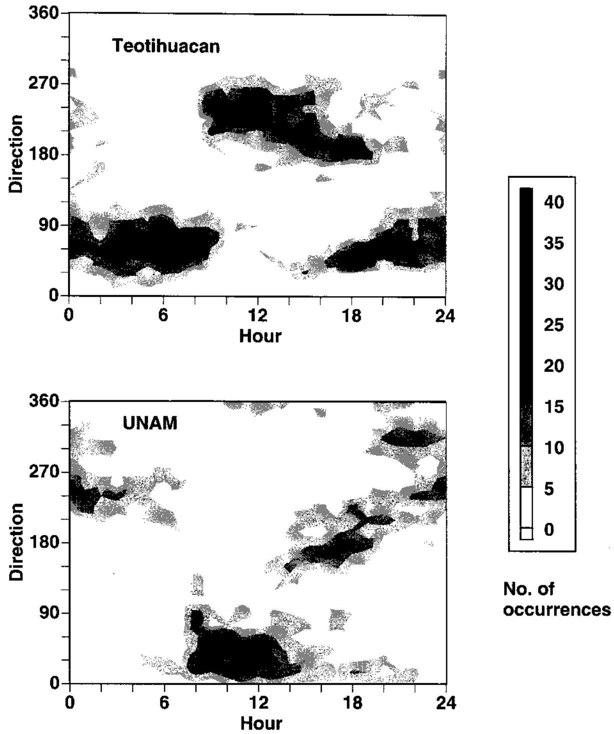

FIG. 10. Distribution of wind directions at 2-m elevation at Teotihuacan (24 February–22 March) and at 10-m elevation at UNAM (25 February–23 March) during the 1997 experiment. Each occurrence represents a period of 15 min.

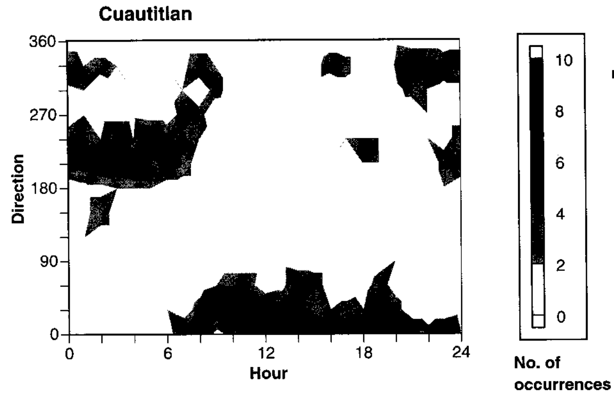

FIG. 11. Distribution of wind vectors at Cuautitlan (28 February–17 March) at 25 m AGL derived from sodar measurements during the 1997 experiment. Each occurrence represents a period of 1 h.

tion of synoptic, regional, and local flows produce a set of complex flow patterns that make simple characterizations of the boundary layer behavior difficult for any given day. Despite this, several recurring flow patterns can be found in the data. One of these patterns, the southeasterly flow through the gap in the mountains near Chalco, had not previously been described in the literature but appears to occur regularly and may have significant effects on the circulation patterns in the basin. Corresponding flows were anticipated over the southern mountains ringing the basin but were not observed. Regional flows entering the northern part of the valley had been identified earlier but were measured in far greater detail in this experiment than had previously been possible. Evidence for local slope flows up the sidewalls of the mountains southwest of the city was also found. Mixed layer depths, estimated from potential temperature soundings, ranged from 2500 to 3500 m and were marked by a period of rapid growth during the late morning and early afternoon. Substantial vertical shear of wind directions was found at heights well below the top of these mixed layers. Significant differences in potential temperature between the boundary layers inside and outside the basin were found. Initial analyses of the data suggest that observed wind patterns are broadly consistent with the hypothesized mechanisms proposed to explain them but that many details of the flow patterns will require considerable additional analysis if they are to be understood fully.

The data collected during the four-week experiment should prove useful for a wide range of modeling and analytical studies. The data are now being analyzed to obtain a detailed description and understanding of the regular flows that occur at Chalco, Teotihuacan, and elsewhere in the region. They are also being used to determine energy budgets and divergence estimates that will yield additional insights into the physics governing the wind patterns in the Mexico City basin. In addition, the data are proving to be an excellent resource with which to evaluate the performance of meteorological models. In conjunction with mesoscale and dispersion models, they have already been used to investigate the transport and diffusion of pollutants in the Mexico City basin (Fast and Zhong 1998; Zhong et al. 1998; Fast 1998), and further studies with coupled meteorological and atmospheric chemistry and aerosol models are under way.

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