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Title: AN INVESTIGATION OF FLOW REGIMES AFFECTING THE MEXICO CITY REGION

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11.7 AN INVESTIGATION OF FLOW REGIMES AFFECTING THE MEXICO CITY REGION

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1. INTRODUCTION

The Mexico City region is well-known to the meteorological community for its overwhelming air pollution problem. Several factors contribute to this predicament, namely, the 20 million people and vast amount of industry within the city. The unique geographical setting of the basin encompassing Mexico City also plays an important role. This basin covers approximately 5000 km^2 of the Mexican Plateau at an average elevation of 2250 m above sea level (asl) and is surrounded on three sides by mountains averaging over 3500 m asl, with peaks over 5000 m asl. Only to the north is their a significant opening in the mountainous terrain. Mexico City sprawls over 1000 km^2 in the southwestern portion of the basin.

The subtropical latitude of Mexico City (~19-20°N) dictates that large-scale pressure gradients will generally be weak, allowing thermally direct local circulations to prevail, with upslope conditions during the daytime and downslope flow at night (Jauregui, 1988). These flows tend to recirculate the air between the basin and the surrounding mountain slopes. In wintertime, dry conditions prevail in the basin, with the clear skies and longer nights leading to strong surface-based inversions in the nighttime and early morning, which trap vehicle emissions and industrial effluents near the surface. By day, sufficient solar insolation occurs to produce a deep boundary layer awash with photochemical smog. All of these meteorological factors combine to make Mexico City one of the most polluted on the planet.

In recent years, several major research programs have been undertaken to investigate the air quality problem within Mexico City. One of these, the Mexico City Air Quality Research Initiative (MARI), conducted in 1990-1993, was a cooperative study between researchers at Los Alamos National Laboratory and the Mexican Petroleum Institute (Guzman and Streit, 1993). As part of this study, a field campaign was initiated in February 1991 during which numerous surface, upper air, aircraft, and LIDAR measurements were taken. Much of the work to date has focused upon defining and simulating the local meteorological conditions that are important for understanding the complex photochemistry occurring within the confines of the city (Williams *et al.*, 1995). It seems reasonable to postulate, however, that flow systems originating outside of the Mexico City basin will influence conditions within the city much of the time.

To investigate these potential influences, the present study uses surface station, tethersonde, and rawinsonde data taken during the MARI field campaign of February 1991 to interpret results from the Regional Atmospheric Modeling System (RAMS) for a continuous three-day simulation of 20-22 February 1991. Upper-level winds over central Mexico went from strong and southwesterly to weak and westerly during this three-day period, while boundary layer winds within the city were highly variable. Air quality within Mexico City also ranged from moderately to severely polluted over the three-days. From these diverse meteorological conditions, we hope to broaden our understanding of boundary layer flow interactions within the Mexico City region and their effect upon pollutant dispersion.

2. DATA SOURCES

Local data include ten surface stations within Mexico City measuring basic meteorological parameters, in addition to several pollutant species. Rawinsonde data from the Mexico City International Airport (19.43°N, 99.07°W, 2231 m asl) were also obtained. As part of the special observing network for the MARI field campaign, rawinsondes were released from the airport seven times a day for the month of February, with the highest density of balloon flights during the afternoon. Tethersonde data were taken at the Polytechnic University within the city at 19.5°N, 99.14°W and at 2240 m asl. Gridded 2.5° data from the National Meteorological Center (NMC) are used to describe the synoptic conditions during the three-day period of interest, and to initialize and nudge the mesoscale model throughout the simulation.

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3. MODELING DETAILS

3.1 Meteorological Model

The numerical simulations are performed with the Regional Atmospheric Modeling System (RAMS), which has the flexibility to investigate a wide variety of meteorological phenomena. This terrain-following, primitive equation model has been most recently described in Pielke *et al.* (1992) and additional details are included in the references from that paper. A compressible, nonhydrostatic dynamical framework of the RAMS model is utilized in this study. At the lower boundary, surface temperature and moisture fluxes are predicted from energy balance equations for water, bare soil, and vegetated surfaces.Within the surface layer, fluxes are based upon the parameterization of Louis (1979), which uses Monin-Obukhov similarity theory to describe the constant flux layer. Sub-grid scale turbulence is parameterized according to the Mellor-Yamada (1982) scheme, which predicts ensemble average turbulent kinetic energy and vertical diffusion within the model, while horizontal diffusion is accomplished with an eddy viscosity based upon the local deformation field, with additional enhancements including a Richardson number dependence.

RAMS features a grid nesting capability which allows the model to increase the horizontal resolution over a region of interest with additional grids. In this study, grid nesting is used to provide higher topographic resolution over the basin encompassing Mexico City and the surrounding mountain ranges.The simulation includes 30 layers in the vertical direction, with 0.1 km vertical resolution in the lowest layer, which increases geometrically up to 0.8 km at 6.0 km above ground level (agl). The top of the model domain is at 15.5 km agl. A damping scheme is applied in the five vertical layers below the upper boundary in which vertically propagating gravity waves are gradually suppressed to reduce wave reflection off of the rigid lid at the top boundary.

Topography is specified on the coarse grid from a global 5-minute latitude/longitude data set, while the nested grid uses a 15-second data set. Vegetation is specified for both grids from a 1-degree latitude/longitude data set. Soil type was specified as sandy clay loam over the entire domain of both grids. Soil moisture was set at a relatively dry 30 percent of saturation over the entire model domain, since February is toward the end of the lengthy dry season in central Mexico. Given the dry, stable wintertime conditions, water vapor is included in the simulation only for its effect upon the radiative fluxes, otherwise it is a passive tracer. While clouds were present over some parts of the simulation domain on the case days, their influence on the circulations of interest appeared to be relatively minor, and hence, no condensation processes were included in the simulation.

3.2 Dispersion Model

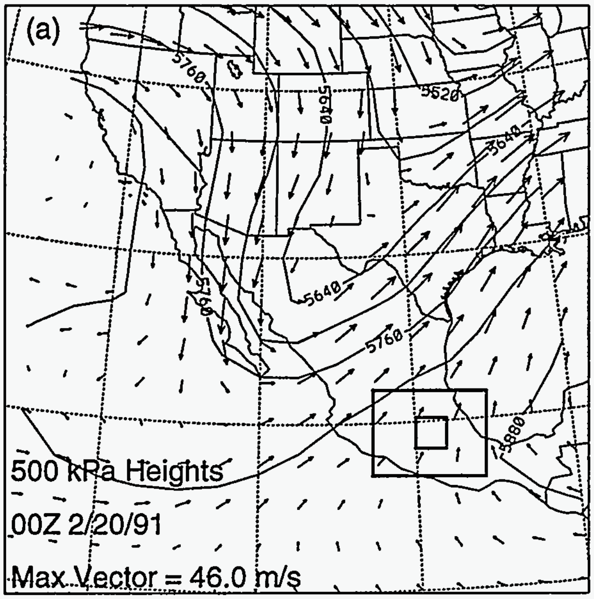
The HYbrid Particle and Concentration Transport model (HYPACT) was used in the study to simulate the motion of atmospheric tracers. The basic function of HYPACT is to track particles in three spatial dimensions and in time from sources that are potentially much smaller than the RAMS grid spacing. The particles are then advected according to the RAMS model resolved and subgrid-scale turbulent winds. The atmospheric model fields are determined at the location of each particle by interpolation in both space and time. Tracer transport and dispersion is used in this study primarily as a means of visualizing different flow regimes and their interaction.

4. SYNOPTIC REGIME

Shown in Fig. 1 are the large-scale 500 kPa heights and flow at the initial (00Z 2/20/91, Fig. 1a) and final (12Z 2/23/91, Fig. 1b) times of the 84-hour simulation. At the initial time (Fig. 1a) an unusually strong trough is in place over Mexico. The influence of this trough extends southward at the 500 kPa level through the subtropics to nearly 10°N. The trough induces strong southwesterly flow of 17 ms^{-1} over the Mexico City region. The trough then forms into a cut-off low over northern Mexico during the following 24-hour period, with little movement. Southwesterly upper level winds continue although the speed gradually weakens. Over the next 48-hours until the end of the simulation, the cut-off low slowly drifts northeastward and becomes entrained into the main circulation branch over the midwestern United States. Meanwhile, a ridge builds over central Mexico, which weakens the upper-level flow to 5.6 ms^{-1} from the west by 12Z 2/23/91 (Fig. 1b).

5. RESULTS

The RAMS model is initialized at 00Z 2/20/91from NMC 2.5° gridded analyses and run continuously for an 84-hour period. Successive NMC 2.5° gridded analyses are also used to nudge the model boundaries and weakly in the interior via a Davies (1977) relaxation method throughout the simulation. This has the effect of continuously ingesting some influence from large-scale conditions into the model. The period of interest for each of the case days is primarily in the late afternoon to early evening, when the boundary layer and its associated flow systems are most well-developed. Thus, here we present a brief synopsis of the model results during this period for each case day, examining the important circulations within, and surrounding the Mexico City region.



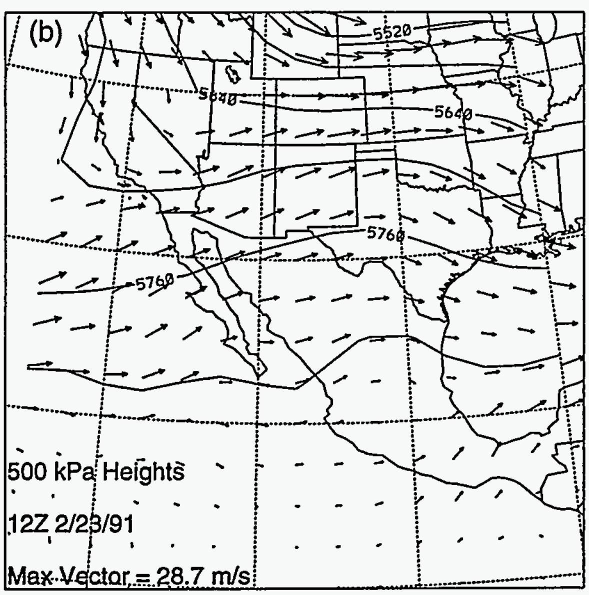


Figure 1. Geopotential heights (60 m contours) and wind flow vectors at 500 kPa for (a) 00Z 2/20/91, and (b) 12Z 2/23/91. Location of the two RAMS grids outlined in (a).

5.1 Strong Synoptic Flow Case - 2/20/91

As discussed above, the synoptic-scale flow was unusually strong and from the southwest on 20 February 1991. The RAMS simulation maintained strong winds over the mountain ranges surrounding the Mexico City from 00Z to 12Z 20 February. This strong southwesterly upper-level flow induced a mountain wave response over the Ajusco mountains located to the south of the city (see Fig. 2 for location), with accelerated flow along the lee (north) slope which faces the city. Strong surface heating by 16Z 2/20 generated upslope flow and turbulent mixing over the basin. These local circulations effectively suppressed any intrusion into the basin by the wave-induced southerly flow until late afternoon., when surface heating decreases. This reduces the forcing mechanism for the local winds within the basin, allowing the wind field to re-adjust to the large-scale pressure gradient. The adjustment process begins with an amplification of the mountain wave, which accelerates the southerly flow into the basin (see Fig. 2).These results were in good agreement with surface data taken within the city where many stations showed a rapid increase in wind speed during the afternoon hours to southerly winds of over 10 ms^{-1}. This strong southerly flow effectively flushed the pollutants from the city.

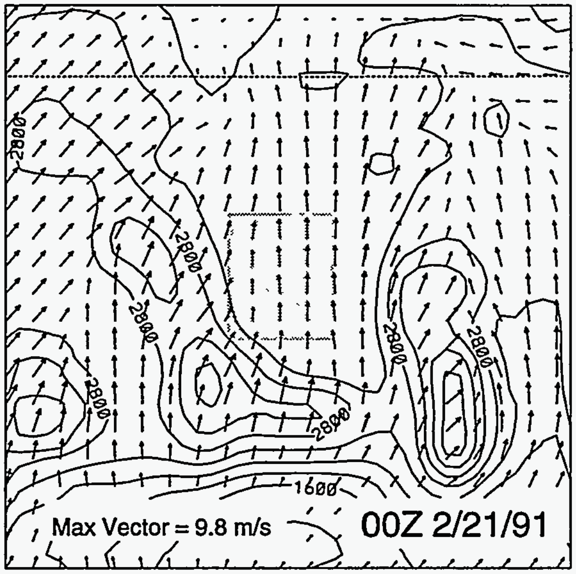


Figure 2. Topography (300 m contours) and wind vectors at 50 m agl on the nested grid. Location of Mexico City is shaded.

5.2 Strong Thermal Flow Case - 2/21/91

The strong southerly near-surface wind simulated over Mexico City on 2/20/91 gradually weakens by midnight and a surface-based inversion evolves due to local cooling over the basin. During this same late evening period, downslope winds from the surrounding mountain slopes generate a convergent drainage flow pattern over the basin. This tendency for convergent surface flow over the Mexico City basin is maintained until the diurnal heating cycle commences in earnest by about 16Z (1000 LST) 2/21. Again, ample surface heating generates local upslope wind systems which act to vent some of the near-surface air and accumulated pollutants up the slopes. This effect can be seen in Fig. 3 at 20Z (1400 LST), which shows particle trajectories from a continuous release over the 25 km^2 area representative of Mexico City. Advection of particles up the slopes is an efficient means of injecting material aloft where southwesterly flow carries it away from the basin. A tendency for recirculation of the particles over the basin also exists, however, due to compensating subsident motion within the air mass over the basin.

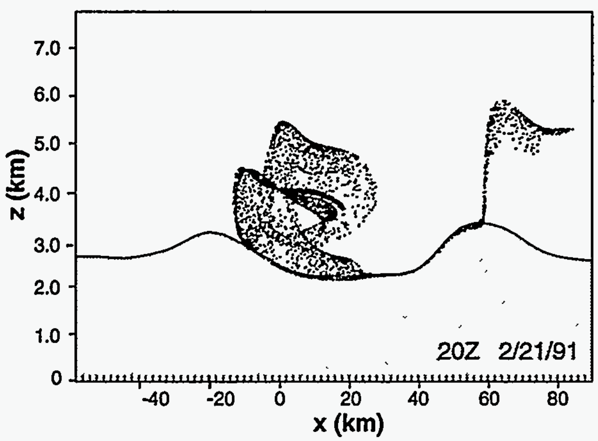


Figure 3. West-east cross-section through Mexico City (y = 0.0 km in Fig. 5) of particle trajectories at 20Z 2/21 emitted from an area source in the basin.

One of the primary objectives of this study is to examine the influence of meso- and synoptic-scale flow systems upon the Mexico City basin. The complex terrain of central Mexico includes a myriad of mountain ranges and valleys. But one of the primary terrain features is the slope which separates the elevated Mexican Plateau from the coastal plains along the Gulf of Mexico. This slope rises some 2 km over a distance of approximately 90 km, is fairly continuous in the southeast-to-northwest direction, and is located only 50 km from the northern end of the Mexico City basin (see Fig. 4). To give some perspective, the aspect ratio of this slope is similar to that between Denver and the Continental Divide along the Colorado Front Range. Bossert and Cotton (1994a) have shown that a prominent mountain-plain circulation evolves over the Front Range slope due to summertime surface heating. Given the subtropical latitude, we might expect that even in February a similar circulation could evolve along the Mexican Plateau slope. This is indeed the case, as shown in Fig. 4 at 20Z (1400 LST), where vigorous regional upslope winds form the low-level branch of a deep, thermally-driven circulation system. The fate of this regional slope flow is of particular interest to this study. Bossert and Cotton (1994b) have shown with idealized two-dimensional simulations that a mountain-plain circulation in low latitudes, between a heated lowland area and a plateau, develops into a vigorous density current which propagates across the plateau for several hundred kilometers.

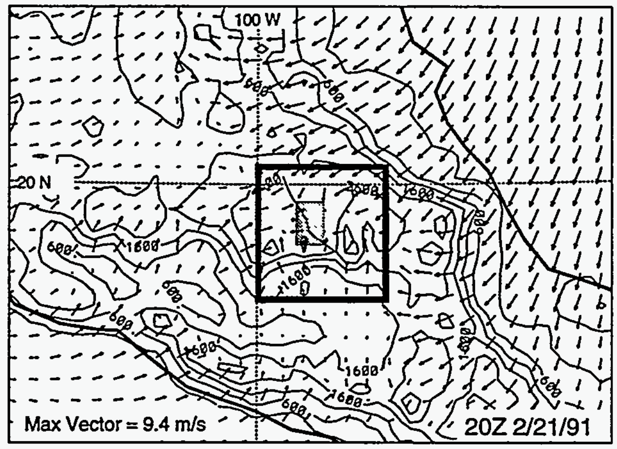


Figure 4. Topography (300 m contours) and wind vectors for Grid 1 at 20Z 2/21. Location of the nested grid is outlined, with Mexico City shaded in center.

Equivalent potential temperature provides a useful means of tracking the air masses associated with the various circulation systems in the simulation The regional slope flow advects moist, potentially cooler air from the lowlands toward the Mexican Plateau. Drier subsident flow tends to prevail over the Mexico City basin. The equivalent potential temperatures and flow vectors at 22Z (1600 LST) 2/21 are shown in Fig. 5 for the nested grid. The figure demonstrates in a dramatic fashion the clash of air masses simulated to take place at this time over the basin. In the upper part of the figure lies the moist regional slope flow with uniform northeasterly winds of 8 ms^{-1}. Another distinct, but less moist circulation system is encroaching from the south. In between is the dry basin air mass with weak divergent winds, which is now displaced north of the city by the southerly flow. As shown, the boundary between the plateau slope and Mexico City basin air masses is a well-defined frontal interface. The dominant regime is the northeasterly flow from the Mexican Plateau slope, which continues to propagate into the basin, displacing the stagnant basin air mass upward. This provides a dramatic ventilation mechanism for the Mexico City basin by lofting the in-situ air mass into the faster southwesterly flow above the mountaintop level.

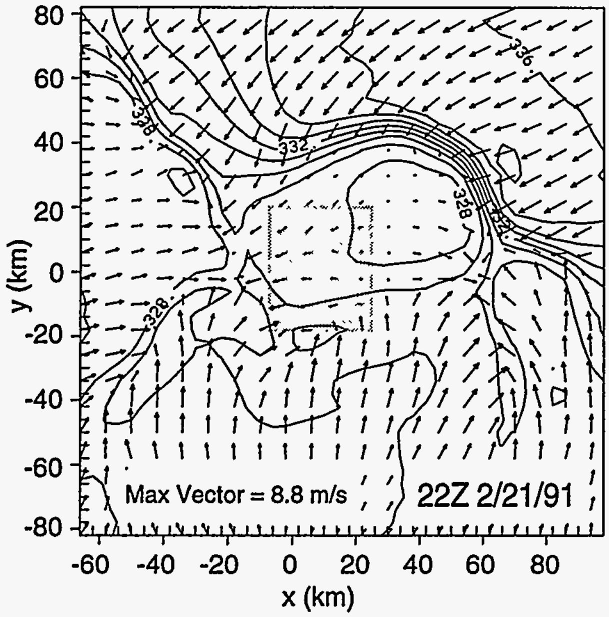


Figure 5. Equivalent potential temperature (1^oK contours) and wind vectors at 280 m agl for Grid 2 at 22Z 2/21/91. Location of Mexico City is shaded.

This effect is demonstrated via particle trajectories in Fig. 6 at 01Z (1900 LST) 2/22. The stratified northeasterly flow, shown on the right side of the figure, is approximately 1.2 km deep and propagates into the basin as a density current, undercutting the warmer, neutrally stratified basin air mass with very little mixing.

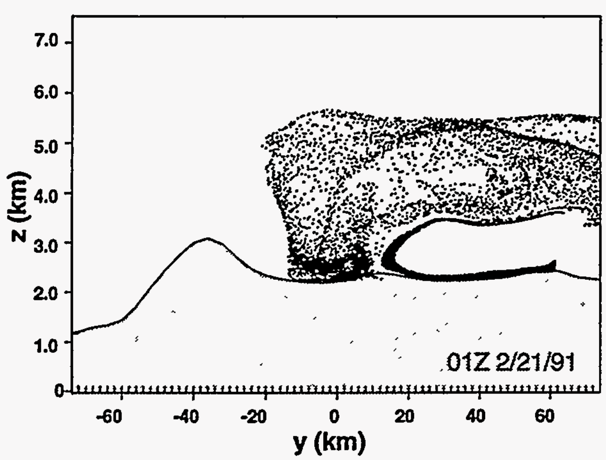


Figure 6. South-north cross-section through Mexico City (x = 18 km in Fig. 5) of particle trajectories at 01Z 2/22 emitted from an area source and a line source (located at y = 62 km)

Observational evidence for the propagation of the Mexican Plateau slope flow into the Mexico City basin is provided by the tethersonde in operation at the Polytechnic University. Figure 7 shows that the profile taken near 0330Z (2130 LST) 2/22 has a deep easterly flow with peak winds of 5-6 ms^{-1} at 250 m agl. This deep easterly flow persists into the next profile taken approximately 45 minutes later at 0415Z, but is perturbed up to 400 m agl in later profiles by local flow systems. Rawinsondes taken at the Mexico City Airport (located 10 km SW of the tethersonde site) at 00Z and 06Z 2/22 (not shown) indicate that the slope flow air mass had not reached the airport by 00Z, but a 2 km deep easterly flow of 2-3 ms^{-1} between 0.7 and 2.2 km agl was in place at 06Z. It is important to note that the large-scale pressure gradient from the surface to 700 kPa favored easterly component flow by 06Z. This easterly flow appears to have augmented the plateau slope flow in this case.

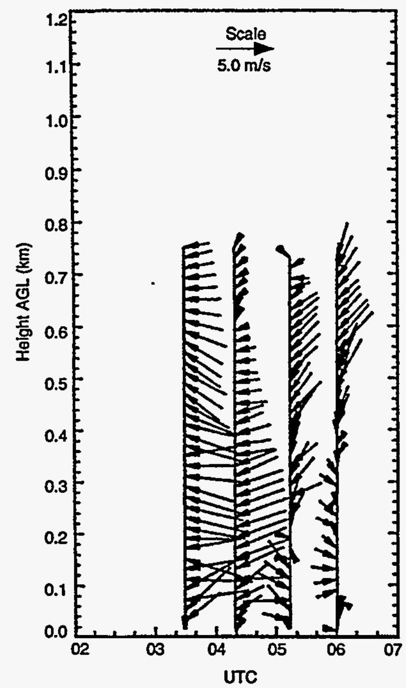


Figure 7. Tethersonde profiles from the Polytechnic University within Mexico City for the night of 2/21/91.

5.3 Strong Regional Flow Case - 2/22/91

Observational evidence and the simulation results both indicate that throughout the rest of the night of 2/21-2/22 the flow below 2.5 km agl remains weak and from an easterly direction, due to high pressure in the lower troposphere east of the Mexican Plateau. Southwesterly flow continues aloft, but weakens considerably through the night due to an approaching ridge from the west. Weak flow persists into the daytime hours, which allows the development of strong, thermally-driven circulation systems and the buildup of a distinct, relatively west. Weak flow persists into the daytime hours, which allows the development of strong, thermally-driven circulation systems and the buildup of a distinct, relatively stagnant air mass over the Mexico City basin. However, the weak easterly flow in the lowest 2.5 km of the troposphere allows for more rapid propagation of the Mexican Plateau northeasterly slope flow into the basin. The simulation suggests that this occurs in mid-afternoon, and has the effect of piling up the stagnant basin air mass against the mountains in the southwestern part of the basin for several hours in the afternoon before lofting it up and over the Ajusco mountains in early evening.

6. DISCUSSION

The simulation of three case days with diverse meteorological conditions over the Mexico City region in February 1991 has shown that one must venture beyond the local-scale to understand the complex boundary layer flow structure and dispersion characteristics within the Mexico City basin. The simulation appears to reproduce much of the wind phenomena, caused by external processes, that led to changes in circulation patterns within the basin. An important external influence was the gradual weakening throughout the case study period of initially strong southwesterly gradient level flow, which allowed the local and regional-scale thermal circulations to control the basin meteorology and transport to varying degrees.

Implicit in the work described herein is the hypothesis that the externally driven wind systems advect relatively clean air into the basin Thus, intrusions into the basin from these flows should help to relieve the pollution within the city. More analysis is necessary to confirm this hypothesis. Interestingly, ozone measurements taken at 10 stations around the Mexico City region tended to be well-correlated with the basin flow scenario developed in the simulation. For example, maximum concentrations on the 20th peaked before noon and then rapidly decreased, due to flushing of the basin air mass by the strong mountain wave induced southerly flow. Similarly, peak concentrations on the 21st occurred near noon in the central and northeastern parts of the city, where the simulation showed the polluted basin air mass to be in place for the longest period. On the 22nd, the ozone pollution was severe in the early afternoon at stations located in the southwestern part of the city, which is again where the stagnant basin air mass was positioned for an extended period, due to forcing from the regional northeasterly flow. Other pollutant species need to be examined for a similar signature, since ozone is photochemically active and, thus, has a very strong diurnal range that complicates the analysis.The results from this study suggest that a complex mix of flow systems can envelope the Mexico City basin, but that they may also be predictable. Such information would be extremely valuable for planning pollution control strategies within the city.

7. ACKNOWLEDGMENTS

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