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# Transport and dispersion of blowing dust in the Mexico Basin

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## Introduction

The Mexico City Metropolitan Area (MCMA) is one of the world's largest metropolitan areas, containing nearly 20 million inhabitants within the Mexico City Basin. Mountainous terrain, at subtropical latitude and at high elevation surrounds the region where the MCMA lies. As in many large cities, and especially the ones located in valleys with high solar radiation, Mexico City experiences air pollution problems, especially for ozone and suspended particles. A recent study [1] shows that the daily standard for $PM_{10}$ has been exceeded on more than 40% of the days in some years (although in 1999 the standard was exceeded on fewer than 10% of the days).

High concentrations of $PM_{10}$ in the MCMA can be attributed to a combination of meteorological conditions and emission patterns. A typical pattern that produces high $PM_{10}$ concentrations in the Mexico Basin cannot be described by the typical conceptual description of most mid-latitude valleys and basins [2,3]. Collins and Scott [4] stated that air quality problems in the Mexico Basin are exacerbated by strong temperature inversions that form within the elevated basin. A more recent study of the boundary layer evolution and diurnal flow circulation over the Mexico Basin and Mexican plateau [3] contradicts this assertion. With data collected in a measurement campaign in February and March 1997 [5,6] Whiteman and co-workers[3] were able to show the absence of a temperature inversion usually associated to mid-latitude basins without the presence of reversing valley wind systems. For March they also noticed that the mean morning low-level stability was only marginally greater than in the free atmosphere surrounding the Mexican plateau at the same altitude. In this sense, the Mexico Basin does not exhibit one of the chief meteorological characteristics of mid-latitude basins, namely the formation of strong nighttime temperature inversions. Rather the atmospheric wind conditions inherent to the MCMA play a major role in the air quality problem. Furthermore, the particulate problem in the Mexico Basin region during the end of winter or beginning of spring is not solely attributed to manmade sources but can be influenced by non-local sources of natural origin surrounding the periphery to the north and northeast sector of the Basin [7,8].

The Mexico Basin periodically experiences windblown dust events that cause exceedances of the national ambient air quality standard for $PM_{10}$ in the densely inhabited areas of the MCMA. Blowing dust normally involves local entrainment of dust and is associated with moderate or large winds occurring in early spring when temperatures are high and humidity is low. Climatological summary of the airborne dust environment in the region reveals that the intensity and frequency of dust events downwind of geological sources takes place in the month of March [9]. Analysis of the IMADA database using chemical concentrations of five crustal species (Al, Si, Fe, Mg, K and Ca) shows [8] that geological material was the major contributor to $PM_{10}$. In fact, 40-55% of the $PM_{10}$ mass was of geological origin at two sites (NET and XAL). This means that deposition mass fluxes at local sites near potential soil sources are quite significant when compared to the rest of the sources in the urban area.

Particulate matter was considered in the 1989 Emission Inventory (EI) as TSP, and an updated version produced in 1994. Particle emission was attributed mainly to soil erosion encompassing approximately 95% of the total particles [10]. In the 94-EI, particle emissions from sources other than erosion were considered for the first time. Primary $PM_{10}$ emissions from the most important sources, including the industrial sector, were considered in the 1996 EI. The 1998-EI, which includes economic activity data is presented in the Federal District Government web page [11] with a soil erosion apportionment of 40%. This last inventory does not report emission estimates for TSP, but contains estimates for primary sources of $PM_{10}$ and $PM_{2.5}$. Differences in methodology and changes in activity data among the 1994, 1996 and 1998 emissions inventories have made difficult to correlate emissions figures with pollution control strategies in the MCMA.

The latest phase of the Program to Improve the Air Quality in the Valley of Mexico, also known as Pro Aire [12], is about to go into effect for the next ten years. Before this program becomes officially implemented the ability to model transport and dispersion of $PM_{10}$ is necessary for areas that may be in non-attainment status for the $PM_{10}$ standard, and to assess the PM contribution the emission inventory.

Previous air quality studies on MCMA focused on the origin of high concentrations of particles including the spatial and temporal distribution of some gaseous pollutants [13,14]. Some drawbacks to those studies can be noticed. First, the domain of study excluded the regions that are prone to soil erosion. Second, the size of the domain did not fully consider the entire mountainous range that surrounds the urban area to the east and west, which caused computational difficulties for the meteorological runs.

## Air Quality Field Study

The ambient monitoring component of IMADA-AVER took place over a four-week period from February 23 through March 22, 1997 [5]. Of the 28 days monitored with particle samplers, samples taken from March 2 through March 19, 1997 (18 days) are analyzed for elements, ions, and elemental and organic carbon. This period contains three distinct episodes of pollution buildup and cleanout. The period before March 8 was relatively dry, while the subsequent episodes occurred during moist weather conditions, interspersed with fogs, clouds, and rainstorms. Meteorological data included radar wind profiles, remote acoustic sounding system (RASS) temperature sensors, and temperature and humidity profiles by airsonde and surface meteorological towers [13]. For particle measurements the following air quality monitoring stations within the MCMA were used: Xalostoc (XAL), Merced (MER), Cerro de la Estrella (CES), Pedregal (PED), Netzahualcoyotl (NET) and Tlalnepantla (TLA). Samples from the first three sites were collected every 6 hours and for the last 3 every 24 hr. From these particle measurements the total $PM_{10}$ and $PM_{2.5}$ concentrations as well as their geological origin were determined [15,16].

## Modeling Episodes

In this study, days 5 and 6 of March 1997 were chosen for modeling because they are a manifestation of contrasting meteorological features and distinct air quality conditions. For instance, on day 5 maximum temperature and relative humidity were recorded as 28°C and 50 %, while on day 6 these two drastically changed to 18°C and 80%, resulting in a significant visibility increase. Additionally on day 5 the highest PM concentrations were observed dropping to practically negligible values the following day when compared to national ambient air quality standards. It must be noted that these days were not considered in previous studies of transport and dispersion of pollutants due to the fact that attention was focussed on the meteorology and transport of gaseous pollutants within the MCMA. Also these days were considered by other authors to be atypical in the sense that synoptic conditions led to unusually strong wind within the MCMA [3].

## Wind Erosion Model

Emissions from rural areas are primarily concerned with agricultural activity on the Mexico Basin. Windblown dust sources on the north and northeast areas outside of the MCMA invariably intensify in the month of March and the impact of these fugitive PM emissions has never been assessed through the use of mathematical modeling. When these sources are disturbed their ability to emit windblown dust is enhanced during dry periods of high wind events. These emissions are typically associated with disturbed land, such as agricultural fields under cultivation, or uncultivated soil with minimum or no vegetation coverage at all. In this work, use was made of an existing algorithm that was developed using wind tunnels and field studies to produce a wind-erosion-prediction equation [17]. The wind erosion equation is currently the most widely used method for assessing average annual soil loss by wind from agricultural fields. The Natural Resources Conservation Service (NRCS) and other national agencies throughout the US use it. Saxton and co-workers [18] present a newer method to estimate wind erosion and dust emissions and concentrations on an event basis but lack of field measurements inherent to the MCMA impedes its application at this time. Details on the wind erosion equation and the used values to apply the equation for the MCMA soil sources can be found elsewhere [11].

## Modeling Approach

The CALMET/CALPUFF modeling pair was selected as a combination of a wind field generator and a pollutant transport model. The CALMET model along with CALGRID [19] were developed by the state of California for the purpose of modeling photochemical oxidant formation and transport in 1987. CALGRID was then integrated into the CALMET/CALPUFF modeling framework to create a complete modeling system for both reactive and non-reactive pollutants. Three main components integrate the selected modeling system: CALMET (a diagnostic 3-D meteorological model), CALPUFF (the transport and dispersion model), and CALPOST (a postprocessing package) [21]. Each of these programs has a graphical user interface (GUI). In addition to these components, there are several other processors that may be used to prepare geophysical (land use and terrain) data in many standard formats, meteorological data (surface, upper air, precipitation, and buoy data), and interfaces to other models such as the Penn State/NCAR Mesoscale Model (MM5).

**The diagnostic meteorological model, CALMET**

The first component of this system, CALMET, is a diagnostic wind field generator [20] that uses surface and upper air meteorological data to predict winds and turbulence parameters in each grid of the modeling domain for each hour of a modeling period. Meteorological surface stations used for this work are located throughout the Mexico City Valley. The ten meteorological stations that conform the surface network were deployed as follows: Merced (478.5,2147.5), Chalco (509.5, 2128.4), Tacubaya (479.0, 2145.0), Teotihuacan (515.7,2176.0), UNAM (480.0,2136.2), Tulancingo (566.0,2220.5), ENEP Acatlan (474.6,2154.5), Tlanepantla (478.5,2159.3), Pedegral (478.6,2136.7), Hangares (491.3,2147.5). The upper air soundings were released at four sites with coordinates given as Chalco (509.5,2128.4), Cuautitlan (480.1,2177.1), UNAM (480.0,2136.2), and Teotihuacan (515.7,2176.0). More specifically, the origin (southwest corner) of the computational domain in UTM coordinates was (434,2080) kilometers. It was assumed that a five-kilometer horizontal resolution was reasonably accurate for model resolution, while allowing for an acceptable execution time. The orthogonal axis extends to the north and east creating a uniform grid system of horizontal squares of surface area equal to 25 $km^2$. CALMET performed 24-hour simulations on two consecutive days for the 14 UTM zone. The maximum radius of influence over land in both the surface layer and aloft was taken as 5 kilometers with a maximum acceptable divergence in the divergence minimization procedure of $5.0 \times 10^{-6}$. The complex topography of the MCMA considers 13 land use categories.

**The Air Quality Model CALPUFF**

Once the predicted tridimensional wind field and micro-meteorological variables are generated and the area source emission of soil dust inventoried, these are input into the next component of the modeling system, CALPUFF. The transport and dispersion model, CALPUFF, advects "puffs" of PM emitted from modeled sources, simulating the dispersion and transformation process at each grid cell. In our case the pollutant has been assumed to behave as a passive scalar and hence no chemical transformation takes place. The primary output files from the non-steady-state Lagrangian Gaussian puff model contain hourly concentrations at all receptor locations but only MER, CER, and XAL were used for comparison.

The CALPUFF model uses the same grid system as CALMET, consisting of 9 layers over the 28x32 horizontal grid cells. The vertical layers were specified with variable spacing at heights of 20, 80, 160, 300, 600, 1000, 1500, 2000, and 2130 meters. The vertical concentration distribution in the near field is considered to be Gaussian. Dispersion coefficients are computed from internally calculated from velocity variances using micrometeorological variables supplied by CALMET. CALPUFF models dry deposition and the emitted $PM_{10}$ species are modeled assuming they behave as particles. The mean and standard deviation are used to compute a deposition velocity for size-ranges, and these are then averaged to obtain a mean deposition velocity. Some miscellaneous dry deposition parameters include the reference cuticle resistance, 30.0 s $cm^{-1}$, and the reference ground resistance, 10.0 s $cm^{-1}$. The area sources (tons/$m^2$/year) were taken as a composite of irregular polygon surfaces that match a soil eroded maps obtained with a satellite imaging technique [7]. The total surface area susceptible of erosion is approximately 1200 squared kilometers, which is comparable to the MCMA. The geophysical parameters that define the soil dust properties were taken as default values as given in reference [17] since these have not been measured.

## Results

Figure 1 shows the location of agricultural non-irrigated areas as dark regions, which are usually dry from January to May and hence these locations are susceptible to windblown dust events. Figure 1 also shows the political boundaries of the MCMA where all major socioeconomic activity takes place. Significant terrain features are found to the southwest and southeast of the domain. Between the two mountain ranges there is a mountain pass where topographically confined airflow is channeled into and outside the MCMA. The surrounding mountain ranges act as barriers to air pollutants restricting the horizontal ventilation.

Figure 2 shows two panels for day 5 of March at 08:00 hours as simulated by CALMET and CALPUFF. Figure 2a shows the surface wind vectors and windblown dust concentration contours while Figure 2b presents mixed layer depths. Predictions at this hour of the day are similar in shape and intensity to the earlier hours of simulation. At 08:00 hours light-to-moderate easterly winds blow over the two major dust sources located northeast of the MCMA causing entrainment and suspension of dust. Over the eastern mountain range, cool air descends with a westerly component, leading to air streams that causes minor convergence at the center of the MCMA. Two scenarios are observed in Figure 2 in regard to the soil sources. First, winds with a northerly component are able to advect dust plumes to the southeastern part of the MCMA where both monitoring receptors and CALPUFF results show lower PM concentrations. Second, the mountains on the southeast corner of the domain impede the penetration of the plumes forcing suspended dust to circle around the high mountainous range (altitudes of up to 3400 meters asl). The mixing layer height remains relatively shallow over the domain of interest for much of the morning period, but PM concentrations tend to remain relatively high near the erosion sources. The western portion of the MCMA remains unaffected by windblown dust due to in part to westerly winds that counteract the effect of the spreading dust cloud.

The predictions at 14:00 hours represents a transitional period characterized by low concentration of particulate matter measured at the monitoring locations within the MCMA from 10:00 to 15:00 hours (not shown). A significant increase in mixed layer heights over the MCMA going from 500 m to 2000 m in less than 5 hour highlights this period. In addition, the wind field displays large wind speeds (about 7 m/s) relative to early hours with a northeasterly component throughout much of the MCMA. This is in accord with the lower PM concentrations measured (not shown) during this time over the MCMA particularly at the industrial and urban areas.

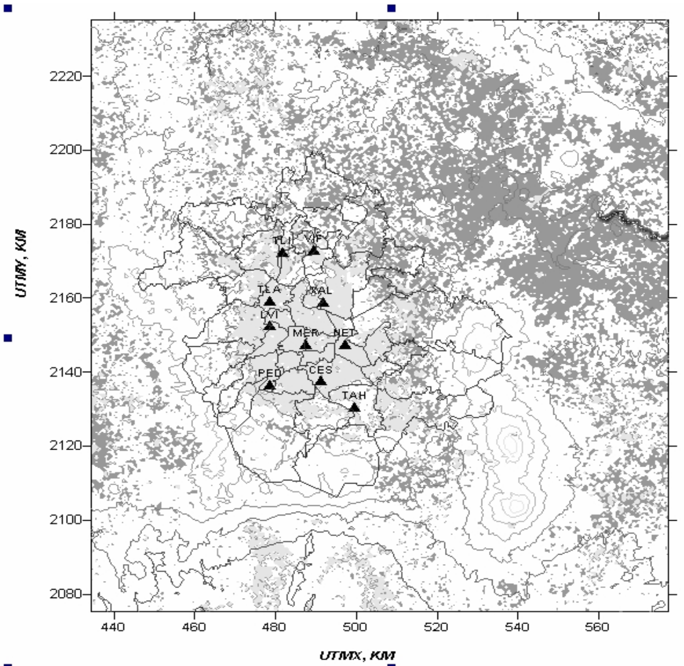


Figure 1: Map of topography, political boundaries, receptors sites and soil dust areas (dark gray) of the

MCMA

Figure 3 shows similar vector and scalar fields as Figure 2 except shown at hour 19:00. The winds have a well-defined northeasterly component all over the physical domain and they are responsible for transporting measurable amounts of geological dust to the densely populated areas of the MCMA. This constitutes the second most important scenario of March 5 during this hour in which PM concentrations over the southern part of the MCMA attained a second maximum before they slowly decayed in the late evening hours.

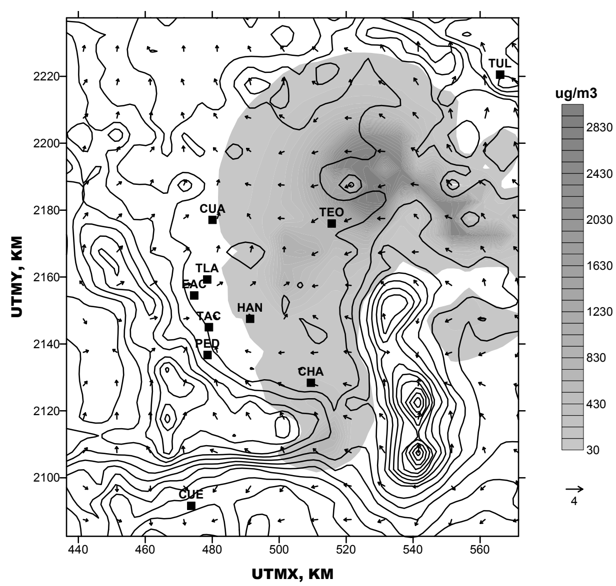


Figure 2a: Surface winds and dust concentrations for March 5 at 08:00 hr.

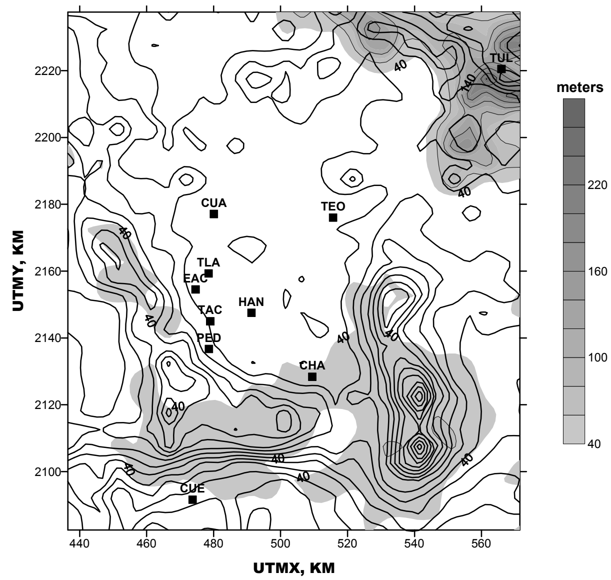


Figure 2b:Mixed layer depth and topography for March 5 at 08:00 hr.

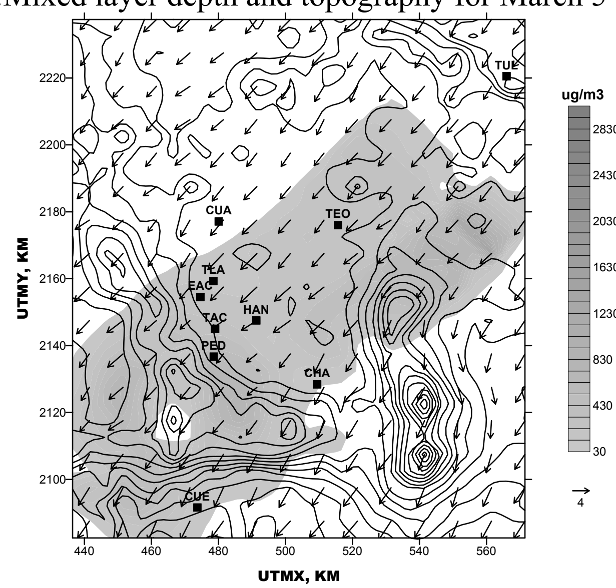


Figure 3a: Surface winds and dust concentrations for March 5 at 19:00 hr.

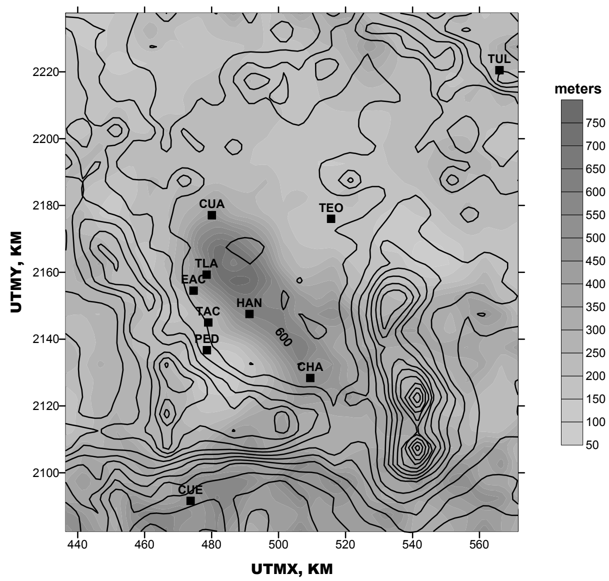


Figure 3b: Mixed layer depth and topography for March 5 at 19:00 hr.

The diurnal evolution of predicted PM concentrations of geological origin for day 6 show (not shown) a similar spatial behavior as those found during the simulation of day 5 but with significantly lower values. The key feature to note here is that from day 5 to 6 a strong northerly basin-to-valley wind was driven by a cold and humid air mass as evidenced from a large temperature drop to the north of the MCMA in the evening of day 5. This cold air mass pushed its way through the basin and helped maintained the strong northerly wind blowing thorough most of day 6, thus resulting in a cleaner airshed and a high visibility index.

Figure 4 shows the scatter diagrams of predicted windblown dust concentrations (Cp) versus the observed ones (Co) for days 5 and 6. On day 5 the predicted concentrations show a much better correlation to the geological component of measured PM concentrations when compared to day 6. The significant agreement between predictions and observations for day 5 suggest that much of the suspended PM in the airshed came from soil sources located on the northeast sector of the MCMA. The poor agreement between predictions and observations for day 6 indicates that the PM concentrations measured at the receptor sites had a more significant contribution of local geological sources than agricultural soil sources.

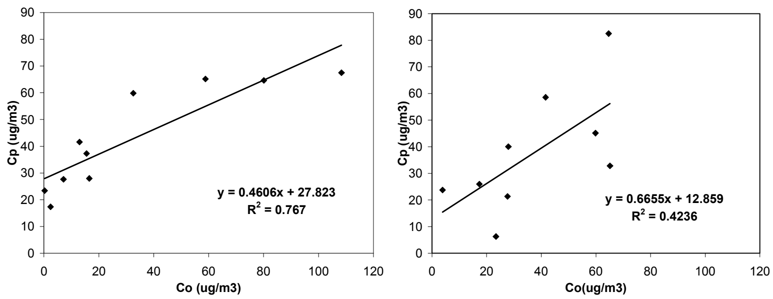


Figure 4: Predicted vs observed PM concentrations for day 5 (left panel) and day 6 (right panel) of March 1997.

## Conclusions

Two contrasting scenarios were studied and simulated during days 5 and 6 of March 1997 with observational data from the IMADA campaign. On day 5 high wind blown dust concentrations were measured at selected sites within the MCMA. The simulation of the spatial and temporal evolution of PM concentrations showed reasonable agreement with the observed particle measurements of geological origin for day 5. Furthermore, on day 5 an important portion of the measured concentration was of geological origin while on day 6 this situation was reversed in the sense that sources other than geological contributed to the total PM concentrations. Until now there have not been any systematic long term studies on blowing dust events in the MCMA that have been undertaken at the local scale.

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