Evaluation of the Boundary Layer Characteristics and Pollutants in Mexico City Predicted by WRF

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1. Introduction

During March and April of 2006, the MIRAGE-Mex (Megacity Impacts on Regional and Global Environments – Mexico City, supported by NSF) and MAX-Mex (Megacity Aerosol Experiment in Mexico City, supported by DOE) field campaigns will be conducted to better understand the evolution of oxidants and aerosols associated with megacities and their impact on climate and on air quality further downwind. Several research aircraft will be deployed to obtain air chemistry measurements over Mexico City and up to several hundred kilometers downwind. It is anticipated that mesoscale models, including the Weather Research and Forecasting (WRF) model, will be run operationally during the field campaign to support aircraft operations by forecasting the location of the urban pollutant plume and determining whether the upcoming meteorological conditions meet the science objectives.

Mexico City is located at about 20 N latitude within a basin at an elevation of 2.2 km MSL. During the spring the afternoon convective boundary layer (CBL) is frequently 2 - 4 km deep so that pollutants can be mixed directly into the mid-troposphere (~500 hPa) and subsequently transported far downwind by synoptic-scale winds. Heating of the terrain in central Mexico produces upslope flows over the mountains and thermally-driven circulations that converge in the basin late in the afternoon. Venting processes over the surrounding mountains and convergence over a portion of the city may contribute to the vertical mixing of pollutants in the region. Predicting the location and spread of the downwind pollutant plume depends on accurate forecasts of the complex wind fields and vertical extent of turbulent mixing within the basin and over the source of primary anthropogenic trace gas and particulate emissions.

In this study, meteorological measurements made during a previous field campaign are used to evaluate WRF forecasts of the CBL depth, temperature, humidity, and winds in the Mexico City basin. This will enable forecasters to better understand model performance prior to the 2006 field campaign. Because of the importance of operational CBL forecasts, simulations were performed and evaluated using two boundary layer parameterizations. The chemistry version of WRF (Grell et al. 2005; Fast et al., 2004) is also used to determine how different boundary layer parameterizations affect the transport and mixing of ozone and particulates over and downwind of the city.

2. 1997 IMADA-AVER Field Campaign

As part of the IMADA-AVER field campaign, meteorological measurements were collected in Mexico City between 24 February and 22 March 1997 (Doran et al., 1998). Hourly vertical wind profiles within 4 km of the ground were obtained from four 915 mHz radar wind profilers located at the Cuautitlán, Teotihuacán, UNAM, and Chalco sites shown in Fig. 1. Temperature and humidity profiles were obtained at the same locations from radiosondes launched five times per day (0800, 1100, 1330, 1630, and 1930 LST) during intensive operational days. Radiosondes were launched less frequently on other days.

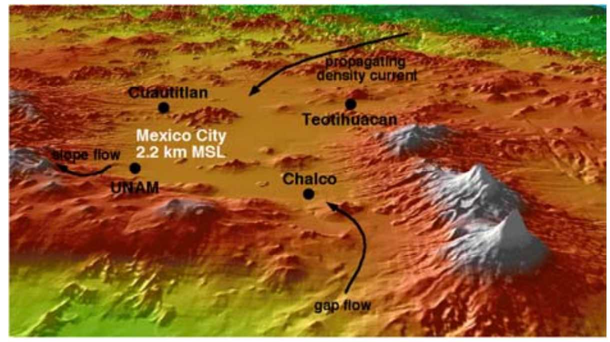

Fig.1. Topography in the vicinity of Mexico City (looking north) and the locations of the four boundary layer profiling sites. The basin is about 50 km wide.

Heating of the higher terrain surrounding Mexico City produces daytime upslope flows that draw air from the plateau north of the city into the basin (de Foy et al. 2005; Jauregui 1988). Late in the afternoon, the temperature gradient between the warm basin CBL and the cool ambient air south of the basin produces strong winds through the gap in the terrain near Chalco (Doran and Zhong 2000). A propagating density current (Bossert 1997) is also produced late in the day that brings in cooler air from the Gulf of Mexico into the north end of the basin. These converging flows may enhance vertical mixing and venting of pollutants out of the basin (Fast et al., 1998); however, the 2006 field campaign will provide the first measurements that describe how the interaction of the thermally-driven circulations and synoptic flows affect air chemistry evolution.

3. Model configuration

Three nested domains were employed by WRF with horizontal grid spacings of 22.5, 7.5 and 2.5 km. The outer domain encompassed most of Mexico and the inner domain included the Mexico City basin and much of the central plateau north and east of the city where

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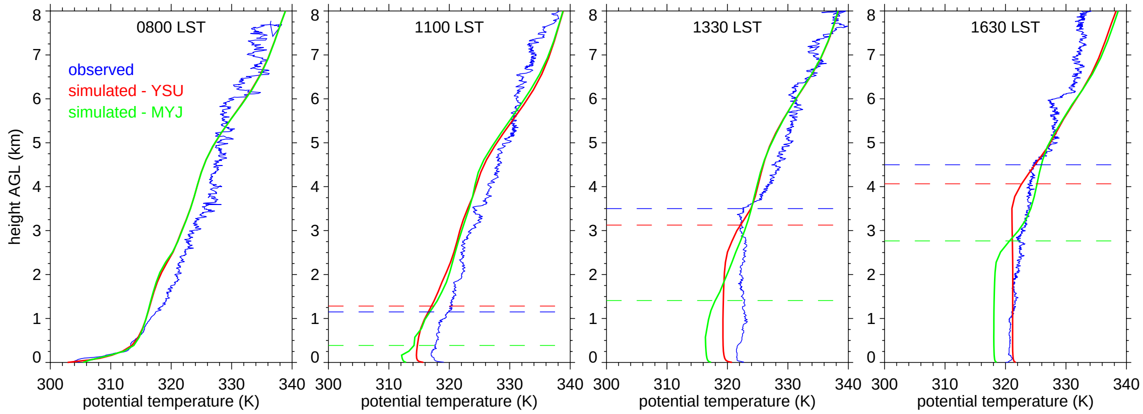

Fig. 2. Observed (blue) and simulated (red and green) potential temperature profiles at Cuautitlán on 1 March 1997. The dashed lines denote the height of the CBL. Simulated CBL height diagnosed by WRF and the observed CBL height determined by visual inspection of potential temperature and specific humidity profiles.

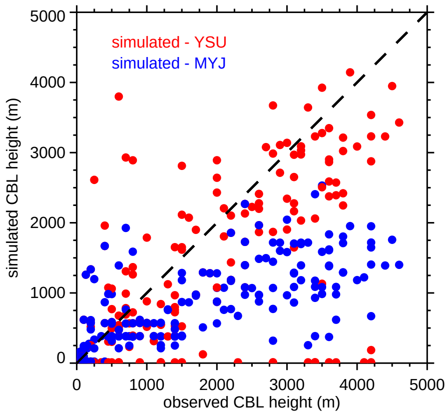

Fig. 3. Comparison of observed and simulated CBL heights from all seven simulation periods. Blue and red dots denote results from the YSU and MYJ simulations, respectively.

the research aircraft will likely collect measurements. Initial and boundary conditions at 3-h intervals were obtained from the North American Regional Reanalysis. Parameterizations included the Goddard shortwave radiation scheme, RRTM longwave radiation scheme, a simple thermal diffusion land surface scheme, and the Lin et al. microphysics scheme.

Seven 48-h periods were simulated starting at 12 UTC on 24, 27 February and 1, 3, 10, and 13 March. Two sets of simulations were performed: one employing the YSU (Hong and Pan 1996) boundary layer parameterization and the other employing the MYJ (Janic 2002) boundary layer parameterization.

4. Results

An example of the observed and predicted potential temperature profiles is shown in Fig. 2 for the Cuautitlán site from the first day of the 1-2 March simulation. The observed profile at 08 LST shows a surface stable layer about 250 m deep resulting from radiational cooling during the night. The observed CBL height, that was about 1 km in the late morning at 11 LST, grew dramatically during the afternoon to 3.5 km and 4.5 km at 1330 and 1630 LST, respectively. The predicted profiles at 08 LST are two hours after the model initialization and are therefore nearly identical. The predicted height from the YSU simulation was similar to the observed height at 11 LST; however, a shallow boundary layer was produced by the MYJ simulation at this time. Although the predicted CBL heights and boundary layer potential temperatures from both simulations was lower than observed during the afternoon, the CBL heights and potential temperatures from the YSU simulation were much closer to the observed values.

A comparison of the observed and predicted CBL depths for all the simulation periods is shown in Fig. 3. The MYJ simulations consistently under-predicted the height of the CBL with a bias of -833 m and a correlation coefficient of 0.77. There were only a few periods in which the predicted CBL height from the MYJ simulation was too high. The bias and correlation coefficient in the predicted CBL height from the YSU simulation was -411 m and 0.71, respectively. The small predicted values from the YSU simulation along the x-axis occurred because the nocturnal stable layer formed an hour or two earlier than observed during the evening transition period. When the 1930 LST period is omitted, the bias of the YSU and MYJ simulations were -194 and -818 m, respectively, with correlation coefficients of 0.85 and 0.83.

An example of the observed and predicted wind profiles is shown in Fig. 4 for the Cuautitlán site on 1 March. A trough of low pressure over the western U.S. produced southerly synoptic winds between 6 and 10 m s^{-1} over Mexico on this day. The wind speeds aloft decreased to 4-6 m s^{-1} between 13 and 14 LST as they were entrained into the growing CBL. After 16 LST, winds within 2 km of the ground became westerly and stronger than 8 m s^{-1}. Strong wind shears within the CBL were observed over Cuautitlán on this day, similar to data collected from other sites and on other days.

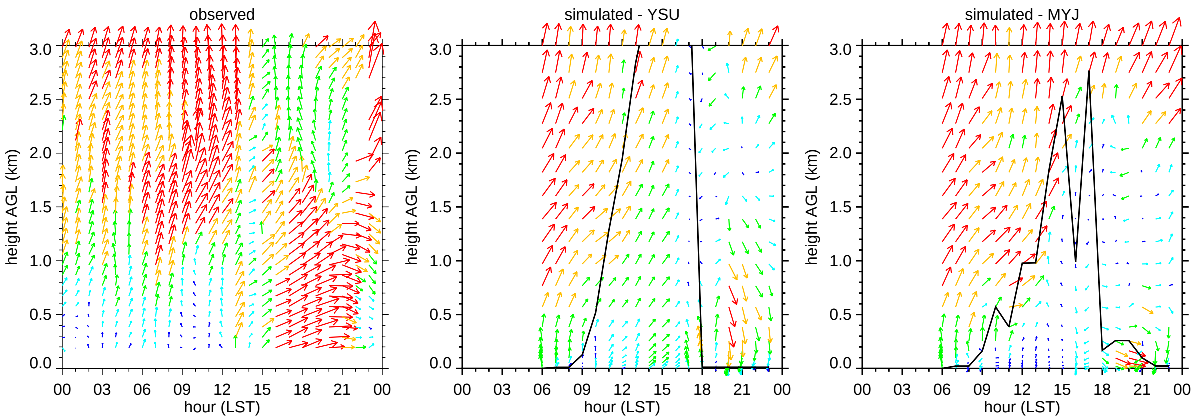

Fig. 4. Observed and simulated wind profiles at Cuautitlán on 1 March 1997. Blue, light blue, green, orange, and red denotes winds speeds of 0-2, 2-4, 4-6, 6-8, and < 8 m s^{-1}, respectively. Black line denotes boundary layer depth diagnosed by WRF.

While the wind profiles from both simulations were qualitatively similar to the observations above the CBL, the predicted wind speed and directions within the CBL were significantly different. The YSU simulation produced a sharp decrease in wind speeds at 3 km AGL as the predicted CBL grew to that height an hour after the observed decrease in wind speeds. The winds at that level from the MYJ simulation remained high because the predicted CBL height never exceeded 3 km AGL. Within the CBL, the predicted winds from the YSU simulation were coupled with the ambient winds up to 16 LST. Conversely, the wind speeds from the MYJ simulation were often lower than the observations and those produced by the YSU simulation. During the early evening between 19 and 21 LST, the MYJ simulation produced a short period of strong westerly flow near the surface similar to the observations; however, the predicted winds speeds between 0.3 and 1.5 km AGL were too weak. The wind speeds from the YSU simulation were between 6 and 10 m s^{-1} up to 1 km AGL at this time, but they were northerly while the observations were westerly.

WRF-chem was also used to simulate ozone and particulates produced by the anthropogenic primary precursor emission sources in Mexico City. Anthropogenic emission rates from other urban areas and biogenic emission rates important for regional chemistry (Tie and Madronich, 2004) were turned off to isolate the location megacity pollutant plume.

Simulations for the 1-2 March period are shown here that employ the two boundary layer parameterizations. The predicted ozone mixing ratios from both simulations at ~ 900 m AGL at 15 LST 1 March is shown in Fig. 5. Both simulations predicted ozone to be formed and transported northeast out of the Mexico City basin as a result of the ambient southwesterly flow, although the plume from the MYJ simulation was transported in a more easterly direction. The lighter winds produced by the MYJ simulation also produced more convergence in the basin so that ozone was also high over the city. The YSU simulation produced flow through the gap in the terrain at the southeastern end of the valley that transported more of

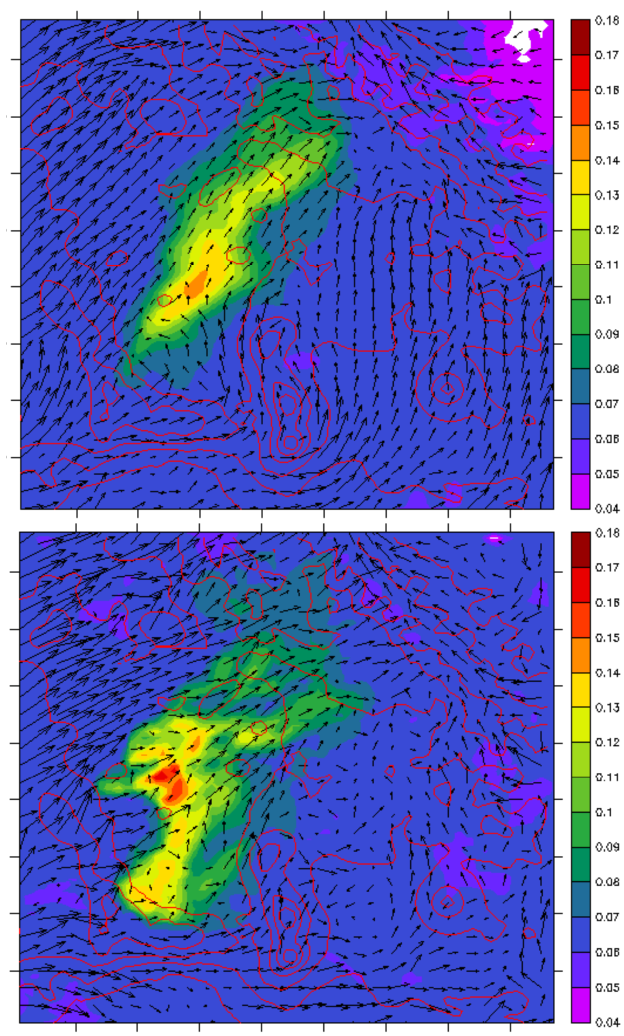

Fig. 5. Predicted ozone mixing ratios (ppm) at 15 LST 1 March, 1997 ~ 900 m AGL from the YSU (top) and MYJ (bottom) simulations. Red contours denote topography and black vectors denote winds.

the pollutants north out of the basin. Maximum ozone Mmxing ratios from the MYJ simulation were about 30 ppb higher than the YSU simulation because the shallower CBL produced less dilution and enhanced photochemical production of ozone

Despite differences in the predicted meteorology between the two simulations on this day, the similarity of the horizontal extent of the pollutant plumes may not influence decisions on whether nor not to initiate research aircraft operations northeast of Mexico City for this case. However, the vertical distribution of pollutants is another important consideration in guiding aircraft flight paths. Near the northern boundary of the inner grid, the YSU simulation produced a layer of ozone lofted above the surface (not shown). No such layer was produced from the MYJ simulation.

5. Future Work

At the conference, statistical measures will be presented to quantify the performance of the YSU and MYJ simulations in simulating the temperature, humidity and wind profiles in the Mexico City basin. The wind patterns will also be examined to determine how well the model reproduces the timing and magnitude of the thermally-driven circulations shown in Fig. 1. Results from WRF-chem for all seven simulations that include different synoptic conditions will illustrate the sensitivity of the downwind plume evolution that could affect aircraft flight operations during the 2006 field campaign. Since both simulations contain meteorological forecast errors, an ensemble approach would be useful to determine the probable plume extent.

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7. Links

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http://www.asp.bnl.govMAX-Mex.html