Neighborhood scale air quality modeling in Houston using urban canopy parameters in MM5 and CMAQ with improved characterization of mesoscale lake-land breeze circulation

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9.2 NEIGHBORHOOD SCALE AIR QUALITY MODELING IN HOUSTON USING URBAN CANOPY PARAMETERS IN MM5 AND CMAQ WITH IMPROVED CHARACTERIZATION OF MESOSCALE LAKE-LAND BREEZE CIRCULATION

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1. INTRODUCTION

Advanced capability of air quality simulation models towards accurate performance at finer scales will be needed for such models to serve as tools for performing exposure and risk assessments in urban areas (Ching et al., 2004). It is recognized that the impact of urban features such as street and tree canopies on air quality simulations will become more pronounced as the grid sizes decreases. This paper will focus on (a) methods to introduce urban features into the MM5, the predictive model to provide accurate, temporally and spatially resolve meteorological fields and as a preprocessor for (b) running the Community Multiscale Air Quality (CMAQ) (Byun and Ching, 1999) modeling system run at neighborhood scales (order 1 km grid horizontal resolution) (see also http://www.epa.gov/asmdnerl/models3/doc/science/science.html)

The difficulty of performing predictions of air quality and pollutant dispersion at high spatial resolution is exacerbated by the need for high quality, high definition of the meteorological fields that govern transport and turbulence in urban areas. Air quality fields are now being modeled at finer spatial resolution to reveal "pollutant hot spots" in urban areas. These fine resolution mesh simulations will need to be driven by meteorology at commensurate mesh sizes. The presence of urban street and tree canopies can affect the emission dispersion and transport, and play a major role in defining the spatial variability of the air quality fields. Preliminary results (Ching et al., 2003) using a set of urban canopy parameters for Philadelphia based on simple surveys of urban building geometries (Otte et al., 2004) have shown that the resulting MM5 and CMAQ fields are significantly impacted by the introduction of urban canopy parameters (UCPs) of buildings at 1.3 km mesh size. Given the sensitivity of the meteorology prediction to this set of UCPs, it is important to further examine the predictive consequence with data on building and vegetation on high spatial definition and accuracy. The basis for this study is the implementation of the DA-SM2-U/MM5 system (Dupont, et al., 2004). Further, as Houston, Texas will be the area for this study, the mesoscale circulation associated with its lake-land breeze will exerts an important influence and has implications for the fine scale modeling and so this subject will also be part of our study.

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2. STUDY APPROACH

A set of urban canopy parameters (UCP) have been derived for a 1 km grid mesh from high definition building and vegetation database from airborne lidar measurements, ancillary data from satellites, high altitude photography, as well as detailed residential, commercial and industrial maps and for a modeling domain encompassing Harris County and surrounding areas (Burian et al., 2004a,b). A total of 23 UCP (combination of vertical profiles and surface values and shown in Table 1 listed according to the following categories, canopy, building, vegetation and other.

These gridded UCPs were specifically developed for the DA-SM2-U/MM5 system (Dupont et al., 2004), which incorporated a canopy drag approach into an advanced urbanized surface layer model (SM2-U) which was further implemented into the NCAR-Penn State Mesoscale Meteorological Model, Version 5 (MM5). Our effort provides the first implementation of this detailed set of gridded UCPs into the DA-SM2-U/MM5 system. We chose to simulate a case study for August 30, 2000 for a domain encompassing the greater Houston-Galveston area. The period of interest also correspond to the TEXAS 2000 photochemical oxidant and PM study. Simulations were made at grid sizes of 36 km, 12 km, and 4 km using 30 sigma layers in the vertical. For the UCP driven version run at 1 km grid size, six (6) additional sigma layers were introduced near the surface to simulate the flows within the building and vegetative canopy region. Subsequently, the impact of introducing urban canopy features into the MM5 for the simulation of air quality using the CMAQ modeling system is examined. The MM5 and CMAQ were run in standard one-way nesting mode (Byun and Ching, 1999) and the system applied at 36, 12, 4, and 1 km grid mesh sizes. The meteorological output from MM5 was applied to CMAQ by invoking the MCIP, a Meteorology-Chemistry Interface Processor. Emissions for CMAQ were obtained using the Model-3 SMOKE processor, which produces gridded, hourly emissions outputs at the different grid mesh sizes and chemically speciated for the chemical mechanism used in the CMAQ modeling system. For this study, we used CBIV-AT, an advanced research version of the Carbon Bond-IV mechanism (CBIV) modified to predict gaseous air toxics species such as formaldehyde, acetaldehyde, acrolein, and others.

Table 1: Urban Canopy Parameters (UCP) for Houston Texas

Canopy UCPs:	Building UCPs:	Vegetation, Other UCPs:
Mean canopy height Canopy plan area density Canopy top area density Canopy frontal area density Roughness length Displacement height Sky view factor	Mean building height Standard deviation of building height Building height histograms Building wall-to-plan area ratio Building height-to-width ratio Building plan area density Building rooftop area density Building frontal area density	Mean vegetation height Vegetation plan area density Vegetation top area density Vegetation frontal area density Mean orientation of streets Plan area fraction surface covers Percent directly connected impervious area Building material fraction

3. RESULTS

We first present results from the 1 km grid simulations using DA-SM2-U/MM5 with the gridded UCP for Houston area. The figures 1-6 are for August 30, 2000 at 2000GMT (3pm local time). Figure 1 presents planetary boundary layer (PBL) parameters simulated by this model. The patterns show complex but highly resolved spatial patterns. The northern edge of Galveston Bay appears on the far right hand side of each of the figures; the model predicted reduced heat and momentum fluxes and mixing heights as expected.

Figure 2 shows simulations of formaldehyde (HCHO) from the CMAQ-AT modeling system for both 4 km and the 1 km grid sizes. The panel on the top right is the result of the 1 km grid simulations driven by the DA-SM2-U version of MM5. Regions of high concentration are exhibited in the results. These are the so-called “hot spots” that can be associated with increased exposure and an increased probability of health risk. The panel on the top left is a 4 km simulation reconstructed by aggregating 16 of the 1 km outputs per 4 km cell. The magnitude of the concentration for the hot spots from the 1 km results are reduced in this display. The CMAQ run performed at a native 4 km (Parent) resolution is shown in the bottom left panel. While the general pattern is similar to that from the aggregated results, the hot spot features are considerably diminished. This is not an unexpected result; the modeled concentration as impacted by atmospheric chemistry, transport, deposition processes that operate at a 1 km resolution yield results that are not expected to be reproducible with coarser resolution modeling and its inherent artificial dilution effects associated with representing emission at coarse resolution. Finally, the bottom right hand panel displays resulting differences between the reconstructed 4 km set from aggregation of the 1 km results minus the native 4 km simulation and normalized using the aggregated mean results. The figure displays both positive and negative differences of several tens of percentage magnitude. We will see other pollutants exhibiting similar behavior but somewhat different degrees of differences in magnitude and pattern (cf Figure 4 and 6 below).

PBL Parameters (2000 GMT)

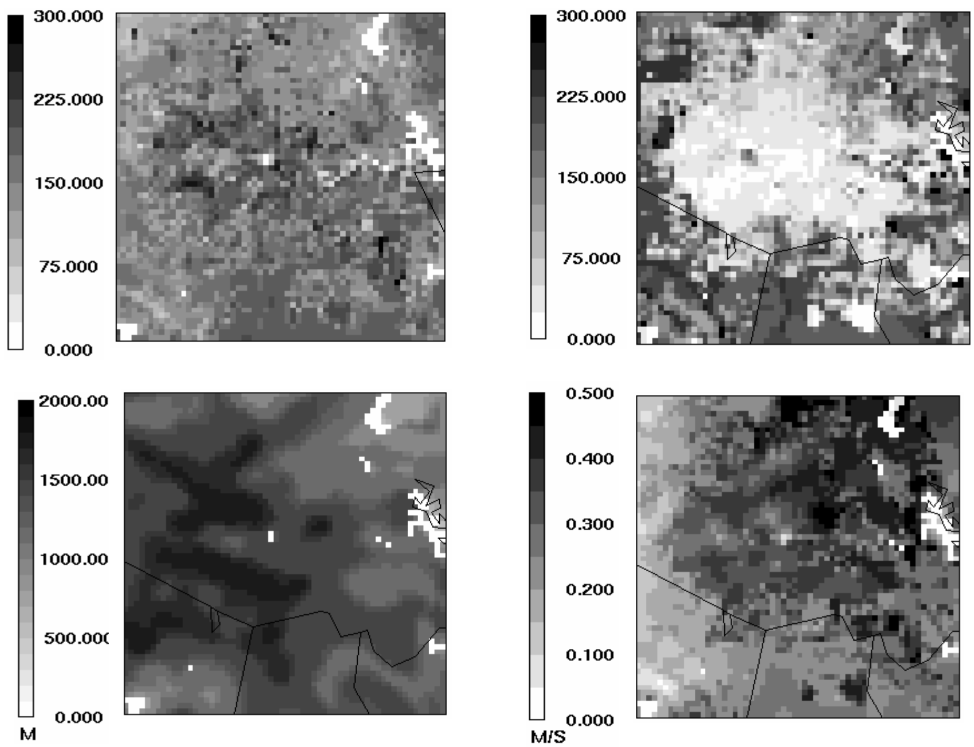

Figure 1. PBL parameters from 1 km grid simulations of DA-SM2U/MM5 (with high resolution UCPs) at 2000 GMT as follows: Top left, Sensible heat Flux (w/m^2) ; Top right, Latent Heat Flux (w/m^2); Bottom left, Mixing height (m); Bottom right, ustar (m/s).

Another example showing differences as well as value using higher resolution modeling is illustrated in Figure 3. This example reflects two (of many other) ways to depict the degree of sub grid variability associated with the 4 km resolution concentration variations that are possible using the finer 1 km predictions. The results are obtained by sampling the 16 1 km grid values for the maximum (peak) and the range (maximum –minimum) values in each 4 km cell, and for all cells in the modeling domain. On the left hand side, we see normalized peak-to-mean values exceeding 50% throughout the model domain and several areas which exceed factor-of- two values. The normalized range-of-values also exceeding 50% applies throughout the entire modeling domain. Several grid cells have sub grid variabilities exceeding factor of two or more. Such results are not possible with purely interpolation-based methodologies. Figures 4-5 and 6-7 present results for ozone and NOx, respectively. They are set up in identical manner to figures 2 and 3. The notable feature for the ozone results is the ability of the 1 km grid mesh simulations to resolve the titrating effect of high NOx along highway corridors and industrial areas especially along the ship channel region (Top right hand panel of Figure 4). The results of aggregating the 1 km results to 4 km grid size shown in the top left hand panel also show evidence of the titration effect, but greatly filtered. The native 4 km simulation mutes this effect even further. Even with such filtering, differences shown in the bottom right hand panel shows differences exceed 50% and are mostly negative near highways and industrial areas.

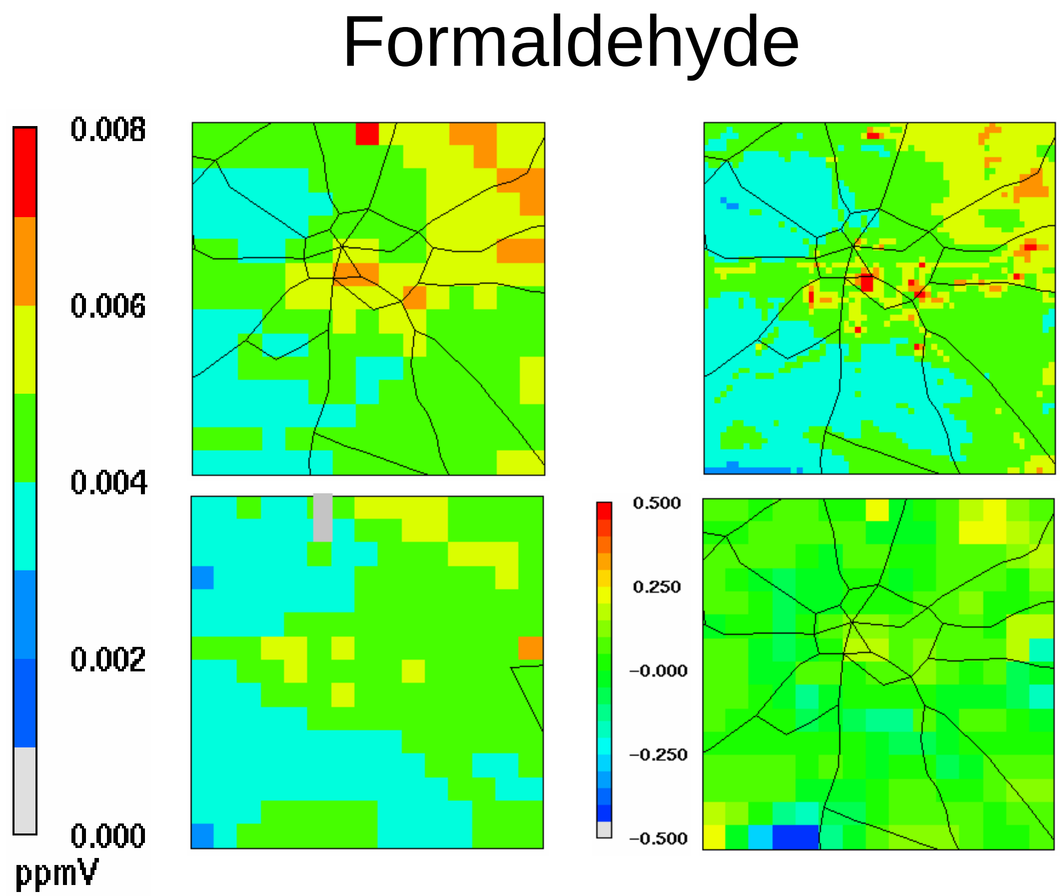

Figure 2. Formaldehyde at 2000GMT (3 pm local time) as simulated using CMAQ as follows: Top left- 4 km grid means from aggregate of 1 km grid values; Top right, 1 km gridded field; Bottom left, Parent 4 km grid results; Bottom right, difference of 4 km aggregated mean from 4 km Parent normalized to the 4 km aggregated mean.

In Figure 5, results for ozone are similar to that for formaldehyde in that the range-to-mean values exceed 50% throughout the modeling domain. Also, the peak values are comparable or greatly exceed their respective cell mean values throughout the modeling domain. The results for NOx are shown in Figures 6 and 7. While these results are qualitatively similar to that of ozone, some additional features are noteworthy. First, the 1 km grid size simulation shows the areal coverage of high NOx to be considerably larger than that simulated at 4 km grid sizes. The normalized difference in the bottom right panel shows a much larger areal extent of positive differences, exceeding 50% throughout most of the modeling domain and not limited to the highways and industrial areas. Likewise, the sub-grid variability indicators in Figure 7 show peak-to-mean values exceeding 50% throughout the modeling domain, but with ratios higher and more extensive than for ozone. This is to be expected because NOx gradients are sharper and more localized. The same conclusion is reached for the range-to-mean display. It appears that photochemical modeling at 1 km produces results that yield both a high degree of spatial variability as well as predicting important differences as compared to coarser grid simulations.

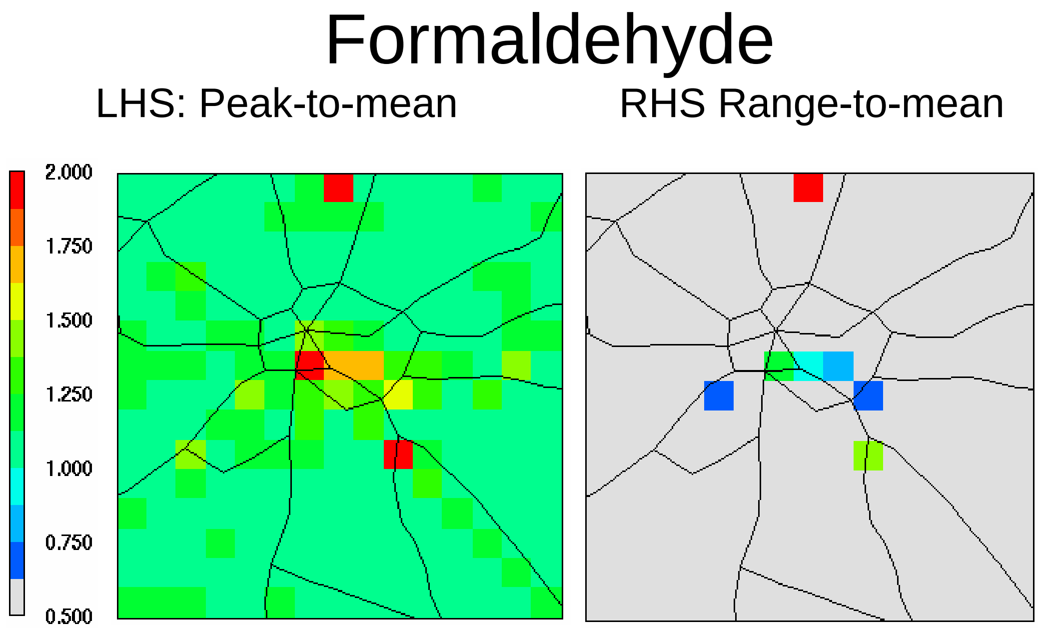

Figure 3. Formaldehyde simulations : August 30, 2000GMT: Left side: Gridded values are the peak values 1 km grid cell value within each 4 km grid cells divided by the mean for each such the cell. Right side, range of concentrations from the 16 1 km grid cell within each 4 km grid cell also normalized to the mean value for each such cell.

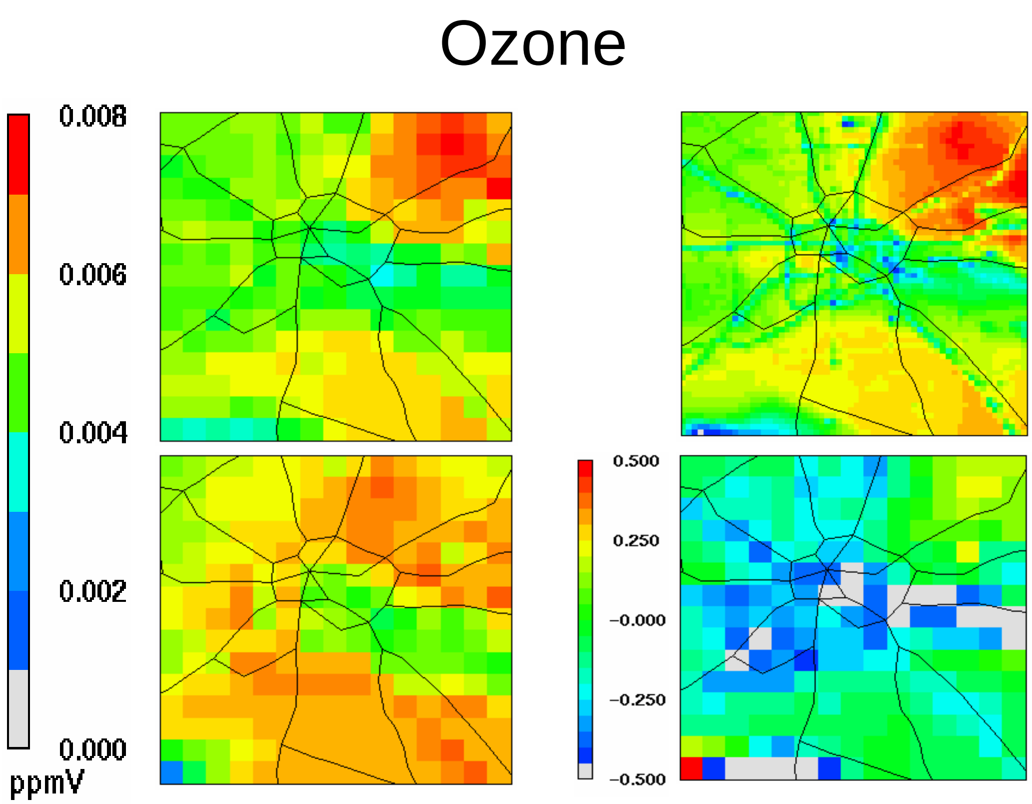

Figure 4. Same as 2 but for ozone

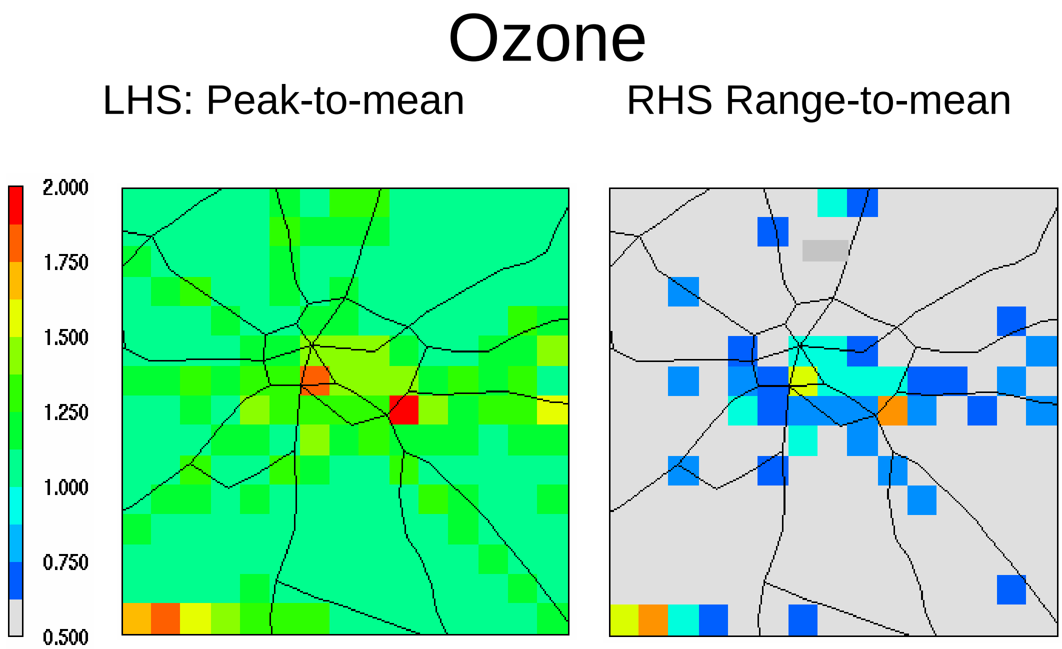

Figure 5. Same as 3 but for ozone

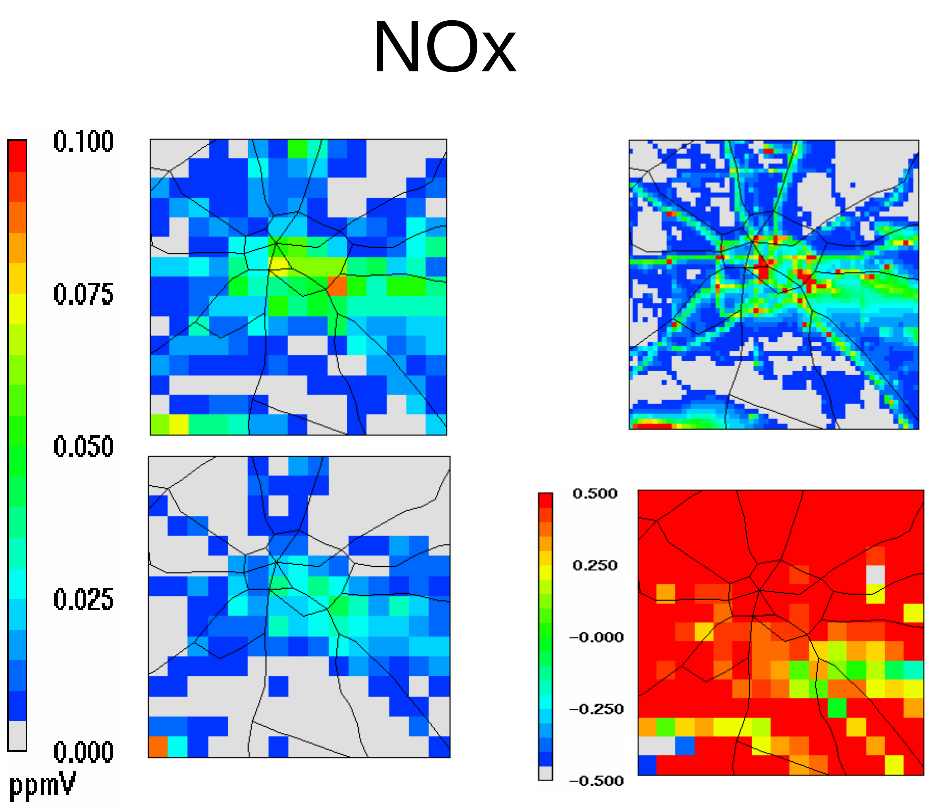

Figure 5. Same as 2 but for NOx

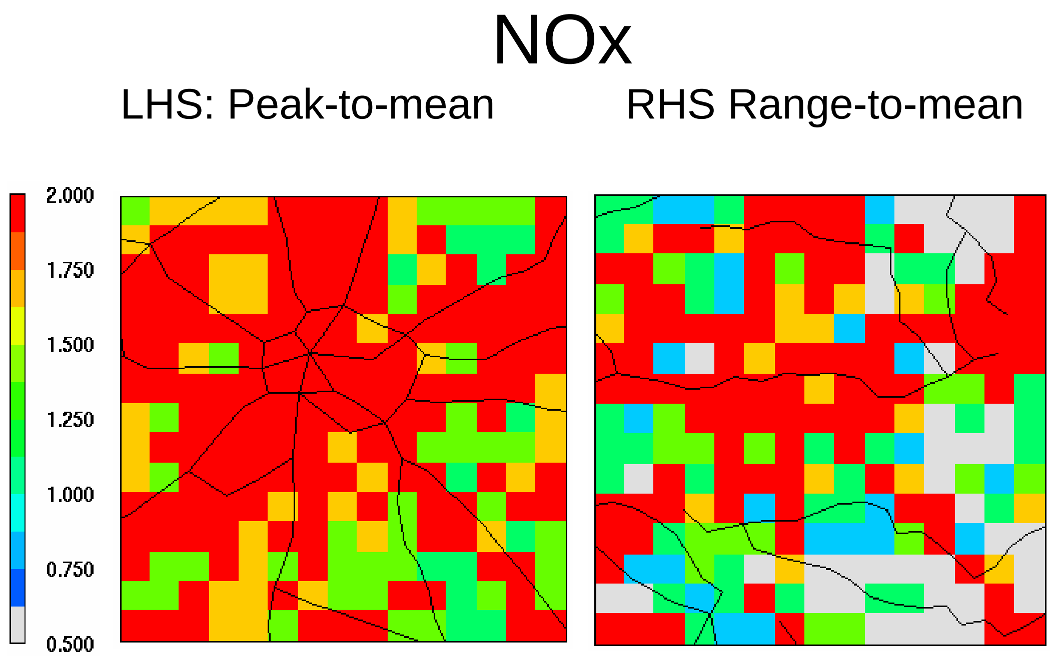

Figure 6. Same as 3 but for NOx

4. DISCUSSION

The results described in this paper should be considered a work-in-progress. The presentation at the Symposium will provide additional details regarding: (a) sensitivity studies with comparisons between results of the "urbanized" MM5 system and the standard version of MM5 run at 1 km resolution and its impact on the prediction with the CMAQ system; (b) a sensitivity study to examine the degree of accuracy of the input boundary condition of the flow field from the coarser 4 km grid nest. In this regard, it is important to recognize that pollutant transport in the Houston area is strongly affected by breezes induced by the Gulf of Mexico, and the close proximity of Galveston Bay. In an effort to resolve the bay/sea breeze evolution, high resolution (~1 km) sea surface temperature observations taken from the Polar-orbiting Operational Environmental Satellites (POES) Advanced Very-High Resolution Radiometer (AVHRR/2) sensor are used in a sensitivity run. A comparison of Bay temperatures shows a difference as large as 4^{o} C warmer in the sensitivity as compared to the base or control simulation) (Figure 7a). The results show the Bay water temperature warms up to 4 degrees while remaining constant in the control simulation. Figure 7b shows the resulting difference in the near surface wind direction at Site C608 (of the Texas 2000 study) which is ~6 km west of the northwestern part of Galveston Bay. As a result, the accuracy of the near surface land-bay breeze circulation simulations at 4 km grid resolution in the MM5 predictions was greatly improved. The sensitivity run clearly reproduces the observed wind directions and the wind shift at the time of the Bay breeze passage; the control run does not capture the details of the Breeze passage. Consequently, this provides a much more reasonable set of IC/BC for the nested, 1 km grid predictions. The presentation at the Symposium will further allow us to demonstrate the degree to which the flow and air quality prediction will depend on the introduction of more accurate temporally resolved sea surface temperatures (of the proximate Galveston Bay) and the subsequent improvement in representation of the modeled land-sea (lake) breeze features.

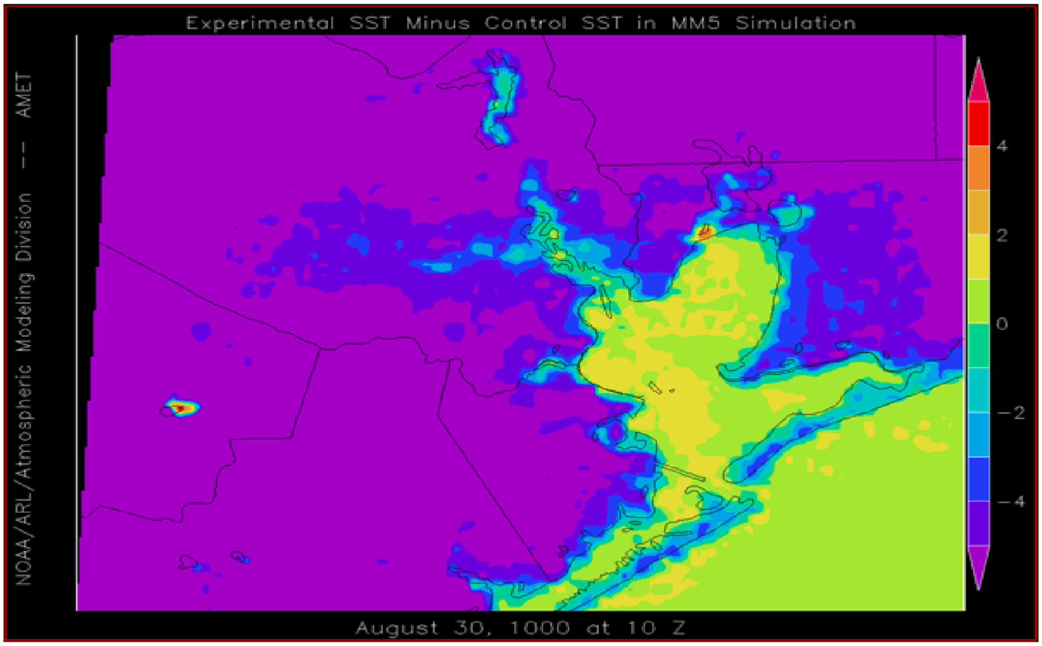

Figure 7a: Difference between the 4 km grid control using standard MM5 sea surface temperature vs. the Sensitivity simulation which uses POES-AVHRR/2 data

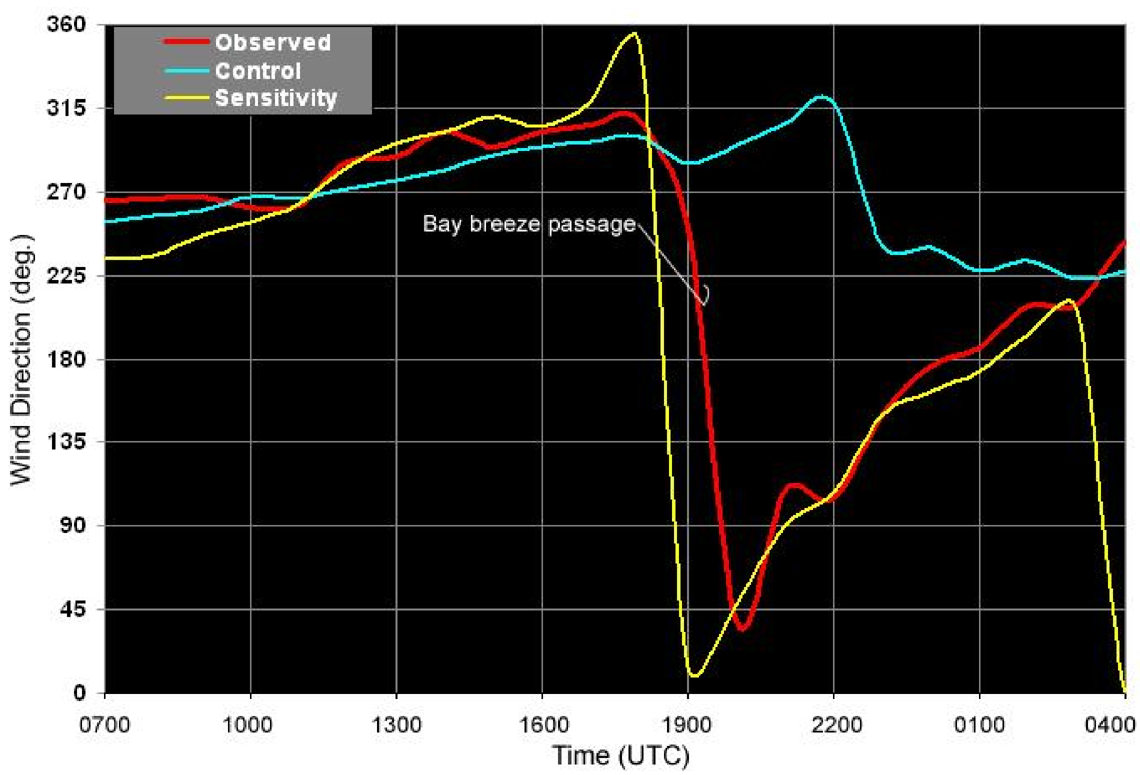

Figure 7b: Same as 7a showing modeled wind direction and observations at site C108. The passage of the Bay breeze front is indicated by the shift in wind direction.

5. SUMMARY

We have successfully implemented the DA-SM2-U/MM5 system using a sophisticated set of gridded UCPs based on high resolution building and vegetation data. We have now achieved the development of modeling tools that can resolve physically, flows in urban areas that are impacted by the presence of canopy features at 1 km grid sizes. This method reduces the problems or uncertainties associated with simple interpolation schemes that cannot be expected to accurately represent the flow in urban areas. Also, we have demonstrated that the CMAQ system can be successfully driven using these meteorology fields as inputs for simulating air quality (and air toxics species) at relatively high spatial resolution. We have further shown that by employing a finer grid resolution mesh, that areas of enhanced pollutant concentration become evident, a situation that will permit the resolution of pollution "hot spots" for more accurate human exposure and risk assessments. Clearly, efforts to evaluate all these findings will be necessary.

Thus, the combination of UCP-driven meteorology for fine scale modeling and more accurately modeled lake-land breeze circulations will, in our opinion, provide a strong scientific basis for advancing the simulations of the flow and air quality for Houston and other urban areas with similar climatic features.

Disclaimer*: This paper has been reviewed in accordance with United States Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.*

6. REFERENCES

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