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Adaptive Grid Modeling for Predicting the Air Quality Impacts of Biomass Burning

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1. INTRODUCTION

Wildland fires are essential in creating and maintaining functional ecosystems and achieving other land use objectives (Hardy and Leenhouts, 2001). However, biomass burning produces combustion byproducts that are harmful to human health and welfare (Hardy and Leenhouts, 2001; Battye and Battye, 2002). Guided by the Endangered Species Act (ESA), the Department of Interior (DoI) through the Fish and Wildlife Service (FWS) mandates that some military installations and air force bases in the South-Eastern United States use prescribed burning to recreate the natural fire regimes needed to maintain the health of its native long leaf pine forestland thus protecting the habitat of the endangered Red Cockaded Woodpecker (RCW). Proper management may require as much as 1/3 of the forest to undergo treatment by fire each year. These activities, however, can contribute significantly to already burdened local and regional air pollutant loads. In recognition of the conflicting requirements between the ESA and Clean Air Act (CAA) statutes, the Strategic Environmental Research and Development Program (SERDP), supported by Department of Defense (DoD), initiated a program to determine the effects of biomass burning from military installations. As part of this effort, we focused on determining the effects of biomass burning from military reservation, Fort Benning in Georgia, to the local and regional air quality, specifically, in Columbus metropolitan area.

Fort Benning, which covers an area of approximately 182,000 acres, is located in the lower part of central Georgia and Alabama, six miles southeast of Columbus, Georgia, as shown in Figure 1. Thus emissions from this facility may be affecting the air quality in Columbus, which is reported to violate air quality standards for Ozone (EPD, 2003). The Columbus Environmental Committee is viewing the prescribed burning operation as a potential contributor to the ozone problem. This became a public relations concern for Fort Benning (Larimore, 2000).

Approximately 30,000 acres must be prescribed burned each year at Fort Benning, during the growing season (i.e., March through August). This period falls within the “ozone season.” In order to restore the RCW habitat, longleaf seedlings are planted. Prescribed burnings continue from August through October for site preparation purposes, which also overlaps with the ozone season. These fires reduce unwanted vegetation that would compete with longleaf seedlings. Operational and safety constraints limit the burnings to an average of 300 acres per day (Environmental Management Division, 2000). For example, although an attempt is made to burn all RCW clusters during the growing season it is logistically impossible due to the number of clusters (75-80 annually) and scheduling conflicts with training. Natural firebreaks, such as roads, trails, drains, and creeks dictate the size of burn areas. All these limitations make it necessary to continue the burnings throughout the year. In realization of the Columbus ozone problem, the majority of the burnings (70-75%) were shifted to the January-April period, which is outside the “ozone season.”

Currently, the only external constraint on prescribed burning arises as a result of smoke management concerns. Smoke complaints and the threat of litigation from smoke-related incidents / accidents

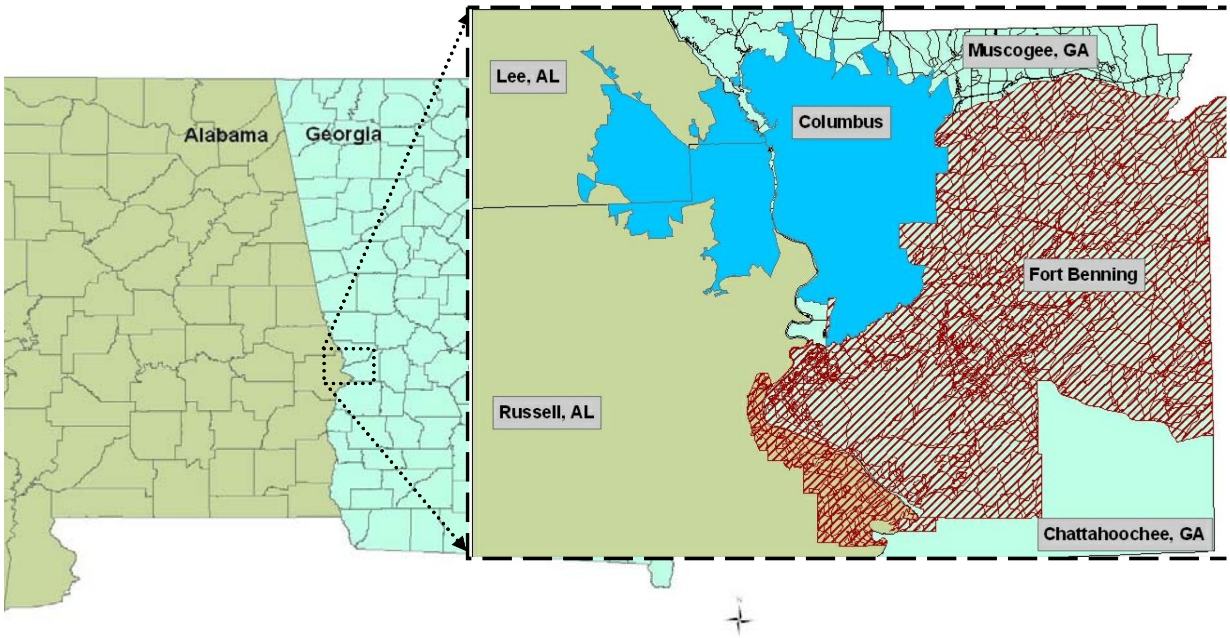

Figure 1 Location of Study Area

are the primary concerns. Fort Benning follows voluntary (not mandated by state or federal government) smoke management guidelines in an effort to minimize the adverse impacts from smoke. An additional concern is the effect of prescribed burning on ozone levels in Columbus. Forest fires produce nitrogen oxide and hydrocarbon emissions that form ozone (Cheng *et al.*, 1998; Battye and Battye, 2002; Ottmar, 2001). These pollutants may be transported downwind, mix with emissions from other sources and contribute to the poor air quality in urban areas. Sulfur dioxide and particulate matter emissions from forest fires are also of concern but, in general, they do not have a direct influence on the urban ozone problem. The ozone alert season is from 1 May through 30 September in Georgia. It is during this season that emissions from prescribed burning operations could affect smog levels in Columbus. In collaboration with the Partnership for a Smog-Free Georgia (PSG), Fort Benning is avoiding prescribed burns when meteorological conditions are conducive to ozone buildup. However, more complex methods are required to identify the real effects of biomass burning from Fort Benning on ozone problem in Columbus region.

Main objective in this study is to improve the ability to model the air quality impacts of biomass burning on the surrounding environment. For this purpose we equipped an advanced air quality model, Multiscale Air Quality Simulation Platform (MAQSIP) (Odman and Ingram, 1996), with two newly developed techniques; Adaptive Grid Modeling, and Direct Sensitivity Analysis to accurately isolate and determine the effects of biomass burning on ozone formation. In this paper we first describe the methods utilized and then discuss the important findings of the study.

2. METHODOLOGY

The atmospheric and chemical modeling systems currently used by various agencies tend to focus on a single scale that seems to be the most relevant to a particular air pollution problem. Global scale models address climate issues while regional scale models are used for the tropospheric ozone, regional haze or acid deposition studies. Urban scale smog models are being replaced with urban-to-regional scale models in most places where transport from other upwind sources play an important role. On the local scale, models are used to deal with problems such as accidental releases. The domains of local scale models are limited by design; therefore, they cannot be used for regional scale impact studies.

One of the most advanced urban-to-regional scale models is the MAQSIP. Urban-to-regional scale models are used in developing emission control strategies for problems such as urban and regional ozone, acid deposition, or regional haze which is attributed to primary (emitted) and secondary (formed in the atmosphere) fine particulate matter. While these models are equipped with special tools to treat emissions from large power plants (Karamchandani et al, 2000), they lack the ability to resolve emissions from relatively small area sources such as those from prescribed burnings. To account for such area sources, the models rely on grid resolution. Prescribed burnings are performed over areas as small as one square kilometer (approximately 200 acres). This scale is too small for typical regional applications. Therefore, emissions from prescribed fires are blended with emissions from many other sources within the same grid cell of regional scale models. This would make it impossible to conduct an impact study that would target emissions from biomass burnings.

Another limitation of current air quality models is related to numerical errors involved during the simulations. Let us suppose that the grid cell size could be reduced to one square kilometer by using nested-grid techniques (Odman et al, 1997). In that case, a typical prescribed burning unit would cover a single grid cell. The effect of having or not having prescribed burning emissions from a single grid cell would be a small perturbation for air quality models. As the perturbation gets smaller in size, numerical errors that affect the simulation results become more important. The results of an impact study such as the one proposed here would be highly uncertain if the models were used as is. Therefore, urban-to-regional scale models, in their current state, are not very reliable tools for determining the impact of prescribed burning emissions to the surrounding environment.

The study of the impact of biomass burning from DoD facilities requires investigation of the interaction between various scales due to the fact that both the location of the facilities and the lifetimes of emitted pollutants are conducive to long-range transport. Below, we describe a methodology to improve current urban-to-regional scale air quality models with two modeling techniques. These techniques improve representation of the transport and transformation processes over a wide range of scales and provide more reliable source-receptor relationships. The product is a more reliable tool that can predict accurately the ultimate fate of pollutants emitted from specific sources such as DoD facilities.

2.1. Adaptive Grid Modeling

We developed an adaptive grid modeling approach to reduce the uncertainty in air quality predictions. By clustering the grid nodes in regions that would potentially have large errors in pollutant concentrations, the model is expected to generate much more accurate results than the traditional fixed, uniform grid counterparts. The repositioning of grid nodes is performed automatically through the use of a weight function that assumes large values when the curvature (change of slope) of the pollutant fields is large. The nodes are clustered around regions where the weight function bears large values, thereby increasing the resolution where it is needed. Since the number of nodes is fixed, refinement of grid scales in regions of interest is accompanied by coarsening in other regions where the weight function has smaller values. This yields a continuous multiscale grid where the scales change gradually. Unlike nested grids, there are no grid interfaces, which may introduce numerous difficulties due to the discontinuity of grid scales. The availability of computational resources determines the number of grid nodes that can be afforded in any model application. By clustering grid nodes automatically in regions of interest, the adaptive grid technique uses computational resources in an optimal fashion throughout the simulation.

A detailed description of the technique can be found in Srivastava et al. (2000). Here we will not repeat that information; instead, we will try to illustrate the technique and its potential with relevant applications. The adaptive technique was applied to problems with increasing complexity and relevance to air quality modeling. First, it was applied to pure advection tests (Srivastava et al., 2000). In a rotating cone test, the adaptive grid solution was more accurate than the fixed uniform grid with the same number of grid nodes. The error in maintaining the peak of the cone was only 13% compared to 39% with the fixed grid: an accuracy that could only be achieved by using 22 times more grid nodes with a fixed uniform grid. Srivastava et al. (2001a) conducted a third test with concentric conical puffs of NO_x and VOCs reacting in a rotational wind field. The parameters of this problem are such that, after a certain time, ozone levels drop below the background near the base of the conical puffs but they peak near the vertex of the cones. This feature was resolved by the adaptive grid solution while it was completely missed by the uniform fixed grid solution. When nine times more grid nodes were used, the fixed grid was finally able to reveal this feature but not as accurately as the adaptive grid technique.

Next, the adaptive grid technique was applied to the simulation of a power plant plume (Srivastava et al., 2001b). A two dimensional plume with a VOC/NO_x emission ratio of 14% was advected with uniform winds and diffused over a background with a VOC/NO_x ratio of 35. Other parameters were chosen to make the dispersion as realistic as possible. After about 12 hours of simulation, the composition of the plume was analyzed taking cross sections at various downwind distances. At 10 km downwind, the adaptive grid solution showed a NO_x rich, but ozone deficient core. This feature, which is also observed in actual power plant plumes, was completely missing in the uniform grid solution, which artificially diffused the NO_x and displayed highest ozone levels at the core of the plume. The adaptive grid, on the other hand, had ozone bulges developing near the plume edges. At a downwind distance of 30 km, these bulges continued to grow as NO_x diffused slowly from the core to the edges (at a rate more in line with physical diffusion) and radicals were entrained into the plume. This plume structure started disappearing after about 80 km. At a downwind distance of 135 km, the plume was fully *matured* with an ozone peak at the center. The peak ozone concentration was larger than one predicted by the fixed uniform grid. A similar evolution of the plume was observed in the fixed uniform grid solution when the number of grid nodes was increased by a factor of nine. However, this solution was about five times more expensive than the adaptive grid solution.

After these and other testing of the algorithm (Odman et al., 2001; Khan et al, 2003), finally an adaptive grid AQM was developed (Odman et al., 2002). The model was applied to an ozone simulation in the Tennessee Valley (Khan and Odman 2003). Ozone results from this application were evaluated and showed significant improvement over those from fixed grid models, even those employing up to four times more grid cells. In several cases the agreement with observations was better compared to fixed grid models. When the reasons were investigated it was found that the complex source-receptor relationships, especially the long-range ones were much better resolved with the adaptive grid.

2.2. Direct Sensitivity Analysis

Sensitivity analysis is essential in determining source-receptor relationships and designing emission control strategies. The traditional "brute-force" method involves running the model several times, each time perturbing one type of emission (e.g., NO_x or VOC) from a different source. If the perturbation is small, the brute-force method may not yield accurate sensitivities due to numerical errors propagating in the model. Our group has developed a new and powerful direct sensitivity analysis technique to study the response of air quality to various types of emissions (Yang et al, 1997). Unlike the brute force approach, this technique is not limited by the magnitude of the perturbation and, in theory, it can be used for even infinitesimal changes in emissions. Therefore, the technique has the potential of improving current models to a level where they can be used for impact analysis of relatively small sources such as military installations.

Air quality models are based on the atmospheric diffusion equation:

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (\mathbf{u}\, c_i) = \nabla \cdot (\mathbf{K} \nabla c_i) + R_i + S_i \qquad (1)$$

Here, c_i is the concentration of the ith pollutant species, $\mathbf{u}$ describes the velocity field, $\mathbf{K}$ is the diffusivity tensor, $R_i(c_1, c_2, ...)$ is the chemical reaction term and S_i is a source term for certain types of emissions. The local sensitivity of the concentration of a species (e.g., ozone) to a certain emission type (e.g., NO_x or VOC) from a particular source can be defined as:

$$s_{ij}(t) = \frac{\partial c_i(t)}{\partial E_j} \qquad (2)$$

Here, s_{ij} is the sensitivity of c_i to emission E_j. Since the sensitivities to different emissions can vary by many orders of magnitude, it is necessary to define semi-normalized sensitivity coefficients, s^*_{ij}.

$$s^*_{ij}(t) = \tilde{E}_j \frac{\partial c_i(t)}{\partial E_j} \qquad (3)$$

where $\tilde{E}_j$ is the unperturbed emission field (i.e., without fire). Using direct derivatives of Equation (1) the following equation can be obtained for sensitivities.

$$\frac{\partial s^*_{ij}}{\partial t} = -\nabla\left(\mathbf{u}s^*_{ij}\right) + \nabla\left(\mathbf{K}\nabla s^*_{ij}\right) + J_{ik}s^*_{kj} + \frac{\partial R_i}{\partial \varepsilon_j} + \frac{\partial S_i}{\partial \varepsilon_j} - \nabla\left(\mathbf{u}c_i\right)\delta_{ij} + \nabla\left(\mathbf{K}\nabla c_i\right)\delta_{ij} \qquad (4)$$

Here, s^*_{ij} is the semi-normalized sensitivity coefficient, J_{ik} is the Jacobian matrix, ε_j is a scaling variable with a nominal value of 1, and δ_{ij} is a binary variable (either 1 or 0).

The similarity between Equations (1) and (4) allows us to use the same or very similar numerical solution techniques and calculate local sensitivities to emission sources simultaneously along with the species concentrations. This also makes the implementation of the technique in any model relatively straightforward. The technique is also computationally efficient because several of these sensitivities (the number being limited by available core memory) can be calculated simultaneously with a fractional increase in CPU time. The emission sources can be discerned by type as point, area, mobile, or biogenic, and by composition such as SO_2, NO_x, or VOC. Also, the location of the emission source can be specified, for example, as the boundaries of a DoD facility (to the grid scale resolution). The technique would predict the sensitivity of air quality at any desired location in the modeling domain (e.g., sensitivity of ozone concentrations at a downwind urban center) to a fractional change in the emissions from the source of interest.

The technique has been evaluated in an application to the Southern California where the sensitivities of ozone concentrations to the domain wide reductions of mobile and area sources of NO_x were compared to a brute-force method (Yang et al., 1997). This technique was used in an integrated modeling system focusing, simultaneously, on ozone, particulate matter and acid deposition (Boylan, et al., 2001). We investigated the sensitivity of particulate matter concentrations to the reductions of SO_2 and NO_x emissions in the Southern Appalachian Mountains region. We also investigated the sensitivity of ozone concentrations to NO_x and VOC emissions from different states, using state boundaries as sub-regions. As part of that project, we compared our method to the brute-force approach for ozone sensitivities to domain wide NO_x and VOC emissions. The general agreement between the direct sensitivity and the brute-force method shows that the former is a reliable tool. Whenever we observed differences, we were able to relate the difference to the numerical errors associated with the brute force technique and show that the direct sensitivity method yields results that are more accurate.

3. AIR QUALITY SIMULATIONS

3.1. Episode Selection

The episode selection is based primarily on the availability and quality of meteorological and emissions data and the impact potential of prescribed burns at Fort Benning on regional air quality. As part of Fall Line Air Quality Study (FAQS), we have already simulated several episodes during summer of 1999 and 2000 in Georgia using MM5 meteorological model and SMOKE emissions model. The ideal scenario for our case study is one with southeasterly winds, biomass burning performed at Fort Benning and high ozone levels observed at Columbus. Based upon contacts with Land Management Brach at Fort Benning we obtained the locations, date, and time of biomass burning efforts (Westbury, 2002). There were biomass burnings at Fort Benning between August 15 and August 18 2000. Also ozone levels in Columbus region were over the standards at least four times and prevailing winds were southeasterly during the same period. Therefore, we decided to simulate the period from August 15 through August 18, 2000.

3.2. Data Preparation

Data preparation efforts included meteorological and emissions data preparation as well as post-processing. Meteorological data were obtained from FAQS. Detailed information on meteorological data preparation is given elsewhere (Hu *et al.*, 2003). Similarly emissions data were obtained from FAQS study. More information on emissions data can be obtained elsewhere (Unal et al., 2003; Hu et al., 2003). For biomass burning emissions First Order Fire Effects Model (FOFEM) Version 5, developed by Intermountain Fire Sciences Laboratory was utilized. In this model fuel type was assumed as natural fuel with long leaf pine trees. For some of the pollutants, such as speciated VOCs and NOx, emission factors provided by Battye and Battye (2002) were utilized.

3.3. Static Grid Simulation

To verify model efforts, a 4×4 km Static Grid version of the MAQSIP model was used in simulation for the selected episode. Lambert Conformal projection with parameters of 30^0N, 60^0N, and 90^0W, centered at 40^0N and 90^0W, was utilized for the domain. The 4×4 grid has 102 columns and 78 rows with 13 vertical layers. The results of the Static Grid run were compared with outputs from the FAQS project for the same location and time period. The comparison showed that Static Grid results were similar to FAQS results.
A separate run was made with emissions including fire as well. The difference between the concentrations of these two simulations yields an static grid “brute-force”.

3.4. Adaptive Grid Simulation

The adaptive grid also used the same domain definitions as for the static grid. In adaptive runs inert fire tracer concentrations are used to calculate the weight function that drives the adaption. The tracer is assumed to be a product of the fires at Fort Benning emitted at the same rate as NO emissions from fire. The tracer is transported and deposited the same way as other fire species but it is non reactive. Two different runs were made with the Adaptive Grid model. These runs include: one run with base emissions; and one run with base emissions plus fire emissions, which also has the direct sensitivity calculations. In both runs the grid adapted to the same fire tracer, therefore the grids are identical in both simulations. The difference between the concentrations of these two simulations yields an adaptive grid “brute-force”.

4. RESULTS AND DISCUSSIONS

First we compared the Adaptive Grid model with the Static Grid version. The tracer concentrations predicted by the two models as a result of fires at Fort Benning are shown in Figures 2 and 3. On August 15, 2000 at 19:00 UTM, two different fires happened at two different cells of the Static Grid, which is clearly observed in Figure 2. The fire to the south is emitting at a higher rate than the northern one, since the area burned is almost 1.5 times bigger. It should be noted that Static Grid distributes emissions uniformly to the whole cell area where the fire takes place.

Figure 3 presents concentrations of the inert fire tracer as well as the grid orientation around Fort Benning at 19:00. From Figure 3 it is clear that Adaptive model increases the grid resolution around the fire at Fort Benning. Figure 3 also gives an enlargement of the figure where adaption occurs. At the points where fires occur, adaptive grid size reduces almost to 400m by 400 m, one tenth of the Static grid size. As seen in Figure 3, two distinct plumes from fires at Fort Benning are clearly visible during the simulation. Note that concentration gradients are much better resolved by the Adaptive Grid model than by the Static Grid model.

Another way of evaluating the results of an air quality simulation is to compare them to air quality observations from the existing monitoring network. Unfortunately, there are no measurements along the trajectory of the fire plumes during the simulated period. Special air quality measurements are required for this purpose.

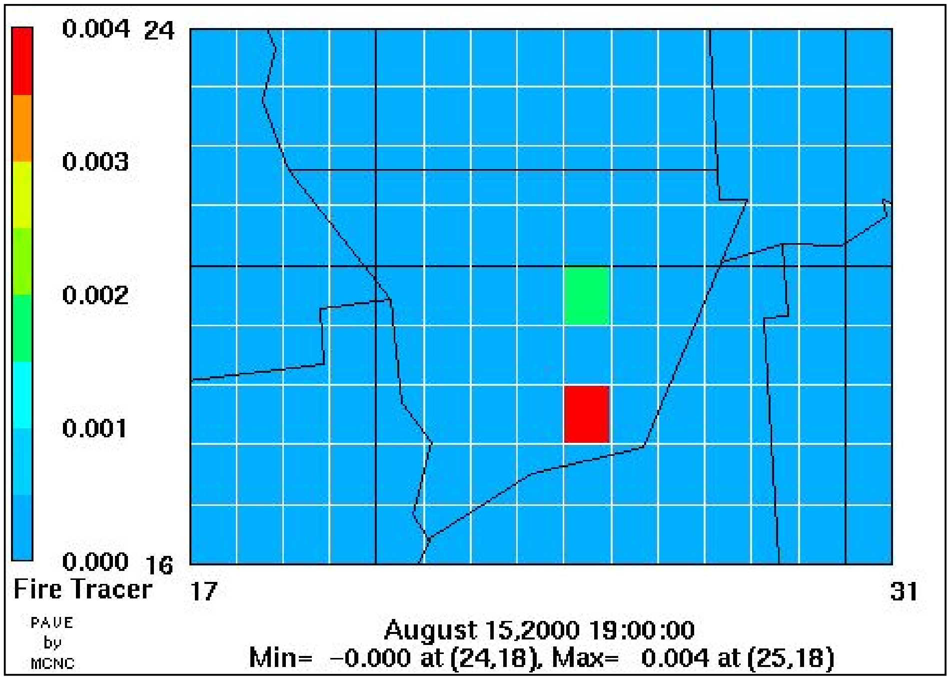

Figure 2 Static Grid Result for Inert Fire Tracer Concentrations (ppm)

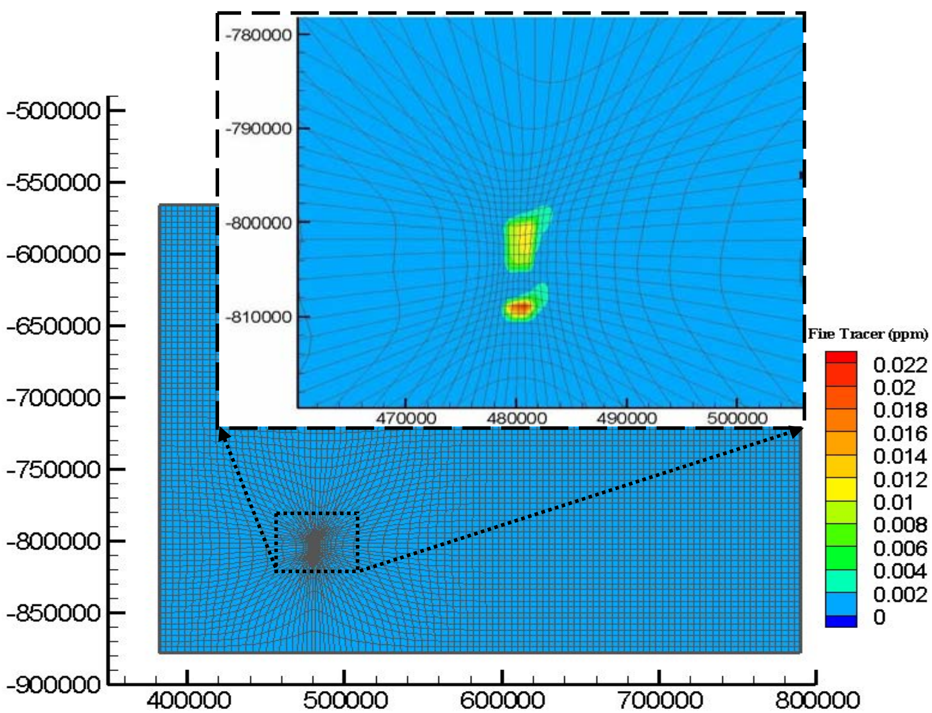

Figure 3 Adaptive Grid Result for Inert Fire Tracer Concentrations (ppm)

Researchers at Georgia Tech are currently collecting air quality data in the vicinity of Fort Benning as part of a study supported by SERDP to characterize pollutants emitted from prescribed burning (Baumann *et al.*, 2003). Data from this study were not available for the selected episode. However, as part of our future work we are planning to utilize these data for evaluation of our model.

Recall that another objective of this study was to utilize direct sensitivity method to estimate sensitivity of ozone to NO emissions from fires. For this purpose, we equipped our Adaptive Grid model with direct sensitivity technique. Figure 4 presents this sensitivity in the afternoon of August 15. While the fires reduce the ozone concentrations near the source by as much as 16 ppb, they result in an increase by as much as 7 pbb further downwind. Such a distinction between the near and the far field impacts is not so clear in the “brute-force” sensitivities calculated by the Static Grid model, as shown in Figure 5. The impacts of the fires on the air quality in Columbus are minimal on this particular day.

5. CONCLUSIONS AND FUTURE WORK

The objective of this study is to determine the air quality impacts of biomass burning on the surrounding environment. Fort Benning military reservation, Georgia, was utilized as a case study.

Current air quality models lack the capability of dealing with multi-scale air quality problems. In this study we utilized an Adaptive Grid model which inherently has the ability of continuous multiscale gridding. This method also reduces uncertainty in air quality predictions by clustering the grid nodes in regions that would potentially have large errors in pollutant concentrations.

We successfully implemented the Adaptive Grid model in our study and observed that concentration gradients are much better resolved by the Adaptive Grid model than the Static Grid version. This is due to the fact that Adaptive Grid model has 400m by 400m grid cells at locations where fires occur compared to 4km by 4km Static Grid cells.

It should be noted that we did not have the air quality observations data to compare our simulation results for the selected episode. However, we are going to compare our results to a database that is being developed by researchers at Georgia Tech.

Another important aspect of this study is to implement direct sensitivity technique to our Adaptive Grid model. We successfully achieved this task and showed that our results are superior to the results of “brute-force” technique that we utilized with the Static Grid version. The Static Grid can not resolve the difference between the near and far field impacts as Adaptive Grid does. It was found that the impact of the fires ranged from 16 ppb reduction to 7 ppb increase in ozone concentrations. The impact of the fires on the air quality in Columbus area was minimal during the selected period.

Overall, we successfully incorporated two new techniques into a regional-scale air quality model. This study showed that Adaptive Grid model equipped with direct sensitivity method can accurately determine the impact of small-scale emission events on the air quality in larger scales. We showed that these techniques can be utilized to determine the impact of biomass burning.

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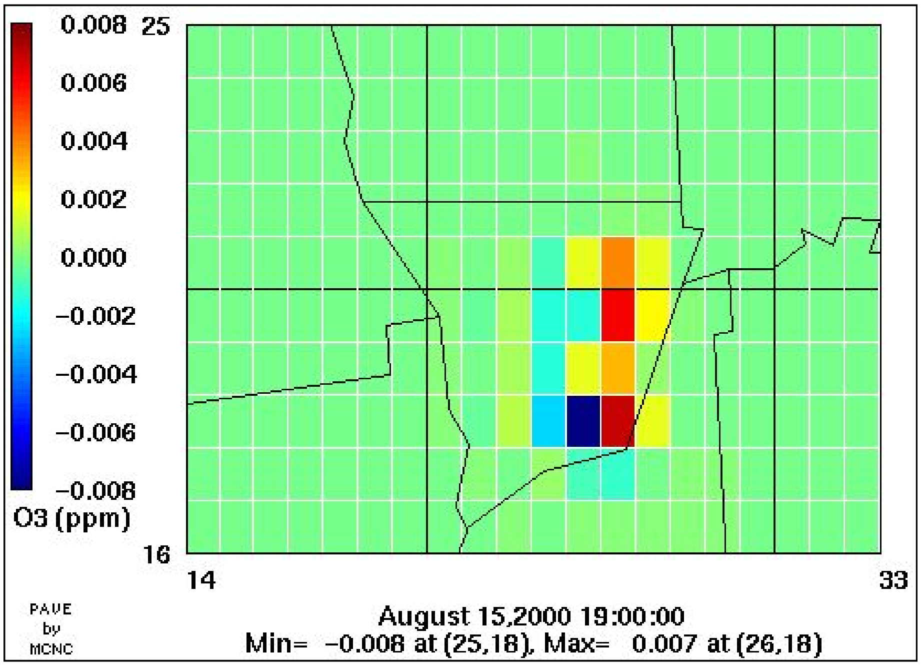

Figure 4 Static Grid Result for Brute Force Sensitivity of O_3 (ppm) to Fire Emissions

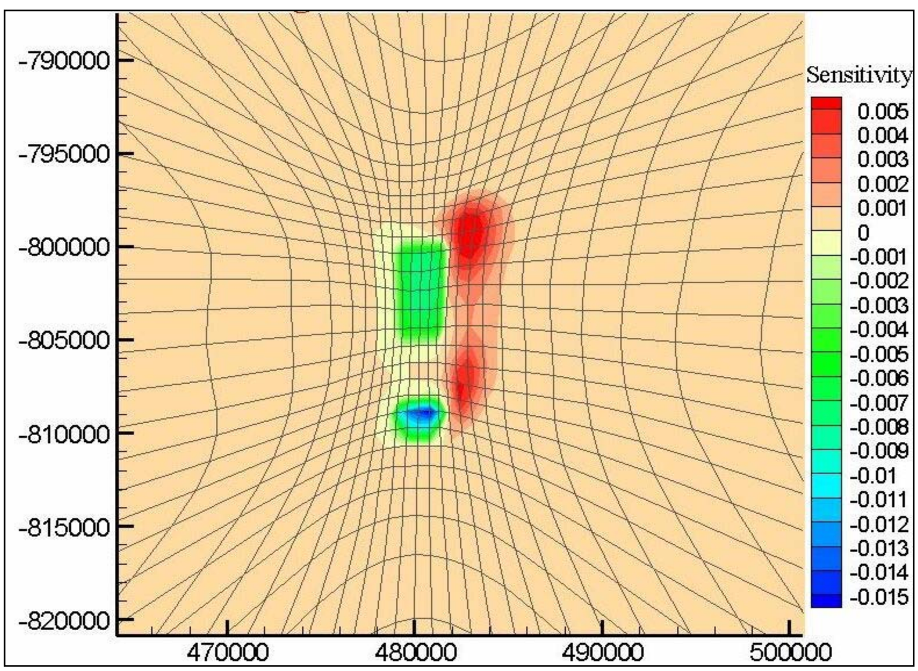

Figure 5 Adaptive Grid Result for Direct Sensitivity of O3 (ppm) to Fire Emissions