CMAQ/BenMAP-BASED HEALTH-BENEFITS ANALYSIS IN SUPPORT OF THE GEORGIA SIPs FOR O_3 AND $PM_{2.5}$

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1. INTRODUCTION

In response to US-EPA's designation of several areas in Georgia as non-attainment for O_3 and $PM_{2.5}$, the Georgia Environmental Protection Division (GA-EPD) has conducted a sensitivity analysis using the CMAQ/MM5/SMOKE modeling system to develop efficient control strategies. The sensitivity analysis included the responsiveness of O_3 (ppb/ton-per-day) and $PM_{2.5}$ (ng/m^3/TPD) to 10% emission reductions of anthropogenic non-EGU NO_x, VOCs, SO_2, NH_3, and primary carbon $PM_{2.5}$ (EC and OC), and to the installation of SCRs (NO_x control) and scrubbers (SO_2 control) at a number of large coal-fired power plants.

Based on the US-EPA modeling guidance (US-EPA, 2006), CMAQ is used in a relative way to evaluate/demonstrate future attainment in each of the monitoring locations within the non-attainment areas. However, the goal of attaining the National Ambient Air Quality Standards (NAAQS) at monitor locations does not necessarily coincide with the notion of reducing overall population exposure to air pollutants, due to the spatial extent of benefits resulting from reductions in O_3 and $PM_{2.5}$ from various controls. For example, results from the sensitivity analysis have shown reductions in O_3 to occur along the path of the plume in the case of major point-sources, while a more spatially homogeneous pattern was observed for ground level NO_x controls. In addition, reductions in emissions of primary carbon seem to influence a limited area surrounding the source, while SO_2 controls at major point-sources have more of a regional impact.

2. METHODS

To include health-benefits considerations in the State Implementation Plan (SIP) development process, GA-EPD is utilizing US-EPA's Benefits Mapping and Analysis Program (BenMAP) (Abt Associates, 2005), in conjunction with CMAQ, to model and maximize the health benefits (avoided mortality and morbidity and associated economic value) of various control strategies being considered. BenMAP derives these estimates of health related benefits by utilizing concentration-response (CR) functions, which relate a change in the concentration of a pollutant with a relative change in the incidence of a health endpoint. Inputs to the model include grid-level population data, the change in ambient air pollution level (modeled by CMAQ), health effect estimates (CR functions), the baseline incidence rate of the health endpoint, and economic values associated with each health endpoint (Abt Associates, 2005).

3. RESULTS

3.1 CMAQ-based sensitivity analysis

The sensitivity of O_3 and $PM_{2.5}$ in Atlanta to emissions of precursors indicated that O_3 abatement may be most efficiently achieved by controlling NO_x emissions, from both ground-level and EGU sources (rather than VOCs; Table 1), while $PM_{2.5}$ reductions may be most efficiently achieved by a combination of primary carbon, SO_2 and possibly ammonia controls (Table 2). The results presented in Tables 1and 2 are based on modeling results using the Models-3 modeling system as applied in Georgia (Marmur et el., 2005), for a summer (5/25-6/24) and a winter (11/19-12/18) episode. The sensitivity of O_3 is reported for days in which modeled baseline (2002) levels were above 85 ppb, while for $PM_{2.5}$ the results reported are a weighted "annual" average of all days within the two episodes. The results from the sensitivity analysis (Tables 1,2) are useful for initial development of the SIP, giving preference to controls showing the largest reductions in O_3 and $PM_{2.5}$.

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Table 1. Sensitivity of O_3 in Atlanta (Confederate Ave. site) to various emissions controls scenarios

Control scenario (ground level or EGU controls)	Average reduction (ppb)	Reduction per TPD controlled (ppt/ton-per-day)
10% ground level NO_X in Atlanta	**1.36**	**35.7**
10% ground level VOCs in Atlanta	0.08	1.5
2 SCRs at Plant McDonough	**0.42**	**60.4**
4 SCRs at Plant Scherer	**0.41**	13.7
2 SCRs at Plant Branch	0.07	4.6
3 SCRs at Plant Hammond	0.03	2.2
2 SCRs at Plant Yates	0.11	9.9

Table 2. Sensitivity of $PM_{2.5}$ in Atlanta (Fire Station #8 site) to various emissions controls scenarios

Control scenario (ground level or EGU controls)	Average reduction ($\mu g/m^3$)	Reduction per TPD controlled ($ng/m^3/TPD$)
10% ground level primary carbon	**0.25**	**85.7**
10% ground level SO_2	0.01	**1.9**
10% ground level NO_x	0.00	-0.09
10% ground level NH_3	**0.09**	**22.5**
10% ground level VOCs	0.01	0.11
2 Scrubbers at Plant Bowen	**0.091**	0.50
4 Scrubbers at Plant Branch	**0.098**	0.63
2 Scrubbers at Plant McDonough	**0.070**	1.39
4 Scrubbers at Plant Scherer	**0.150**	0.56
4 Scrubbers at Plant Hammond	0.030	0.42
1 Scrubbers at Plant Wansley	0.044	0.44
2 Scrubbers at Plant Yates	0.037	0.71

3.2 Exposure/Health-benefits analysis using BenMAP

To account for additional considerations in the SIP development process, such as maximizing the overall reduction in population exposure to O_3 and $PM_{2.5}$ (ppb*persons/TPD; $\mu g/m^3$*persons/TPD) and the associated health (reductions in mortality and morbidity) and monetary benefits, we used the US-EPA's BenMAP program. Each one of the modeled sensitivity cases was processed through BenMAP and reductions in population exposure and related benefits were quantified.

A key step in BenMAP is the (user) choice of concentration-response (CR) functions to be used. These functions often differ in both magnitude of the response estimate (e.g., % increase in mortality for a given pollution increment) and in the metric used to quantify pollutant levels. The latter factor is more typical of O_3 related epidemiologic studies, in which a wide range of metrics has been used (1-hour max; 8-hour max; 8-hour mean; 24-hour mean; 5-hour mean). Summaries of the CR functions used in this analysis are given in Table 3 (ozone) and Table 4 ($PM_{2.5}$).

Table 3. Ozone CR functions used in the health analysis

Health Endpoint	Metric	Author and Year[1]
Resp. HA[2]	24-hour mean	Schwartz, 1995
Resp. HA	1-hour max	Burnett et al., 2001
Resp. HA	24-hour mean	Schwartz, 1995
Resp. HA	24-hour mean	Moolgavkar et al., 1997
Resp. HA	24-hour mean	Schwartz, 1994
Resp. HA	24-hour mean	Schwartz, 1994
Resp. HA	24-hour mean	Moolgavkar et al., 1997
Resp. HA	24-hour mean	Schwartz, 1994
Resp. ER[3] visit	5-hour mean	Cody et al., 1992
Resp. ER visit	5-hour mean	Weisel et al., 1995
Resp. ER visit	1-hour max	Stieb et al., 1996
Resp. ER visit	24-hour mean	Stieb et al., 1996
Resp. ER visit	8-hour max	Jaffe et al., 2003
Mortality	24-hour mean	Samet et al., 1997
Mortality	24-hour mean	Moolgavkar et al., 1995
Mortality	1-hour max	Ito and Thurston, 1996
Mortality	24-hour mean	Bell et al., 2005
Mortality	24-hour mean	Bell et al., 2005
Mortality	24-hour mean	Bell et al., 2004
Mortality	1-hour max	Ito et al., 2005
Mortality	1-hour max	Ito et al., 2005
Mortality	1-hour max	Levy et al., 2005
Mortality	1-hour max	Levy et al., 2005
School Loss	1-hour max	Chen et al., 2000
School Loss	8-hour mean	Gilliland et al., 2001
Acute Resp. Symp.	1-hour max	Ostro and Rothschild, 1989
Worker Prod.	24-hour mean	Crocker and Horst, 1981

[1] see Abt Assoc., 2005, for complete details
[2] HA: Hospital Admissions
[3] ER: Emergency Room

Table 4. $PM_{2.5}$ CR functions used in the health analysis

Health Endpoint	Metric	Author and Year[1]
Mortality	Quarterly mean	Pope et al., 2002
Acute Myocardial Infarction	24-hour mean	Peters et al., 2001
HA[2], Resp.	24-hour mean	Moolgavkar, 2000
HA, Resp.	24-hour mean	Moolgavkar, 2003
HA, Resp.	24-hour mean	Ito, 2003
HA, Resp.	24-hour mean	Ito, 2003
HA, Resp.	24-hour mean	Sheppard, 2003
Chronic Bronchitis	Quarterly mean	Abbey et al., 1995
Acute Bronchitis	Quarterly mean	Dockery et al., 1996
HA, CVD[3]	24-hour mean	Moolgavkar, 2003
HA, CVD	24-hour mean	Moolgavkar, 2000
HA, CVD	24-hour mean	Ito, 2003
HA, CVD	24-hour mean	Ito, 2003
HA, CVD	24-hour mean	Ito, 2003
ER[4] Visits, Resp.	24-hour mean	Norris et al., 1999
Acute Resp. Symptoms	24-hour mean	Ostro and Rothschild, 1989
Lower Resp. Symptoms	24-hour mean	Schwartz and Neas, 2000
Asthma	24-hour mean	Ostro et al., 2001
Asthma	24-hour mean	Vedal et al., 1998
Asthma	24-hour mean	Ostro et al., 2001
Asthma	24-hour mean	Ostro et al., 2001
Work Loss Days	24-hour mean	Ostro, 1987
Upper Resp. Symptoms	24-hour mean	Pope et al., 1991

[1] see Abt Assoc., 2005, for complete details
[2] HA: Hospital Admissions
[3] CVD: Cardiovascular Disease
[4] ER: Emergency Room

Overall reductions in population exposure to O_3 (total for Georgia), associated with several sensitivity cases (Figure 1), illustrate the complexities in quantifying the health benefits of O_3 reductions. Opposite trends are observed depending on the choice of metric and season. Hence, the choice of CR function to be used in BenMAP would have a strong impact on the quantification of the change in mortality/morbidity and associated monetary value. Specifically, the choice of CR function for mortality, available based on both the 1-hour max and the 24-hour mean concentrations, would yield conflicting results. Of note is that monetary benefits from reduced mortality typically far overweigh morbidity related benefits (Hubbell et al., 2005).

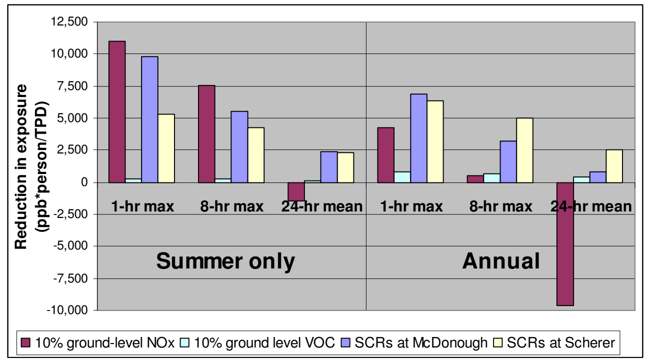

Fig. 1. Reductions in exposure to O_3 (ppb*person/TPD) as a function of emissions control scenario, O_3 metric, and season. Increases in exposure to the 24-mean metric are observed for ground level NO_x controls.

Overall reductions in population exposure to $PM_{2.5}$ (total for Georgia) associated with several sensitivity cases (Figure 2) generally follow the same trends as shown in Table 2. Ground level controls of primary carbon, though limited in the spatial extent (Figure 3), occur, in the case modeled here, in the most densely populated area of Georgia (Atlanta), and hence yield a substantial reduction in exposure (measured both as $\mu g/m^3$*person/TPD and $\mu g/m^3$*person). SO_2 controls (scrubbers, assuming 95% removal efficiency) at major coal-fired power plants in Georgia also yield substantial reductions in exposure ($\mu g/m^3$*person) to ambient $PM_{2.5}$.

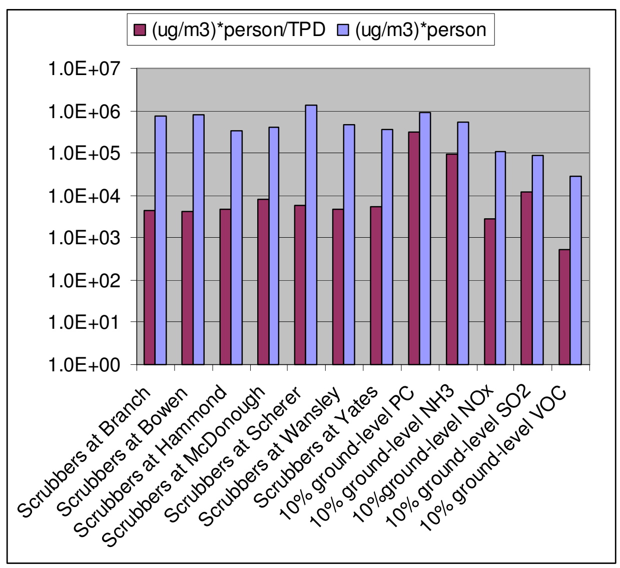

Fig. 2. Annual (average of a summer and a winter episode) reductions in exposure to $PM_{2.5}$ ($\mu g/m^3$*person/TPD and $\mu g/m^3$*person) for various emissions control scenarios.

Valuation of the monetary benefits of several $PM_{2.5}$ controls (Table 5) can serve as a basis for a cost-benefit analysis, comparing health-related benefits to control cost estimates.

Table 5. Annual[1] monetary benefits from various $PM_{2.5}$ control strategies

Control scenario (ground level or EGU controls)	Benefits (10^6\$)	Benefits(10^6\$) / ton-per-day
10% ground level primary carbon	223	78.0
10% ground level SO_2	22.7	2.96
10% ground level NO_x	29.1	0.75
10% ground level NH_3	127	23.2
10% ground level VOCs	7.23	0.14
2 Scrubbers at Plant Bowen	211	1.10
4 Scrubbers at Plant Branch	206	1.22
2 Scrubbers at Plant McDonough	107	2.07
4 Scrubbers at Plant Scherer	375	1.62
4 Scrubbers at Plant Hammond	93.5	1.28
1 Scrubbers at Plant Wansley	124	1.26
2 Scrubbers at Plant Yates	95.9	1.53

[1] Represented by averaging a summer and a winter episode

4. DISCUSSION

Reductions in emissions of $PM_{2.5}$ and its precursors yield a reduction in overall population exposure to $PM_{2.5}$ in Georgia. The spatial extent of reductions in $PM_{2.5}$ varies based on the pollutant examined (Figures 3 and 4), however the overall reductions in exposure would depend on the product of change in $PM_{2.5}$ levels and population in each model grid cell. For example, controlling local emissions of primary carbon may introduce a substantial reduction in population exposures, in highly populated areas. Some locally increased levels of $PM_{2.5}$ were observed in the case of ground-level NO_x controls (due to elevated wintertime O_3 leading to increased $SO_2 \rightarrow SO_4^{-2}$ oxidation), but this increase in exposure is outweighed by larger reductions in $PM_{2.5}$ in other NH_3-rich/NO_x-limited areas (Figure 5).

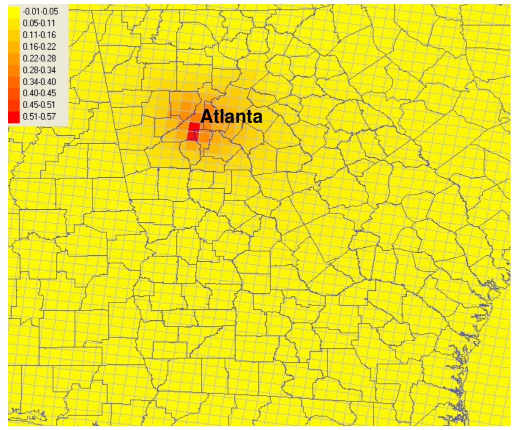

Fig. 3. Modeled annual average reduction in $PM_{2.5}$ ($\mu g/m^3$) due to a 10% reduction in ground-level primary carbon emissions in Atlanta. Reductions occur in proximity of the controlled sources/region.

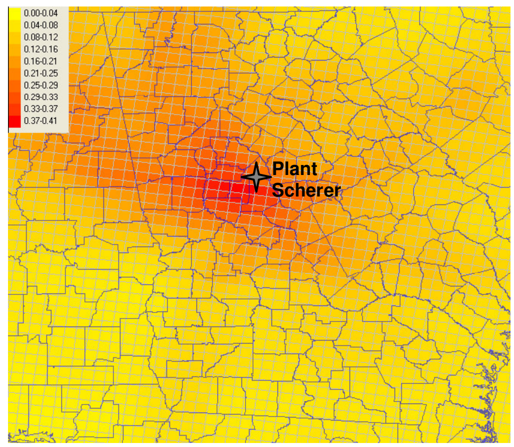

Fig. 4. Modeled annual average reduction in $PM_{2.5}$ ($\mu g/m^3$) from the installation of scrubbers at Plant Scherer. A regional reduction in $PM_{2.5}$ is observed.

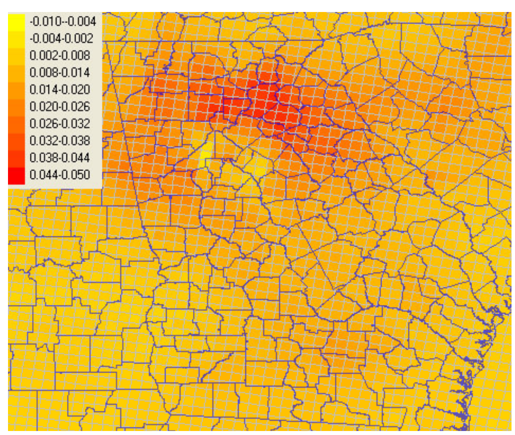

Fig. 5. Modeled annual average reduction in $PM_{2.5}$ ($\mu g/m^3$) associated with a 10% reduction in ground-level NO_x emissions in Atlanta. Some small local increases in $PM_{2.5}$ are observed, but are outweighed by larger reductions in other NH_3-rich/NO_x-limited areas.

Quantifying the health benefits associated with various O_3 control strategies is a complex issue, and the quantification would depend on the choice of O_3 metric to be used, exposure period (year-round or “ozone season” only) and threshold applied. Potential increases in 24-hour mean O_3 concentrations associated with NO_x controls are due, in this case, to reduced nighttime titration of O_3, as shown by the diurnal patterns in Figure 6. This is more evident in the case of ground-level NO_x emissions than the case of elevated point source emissions (e.g., Plant McDonough in Figure 6), as in the latter case nighttime NO_x is typically emitted above the mixing layer. Potential increases in exposure to 24-hour mean O_3 levels from ground-level NO_x controls occur mainly during wintertime (Figure 1), and the effect of including wintertime O_3 in the analysis is also evident in the case of exposure to 1-hour and 8-hour maximum O_3 levels.

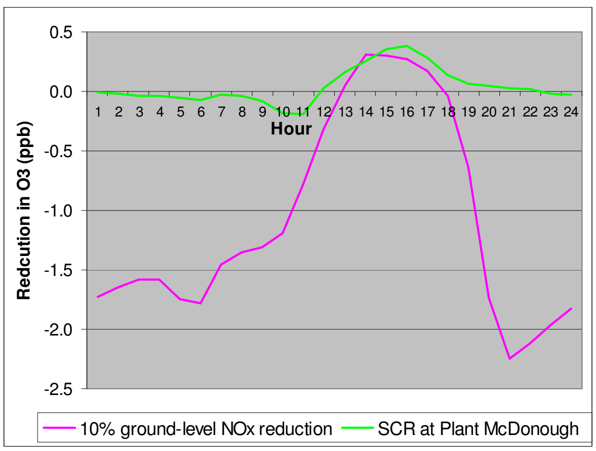

Fig. 6. Summertime average diurnal patterns of reductions in O_3 in Atlanta, associated with ground level and point source NO_x controls. A decrease in peak daytime concentrations of O_3 is observed. However, increased O_3 concentrations are observed (mainly) in nighttime, due to reduced titration of O_3 by NO_x.

The issue of whether to include wintertime and nighttime (incorporated in the 24-hour values) O_3 in the health assessment is a complex one. From a regulatory perspective, O_3 is considered a “seasonal” pollutant, and the NAAQS refers to peak summertime concentrations (the “ozone season”). However, recent evidence (Bell et al., 2006) suggests associations between ozone and mortality at levels far below the current 8-hour standard, with significant associations reported even at O_3 levels of 25 ppb (24-hour average). On the other hand, nighttime personal exposure to O_3 is likely much lower than daytime (as the majority of the population is indoors and less active), however such effects are not accounted for in BenMAP. Recent evidence (Darrow et al., 2006) suggests significant associations between daytime and 24-hour O_3 concentrations and cardio-respiratory outcomes, but no significant associations were found between such outcomes and nighttime O_3. This may suggest that the associations and risk-ratios reported for 24-hour O_3 are in large a reflection of peak daytime O_3. Finally, another issue that needs to be noted and considered regarding nighttime and wintertime O_3 is model performance, which is poorer compared to that of peak daytime concentrations (Table 6).

Table 6. Correlation coefficients (R) between modeled and observed O_3 (at the Atlanta Jefferson St. site) for various O_3 metrics

O_3 metric	Summer	Winter
1-hour max	0.87	0.35
8-hour max	0.88	0.51
24-hour mean	0.68	0.66

Preliminary estimates of the monetary benefits associated with various O_3 control strategies (Figure 7) further demonstrate the effects of choice of CR function and season/threshold on the estimate obtained. For all cases reported here a combination of 1-hour-max and 24-hour-mean mortality CR functions was used, except for the “Ground NO_x (summer, 1-hr metric)” case.

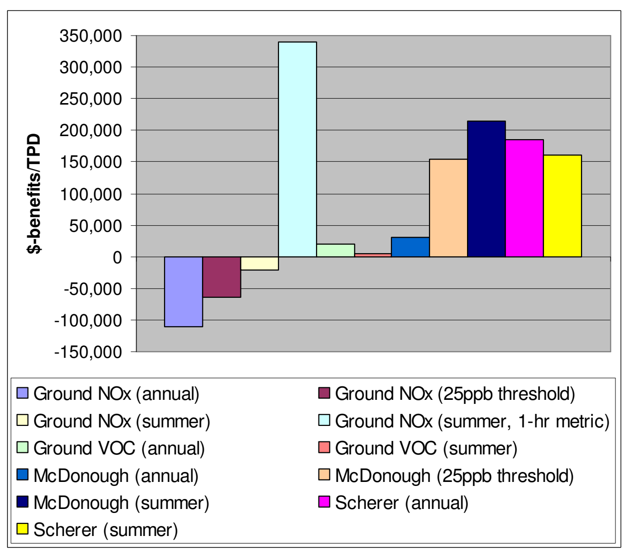

Fig. 7. Preliminary estimates of the monetary benefits associated with various O_3 control strategies.

5. SUMMARY

BenMAP was used in combination with results from a CMAQ sensitivity analysis to estimate the health benefits associated with various O_3 and $PM_{2.5}$ control strategies. Despite uncertainties in the quantification of $PM_{2.5}$ related benefits (such as choice of CR function etc.), consistency was observed and benefits were reported for all cases examined. The case of O_3 was more complex, and the choice of CR function (based on different O_3 metrics) had a substantial impact on the benefits quantification process. However, even under the most beneficial O_3 control scenario reported here ($340,000/ton; Figure 7), O_3 related benefits were still substantially lower (on a per-ton basis) than benefits associated with most $PM_{2.5}$ control strategies ($140,000-$78,000,000/ton; Table 5).

6. REFERENCES

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