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PROFILE

An Integrated Framework for Multipollutant Air Quality Management and Its Application in Georgia

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Abstract Air protection agencies in the United States increasingly confront non-attainment of air quality standards for multiple pollutants sharing interrelated emission origins. Traditional approaches to attainment planning face important limitations that are magnified in the multipollutant context. Recognizing those limitations, the Georgia Environmental Protection Division has adopted an integrated framework to address ozone, fine particulate matter, and regional haze in the state. Rather than applying atmospheric modeling merely as a final check of an overall strategy, photochemical sensitivity analysis is conducted upfront to compare the effectiveness of controlling various precursor emission species and source regions. Emerging software enables the modeling of health benefits and associated economic valuations resulting from air pollution control. Photochemical sensitivity and health benefits analyses, applied together with traditional cost and feasibility assessments, provide a more comprehensive characterization of the implications of various control options. The fuller characterization both informs the selection of control options and facilitates the communication of impacts to affected stakeholders and the public. Although the integrated framework represents a clear improvement over previous attainment-planning efforts, key remaining shortcomings are also discussed.

Keywords Air pollution control · Cost–benefit analysis · Ozone · Fine particulate matter · State implementation plans · Attainment

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Introduction

The Clean Air Act requires the United States Environmental Protection Agency (U.S. EPA) to establish National Ambient Air Quality Standards (NAAQS) for the protection of public health and the environment. U.S. EPA currently administers NAAQS limits for six criteria pollutants: lead, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter (PM), and ozone. With the promulgation of more stringent standards for ozone and fine particulate matter ($PM_{2.5}$, denoting particles with aerodynamic diameter less than 2.5 microns) (U.S. EPA 1997a, 1997b), these two pollutants now comprise the bulk of NAAQS violations. Both pollutants have been linked to significant health impacts in humans, including respiratory problems and premature mortality (e.g., Brunekreef and Holgate 2002, Bell and others 2005). Many metropolitan regions, especially in the eastern United States and California, now confront nonattainment for both the ozone and $PM_{2.5}$ standards (U.S. EPA 2004c, 2005a). In addition, the Regional Haze Rule (U.S. EPA 1999) requires the remedying of visibility impairment at designated pristine sites known as Class I areas.

As part of the air quality management system, states are responsible for developing implementation plans (SIPs) to attain each NAAQS limit and to address regional haze. Although ozone, $PM_{2.5}$, and haze (which is caused

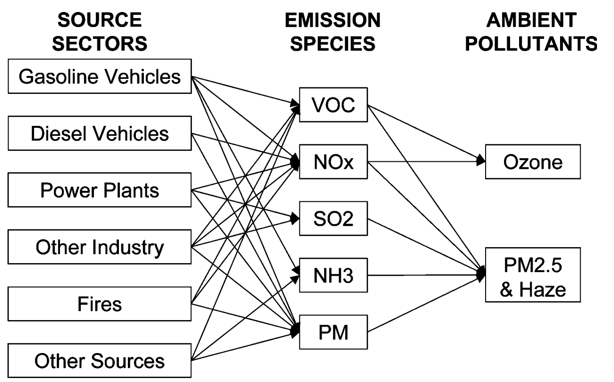

Fig. 1 Interrelated origins of ozone, fine particulate matter ($PM_{2.5}$), and haze

primarily by fine particles) share common emissions sources and precursor species (Figure 1), states confront disjoint attainment deadlines, region boundaries, and modeling protocols for each pollutant. A seminal review by the National Research Council (NRC 2004) highlighted some of the shortcomings resulting from this disjoint consideration of pollutants:

> Air pollutants occur in complex mixtures, and yet SIPs are constrained to address only individual criteria pollutants. As a result, the entire, relatively cumbersome SIP process must be undertaken for a pollutant such as ozone and then again for PM in a separate process and on a different timetable, despite the fact that the exposures are simultaneous, the sources are often the same, and the two pollutants share many common chemical precursors. (p. 130)

Although the NRC report focused on air quality management in the United States, a lack of integrated assessment across multiple priorities afflicts environmental planning in countries worldwide (Sexton 1999). The NRC recommended a shift toward a multi-pollutant paradigm that seeks cost-effective and simultaneous reduction of multiple pollutants to improve overall air quality (NRC 2004).

The multi-pollutant paradigm heightens the importance for policymakers to consider not only costs but also health improvements and other benefits of pollution abatement in developing attainment plans. As demonstrated by Chestnut and others (2006), consideration of benefits may yield a multi-pollutant attainment strategy with greater net benefits than one optimized for cost alone, due to the overlapping impacts of control measures and the different benefits associated with controlling each pollutant. In practice, however, benefits have typically remained poorly quantified, both due to lack of resources and because states are mandated to demonstrate regulatory attainment, not to deliver a particular level of benefits to society.

With growing awareness of multi-pollutant linkages (NRC 2004) and the emergence of improved resources for evaluating costs (e.g., AirControlNET (E.H. Pechan 2005)) and benefits (e.g., BenMAP (Abt Associates 2005)), the Georgia Environmental Protection Division (Georgia EPD) has sought a more comprehensive approach to air quality management. The State of Georgia currently confronts nonattainment of ozone and $PM_{2.5}$ standards in several of its metropolitan regions and must also demonstrate progress toward reducing regional haze in its three Class I areas (Figure 2). Here, we present the approach adopted by Georgia EPD to integrate cost and benefit assessments with atmospheric sensitivity analysis for the development of multi-pollutant attainment strategies. Although the case presented here describes the specific actions of one state agency, the general approach could be applied by any environmental agency seeking to attain multiple pollutant standards.

Traditional Approach

The process that Georgia EPD and most other environmental agencies have traditionally followed for developing air quality attainment strategies is summarized in Figure 3. Under this process, an agency identifies a menu of emission control options and assesses the cost and feasibility of each measure. The agency then selects an overall control strategy and applies a photochemical model by a specified process (e.g., U.S. EPA 2005b) to determine whether that ensemble of measures is sufficient to attain the standard. An iterative selection of additional measures then proceeds until attainment is demonstrated and the strategy is implemented.

When only a single pollutant or precursor emission species is targeted, the above process may prove adequate. In particular, if the impact of each emitted ton is roughly uniform, then cost per ton and other practical considerations will be sufficient bases for prioritizing control measures. Omitting consideration of health and other benefits may hinder the communication of impacts to stakeholders and the public, but likely would not skew option prioritization in this case because benefits would scale proportionally with emissions reductions. However, if per-ton impacts vary markedly with the time or location of emission origin, modeling only the aggregate strategy will fail to distinguish the relative effectiveness of each measure.

The inadequacies of the traditional approach become more pronounced in the case of multi-precursor and multi-pollutant attainment strategies. Modeling only the aggregate impact of an overall strategy cannot determine which component measures yield the greatest impact. If the initial strategy is modeled to be insufficient for attainment,

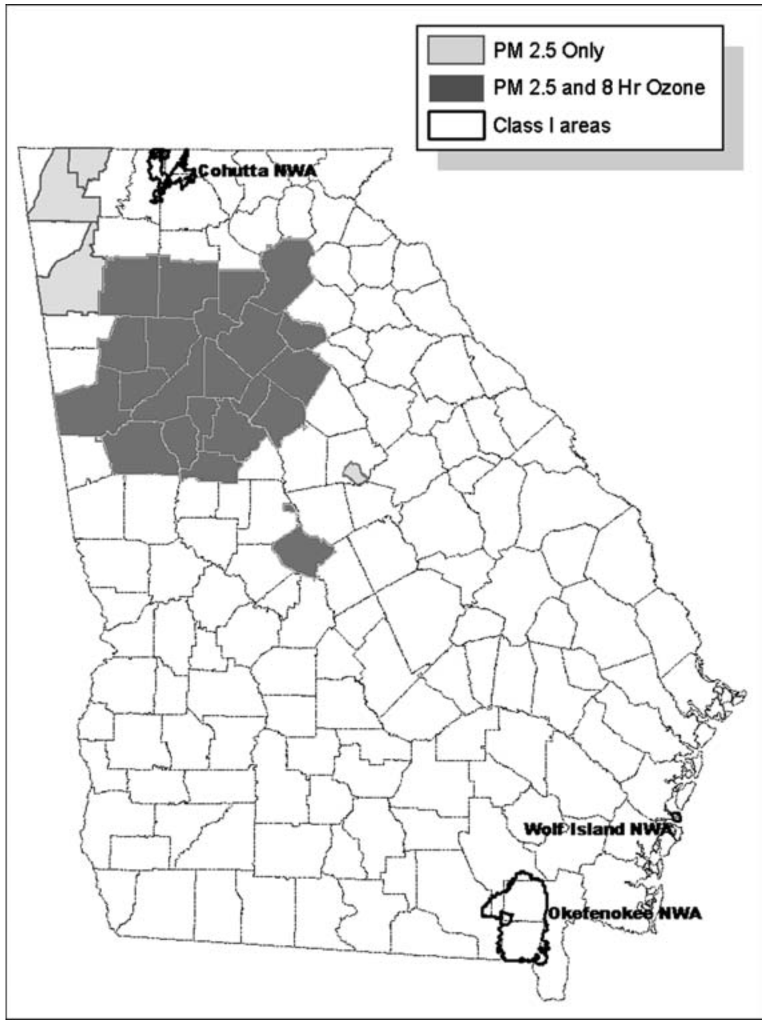

Fig. 2 Ozone and fine particulate matter ($PM_{2.5}$) non-attainment regions and Class I visibility protection areas in Georgia

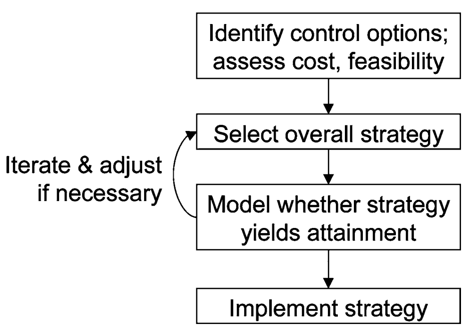

Fig. 3 Traditional framework for developing single-pollutant air quality attainment plans

additional measures cannot be effectively prioritized without knowledge of the relative sensitivity of ambient concentrations to each precursor. Furthermore, the isolated treatment of each attainment demonstration and lack of assessment of benefits in the traditional approach precludes cross-pollutant prioritization that could enhance overall cost-effectiveness (Chestnut and others 2006).

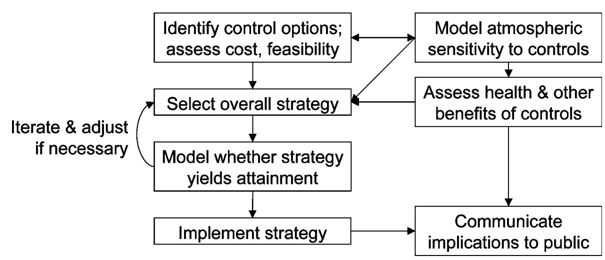

Fig. 4 Integrated framework for developing multi-pollutant air quality attainment plans

Integrated Framework

Overview

Recognizing the shortcomings of the traditional approach and facing SIP deadlines for multiple pollutants and non-attainment regions, Georgia EPD has adopted an integrated framework for addressing multi-pollutant attainment (Figure 4). Under this framework, emissions sensitivity analysis is conducted early in the process, in parallel with the identification and cost assessment of control options. The sensitivity analysis simulates representative air pollution episodes to compute the responsiveness of ambient concentrations to potential emissions controls, with sensitivities expressed in terms of the change in ambient concentration per unit change in emissions. Observational analysis of monitored air quality data supplements the photochemical models in specific ways described later. Atmospheric sensitivities (units: e.g., parts-per-billion/ton-per-day (ppb/tpd), considering concentrations evaluated on the relevant time frame for that pollutant standard and emissions averaged over the episode) are then linked with cost estimates (units: $/tpd) to provide an objective metric quantifying the cost-effectiveness (units: e.g., $/ppb) of each option toward achieving attainment. These metrics can be computed for each ambient pollutant standard at each monitor, with special attention to conditions at the most polluted monitors. By linking spatial patterns of atmospheric sensitivities with human population distribution and epidemiological relationships, the potential health benefits of each control option can be assessed.

An overall strategy can thereby be developed with fuller consideration of its implications for costs, benefits, and attainment across regions and pollutants. As can be seen by comparing Figures 3 and 4, the selection of measures for the overall strategy can be influenced by far more factors than simply cost and feasibility. Although the integrated approach provides objective metrics for evaluating each option, it must be recognized that other considerations such as practical realities and equity across stakeholders can and should influence the actual selection of measures. Finally, longer-term photochemical modeling must be conducted to demonstrate attainment from the overall selected strategy before it can be incorporated into SIPs and implemented, to account for interactions across measures and other details that cannot be adequately captured by the sensitivity modeling of short-term episodes.

The process of control strategy development for ozone and $PM_{2.5}$ SIPs in Georgia continues to be ongoing as of March 2007. Resources devoted to the modeling and analysis described here include five staff members who have worked to examine the feasibility and cost of potential controls, and four Ph.D.-trained modelers who have conducted the photochemical sensitivity analysis and health assessments. Control options are being evaluated by managers at the Air Protection Branch and by Georgia EPD's Director's Office, with input from an ongoing stakeholder process. Ultimately, the SIPs must be approved by the Board of the Georgia Department of Natural Resources and by the U.S. EPA.

The following sections detail each component of the integrated framework as applied to control strategy development in Georgia.

Cost and Feasibility Analyses

The integrated process begins with a comprehensive effort to identify options for controlling emissions of each precursor. Control options are identified for each major component of the emissions inventory: major industrial facilities known as ''point sources''; ''mobile sources,'' which include both on-road and non-road vehicles and equipment; and ''area sources,'' which include a variety of emitters such as prescribed fires, meat cooking, and residential fuel combustion, as well as businesses whose emissions are too small to be tracked as point sources.

For point sources, Georgia EPD applied AirControlNET (E.H. Pechan 2005) to identify potential retrofit technologies and their associated emissions reductions and costs. The software links emissions inventories with a matrix of control options compiled from existing literature. AirControlNET may omit certain options or fail to account for facility-specific conditions that influence feasibility and cost-effectiveness, but it serves as a helpful initial scoping tool of plausible options. Georgia EPD then conducts an extensive process, including input from affected industries, to analyze the emissions reductions and cost-effectiveness that could feasibly be achieved by controls at each source.

Mobile and area sources are considered on a sector-by-sector basis to identify control options. Because comprehensive assessment software is not available for these sectors, potential costs and emissions reductions are estimated by reviewing available literature or empirical evidence regarding the performance of previous projects. With peer-reviewed literature lacking for many mobile and area source control options, much of this review relies on a variety of gray literature sources (e.g., E.H. Pechan 2002; California Air Resources Board 2004, Sierra Research 2005). Interagency and stakeholder forums such as the Georgia Diesel Working Group, the Southeast Diesel Collaborative, and the Idling Reduction Stakeholder Group have informed the assessment of certain options.

Ideally, the above steps would yield a comprehensive menu of potential control options, their costs, and their impacts on emissions. However, as of March 2007, that process is still ongoing and it has proven difficult to determine the actual feasibility and costs of some potential measures.

Atmospheric Sensitivity Analyses

In order to quantify the response of ozone, $PM_{2.5}$, and regional haze to emissions reductions from various sources, Georgia EPD is using the MM5/SMOKE/CMAQ modeling system to perform episodic emission sensitivity analysis (Boylan and others 2006). This modeling system consists of the NCAR/PSU Mesoscale Modeling System (MM5) meteorological model (Grell and others 1994), the Sparse

Matrix Operator Kernel Emissions (SMOKE) emissions model (Houyoux and others 2000), and the Community Multiscale Air Quality (CMAQ) photochemical model (Byun and Schere 2006). This grid-based modeling system simulates hourly concentrations of ozone, PM, and other air pollutants throughout the modeling domain. Georgia EPD is applying these models to simulate ambient pollutant concentrations for 2002 (base year), 2009 (target year for ozone and $PM_{2.5}$), and 2018 (target year for regional haze) on a modeling domain that covers the entire states of Georgia, Alabama, Mississippi, South Carolina, Tennessee; most of North Carolina and Florida; and small pieces of the surrounding states. This represents a subdomain of modeling developed by the Visibility Improvement State and Tribal Association of the Southeast (VISTAS) regional planning organization (Morris and others 2005).

Future year emissions were projected for each source category to account for ‘‘on-the-books’’ control programs at the federal, state, and local level and expected economic growth. In 2009, it was estimated that Georgia would see a 34% reduction in SO_2 emissions (mostly due to electric-generating unit (EGU) point sources), 23% reduction in NOx emissions (mostly due to on-road mobile and EGU point source reductions), and 14% reduction in anthropogenic volatile organic compounds (VOC) emissions (mostly from on-road and non-road mobile sources) relative to 2002. Because of computational limitations, the specific modeling episodes for sensitivity analysis consist of one summer and one winter 30-day period, selected on the basis of Classification and Regression Tree (CART) analysis for ozone and $PM_{2.5}$ (Douglas and others 2005a, 2005b). CART examines the frequency of various meteorological regimes and can be used to identify episodes best suited for representing longer periods of time (e.g., entire years or summer ozone seasons).

Actual 2002 model estimates for ozone, PM, and gaseous precursors were compared against observations from various monitoring networks in order to assess model performance (Morris and others 2005, Tesche and others 2006). Once satisfactory model performance was achieved, future year emissions were input into the modeling system (with 2002 meteorological fields) to produce future-year modeled pollutant distributions. To increase confidence in the model's ability to predict future design values, EPA guidance (U.S. EPA 2006) suggests that modeling results be used in a relative sense rather than looking at the absolute change in concentrations. Therefore, future design values are calculated by multiplying the 2002 5-year design value (used for EPA's model attainment test) by a Relative Reduction Factor (RRF) where the RRF is the ratio of future modeled mean concentrations to base year modeled mean concentrations. For ozone, only days when the modeled base year ozone concentrations exceeded 85 ppb were included in the RRF calculation.

Currently, 12 ozone-monitoring sites in Atlanta and one in Macon have 5-year design values above the NAAQS. The predicted future design values for these sites are all below 85 ppb except for Confederate Avenue, which has a value of 87. For $PM_{2.5}$, Georgia has 11 monitoring sites in Atlanta and one site in Macon, Floyd County, and Chattanooga that have 5-year design values above the NAAQS. The predicted future design values for these sites are all below 15 μg/m^3 except for Fire Station 8, which has a value of 17.1 μg/m^3, and two other Atlanta sites with values of 15.6 and 15.3 μg/m^3. Thus, for attainment purposes, sensitivity modeling has focused on the Confederate Avenue monitor for ozone and Fire Station 8 for PM (Tables 1 and 2).

‘‘Regional’’ emissions sensitivities examine the impact of emissions from specific geographic regions (e.g., Atlanta 20 county non-attainment area). These regional sensitivities are computed by comparing ozone, $PM_{2.5}$, and haze levels in a standard target year simulation to levels in a similar simulation in which anthropogenic emissions of nitrogen oxides (NO_x), VOCs, SO_2, ammonia, or primary organic and elemental carbon particles (PC) have been reduced by 10% in a given region. The individual sensitivity responses can be scaled up or down to approximate pollutant responses to other magnitudes of emission reduction, although the accuracy of extrapolations diminishes with the size of the extrapolation and the nonlinearity of the response (Hakami and others 2004, Cohan and others 2005).

Georgia point source emissions of NO_x and SO_2 are dominated by seven large coal-fired EGUs at which specific control technologies may be applicable. Thus, rather than considering these EGUs as part of the arbitrary 10% regional emission sensitivity simulations described above, Georgia EPD has directly modeled the potential impacts of installing selective catalytic reduction (SCR) for NO_x and flue gas desulfurization (‘‘scrubbers’’) for SO_2 at the facilities. The potential emissions reductions associated with these sensitivities range from 65% to 95%, depending on the current control technologies operating at each power plant. The final sensitivity results are presented as an absolute change (ppb or μg/m^3) and as a relative change on a tons per day basis (ppt/tpd or ng/m^3/tpd) so that the total impacts and per-ton efficiencies of EGU controls can be considered (Tables 1 and 2). Although the Clean Air Interstate Rule establishes interstate cap-and-trade markets for EGU NO_x and SO_2 emissions, Georgia EPD does not model any changes in out-of-state emissions that might result from additional Georgia EGU emissions reductions beyond the base case.

Table 1 Costs and benefits of scenarios for reducing ozone in Atlanta

Control Scenario	Annual cost (10^6 $)	Emissions reduced[a] (tpd)	Ozone response at monitor[b] (ppb)	Ozone sensitivity at monitor[b] (ppt/tpd)	Annual statewide benefits[c] (10^6 $)	Annual cost per 1 ppt reduction at monitor ($)	Cost per $1 health benefits ($)
10% Atlanta NO_x[d]	N/A	38	1.36	35.7	21.9	N/A	N/A
10% Atlanta VOC[d]	N/A	49	0.08	1.5	0.12	N/A	N/A
SCRs at Power Plant 1	8[e]	7	0.42	60.4	3.7	$19,000	$2.2
SCRs at Power Plant 2	43[e]	34	0.41	13.7	10.4	$106,000	$4.2

[a] On tons per ozone season day basis. SCRs reduce NO_x emissions

[b] Average ozone response and per tpd sensitivity at Atlanta's Confederate Avenue monitoring station to each emission reduction scenario, based on seven CMAQ-simulated days in which the 2002 base case modeled 8-hour ozone concentration was above 85 ppb

[c] Statewide health benefits computed by BenMAP based on ozone concentration-response functions for exposure of up to 8 hours

[d] Hypothetical scenarios of uniformly reducing regional non–power plant emissions by 10%. Actual costs of NO_x and VOC reductions will vary by particular control measure

[e] Costs computed in Year 1999 U.S. dollars based on costing equations from the Integrated Planning Model v. 2.1.9 (U.S. EPA 2004d) and baseline plant characteristics from VISTAS 2009 projections. SCRs are assumed to operate year-round

ppb, parts-per-billion; *ppt*, parts-per-trillion; *tpd*, tones per day; *NO_x*, nitric oxide; *VOC*, volatile organic compounds; *SCR*, selective catalytic reduction; *CMAQ*, Community Multiscale Air Quality

Table 2 Costs and benefits of scenarios for reducing fine particulate matter ($PM_{2.5}$) in Atlanta

Control scenario	Annual cost (10^6 $)	Emissions reduced[a] (tpd)	$PM_{2.5}$ response at monitor[b] (μg/m3)	$PM_{2.5}$ sensitivity at monitor[b] (ng/m3/tpd)	Annual statewide benefits[c] (10^6 $)	Annual cost per 1 ng/m^3 reduction at monitor ($)	Cost per $1 health benefits ($)
10% Atlanta PC[d]	N/A	2	0.25	85.7	223	N/A	N/A
10% Atlanta NH_3[d]	N/A	5	0.09	22.5	127	N/A	N/A
Scrubbers at Power Plant 1	30[e]	49	0.070	1.39	107	$426,000	$0.28
Scrubbers at Power Plant 2	124[e]	278	0.150	0.56	375	$825,000	$0.33

[a] On annual average tons per day basis. Scrubbers reduce SO_2 emissions

[b] Average $PM_{2.5}$ response and per ton-per-day sensitivity at Atlanta's Fire Station 8 monitoring station to each emission reduction scenario, based on CMAQ simulations of a summertime and wintertime episode

[c] Statewide health benefits computed by BenMAP based on concentration-response functions to annual $PM_{2.5}$

[d] Hypothetical scenarios of uniformly reducing regional non–power plant emissions by 10%. Actual costs of primary carbon and ammonia reductions will vary by particular control measure

[e] Costs computed in Year 1999 U.S. dollars based on costing equations from the Integrated Planning Model v. 2.1.9 (U.S. EPA 2004d) and baseline plant characteristics from VISTAS 2009 projections

tpd tons per day, *pc* carbon particles, *CMAQ* Community Multiscale Air Quality

Sensitivity modeling by Georgia EPD shows ozone to be far more responsive to NO_x than to VOCs, indicating that Atlanta is in a NO_x-limited regime. Atlanta ozone is also responsive to the installation of SCRs at two of the major power plants, one located inside and the other larger one located outside of the 20-county Atlanta non-attainment area (Power Plant 1 and Power Plant 2, respectively). Controls at other plants showed substantially less impact on ozone.

Seasonal average $PM_{2.5}$ sensitivities were calculated for the summer and winter episodes, and ''annual'' sensitivities were calculated by assigning different weighting factors to each episode day based on how important that day was to the annual average (Table 2). For $PM_{2.5}$ controls, the largest benefits are achieved from additional controls of regional PC from Atlanta. Controls of regional SO_2, NO_x, and VOCs have a much smaller benefit. Atlanta $PM_{2.5}$ was also responsive to the installation of scrubbers at all major power plants in Georgia, and reported here are the results for the above-mentioned Power Plants 1 and 2. In addition, atmospheric sensitivity analysis indicated that local ammonia emissions contribute strongly to wintertime $PM_{2.5}$, which prompted an intensified search for control options for this often-neglected precursor. Unfortunately, no new ammonia controls were identified as being cost effective.

Overall strategies for ozone and $PM_{2.5}$ are still under development in Georgia. After sensitivity analysis is complete and control measures are selected, it will still be necessary to model the impact of the overall control strategy so that attainment over the full time period can be demonstrated and nonlinear interactions among component measures (Cohan and others 2005) are not neglected. If modeling of an initial overall control strategy indicates that further control is necessary, the sensitivity results can inform the search for additional measures and thereby lessen the need for iterations between modeling and strategy development (Figure 4). Although not currently slated for use by Georgia EPD, advanced sensitivity analysis techniques such as the high-order decoupled direct method (Hakami and others 2004) or response surface modeling (Dennis and others 1999) could also assist in the search for additional controls.

One limitation of air quality modeling and sensitivity analysis is that it relies on the accuracy of the underlying meteorology and emissions inventory. For many emissions components, including primary PM, there are considerable uncertainties in the inventory. Thus, Georgia EPD has chosen to supplement its emissions-based modeling with observational analyses to better understand the sources of ambient pollutants. In particular, observation-based source apportionment analyses have been conducted using the Chemical Mass Balance model (U.S. EPA 2004a, 2004b) and positive matrix factorization (Paatero 1997) upon speciated $PM_{2.5}$ measurements to estimate the contribution of various emissions categories to overall concentrations (Marmur 2006a). Taken together, inventory-based sensitivity analysis and observation-based source apportionment provide a fuller picture of the likely impacts of controls and the associated uncertainties (Marmur and others 2005, 2006).

Benefits Analysis

The control of air pollution may yield significant benefits for a wide range of factors including human health, visibility, agriculture, forestry, building materials, and natural ecosystems. However, the protection of human health is the driving motivation behind the Clean Air Act. Comprehensive assessments of air pollution abatement benefits (e.g., U.S. EPA 1997c) generally find health effects to dwarf all other impacts on a monetized basis. Thus, efforts to quantify the benefits of air pollution control have largely focused on health impacts.

Georgia EPD is applying the Environmental Benefits Mapping and Analysis Program (BenMAP) (Abt Associates 2003) to assess reductions in population exposure to ozone and $PM_{2.5}$ and the potential health benefits associated with these reductions. BenMAP derives these estimates of health-related benefits by utilizing concentration-response (CR) functions, which relate a change in the concentration of a pollutant to a relative change in the incidence of morbidity and mortality (e.g., Pope and others 2002). Spatial estimates of ambient pollutant concentrations (as modeled by CMAQ) are input into BenMAP, which considers population distributions and CR functions to compute the health impacts resulting from those pollutant levels. BenMAP can also associate each health outcome with a monetized per-incident value to translate morbidity and mortality into associated economic valuations.

BenMAP can be applied to compare the health impacts of various control options considered by atmospheric sensitivity analysis, or to quantify the health impacts of an overall strategy modeled by CMAQ. Benefits analysis allows environmental authorities to evaluate and prioritize various options from the standpoint of reducing overall population exposure to air pollution, on top of the requirement to show attainment at specific monitoring sites (which is also the driving factor for sensitivity analyses). Communicating the benefits of air quality control strategies to decision-makers, stakeholders, and the general public helps to translate unfamiliar quantities such as $\mu g/m^3$ of PM into tangible impacts such as premature death, asthma attacks, and associated monetary valuations.

Examples of statewide valuations are reported for the sensitivity cases discussed in the previous section (Tables 1 and 2). Ozone benefits presented here are based on CR functions for exposure of up to 8 hours (Marmur 2006b). These once more indicate the efficiency of NO_x controls for reducing ozone levels in Georgia (Table 1). Although the ozone benefits at the Confederate Avenue monitor of controlling Power Plants 1 and 2 are nearly identical, the statewide health benefits are almost three times higher for controlling Power Plant 2. This reflects the much larger size of Power Plant 2 and the closer proximity of Power Plant 1 to the monitor. A similar pattern is observed for $PM_{2.5}$ (Table 2), where the installation of scrubbers at Power Plant 2 produces $PM_{2.5}$ benefits at Fire Station 8 that are twice those of Power Plant 1; however, the statewide monetary benefits are more than three times higher due to the regional nature of sulfate. Controls of PC emissions also show a large benefit, because of the location of emissions in a highly populated area.

Cost-Effectiveness Comparisons

Considering the costs, atmospheric sensitivities, and health benefits together, the cost-effectiveness of control options can be compared with respect to regulatory attainment (cost per ambient improvement at the monitor) and health effect mitigation (cost per health benefit achieved) objectives. These metrics are computed by dividing the cost of a measure by the modeled ambient and health effect responsiveness.

As an illustrative example of cost-effectiveness comparisons, the final two columns of Tables 1 and 2 evaluate options for the two power plants discussed earlier. The more favorable cost-effectiveness of controls at Power Plant 1 than at Power Plant 2 reflects higher initial emission rates per Btu at Power Plant 1 and its closer proximity to densely populated regions and the Atlanta monitors. On a health effects basis, the results suggest more favorable cost-effectiveness for scrubbers than for SCRs, because of the greater monetized health impacts attributed to $PM_{2.5}$ than ozone. This does not necessarily argue against installation of SCRs, because both ozone and $PM_{2.5}$ standards must be attained and there may be other benefits beyond the health effects quantified here.

Conclusions

Incorporation of sensitivity analyses and cost and benefits assessments up front in the environmental management process can potentially enhance the selection of multi-pollutant control measures and the communication of the associated implications to the public. With that incorporation, each control option can be considered for its contribution both toward the attainment of air quality standards and toward the protection of human health. The integrated approach is especially valuable in the context of multi-pollutant attainment planning because it facilitates the comparison of disparate options on common metrics. As industrialized nations tighten standards for various air pollutants, the importance of multi-pollutant approaches will continue to increase.

The ongoing experience of Georgia EPD in shifting to an integrated framework for its air quality planning demonstrates the potential usefulness of this approach as well as some limitations. The emergence of faster and more affordable computers for atmospheric sensitivity analysis and improved tools for health benefits assessment has enabled sophisticated modeling of concentration-emission sensitivities and potential health impacts. Adoption of the integrated approach has already paid dividends in Georgia by (1) prompting a heightened focus on the precursor emissions most responsible for ambient pollutant concentrations, in particular NO_x for ozone and SO_2 and primary particles for $PM_{2.5}$; (2) yielding objective benefit metrics (both in terms of averted health effects and reduced concentrations at monitors per amount of emissions reduced) that inform the strategy selection process; and (3) facilitating Georgia EPD's mission to communicate the rationale and implications of its actions to the public and affected stakeholders. However, the identification and cost estimation of control options has lagged behind the other steps, hampering comprehensive comparisons of measures. Some control measures that may be crucial for attainment require long lead times, so in practice they are being pursued even before the full cost–benefit comparisons are available.

Beyond the particular experience of Georgia, several general shortcomings of the integrated approach should be noted as well. Atmospheric sensitivity analysis and cost and benefit assessments are only as accurate as the assumptions, data, and models that drive them. Important sources of uncertainty include the emissions inventories for photochemical modeling and the CR functions (via epidemiological studies) for estimating air pollutant health effects. Continued improvements are needed in emission inventories, control measure evaluation, and the representation of atmospheric science within air quality models. Analysis tools for other benefits such as visibility and ecosystem protection are even less mature than the health models. Given these uncertainties, the objective metrics are not the final arbiters of environmental decision-making, which should consider unquantifiable factors such as equity, practicality, and political realities.

Nevertheless, the integrated framework represents a clear improvement over previous approaches to attainment planning. As environmental authorities increasingly face multi-pollutant attainment challenges driven by interrelated precursor emissions, cost per ton is no longer a sufficient metric for prioritizing control options. The integrated framework provides a more complete understanding of the implications of each option so that both attainment and health objectives can more effectively be addressed.

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References

Abt Associates Inc. (2005) BenMAP environmental benefits mapping and analysis program user's manual. Prepared for U.S. EPA. Available at: http://www.epa.gov/ttn/ecas/benmodels.html (last accessed February 7, 2006)

Bell ML, Dominici F, Samet JM (2005) A meta-analysis of time-series studies of ozone and mortality with comparison to the National Morbidity, Mortality and Air Pollution Study. Epidemiology 16:436–445

Boylan JW, Marmur A, Khan M, Cohan DS (2006) 8-hour ozone and $PM_{2.5}$ modeling to support the Georgia SIP. Proceedings of the Air & Waste Management Association Annual Conference, Extended Abstract #509

Brunekreef B, Holgate ST (2002) Air pollution and health. Lancet 360:1233–1242

Byun DW, Schere KL (2006) Review of the governing equations, computational algorithms, and other components of the Models-3 Community Multiscale Air Quality (CMAQ) modeling system. Appl Mechanics Rev 59:51–77

California Air Resources Board (2004) Proposed list of measures to reduce particulate matter—PM10 and PM2.5. 109 pp. Available at http://www.arb.ca.gov/pm/pmmeasures/pmmeasures.htm (last accessed June 23, 2006)

Chestnut LG, Cohan DS, Mills DM (2006) Cost-benefit analysis in the selection of efficient multipollutant strategies. J Air Waste Manage Assoc 56:530–536

Cohan DS, Hakami A, Hu Y, Russell AG (2005) Nonlinear response of ozone to emissions: source apportionment and sensitivity analysis. Envir Sci Technol 39:6739–6748

Dennis RL, Arnold JR, Tonnesen GS, Li Y (1999) A new response surface approach for interpreting Eulerian air quality model sensitivities. Computer Physics Communications 117:99–112

Douglas S, Hudischewskyj B, Beckmann S (2005a) Analysis of the relationships between meteorology and ozone for several southern cities. Report for Southern Company

Douglas S, Hudischewskyj B, Beckmann S (2005b) Characterization of meteorology and its relationships to fine particulate mass and visibility in the VISTAS Region. Report for VISTAS

E.H. Pechan & Associates (2002) Control strategy cost analyses for the Southern Appalachian Mountains Initiative. Prepared for Southern Appalachian Mountains Initiative, 108 pp

E.H. Pechan & Associates (2005) AirControlNET Version 4.1 Development Report. Prepared for U.S. EPA. Available at http://www.epa.gov/ttnecas1/costmodels.html (last accessed February 7, 2006)

Grell AG, Dudhia J, Stauffer DR (1994) A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). National Center for Atmospheric Research: Boulder, CO

Hakami A, Odman MT, Russell AG (2004) Nonlinearity in atmospheric response: a direct sensitivity analysis approach. J Geophys Res 109, doi:10.1029/2003JD004502

Houyoux MR, Vukovich JM, Coats CJ, Wheeler NJM, Kasibhatla P (2000) Emission inventory development and processing for the seasonal model for regional air quality (SMRAQ) project. J Geophys Res 105:9079–9090

Marmur A (2006a) Receptor-model based analysis of high particulate-matter days in several urban and rural sites in Georgia in light of the US-EPA proposed new daily ambient air-quality standard. American Association for Aerosol Research 7th International Aerosol Conference, St. Paul, Minnesota

Marmur A (2006b) CMAQ/BenMAP-based health-benefits analysis in support of the Georgia SIPs for O_3 and $PM_{2.5}$. 5th Annual CMAS conference, Chapel-Hill, North Carolina

Marmur A, Unal A, Mulholland JA, Russell AG (2005) Optimization based source apportionment of PM2.5 incorporating gas-to-particle ratios. Envir Sci Technol 39:3245–3254

Marmur A, Park SK, Mulholland JA, Tolbert PE, Russell AG (2006) Source apportionment of PM2.5 in the southeastern United States using receptor and emissions-based models: conceptual differences and implications for time-series health studies. Atmosph Envir 40:2533–2551

Morris RE, McNally DE, Tesche TW, Tonnesen G, Boylan JW, Brewer P (2005) Preliminary evaluation of the community multiscale air quality model for 2002 over the Southeastern United States. J Air Waste Manage Assoc 55:1694–1708

National Research Council (2004) Air quality management in the United States. The National Academy Press, Washington, DC, p 426

Paatero P (1997) Least squares formulation of robust, non-negative factor analysis. Chemometrics Intelligent Lab Syst 37:23–35

Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287:1132–1141

Sexton K (1999) Setting environmental priorities: is comparative risk assessment the answer? In: Sexton K, Marcus AA, Easter KW, Burkhardt TD (eds) Better environmental decisions. Island Press, Washington, D.C. pp 195–219

Sierra Research, Inc. (2005) Assessment of the cost-effectiveness of compliance strategies for selected eight-hour ozone NAAQS nonattainment areas. Prepared for American Petroleum Institute, 56 pp

Sillman S, Alwali KI, Marsik FJ, Nowacki P, Samson PJ, Rodgers MO, Garland LJ, Martinez JE, Stoneking C, Imhoff R, Lee JH, Newman L, Weinstein-Lloyd J, Aneja VP (1995) Photochemistry of ozone formation in Atlanta, GA: Models and measurements. Atmosph Envir 29:3055–3066

Tesche TW, Morris RE, Tonnesen G, McNally DE, Boylan JW, Brewer P (2006) CMAQ/CAMx Annual 2002 Performance Evaluation over the Eastern US. Atmosph Envir 40:4906–4919

U.S. Environmental Protection Agency (1997a) National Ambient Air Quality Standards for particulate matter; final rule. Fed Register 62:38651–38760

U.S. Environmental Protection Agency (1997b) National Ambient Air Quality Standards for ozone; final rule. Fed Register 62:38855–38896

U.S. Environmental Protection Agency (1997c) Final report to Congress on benefits and costs of the Clean Air Act, 1970–1990. EPA-410-R-97-002

U.S. Environmental Protection Agency (1999) Regional haze regulations; final rule. Fed Register 64:35714–35774

US-EPA (2004a) EPA-CMB8.2 users manual (EPA-452/R-04-011), Office of Air Quality Planning & Standards, Research Triangle Park, NC 27711. Available at: http://www.epa.gov/scram001/models/receptor/

US-EPA (2004b) Protocol for applying and validating the CMB model for PM2.5 and VOC (EPA-451/R-04-001), Office of Air

Quality Planning & Standards, Research Triangle Park, North Carolina 27711

U.S. Environmental Protection Agency (2004c) Air quality designations and classifications for the 8-hour ozone National Ambient Air Quality Standards. Fed Register 69:23858–23897

U.S. Environmental Protection Agency (2004d) Documentation summary for EPA base case 2004 (v. 2.1.9) using the integrated planning model. EPA-430/R-04-008. Available at: http://www.epa.gov/airmarkets/progsregs/epa-ipm/past-modeling. html

U.S. Environmental Protection Agency (2005a) Air quality designations and classifications for the fine particles ($PM_{2.5}$) National Ambient Air Quality Standards; Final Rules. Fed Register 70:944–1019

U.S. Environmental Protection Agency (2005b) Guidance on the use of models and other analyses in attainment demonstrations for the 8-hour ozone NAAQS. EPA-454/R-05-002, 120 pp

U.S. Environmental Protection Agency (2006) Guidance on the use of models and other analyses for demonstrating attainment of air quality goals for ozone, PM2.5, and Regional Haze (Draft 3.2–September 2006). U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina