Assessing the Public Health Impact of Regional-Scale Air Quality Regulations

by Valerie Garcia, Neal Fann, Richard Haeuber, and Phil Lorang

The Clean Air Interstate Rule (CAIR) will further reduce regional emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x), thus reducing fine particulate matter ($PM_{2.5}$) and ground-level ozone pollution in the eastern United States. The U.S. Environmental Protection Agency (EPA) estimates that CAIR will provide the largest benefits of any Clean Air Act rule issued in the past 12 years.

Regulations such as CAIR, however, come at a substantial economic cost. Moreover, understanding whether we have sufficiently protected the public is of critical concern.[1,2] Thus, determining whether regulatory actions actually reduce air pollution and improve public health and the environment is an important step in environmental policy implementation.

This article presents an "accountability" framework for evaluating the impact of CAIR that consists of "metrics" (i.e., predictions of changes associated with the promulgation of CAIR) and "indicators" (i.e., actual levels of the same or closely related parameters observed during the implementation of CAIR). The basic challenge in this evaluation is that only the actual value of an indicator parameter will be observable, not the incremental change caused by CAIR. Thus, modeling is used to understand and supplement the observed parameter. The approach presented here addresses the regional-scale transport of pollutants and the indicators and techniques needed to discern a relatively small signal of change embedded in a highly confounded set of outcomes. The NO_x State Implementation Plan (SIP) Call (implemented by the NO_x Budget Trading Program [NBP]) is used as an example to discuss how some of

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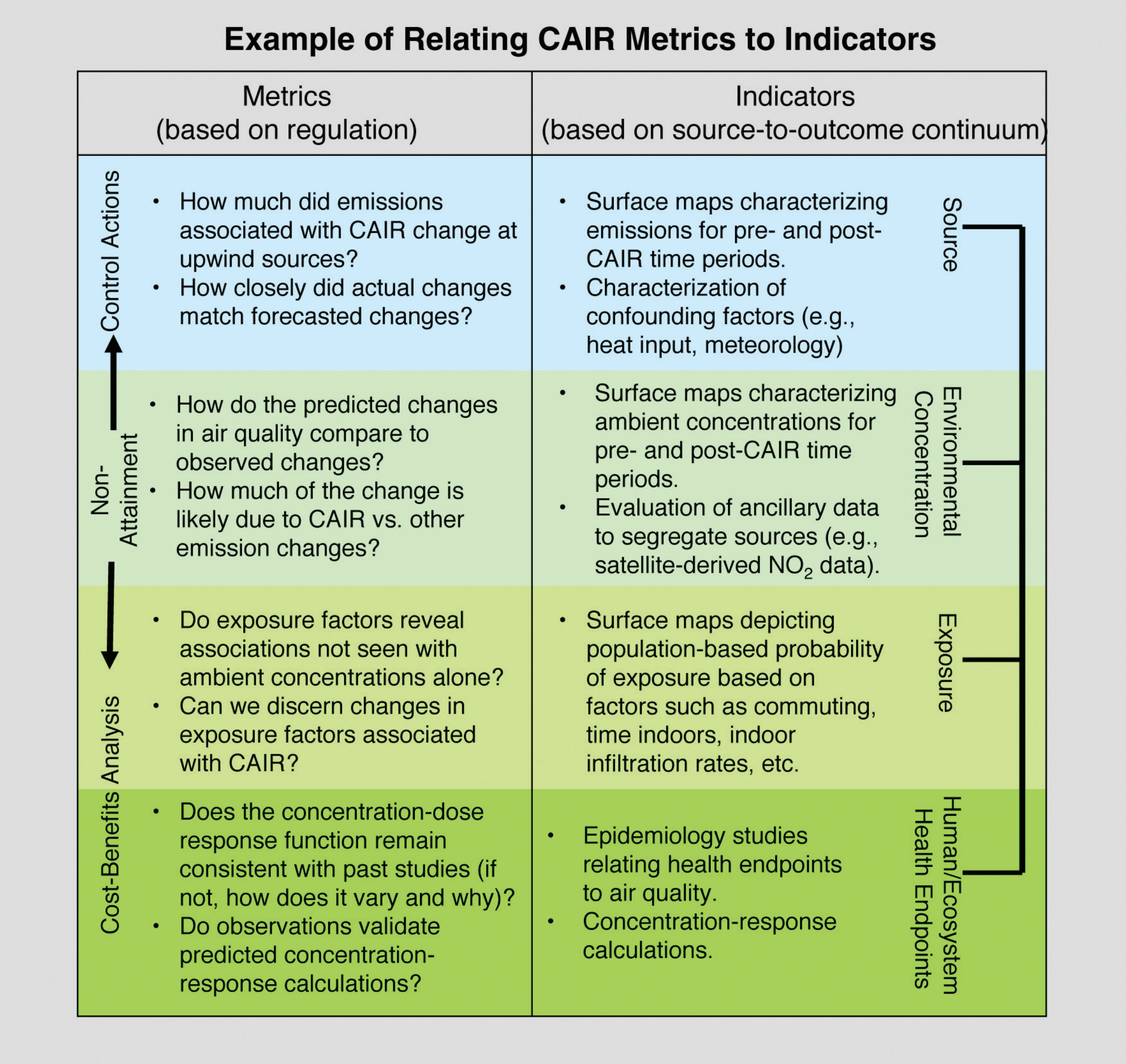
these challenges could be addressed in assessing the impact of CAIR.

Several previous and ongoing studies and analyses have investigated the impact of air quality regulations. For example, Pennell et al.[3] defined accountability as measuring the effectiveness of air quality management actions and suggested a framework for conducting these assessments. The Health Effects Institute has launched a major initiative to assess the health impacts of air quality.[4] In addition, EPA regularly issues reports to assess its regulations, including the annual assessments of the Acid Rain Program[5] and NBP.[6] These previous and ongoing studies and analyses provide a strong foundation for the impact assessment of CAIR.

This article suggests (1) an approach that integrates predicted metrics with measured and modeled indicators that represent actual outcomes and demonstrate linkages across the source-to-outcome continuum,[3,7] and (2) presents additional techniques aimed at disentangling confounded emissions, ambient concentration, and exposure signals of change resulting from regulatory actions. While linking the control actions implemented by CAIR to health endpoints is discussed, the focus is on relating control actions required by CAIR to actual changes in emissions, ambient concentrations, and exposure of humans to pollutants.

Effects of Concern

SO_2 and NO_x contribute to the formation of $PM_{2.5}$. NO_x also contributes to the formation of ground-level ozone. Exposure to $PM_{2.5}$ has been associated with a number of adverse health effects, including premature death,



Example of Relating CAIR Metrics to Indicators

	Metrics (based on regulation)	Indicators (based on source-to-outcome continuum)	
Control Actions	• How much did emissions associated with CAIR change at upwind sources? • How closely did actual changes match forecasted changes?	• Surface maps characterizing emissions for pre- and post-CAIR time periods. • Characterization of confounding factors (e.g., heat input, meteorology)	Source
Non-Attainment	• How do the predicted changes in air quality compare to observed changes? • How much of the change is likely due to CAIR vs. other emission changes?	• Surface maps characterizing ambient concentrations for pre- and post-CAIR time periods. • Evaluation of ancillary data to segregate sources (e.g., satellite-derived NO_2 data).	Environmental Concentration
Cost-Benefits Analysis	• Do exposure factors reveal associations not seen with ambient concentrations alone? • Can we discern changes in exposure factors associated with CAIR?	• Surface maps depicting population-based probability of exposure based on factors such as commuting, time indoors, indoor infiltration rates, etc.	Exposure
	• Does the concentration-dose response function remain consistent with past studies (if not, how does it vary and why)? • Do observations validate predicted concentration-response calculations?	• Epidemiology studies relating health endpoints to air quality. • Concentration-response calculations.	Human/Ecosystem Health Endpoints

respiratory problems, and illnesses such as chronic bronchitis and heart attacks. Similarly, ozone has been associated with the aggravation of asthma and other respiratory conditions, and changes in lung function. In addition, SO_2 and NO_x contribute to sulfur and nitrogen deposition, resulting in the acidification of surface waters, damage to forests and other vegetation, materials damage, and impaired visibility. Nitrogen deposition also contributes to eutrophication of coastal waters, contributing to fish kills and other adverse ecological impacts.[1,2]

Pollutant Transport and Regulatory Actions

Under certain meteorological conditions, SO_2 and NO_x emissions, and $PM_{2.5}$ and ozone formed in the atmosphere, can be transported hundreds of kilometers downwind from the source region, impacting a receiving state's ability to meet the National Ambient Air Quality Standards (NAAQS).[8,9] Prevailing wind patterns and emission densities in the eastern United States leads to the regional-scale transport of pollutants, and hence, is of particular concern to states in the East.[10] The NO_x SIP Call, issued by EPA in 1998, was the first regulation to address the transport of pollutants in the eastern United States by reducing summertime NO_x emissions from major sources (predominantly from electric utilities). CAIR, issued by EPA in 2005, will achieve further reductions in both SO_2 and NO_x emissions in the District of Columbia and 28 eastern states that are predicted to be significant contributors of pollution in downwind states. With enactment of the second phase, CAIR will permanently cap annual emissions from generating sources in the eastern United States at 2.6 million tons and 1.3 million tons for SO_2 and NO_x, respectively.[1]

Accountability Metrics and Indicators

A recent National Research Council review[11] recommended that EPA provide the scientific and technical basis for environmental indicators that link human and ecological health outcomes with air quality. The Clean Air Act Advisory Committee's Air Quality Management Subcommittee further recommended that initial accountability efforts be focused on major rules such as CAIR, and include the establishment of accountability metrics that represent known or estimated findings that drive the issuance of cost-benefits analysis of a regulation.[12] Therefore, this article proposes a system of metrics that represent the assumptions and predictions used to promulgate rules and regulations, and associated indicators to measure and substantiate these assumptions and predictions during the post-implementation phase of CAIR (see "Example of Relating CAIR Metrics to Indicators" opposite).

Metrics

In formulating CAIR, EPA used air quality models to determine which upwind states significantly contribute to a downwind state's nonattainment of NAAQS. This modeling provided a forecast of which areas are expected to remain in nonattainment in 2010 without additional controls, and the amount of upwind emissions contributing to projected 2010 $PM_{2.5}$ and ozone nonattainment in downwind states. EPA relied upon a number of model-derived metrics and criteria in determining which states to include in CAIR. An optional cap-and-trade program (similar to the Acid Rain Program and NBP) was established with emissions budgets for each state based on highly effective emission controls of electric generating units.[1] Examples of metrics associated with the promulgation of CAIR include total NO_x and SO_2 emission reductions at upwind contributing sources, the reduction of ambient pollutant concentrations at downwind receiving areas (e.g., SO_4 and NO_3), and changes in the downwind state's compliance with the NAAQS (see sidebar opposite for other examples of metrics).

EPA also conducted a regulatory impact analysis, including a cost-benefit analysis to estimate the net economic benefits achieved from the emission reductions

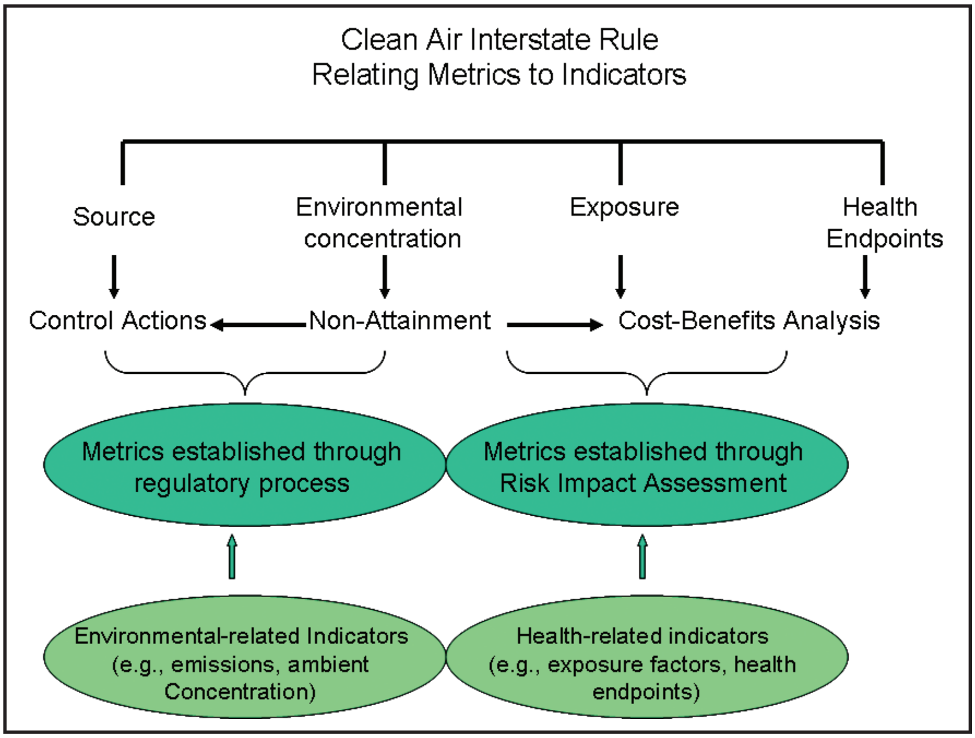


Figure 1. Relating metrics and the regulatory process to indicators and the source-to-outcome continuum.

required by CAIR.[2] The cost-benefit analysis included estimates of private annual compliance costs and human and ecological health benefits adjusted using a 7% and 3% social discount rate. In determining health benefits, EPA used a "damage function" approach that applied health impact functions from epidemiological studies to quantify the relationship between modeled prospective changes in air pollution exposure and adverse health outcomes. Valuation functions were then applied to estimate the economic value of these endpoints.[2] While identifying and validating these metrics is less straight forward than for the CAIR air quality assessment discussed above, metrics representing the predicted adverse health effects and economic costs of controls can be established.[13,14]

Indicators

Indicators, as defined here, are measured and/or modeled values that elucidate change across the source-to-outcome continuum and relate to metrics established through the rule-making process (see Figure 1). In general, indicators should capture changes in source emissions, ambient pollutant concentrations, exposures, and health outcomes. Characterizing the processes that impact the relationships (i.e., linkages) among these indicators is equally important.[3,7] While progress has been made in linking emission changes resulting from a regulatory action to ambient concentrations, linking changes in emissions to human exposure (i.e., differences in an individual's exposure or susceptibility to a pollutant due to factors such as age, genetics, environment, and activities) and health endpoints (e.g., respiratory-related hospital admissions, mortality effect estimates) remains to be a major area of research.[4,7]

Figure 2 summarizes preliminary work being done to assess the impact of the NO_x SIP Call to illustrate the development of indicators and the evaluation of linkages among changes in emissions, ambient concentrations, human exposure, and health endpoints. In this case, direct continuous emissions monitoring systems measures of NO_x from electric generating units and prevailing meteorology were input into the Community Multiscale Air Quality (CMAQ) model to produce a 12 km x 12 km horizontal grid surface for each day of the ozone season for 2002 and 2004. The change in emissions and meteorology between these two time periods was assessed using model sensitivity studies.[15] In addition, observations and CMAQ model simulations for daily 8-hr maximum ozone concentrations were compared between these same time periods to assess changes in emissions and ambient concentrations.[15-17] These analyses are being expanded to include additional years in the comparison.[18]

Research is also underway to transfer these ambient concentration surfaces to exposure surfaces using exposure models (e.g., the Air Pollutant Exposure [APEX] and Stochastic Human Exposure and Dose Simulation [SHEDS] models) that simulate the movement of people through time and space to estimate the probability of exposure by age, gender, and other cohort characteristics of relevance to exposure or health effects. These models will stochastically generate simulated individuals using census-derived probability distributions for demographic characteristics. Daily activity patterns for individuals, obtained from detailed diaries contained in the Consolidated Human Activity Database, will be used to construct a sequence of activity events for simulated individuals consistent with their demographic characteristics, day type, and season of the year, as defined by ambient temperature regimes.[19]

This research (as well as other studies[4]) will investigate whether probability-based exposure factors used in an epidemiology study being conducted by the State of New York will provide additional information beyond the standard practice of using ambient concentrations as a surrogate for exposure in assessing the impact of the NO_x SIP Call.[18] Thus, the final indicator in Figure 2 represents epidemiology studies with linkages directly between ambient concentration and exposure factors.

It is important to recognize that relating regulatory actions directly to improvements in health endpoints using epidemiology studies

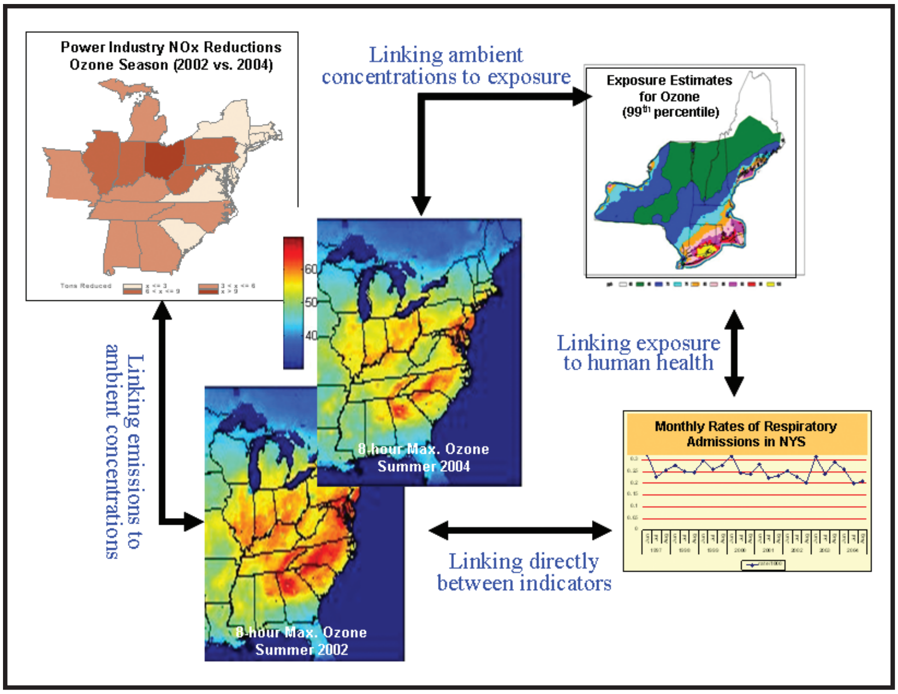


Figure 2. Assessing the impact of regulations to human health endpoints showing the indicators (boxes) and process linkages (arrows) associated with the NO_x SIP Call.

is extremely complex and may require alternative indicators and linkage processes.[4] In its regulatory impact assessment, EPA found that the total projected societal benefits for CAIR were driven primarily by health endpoints related to $PM_{2.5}$ (e.g., the reduction in premature deaths each year accounted for over 90% of total monetized benefits in 2015).[2] While the epidemiology literature has established that $PM_{2.5}$- and ozone-related premature mortality is significant, the rate is small relative to total mortality from all causes. For this reason, it may be difficult, if not impossible, to relate measured changes in air pollution and premature mortality, even for a specific regulatory intervention as large as CAIR. While containing its own limitations and uncertainties,[11] the damage function approach described earlier may be a useful alternative for assessing the health impacts of programs such as CAIR.[13,14]

Addressing Challenges in Linking Indicators

Many challenges and uncertainties exist in our understanding of the relationships among indicators across the source-to-outcome continuum.[7,11] While addressing all of these challenges and uncertainties is beyond the scope of this article, the following section discusses some of the significant challenges associated with discerning a relatively small emissions change resulting from a specific regulatory action within a signal confounded by multiple pollutant sources, the implementation of multiple control actions, and interactions with meteorology.

Multiple Sources and Concurrent Control Activities

Several other national, regional, and local actions have been implemented, or are planned for implementation, to control SO_2, NO_x, and other chemicals related to $PM_{2.5}$ and ozone during the same timeframe as CAIR. As with EPA's other SO_2 and NO_x cap-and-trade programs, CAIR reduces emissions from the electric utilities, which are monitored through continuous emissions monitoring systems. These direct measures provide an opportunity to link changes in emissions with ambient pollutant concentrations and exposure. Some of the other concurrent control actions, however, do not directly involve measured emissions. For example, mobile sources are a large contributor to NO_x emissions, but these emissions are not directly measured and are estimated with substantial uncertainty. An approach planned for the CAIR assessment is to evaluate the change in mobile source NO_2 emissions from satellite-derived NO_2 measures taken over major transport corridors located in the eastern United States.[20,21] While not definitive, analyses such as this, in tandem with other evaluations (e.g., weather patterns), could help discern the magnitude of change from these non-CAIR regulated sources and their contribution to changes in pollution concentration levels at downwind sites.

Meteorology—A Confounding Factor

Meteorology interacts with and among many of the identified indicators. For example, emissions are not only changed by control actions, but are impacted by other factors including changes in energy demands (e.g., air conditioning during the summer, heating during the winter) and technology. In addition to emissions, ambient pollutant concentrations are impacted by meteorology because sunlight affects the rate at which pollutants form, as well as other chemical properties (e.g., particle composition). Exposure of humans to air pollutants is altered by meteorology because individuals change their activities due to weather, such as decreasing their exposure by staying indoors. Finally, human health outcomes, such as hospital admissions or mortality rates are impacted by extreme weather (e.g., hot, humid days directly aggravate or cause illnesses such as heat stress).

Determining the contribution of meteorology versus emissions in the formation of $PM_{2.5}$ and ozone is challenging because of the influence of the direct and indirect effects of meteorology. In its annual assessment of NBP,[6] EPA evaluated "meteorologically adjusted" ozone observations to reveal an expected downward trend across the time period of interest even after accounting for the influence of meteorology. Air quality models can also be used to evaluate the influence of emissions versus meteorology, by holding meteorology or emission inputs constant in the model simulations across years. For example, the results of holding these inputs constant for the comparison of the 2002 and 2004 ozone season revealed a strong influence of meteorology on ozone formation across the two years because of the relatively warmer summer in 2002 and the relatively cooler summer in 2004.[15]

Evaluating emissions in conjunction with daily weather patterns can also help to identify high-pollutant days in downwind locations that are significantly influenced by the transport of pollutants, and can provide evidence that reductions seen at downwind sites are attributable to the transport-related control actions. Stagnant pollutant conditions (e.g., low winds associated with slow-moving high pressure systems) allow precursor chemicals to "age," leading to high ozone levels, particularly in the Southeast. Conversely, faster moving southwesterly wind patterns transport pollutants into the Northeast from major SO_2 and NO_x sources located in the central-eastern part of the United States.[8,11] An evaluation of these wind patterns completed for the comparison between the 2002 and 2004 ozone seasons revealed that the magnitude of change in ozone concentrations is highest for those days associated with a southwesterly flow, indicating that NBP did reduce the transport of ozone to these downwind sites.[17]

Summary

The regulatory community is increasingly recognizing the importance of addressing accountability in its program assessments. In this article, we propose a system of metrics (predictions) and indicators (results) that could be adopted to assess the impact of CAIR, and suggest approaches for discerning a subtle signal of change in emissions embedded in a highly confounded set of outcomes. Previous work, such as EPA's annual progress reports assessing programs like the Acid Rain Program and NBP, provide a strong foundation for conducting the CAIR impact assessment. This article suggests other analyses and methods to augment current practices to inform some of the many components of the assessment confounded by complex interactions and uncertainties. With the intent of informing how indicators are connected, the approaches discussed tap into the information embedded in multiple information sources, including satellite-derived observations, air quality model simulations, probabilistic exposure modeling, and concentration-response approaches.

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References

1. Rule to Reduce Interstate Transport of Fine Particulate Matter and Ozone (Clean Air Interstate Rule); *Fed. Regist.* **2005**, *70* (91), 25162.
2. *Regulatory Impact Analysis for the Final Clean Air Interstate Rule;* EPA-452-R-05-002; U.S. Environmental Protection Agency: Washington, DC, 2005.
3. Pennell, W.; Scheffe, R.; Brook, J.; Demerjian, K.; Hidy, G.; Vickery, J; West, J. Implementing Accountability within a Multipollutant Air Quality Management Framework; *EM* May 2007, 21-24.
4. *Assessing Health Impact of Air Quality Regulations: Concepts and Methods for Accountability Research. Communication 11;* Accountability Working Group, Health Effects Institute: Boston MA, 2003.
5. *Acid Rain and Related Programs: 2006 Progress Report;* EPA-430-R-07-011; U.S. Environmental Protection Agency: Washington, DC, 2007.
6. *NO_x Budget Trading Program 2006: Program Compliance and Environmental Results*; EPA-430-R-07-009; U.S. Environmental Protection Agency: Washington, DC, 2007.
7. Sheldon, L.S. Exposure Concepts for Environmental Management; *EM* July 2008, 8-12.
8. *An Assessment of Tropospheric Ozone Pollution—A North American Perspective*; NARSTO: Pasco, WA, 2000.
9. *Particulate Matter Science for Policy-Makers*; McMurry, P.H.; Shepherd, M.F.; Vickery, J.S.; Eds.; NARSTO: Pasco, WA, 2004.
10. Godowitch, J.; Hogrefe, C.; Rao, S.T. Influence of Point Source NO_x Emission Reductions on Modeled Processes Governing Ozone Concentrations and Chemical-Transport Indicators; *J. Geophys. Res.* **2008**; in press.
11. *Air Quality Management in the United States;* National Research Council, National Academies Press: Washington DC, 2004.
12. *Recommendations to the Clean Air Act Advisory Committee, Phase II Recommendations, Final Report*; Air Quality Management Subcommittee, Clean Air Act Advisory Committee: Washington, DC, 2007.
13. Hubbell, B.J.; Hallberg, A.; McCubbin, D.R.; Post, E. Health-Related Benefits of Attaining the 8-Hr Ozone Standard; *Environ. Health Perspect.* **2005**, *113*, 73-82.
14. *Regulatory Impact Analysis for the PM National Ambient Air Quality Standards;* U.S. Environmental Protection Agency: Washington, DC, 2006; www.epa.gov/particles/actions.html.
15. Gilliland, A.G.; Hogrefe, C.; Pinder, R.W.; Godowitch, J.M., Foley, K.L., Rao, S.T. Dynamic Evaluation of Regional Air Quality Models: Assessing Changes in O_3 Stemming from Changes in Emissions and Meteorology; *Atmos. Environ.* **2008**; doi:10.1016/j.atmosenv.2008.02.018.
16. Gego, E.; Porter, P.; Gilliland, A.; Rao, S.T. Modeling Assessment of Point Source NO_x Emission Reductions on Ozone Air Quality in the Eastern United States; *Atmos. Environ.* **2008**, *42* (1), 994-1008.
17. Godowitch, J.; Gilliland, A.; Draxler, R.; Rao, S.T. Modeling Assessment of Point Source NO_x Emission Reductions on Ozone Air Quality in the Eastern United States; *Atmos. Environ.* **2008**, *42* (1), 87-100.
18. Generating Accountability Indicators for Air Quality: A Framework for Ecosystem and Human Health Accountability. Proposal submitted under the EPA's Advanced Monitoring Initiative, 2006; www.epa.gov/asmdnerl/NOx/index.html.
19. McCurdy, T.; Graham, S.E. Using Human Activity Data in Exposure Models: Analysis of Discriminating Factors; *J. Expos. Anal. Environ. Epidemiol.*, ***2003***, *13*, 294-317.
20. Napelenok, S.L.; Pinder, R.W.; Gilliland, A.B.; Martin, R.V. A Method for Evaluating Spatially-Resolved NO_x Emissions Using Kalman Filter Inversion, Direct Sensitivities, and Space-Based NO_2 Observations; *Atmos. Chem. Phys. Disc.* ***2008***, *8*, 6469-6499.
21. Kim, S.W.; Heckel, A.; McKeen, S.A.; Frost, G.J.; Hsie E.Y. Satellite-Observed U.S. Power Plant NO_x Emission Reductions and Their Impact on Air Quality; *Geophys. Res. Letts.* **2006**, *33*, L22812; doi:10.1029/2006GL027749.