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The National Ambient Air Monitoring Strategy: Rethinking the Role of National Networks

Richard D. Scheffe
U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, NC

Paul A. Solomon
U.S. Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development, Las Vegas, NV

Rudolf Husar
Department of Energy, Environmental and Chemical Engineering, Washington University, St. Louis, MO

Tim Hanley and Mark Schmidt
U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, NC

Michael Koerber
Lake Michigan Air Directors Consortium, Rosemont, IL

Michael Gilroy
Puget Sound Clean Air Agency, Seattle, WA

James Hemby, Nealson Watkins, Michael Papp, Joann Rice, and Joe Tikvart
U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, NC

Ricard Valentinetti
Vermont Agency of Natural Resources, Waterbury, VT

ABSTRACT

A current re-engineering of the United States routine ambient monitoring networks intended to improve the balance in addressing both regulatory and scientific objectives is addressed in this paper. Key attributes of these network modifications include the addition of collocated instruments to produce multiple pollutant characterizations across a range of representative urban and rural locations in a new network referred to as the National Core Monitoring Network (NCore). The NCore parameters include carbon monoxide (CO), sulfur dioxide (SO_2), reactive nitrogen (NO_y), ozone (O_3), and ammonia (NH_3) gases and the major fine particulate matter ($PM_{2.5}$) aerosol components (ions, elemental and organic carbon fractions, and trace metals). The addition of trace gas instruments, deployed at existing chemical speciation sites and designed to capture concentrations well below levels of national air quality standards, is intended to support both long-term epidemiological studies and regional-scale air quality model evaluation. In addition to designing the multiple pollutant NCore network, steps were taken to assess the current networks on the basis of spatial coverage and redundancy criteria, and mechanisms were developed to facilitate incorporation of continuously operating particulate matter instruments.

IMPLICATIONS

The nation's routine ambient monitoring networks have been based on 1970s design concepts developed in the early stages of air quality management programs. Steps to modify national networks to address current and emerging environmental assessment challenges will require broad support across governmental agencies.

INTRODUCTION AND RATIONALE

Numerous revisions to the ambient air monitoring regulations guiding national network operations conducted by state and local agencies and tribes (SLTs) accompanied the 2006 promulgation of the new fine particle standards.[1] In addition to updates addressing a reduced daily fine particulate matter ($PM_{2.5}$) standard (from 65 to 35

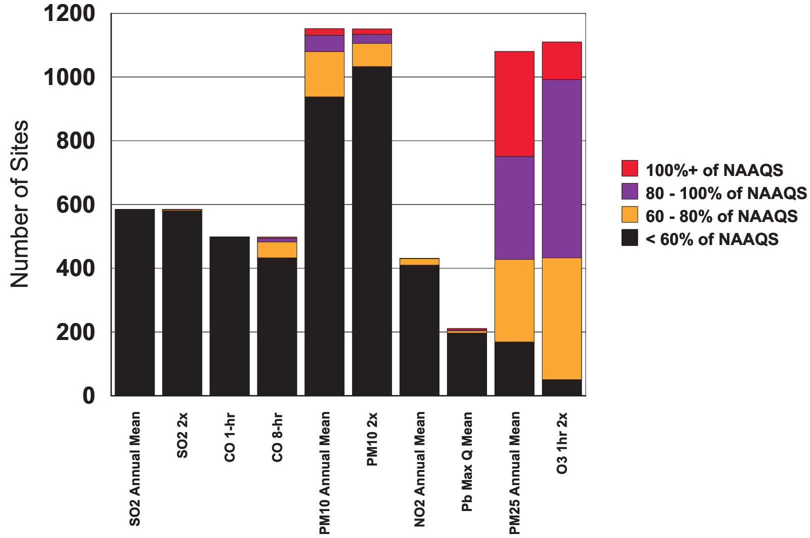

Figure 1. Frequency of measurements relative to the standard for gaseous and PM criteria pollutants.

$\mu g/m^3$), the revised monitoring rule[2] codified key components of the National Ambient Air Monitoring Strategy (NAAMS)[3] that had been under development since 2000. The strategy in large part was driven by a confluence of budgetary pressures and interest from the scientific community stemming from the 1999 deployment of a massive $PM_{2.5}$ monitoring network, as required by the 1997 particulate matter (PM) standard revisions.[4] Implementation and operational costs for the $PM_{2.5}$ network, which have averaged about $50 million annually, raised questions regarding the capacity of the nation's monitoring infrastructure to incur continued layering of responsibilities as new air quality standards and needs emerged. Coincident with this implementation was a renewed interest in our "routine" networks as a critical research tool for various scientific disciplines (health effects, exposure, atmospheric science) conveyed in a series of National Academy of Sciences reports tasked with assessing the U.S. Environmental Protection Agency (EPA)'s PM research program.[5–7] Consequently, national networks were faced with competing needs to be more responsive to scientific interests while working within a so called "zero-sum" resource constraint.

A National Monitoring Steering Committee (NMSC), with representatives from EPA and SLTs, guided development of the strategy, which was subject to scientific review from 2002 to 2005 through the monitoring subcommittee of the Clean Air Scientific Advisory Committee (CASAC). CASAC strongly endorsed the themes and recommendations embodied in the strategy. This paper provides an overview of the NAAMS.

Rationale for a Strategy

Ambient monitoring networks are a critical part of the nation's air program infrastructure. Data from these systems are used to characterize "air quality" and associate consequent health and ecosystem impacts, develop emission strategies to reduce adverse impacts, and account for progress over time. The United States spends well over $200 million annually on routine ambient air monitoring programs, a figure dwarfed by the billions associated with emission reduction strategies and the costs associated with adverse health and ecological effects from PM.[8] Ambient data provide a basis for assessing air program progress, thereby determining the value of those investments. Obviously, the investment in and role played by national networks demand periodic strategic planning. Dramatic and mostly positive changes in air quality have been observed over the last 2 decades, despite increasing population, energy production, vehicle usage, and productivity. Most criteria pollutant measurements read well below national standards (Figure 1). Although many of the criteria pollutant problems largely have been solved, current and future problems in PM, ozone, and air toxics continue to challenge air monitoring programs. Even pollutants viewed as environmental success stories such as airborne lead can re-emerge as public health concerns with modern health effects studies[9] leading to possibly more stringent air quality standards. These challenges reside in very complex air pollution behavior (e.g., nonlinear relationships between emission sources and atmospheric concentrations) with increasing knowledge that very low, and difficult to measure, air pollution levels are associated with adverse environmental and human welfare effects.

New directions in air monitoring are needed to reflect the successful progress in reducing air pollution, to incorporate new scientific findings and technologies, and to balance societal issues such as energy production and economic development.[10] Ambient air measurements produced by SLTs are high-quality, credible environmental data that service a broad spectrum of clients. The challenge is to maintain and improve upon a valued product in an environment where monitoring programs are subject to changes in SLT, federal, and research priorities. New and revised National Ambient Air Quality Standards (NAAQS), changing air quality (e.g., significantly reduced concentrations of criteria pollutants), and an influx of scientific findings and technological advancements challenge the response capability of the nation's networks.

The single-pollutant measurement approach, historically administered in national networks, is not an optimal

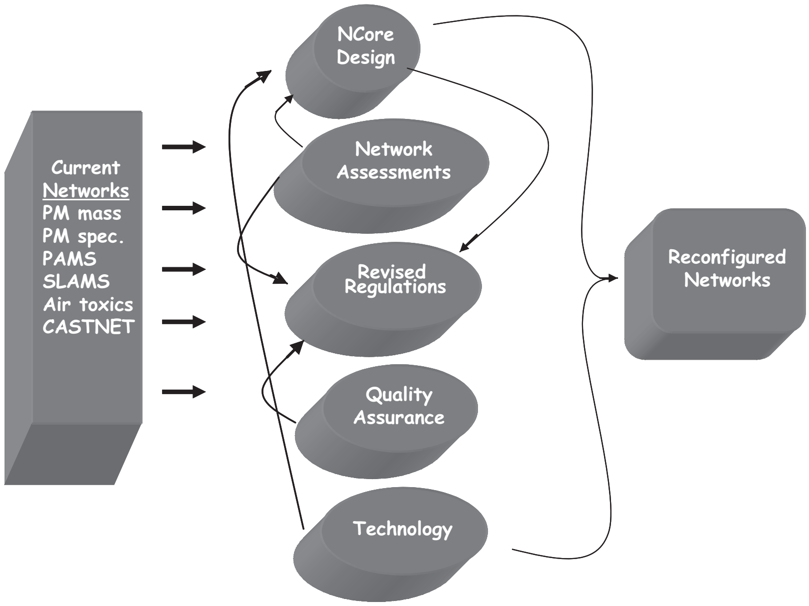

Figure 2. Major components of the NAAMS.

design for integrated air quality management approaches that potentially can be optimized by accounting for numerous programmatic and technical linkages across ozone, $PM_{2.5}$, regional haze, air toxics, and related multimedia interactions[11–13] (e.g., atmospheric deposition). Indeed, the current design of the nation's networks is based largely on the existing single-pollutant-focused monitoring regulations (*Code of Federal Regulations* [CFR], Parts 53 and 58) that were developed in the late 1970s. Complicating a desire to implement change is the need to retain stability in ambient air networks for the detection of long-term air pollution trends as well as maintaining level funding; thus, requiring balancing network configurations to support compliance, research, accountability, and infusion of new monitoring methods.

The NAAMS is built on five components (Figure 2) addressing network assessments, design, quality assurance, rule development, and technology, which collectively are intended to facilitate long-term network modifications. Three key areas underlying design, assessment, and technology are highlighted.

SHIFTING NETWORK DESIGN: THE NCORE MONITORING NETWORK

The new National Core Monitoring Network (Ncore) is an extension of the current air monitoring networks intended to address emerging issues in air monitoring and begin filling measurement and technological gaps that have accumulated over the years. NCore originally was conceived as a three-tiered network (Figure 3) with graduated levels of measurement complexity.

- Level 1: Sustained research grade stations (3–10 locations) to facilitate technology transfer between research and operational communities, analogous to the $PM_{2.5}$ Supersites Program.[12]
- Level 2: Multiple pollutant stations (~75 nationally using high time-resolution instruments to the extent possible) in most major cities, important transport corridors, and background locations intended to capture urban- and regional-scale representative concentrations.
- Level 3: A majority of the single-pollutant $PM_{2.5}$ and ozone sites used primarily for NAAQS compliance and air quality index (AQI) reporting, but also to complement the limited number of Level 2 locations with added spatial resolution for the most important regionally dispersed criteria pollutants.

The final monitoring rule adopted most of the original Level 2 recommendations under the new NCore program, reflecting an inability to fund Level 1 sites and recognizing that inclusion of Level 3 sites as part of NCore might impair monitoring program flexibility of SLTs. These new Level 2 sites require a core group of measurements that include trace gas measurements of carbon

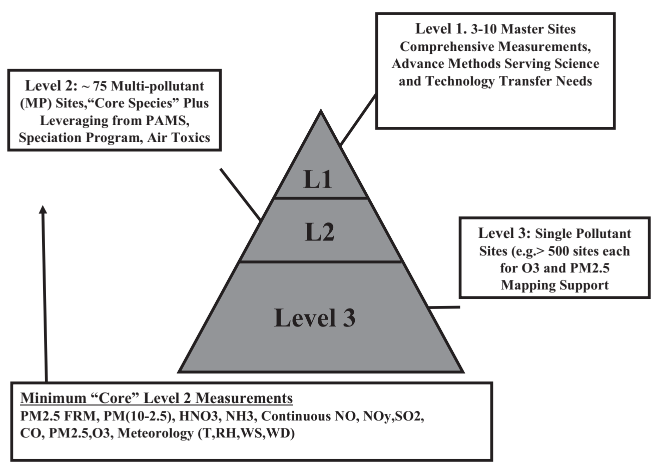

Figure 3. Graded site levels of originally proposed NCore configuration. NH_3 implemented initially as integrated filter-based method after evaluation; continuous methods after development and evaluation. True NO_2 would be added to NCore following method development.

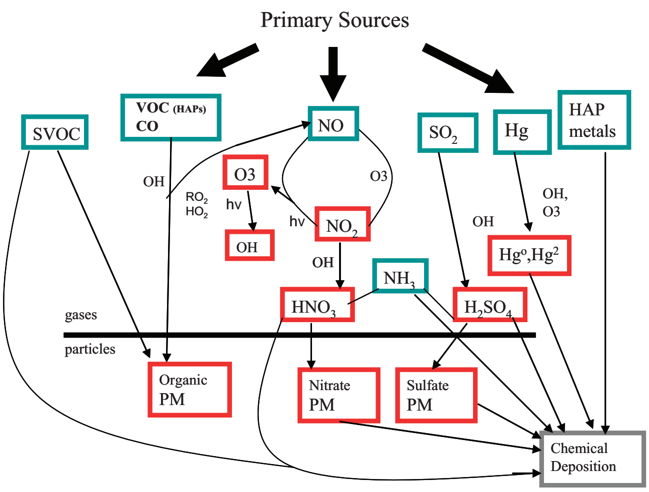

Figure 4. Chemical links illustrating relationships across criteria pollutants and hazardous air pollutants (including mercury) as well as connections across sources, secondarily formed species, gases, PM, and deposition. Primary emissions (green) are distinguished from secondarily formed species (red). Note that this diagram is a highly condensed model that does not capture numerous different heterogeneous processes and complex chemical pathways. Key atmospheric species that are involved in many reactions across pollutant categories include ozone, the hydroxyl radical (OH), and the nitrate radical, which is important in nighttime nitrogen chemistry (latter pathways not shown). Primary PM emissions, although subject to a variety of near-source condensation and transformation processes relevant to total particle mass budgets, are not included because they interact marginally with other atmospheric species. Adopted with permission from Scheffe et al.[11] Copyright 2007 Air & Waste Management Association, *EM*.

monoxide (CO), sulfur dioxide (SO_2), and reactive nitrogen (NO_y). The term "trace" is used to emphasize the intention for broad spatial-scale representative sampling to capture characteristic pollutant concentrations, often in the low parts-per-billion (ppb) and sub-ppb concentration range, indicative of broad population exposures and better aligned with volume-averaged estimates (typically >100 km^3) produced by gridded air quality models. Coarse particle ($PM_{10-2.5}$) mass and chemical measurements would be conducted at all NCore locations to develop an information base to support future reviews of PM air quality standards. Gaseous ammonia (NH_3) and true nitrogen dioxide (NO_2) are intended to become NCore parameters, pending development and/or agreement of appropriate technologies. NO_2 plays a central role in gas-phase atmospheric chemistry processes (Figure 4) and is a key parameter for diagnosing air quality model behavior and the partitioning of deposited nitrogen species, which can influence and degrade terrestrial and aquatic biosystems. NH_3, a poorly characterized species in ambient air, is a relatively ubiquitous compound neutralizing acidic gases and aerosols that participates in secondary particle formation processes. A major component of nitrogen deposition, the volatility of NH_3 induces cycling between air and surface/water media (Figure 4) that challenges emissions characterizations. In addition to these core measurements, the NCore sites would leverage existing $PM_{2.5}$ speciation, Photochemical Assessment Measurements (PAMs), and National Air Toxics Trend (NATTS) platforms offering, in limited locations, an extensive suite of collocated gaseous and aerosol measurements (Figure 5).

The NCore rationale assumes that there are inherent efficiencies and synergistic information gains derived through a wealth of collocated measurements supporting a multipollutant approach.[14] Theoretical efficiencies are derived through economies of scales; gains include reduced operator travel time, centralization of maintenance supplies, system quality assurance audits, and instrument housing facilities. Enhanced information gains would accrue through a combination of adding system constraints to the model evaluation process, increasing the number of variables accessible for assessment purposes such as source apportionment and epidemiological studies, and a generally improved observation base for understanding atmospheric processes. These attributes for a monitoring

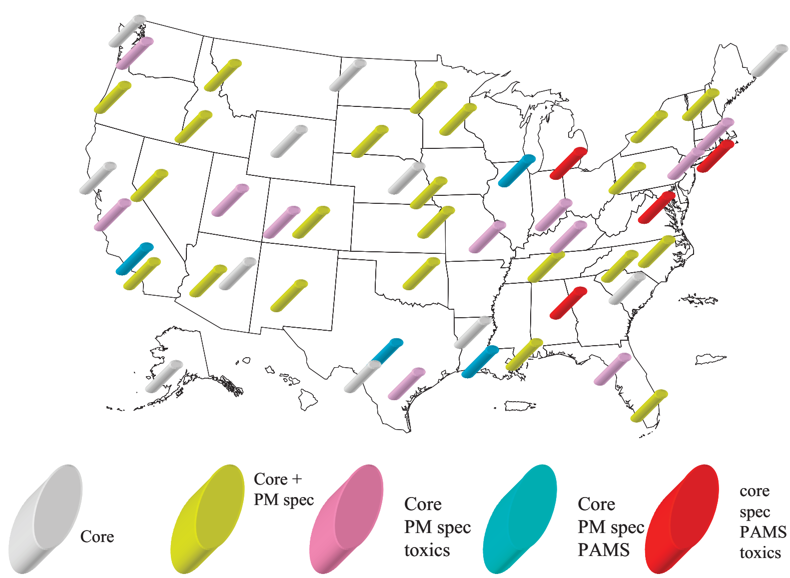

Figure 5. Potential of developing a national system of collocated measurements through leveraging existing networks. The number of collocated measurements would depend on the number of supported networks addressed at a particular location (idealized approach).

network should be viewed as complementing the strong regulatory design of most existing networks. During early stages of formulating NCore, several concerns were raised that a design not focused on highest concentration areas using Federal Reference Methods (FRMs) would be irrelevant to perceived mandates of regulatory agencies. However, building bridges to the research community, air quality modeling platforms, and eventually to other observational platforms (e.g., satellite and aircraft systems) and environmental media are underlying NCore objectives.

NCore Data Objectives and Network Attributes

The NCore Level 2 sites in combination with existing routine networks collectively are intended to address the following objectives, several of which were highlighted in the 2004 National Academy of Sciences (NAS) report,[15] "Air Quality Management in the United States."

(1) Timely data reporting for public alerts based on continuous monitors through AIRNow and related air quality forecasting and public reporting mechanisms.
(2) Emission strategy development, primarily by supporting air quality model evaluation and application and other observational methods.[11]
(3) Accountability by assessing progress of implemented rules and programs through tracking long-term trends of criteria and noncriteria pollutants and their precursors. Ideally, associations between air quality changes and health outcomes would complement these basic air quality accountability efforts.
(4) Epidemiological studies that contribute to ongoing reviews of the NAAQS.
(5) Research support that ranges across technological, health, and atmospheric process disciplines.
(6) Ecosystem assessments that recognize that national air quality networks benefit ecosystem assessments and, in turn, benefit from data specifically designed to address ecosystem analyses.
(7) Compliance that supports establishment of nonattainment/attainment areas.

The following design attributes are used to promote integration themes, technological improvements, and system efficiencies that collectively position the NCore network to address the multiple data objectives listed above.

Collocated Multiple Pollutant Measurements. The variety of air pollution species in gas and particle phases (e.g., ozone, PM, other criteria pollutants, and air toxics) with a broad range of physical and chemical properties are more integrated than the existing single-pollutant program infrastructure suggests. From an emissions source perspective, multiple pollutants or their precursors are released simultaneously (e.g., combustion plume with nitrogen, carbon, hydrocarbon, mercury, sulfur gases, and PM). Meteorological processes that shape pollutant movement and drive thermodynamics (e.g., gas-particle equilibrium), reaction kinetics, and removal processes act on all pollutants, albeit on different time scales.

Numerous chemical and physical interactions exist underlying the dynamics of particle and ozone formation as well as a variety of air toxics components of aerosols. The overwhelming programmatic and scientific interactions across pollutants demand a movement toward integrated air quality measurement.[11] Collocated monitoring of multiple pollutants, especially if measured at high time resolution (≤1 hr) will benefit health assessments, emission strategy development, and a fundamental understanding of atmospheric processes.[14] Health studies with access to multiple pollutant data will be better positioned to tease out confounding effects of different pollutants, particularly when a variety of concentration, composition, time scales, and population types are included. Evaluation of air quality models, which drive development of emission strategies underlying air program policy, benefit through constraints imposed by multiple variables, especially at 1-hr time resolution or shorter, allowing for not only operational evaluation, but diagnostic evaluation, reducing the probability of compensating errors.[16,17] Just as emission sources are characterized by a multiplicity of pollutant releases, related source apportionment models yield more conclusive results from use of multiple measurements.[18,19] Multiple measurements streamline monitoring operations and offer increased diagnostic capabilities to improve instrument performance.[14,20–22]

In addition, as we move aggressively to integrate continuous PM (e.g., both mass and speciation) monitors into the network, it is important to retain several collocated integrated filter-based and continuous instruments because the relationships between these methods are not fully understood[20] and now also are subject to future changes brought on by modifications of aerosol composition and improvement in methods. For example, assuming proportionally greater sulfur reductions, aerosol nitrate gradually will partially replace sulfate,[23–25] which in turn could lead to an increased loss in measured mass due to volatilization of ammonium nitrate from Teflon filters.[26]

Given that we cannot measure everything everywhere within a constrained resource environment, a natural conflict arises between the relative value of spatial richness versus multiple parameters at fewer locations with a base of single-pollutant sites (Level 3). It is assumed that the diagnostic value attained from combining measurements at fewer locations is greater than that derived from single-species measurements at more locations. Part of this assumption recognizes an increased merging of models and observations. As model behavior is improved through multiple collocated measurements, the lack of spatial richness in observed fields can be complemented by model-, or hybrid-model-observation, generated spatial and temporal characterization fields. However, additional long-term or intense field studies are still required in the near term to further understand spatial scales of measurement representativeness[27]on urban and regional scales.

Emphasis on Continuously Operating Instruments. Continuously operating in situ instruments provide near immediate data delivery, enabling processing through reporting tools such as AIRNow that effectively inform the public of near-term air quality conditions. Continuous data add insight to health assessments, addressing subdaily averaging times, source apportionment studies relating impacts to direct emission sources, atmospheric processing and transformation, and air quality models predicated on capturing diurnal air quality patterns of pollutant behavior.[14,16,18,19]

Diversity of "Representative" Locations. A variety of sites representing urban (large and medium size cities) and rural (characterizing background and transport corridors) areas support multiple objectives. National- and regional-level health assessments and air quality model evaluations require data representative of broad urban (e.g., 5–40 km) and regional/rural (>50 km) spatial scales. Long-term epidemiological studies that support NAAQS reviews benefit from a variety of airshed characteristics across different population regimes.

The NCore sites could be utilized to support development of a representative report card on air quality across the nation, capable of delineating differences among geographic and climatological regions. Although "high" concentration levels will characterize many urban areas in NCore, it is important to include cities that also experience less elevated pollution levels or differing mixtures of pollutants for more statistically robust assessments.

Characterization of rural and regional environments to understand background conditions, transport corridors, regional-urban dynamics, and influences of global transport supports the expansion of air quality modeling domains. Throughout the 1970s and 1980s, localized source-oriented dispersion modeling evolved into broader urban-scale modeling (e.g., Urban Airshed Modeling for ozone[28]) to regional approaches in the 1980s and 1990s (e.g., Regional Oxidant Model [ROM][29] and Regional Acid Deposition Model [RADM][30]) to current national-scale approaches (e.g., Community Multiscale Air Quality model [CMAQ][31]) and eventually to routine applications of continental/global-scale models (e.g., Goddard Earth Observing System-CHEMistry [GEOS-chem][32] model). The movement toward broader spatial-scale models coincides with increased importance of our understanding of the regional-rural transport environment on urban and rural conditions. As peak urban air pollution levels decline, background levels impart greater relative influence on air quality. Models need to capture these rural attributes to be successful in providing accurate urban concentrations. Arguably, an important fourth component is the transparent and readily accessible access to NCore data accompanied by sufficient metadata to enable broad use and analysis of NCore products. This information technology component is a critical ingredient toward enabling the community-bridging intentions of NCore.

NETWORK ASSESSMENTS

EPA commissioned a national assessment of our monitoring networks in 2000, with considerations for population, pollutant concentrations, pollutant deviations from the NAAQS, pollutant estimation uncertainty, and the area represented by each site.[3] On the basis of this national assessment, it was determined that substantial reductions in monitors could be made for pollutants that are no longer violating national air standards on a widespread basis, namely lead (although significant revisions to the lead standard are being considered that significantly reduce the level of the standard), SO_2, CO, NO_2 and PM less than 10 μm in aerodynamic diameter (PM_{10}). In parallel, the NCore network recognizes that low concentrations of these pollutants support a variety of health effect, source attribution, and model evaluation analyses. Unfortunately, the source-oriented site locations and method insensitivity of the SO_2 and CO sites do not allow for adequate characterization of representative conditions. Even for those pollutants of greatest national concern, ozone and $PM_{2.5}$, sufficient redundancy was found to suggest site reductions of 5–20% would not compromise the collective network information value from a spatial characterization perspective.

This national assessment catalyzed efforts across the 10 EPA Regional Offices, a process incorporated in the monitoring regulations to be revisited every 5 yr. Although standardized procedures were not adhered to in the regional assessments, differences in air quality, population, monitoring density, and objectives require flexibility in evaluating networks. Recognizing the desire for consistency, the monitoring subcommittee of CASAC met in July 2003 and recommended that regional assessment guidelines be developed for subsequent regional assessments at 5-yr intervals.[33] Network assessments are collaborative efforts among EPA and SLTs that incorporate objective statistical evaluations along with local and policy-based considerations bearing on local decisions to change monitors. Ideally, the combined efforts among national, regional, and local perspectives and needs will result in an optimized realignment of air monitoring networks that will be more efficient, yet more responsive to the many objectives of the strategy. In addition, periodic assessments of NCore will need to be conducted to determine not only if the program is meeting intended goals, but also to probe relevancy with respect to future needs.

Overview of the National Assessment for Ozone

An example national assessment of the criteria pollutant networks was conducted in 2000 to catalyze subsequent regional-level assessments. This assessment considered concentration level, site representation of area and population, and error uncertainty created by site removal as weighting parameters used to determine the relative "value" of individual sites. An indication of site redundancy was estimated through an error analysis on the basis of site-by-site subtraction. The national assessment calculated error uncertainty by modeling surface concentrations (i.e., interpolating between measurement sites) with and without a specific monitor with the difference reflecting uncertainty (Figure 6). Areas of low uncertainty (e.g., <5% error difference for ozone) suggest that removal of a monitor would not compromise the ability to estimate air quality in the region of that monitor because nearby stations would adequately capture air quality spatial features with or without the removed site. The assessment approach was expanded by considering five factors:

(1) Pollutant concentration as an index for health risk. The relevant statistic is the fourth highest

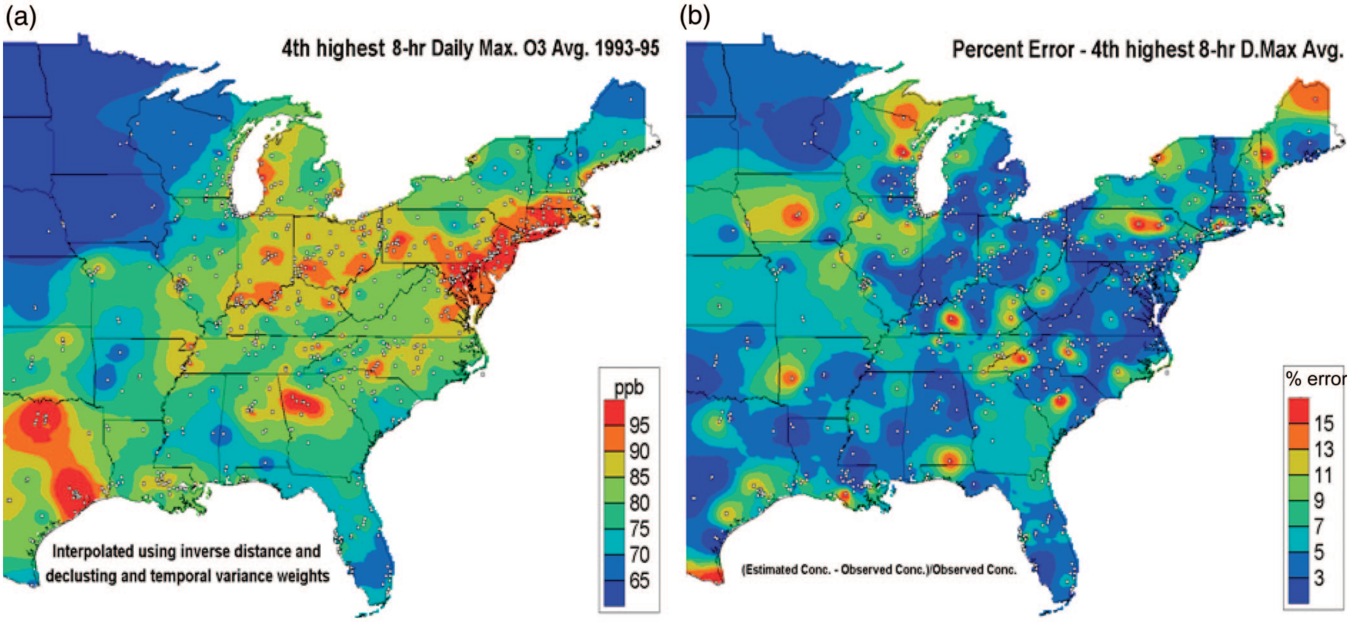

Figure 6. Surface depiction of (b) estimated absolute errors in ozone concentrations produced by removing existing monitors on a site-by-site basis, relative to (a) base case. Areas showing low errors (<5 ppb) suggest neighboring monitors could accurately predict ozone in the area of a removed site. Areas of high error suggest necessity to retain existing monitors and perhaps increase monitoring.

daily maximum concentration over 3 yr. The station with the highest fourth highest daily maximum value is ranked no. 1.

(2) Persons/station measures of the number of people in the "sampling zone" of each station. Using this measure the station with the largest population in its zone is ranked no. 1. Note: Estimating the health risk requires both the population and the concentration in the sampling zone.

(3) Deviation from NAAQS measures the station's value for compliance evaluation. The station ranking is according to the absolute difference between the station value and the NAAQS (85 ppb). The highest ranking is for the station for which the concentration is closest to the standard (smallest deviation). Stations well above or below the standard concentration are ranked low.

(4) Spatial coverage measures the geographic surface area for covered by each station. The highest ranking is for the station with the largest area in its sampling zone. This measure assigns high relative value to remote regional sites and low value to clustered urban sites with small sampling zones.

(5) Estimation uncertainty measures the ability to estimate the concentration at a station location using data from all other stations. The station with the highest deviation between the actual and the estimated values (i.e., estimation uncertainty) is ranked no. 1. In other words, the stations for which the values can be estimated accurately from other data are ranked (valued) low.

Typical outputs for ozone networks (Figure 7) suggest that ozone sites clustered in urban areas yield less powerful information than sites located in sparsely monitored areas, especially in high-growth regions like the southeast. However, this conclusion is more applicable to urban areas with homogeneous conditions. Note that significant ozone gradients do exist from central city to downwind locations, and ozone network design should address broad-based population exposures as well as targeting area-wide high concentrations. This methodology was applied to all criteria pollutants with a variety of weighting schemes to provide a resource for more detailed regional assessments.[3]

Key findings of the national network assessment addressed basic investment and divestment considerations consistent with the NCore design attributes discussed above and reflect both new requirements and themes in recent monitoring regulations as well as the broader evolution taking place across national monitoring networks over the last decade.

Investment Opportunities

The national assessment analysis described above was part of a larger discussion regarding comprehensive network modifications, with the analytical results driving many of the divestment points below. From an investment perspective, new monitoring efforts are needed to support new air quality challenges, including monitoring for air toxics and development, evaluation, and implementation of emerging technologies for criteria pollutants and precursor species. Air toxics have emerged as a top public health concern in many parts of the country, and a national air toxics monitoring network addressing national consistency through NATTS and community-specific issues has evolved since 2001. New monitoring technology, especially continuous measurement methods for pollutants (e.g., fine particles and their chemical components and physical attributes) are needed to provide

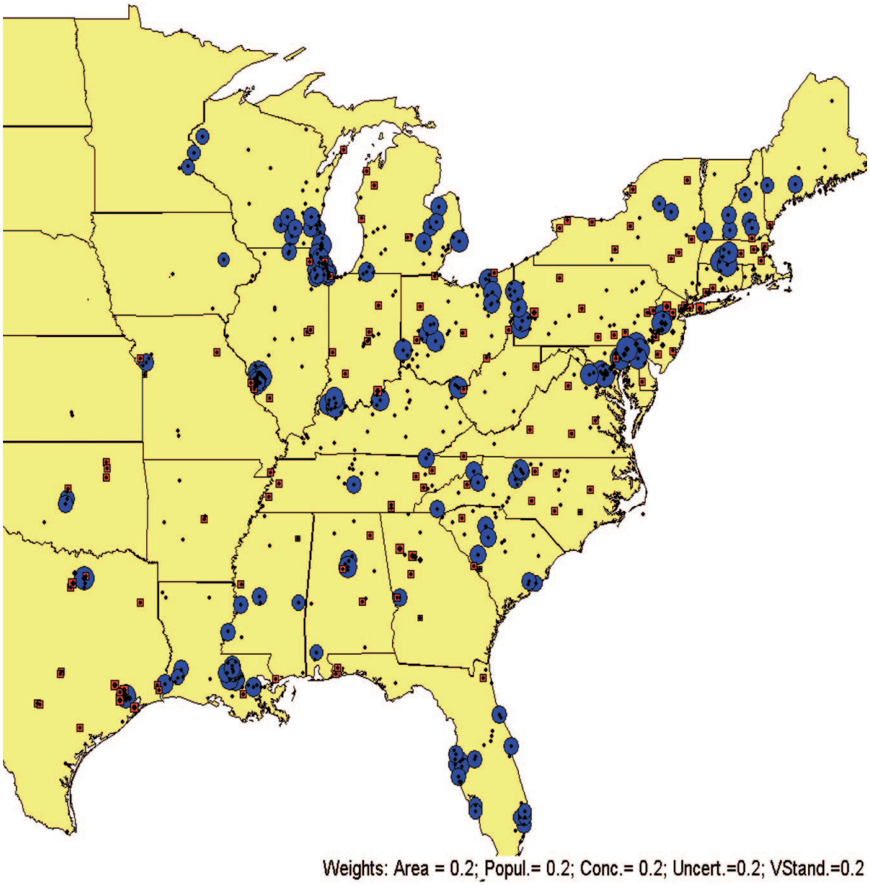

Figure 7. Example assessment of the eastern U.S. ozone network incorporating five evenly weighted factors. Blue circles and red squares indicate the lowest and highest valued sites, respectively.

more complete, reliable, and timely air quality information and to relieve the resource burden of manual sampling. Resources and guidance are needed to further develop, evaluate, and implement continuous monitoring methods in national routine monitoring networks, database development, and data analysis methods to handle these types of data. Continued efforts are needed for development of similar methods in the ultrafine and $PM_{10-2.5}$ size ranges because recent studies are also finding adverse health effects associated with particles in these size ranges.[19] Use of modeling results to add spatial and temporal richness in sparsely monitored areas requires continued development and evaluation to better understand the value and caveats of these approaches for application to human and environmental welfare risk assessments and delineation of nonattainment areas. These recommendations reflect a community wide consensus formed around 2003, yet remain consistent with recommendations generated by the 2004 NAS report, "Air Quality Management in the United States."[15] EPA's PM Supersites Program made significant strives in the area of methods development and evaluation for continuous $PM_{2.5}$, ultrafine, and $PM_{10-2.5}$ monitoring. For example, Solomon and Sioutas[20] provide initial guidance on the implementation of current continuous methods as being ready for routine monitoring, only research studies, or still requiring further laboratory development. Chow et al.[34] provide analytical capabilities (e.g., precision, accuracy, comparability, limits of detection) for integrated and continuous methods deployed during the PM Supersites Program.

Divestment Opportunities

Opportunities exist to reduce existing monitors, resulting in more efficient use of existing monitoring resources and potentially supporting new monitoring initiatives. Many historical criteria pollutant monitoring networks have achieved their objective and demonstrate that there are limited, if any, national or regional air quality problems, including PM_{10}, SO_2, NO_2, CO, and lead. A substantial reduction in the number of monitors for these pollutants is being considered. Consideration is being given to retaining and relocating a certain number of trace-level SO_2 and CO monitors to support air quality and emissions model evaluation and source attribution analyses. Several monitoring sites with only one or a few pollutants should be combined to form multipollutant monitoring stations. Any resource savings from such divestments must remain in the monitoring program for identified investment needs. A reasonable period of time is required to smoothly transition from established to new monitoring activities. Although some will interpret divestments in current monitors as a diminished appreciation of those observations, the intent actually is to improve characterization of key trace gas species. Observations of CO, SO_2, and NO_2 may be as important as any observation given the roles of those observations in a variety of health, deposition, and atmospheric science assessments and are especially critical to multiple pollutant assessments.

Policy Issues

Removal or relocation of monitors with historical regulatory applications creates a challenging intersection between policy and technical applications. Network assessments produce recommendations on removing or relocating samplers largely on the basis of technical merit. In some instances, these recommendations conflict with existing policy, other needs, or the desire of community citizens. For example, a recommendation that an ozone monitor be discontinued in a nonattainment county because of redundancy of neighboring sampling sites creates tension between policy and technical perspectives. From a technical perspective, those resources used for a redundant observation may be better used to fill in missing spatial gaps or to measure different pollutants. Further complicating this scenario are concerns often raised by citizens that associate the removal of monitors with a compromise in public health protection. Reaching a balance between policy and technical perspectives remains a challenge to regulatory-based monitoring programs. Unfortunately, policy concerns tend to slow down incorporation of innovative approaches to characterize air quality.

PROMOTING FLEXIBILITY AND ADVANCED TECHNOLOGIES

The $PM_{2.5}$ network initiated in 1999 incorporated over 1100 gravimetric, filter-based sampling methods meeting FRM or Federal Equivalent Method (FEM) guidelines.[2] FRM and FEM status is required for regulatory applications such as developing design values relative to the NAAQS for establishing an area's attainment status. Filter-based gravimetric methods are labor intensive; typically sample over a 24-hr time frame, thereby losing important temporal resolution; and create significant data delivery delays because of laboratory chemical analysis and processing. Filter-based methods, such as the FRM using Teflon filters, are subject to sampling artifacts, typically negative, which provide an inaccurate and low estimate of $PM_{2.5}$ relative to what is actually in the air.[20] Note that the FRM is a regulatory standard and not an analytical standard. Consequently, there has been interest to use continuously operating $PM_{2.5}$ monitors for over a decade. Continuous $PM_{2.5}$ samplers are widely used by the AIRNow program to inform the public of an area's air quality related to the AQI. Unfortunately, the lack of equivalency demonstrations for such methods has curtailed broader use of continuous aerosol data. Results from the Supersites Program indicate that continuous methods often provide a better estimate of $PM_{2.5}$ than filter-based methods.[20,34] However, because the FRM is subject to such errors and because the relationship is complicated by chemical composition that varies by location, season, and source mix, national demonstrations for equivalency often are not achieved for continuous methods. To address the issue of regional variability in the response of continuous methods relative to FRMs, EPA developed a new category for Class III FEM requirements referred to as Approved Regional Methods (ARMs) and is currently reviewing submitted applications.

These comments on continuous PM measurements reflect a small sample of a variety of technological and resource issues in the ambient monitoring program. Technological advancements in ambient monitoring instrumentation are compromised by policy constraints and a scarcity of well-defined market incentives and resources driving continued methods development and evaluation.

NEXT STEPS

Modifications in the nations routine networks, catalyzed by the monitoring strategy, will facilitate broader integration of observation systems across federal agencies, countries, satellite-based sensors, and research efforts. Well coordinated observation efforts will better establish a basis to address issues spanning a variety of pollutant categories across multiple spatial and temporal scales, influenced by interactions between atmospheric and terrestrial/aquatic systems and climate and air quality. An acceleration of partnerships across agencies and nations is occurring, driven by a combination of dwindling assessment resources, increased analytical demands, and greater recognition of co-dependencies across environmental issues. In addition to multiple pollutant interactions discussed here, challenges of multiple spatial-scale assessments will drive future integration of networks. Gradual lowering of U.S. ozone and PM standards, combined with enhanced growth of emissions in developing regions of India, Asia, and South America, will increase the relative contribution of intercontinental air pollution transport to regional and local areas within the United States, driving assessment approaches that benefit from complimentary use of air quality models and ground- and satellite-based air quality observations.

Interactions between climate and air quality affecting U.S. air quality are assessed through observations and modeling tools that also support long-range transcontinental and within-continent transport scenarios. Local-scale air quality assessment challenges include a broad suite of particle chemical and physical properties and atmospheric chemistry phenomena associated with current exposures in near-roadway environments. Climate interactions and related policies impact virtually all spatial scales. Examples include atmospheric composition modifications affected by penetration of emerging fuels in near-source regions and numerous global- and regional-scale meteorological influences impacting emissions and air quality. Currently, national networks with "representative" monitoring are not positioned to adequately characterize the atmosphere in near-roadway environments proximate to substantial populations. Prohibitively high resource requirements to characterize complex near-field environments using traditional monitoring designs suggest greater reliance on flexible, periodic measurement campaigns that provide an efficient means to capture long-term signal changes.

Observation networks, which currently are focused on regional and urban scales, are challenged to simultaneously expand to more effectively address global and near-field spatial domains. This assortment of multiple

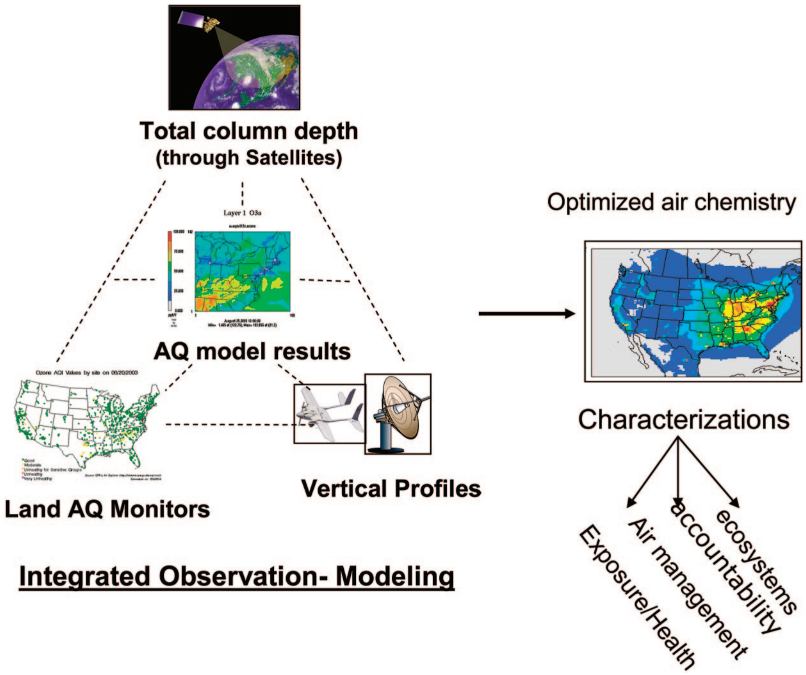

Figure 8. Complementary attributes of observations and models enhancing environmental characterizations.

demands implies resource needs beyond the scope of routine networks and places a premium on partnerships with entities sharing overlapping monitoring and assessment needs. Furthermore, the complexity of space, time, and composition in ambient pollutants leads to increased merging of observations and modeling tools (Figure 8), because it is not practical to cover such a diverse set of needs only through observations.

Accessing and manipulating observational datasets presents challenges to data user groups accessing single systems. Information technology solutions to harmonize datasets could reduce the burden on analysts in accessing, reducing, understanding, and manipulating a spectrum of disparate datasets inherent in integrated assessments. Consistent database formats need to be established and set criteria defined with sufficient variability to enable the efficient inclusion of new methods. Resources for collecting data rarely are complemented by adequate resources to process and analyze information.[35] Demands on data processing elements will necessarily increase as integration considerations expand the breadth of assessments. The Visualization Information Exchange Web System (VIEWS; http://www.vista.cira.colostate.edu/views/) developed by the Regional Planning Organizations (RPOs) in support of visibility assessments and the Health Effects Institute (HEI)'s air quality database (http://hei.aer.com/login.php) are examples of recently developed, publicly accessible, and user friendly air quality data reduction, integration, and analysis/visualization systems.

The federated data system (DataFed; http://www.datafedwiki.wustl.edu/index.php/DataFed_Wiki) is an outgrowth of the Global Earth Observation System of Systems (GEOSS), an attempt to coordinate Earth observations catalyzed by the Group on Earth Observations (GEO; http://www.earthobservations.org/index.html). DataFed provides the architecture to facilitate interoperability of data systems from diverse organizations (Figure 9) and conceptually could link surface-based air quality data integration systems such as VIEWS with observational and modeling systems, expanding the range of environmental characterization relevant to comprehensive integrated environmental assessments. These emerging integrated systems offer vision for addressing information technology facets of comprehensive assessments but will require investments and engagement from participating user communities.

CLOSING REMARKS

EPA sets NAAQS throughout the United States to protect public health and welfare. Air quality monitoring, data analysis, and assessments are currently strained by a declining resource trend. We anticipate needs for more sensitive and highly time-resolved measurements associated with background levels and long-range transport from outside of the United States as pollutant levels decrease under current and planned regulations and the stringency of air quality standards increases. In parallel, a greater appreciation of the atmospheric process complexities and exposures associated with near-roadway environments challenge traditional monitoring designs. Although the scientific community has recognized the value of expanding routine observation programs beyond compliance-focused observations,[36] government agencies responsible for network operations are faced with multiple demands on monitoring programs, which inherently constrains network evolution. Although EPA is engaged in network integration and implementation of NCore to improve multiple pollutant characterization, compliance-focused monitor-

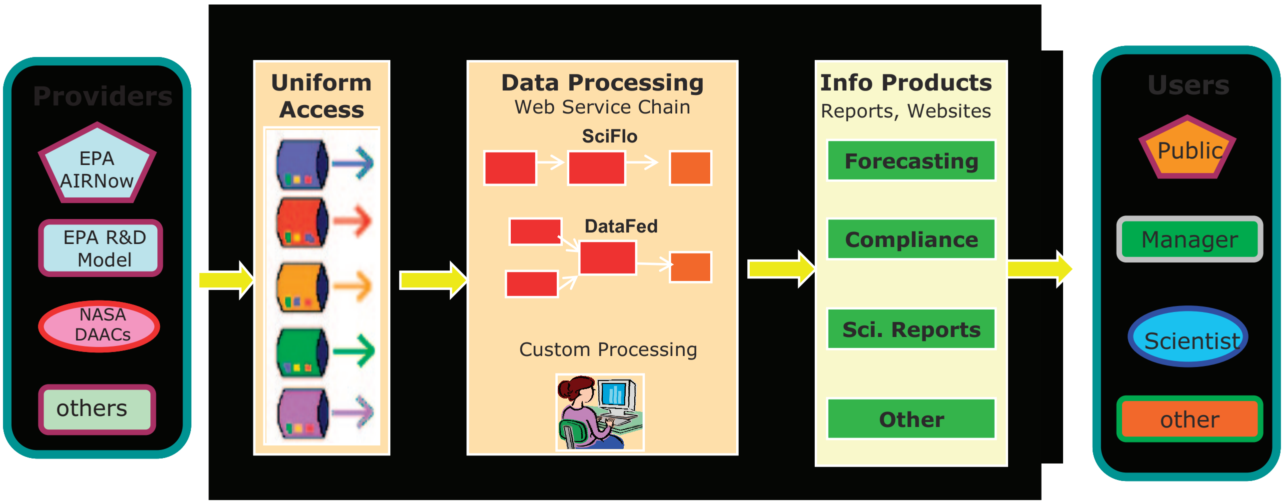

Figure 9. Information flow across disparate databases and users with intermediate processing steps to enable harmonization and facilitate access and interpretation. Figure based on information from DataFed (http://www.datafedwiki.wustl.edu/index.php/DataFed_Wiki).

ing remains an agency priority. The larger air quality community can enable partnerships across federal and SLT agencies to effectively mine satellite data and non-routine observation programs and foster model-observation systems to address a plethora of emerging air quality management challenges.

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About the Authors

Richard Scheffe, Tim Hanley, Mark Schmidt, James Hemby, Nealson Watkins, Michael Papp, Joann Rice, and Joe Tikvart are scientists with the EPA Office of Air Quality Planning and Standards, Office of Air and Radiation in Research Triangle Park, NC. Paul A. Solomon is a research scientist with the EPA National Exposure Research Laboratory Office of Research and Development in Las Vegas, NV. Rudolf Husar is a professor of engineering with Washington University in St. Louis, MO. Michael Koerber is director of the Lake Michigan Air Directors Consortium in Rosemont, IL. Michael Gilroy is a meteorologist with the Puget Sound Clean Air Agency in Seattle, WA. Ricard Valentinetti is the air director with the Vermont Agency of Natural Resources in Waterbury, VT. Please address correspondence to: Richard D. Scheffe, U.S. Environmental Protection Agency Office of Air Quality Planning and Standards, 4201 Alexander Drive, MD-14, Research Triangle Park, NC 27711; phone: +1-919-541-4650; e-mail: scheffe.rich@epa.gov.