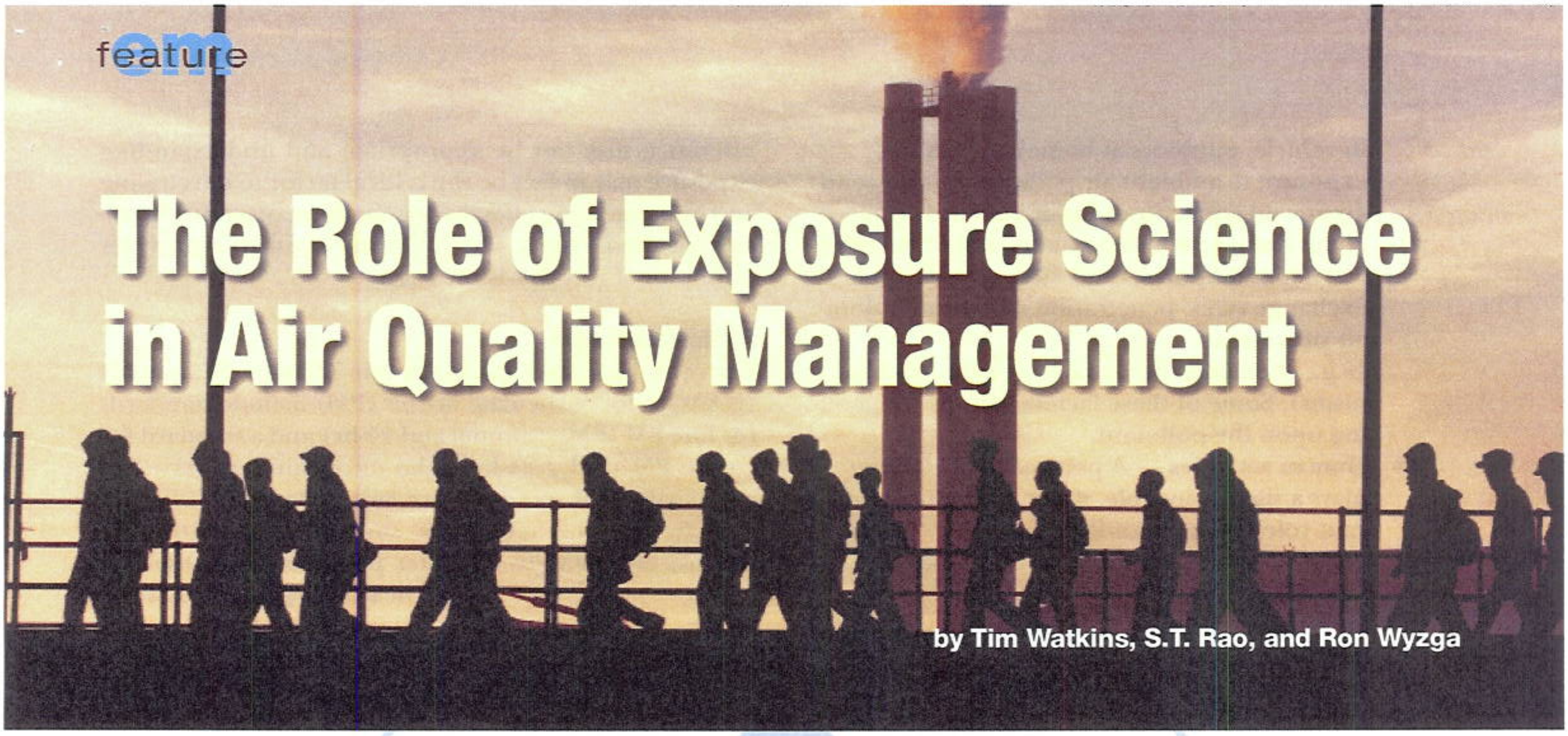

The Role of Exposure Science in Air Quality Management

by Tim Watkins, S.T. Rao, and Ron Wyzga

Air quality standards and regulations are designed to protect public health and the environment. However, there are issues regarding whether the current standards and regulations should be adjusted to be more protective or more effectively target air quality management activities. People experience health impacts because of their exposure to air pollutants. Therefore, an understanding of exposure is vital for properly addressing air quality management issues. This article presents concepts of exposure and how these concepts could be applied to gain a better understanding of the relationships between air quality and human health, which, in turn, should help improve air quality management practices. While air pollution impacts both humans and ecological resources, the focus here is on the human health outcomes.

Exposure and Exposure Science

The U.S. Environmental Protection Agency (EPA) defines exposure as contact (of an environmental pollutant) with the exterior of the person.[1] As a result, exposure provides the critical link between environmental concentrations and health outcomes. Air quality management activities often equate ambient air concentrations with actual human exposures, but understanding exposure to air pollutants requires an understanding of important exposure factors, such as the distribution of the air pollutant in space and time; to what degree the pollutant penetrates inside locations where people spend their time; and where, when, and how people spend their time. The role of each of these factors in understanding exposure is described in more detail below.

- **Spatial and temporal variability of ambient pollutant concentrations** — When ambient concentrations of a pollutant are relatively homogeneous in space and time, human exposures may be more closely approximated by ambient concentrations. However, when there is significant spatial and temporal variability in ambient air concentrations, ambient levels of pollutants at a central site will not be adequate to properly characterize human exposure.
- **Concentrations of ambient pollutants in microenvironments** — Microenvironments are locations where people spend their time (e.g., indoors at home, indoors at work/school,

Tim Watkins and **S.T. Rao** are scientists with the U.S. Environmental Protection Agency's (EPA) National Exposure Research Laboratory, Research Triangle Park, NC, and **Ron Wyzga** is a scientist with EPRI, Palo Alto, CA.
E-mail: watkins.tim@epa.gov.

in-vehicle, outdoors at home). A person's exposure to ambient air pollution will depend greatly on concentrations of ambient pollutant in the microenvironments, which, in turn, will depend upon several factors, such as air exchange rates, penetration rates, and indoor air processes
(e.g., chemistry, decay rates, removal mechanisms). Some of these factors will vary depending upon the pollutant.

- **Human activities** — A person's daily activity plays a significant role, if not the most significant role, in characterizing human exposure. Where a person spends time and how much time is spent in each location will impact that person's exposure.

Exposure is the critical link between ambient air concentrations and human health outcomes.

The source-to-outcome continuum in Figure 1 presents an approach to organize and conceptualize the key elements required to understand and manage air quality.[2] Within this continuum, exposure is the critical link between ambient air concentrations and human health outcomes. The field of exposure science includes research to measure and model factors and human activities that influence magnitude, frequency, and duration of exposure to air pollutant concentrations in various microenvironments. However, understanding human exposures also requires an understanding of the factors that influence the spatial and temporal variability of ambient air concentrations, which, in turn, requires an understanding of air pollution sources, transport and fate of air pollutants, and ambient air concentrations. Therefore, as depicted in Figure 1, exposure science also includes aspects of research related to the characterization of source emissions, atmospheric processes, ambient measurements, and modeling.

The Growing Importance of Exposure

While exposure science has played an important role in supporting the development of existing air quality policies, many existing air quality management policies are based upon studies that associated ambient concentrations with health impacts by inferring that ambient concentrations are equivalent to actual human exposures. For current and emerging air quality management issues this inference may not be appropriate and understanding exposure may in fact be the critical factor to developing and implementing effective air quality management policies for these issues. The following discussion provides examples of why this is the case.

Particulate Matter

Current National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) include standards for fine PM ($PM_{2.5}$; annual and 24-hr) and a standard for coarse PM (PM_{10}; 24-hr). The uncertainties surrounding existing PM standards are largely based on whether specific PM characteristics, such as composition or size fraction, lead to a greater proportion of observed health impacts.[2,3] Existing standards for $PM_{2.5}$ and PM_{10} are based in part upon epidemiological studies that found associations between ambient concentrations of PM and observed health impacts. These studies often used a central site monitor to estimate exposures to PM. Exposure studies that followed the promulgation of the 1997 PM NAAQS showed that central site measurements were highly correlated with personal measurements of $PM_{2.5}$ over time.[4] The high correlation between ambient $PM_{2.5}$ concentrations and personal $PM_{2.5}$ exposures exists, in part, because the variability of ambient $PM_{2.5}$ concentrations across many urban areas is relatively homogeneous.[2] However, the spatial variability of specific PM components or PM of different size fractions (e.g., ultrafine PM or coarse PM) is greater than that for $PM_{2.5}$.[3,5] In addition, there are significant uncertainties regarding the microenvironmental concentrations of PM components and PM size fractions.[3] Therefore, any epidemiological evidence or risk assessment for PM components or PM size fractions will require an improved exposure assessment due to the spatial heterogeneity of ambient concentrations.

In addition to PM NAAQS, there are other national

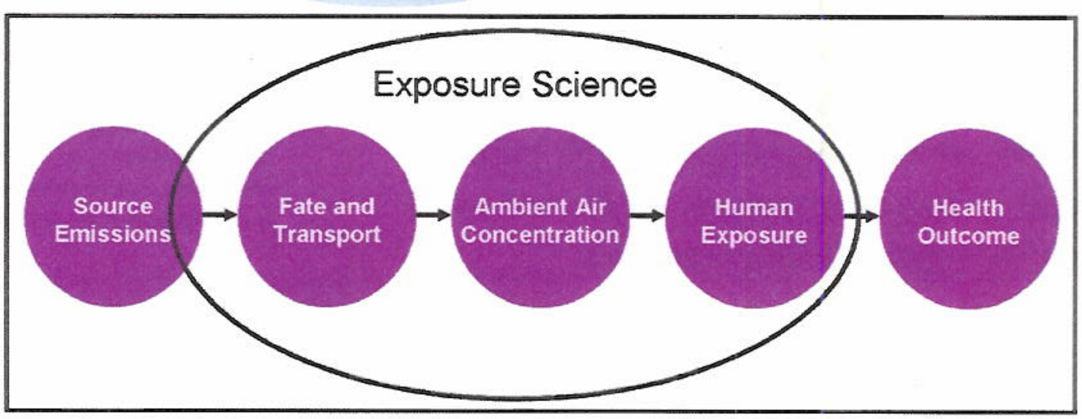

Figure 1. Exposure science: Source-to-output continuum.

regulations designed to address regionally transported PM, such as the Clean Air Interstate Rule. As these rules come into effect, regional background concentrations of secondary PM (e.g., sulfate and nitrate) are expected to be reduced, thereby increasing the relative contributions of local sources of primary PM in urban areas. The nature of the emissions of these local sources will likely result in ambient PM concentrations with more spatial and temporal heterogeneity. For example, there may be stronger diurnal patterns related to traffic or greater spatial gradients near large local sources. As a result, future air quality management activities would benefit greatly from improved exposure assessment and better attribution of sources to ambient air concentrations and exposures.

Ozone

Exposure assessment has been integral in previous reviews of ozone NAAQS[6] and will continue to be central to addressing some of the key uncertainties related to future ozone NAAQS. For example, certain subpopulations who spend more time outdoors (e.g., outdoor workers and children) may be more vulnerable to ozone exposure because indoor levels of ozone are generally very low.[7] Improving the understanding of the activities of these subpopulations will improve exposure assessments that are used to inform future NAAQS. In addition, the nature of human activities is also an important factor in understanding ozone exposure. Activities that increase breathing rates can lead to higher ozone exposures,[7] so developing an improved understanding of how individual activity levels relate to ozone exposures will also improve ozone exposure assessments conducted as part of NAAQS reviews.

Toxic Air Pollutants

The regulatory program for stationary sources of toxic air pollutants in the United States includes both a technology-based phase and a risk-based phase. Regulations based on technology have been completed and risk-based regulations are currently under development. There is significant uncertainty in toxic air pollutant risk assessments, and much of this uncertainty is associated with exposure.[8] For example, many toxic air pollutants exhibit significant spatial and temporal variability. In addition, some toxic air pollutants have significant indoor sources that contribute to microenvironmental concentrations and confound estimates of exposures to toxic air pollutants of ambient origin. Hence, improved estimates of exposure will be important to making effective environmental policy decisions.

Air Pollution Hotspots and Environmental Justice Issues

Recent concerns have emerged regarding whether existing regulations provide ample protection for certain subpopulations that may be vulnerable due to elevated

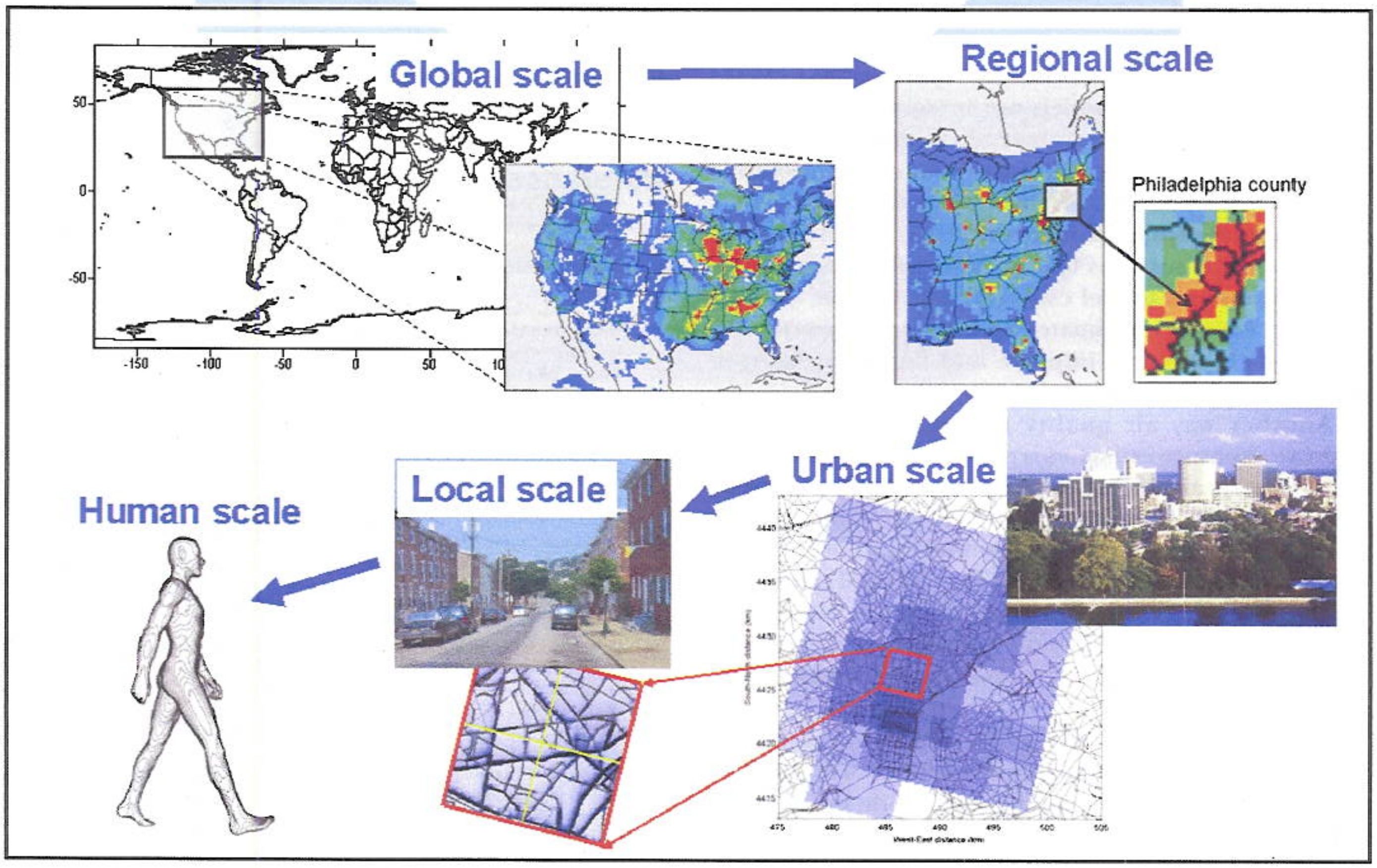

Figure 2. The multiple scales of exposure science.

exposures in "hotspots" (i.e., locations where pollutant concentrations are substantially higher than concentrations indicated by ambient monitoring in surrounding areas).[8] In many cases, these issues are centered on environmental justice.[8] An example of such an issue is near-road exposures and health effects. Exposure assessment will be central to addressing these issues. Improved characterization of the variability of ambient concentrations, microenvironmental concentrations, and human activities will all be required to evaluate environmental policies to address potential hotspots and environmental justice issues.

Improving Exposure Assessment with Models

Ideally, actual human exposure measurements would be available to inform air quality management activities. The reality is that this is just not possible in most instances. Improved exposure estimates may be obtained through more spatially, temporally, and compositionally refined air quality monitoring and through conducting human exposure monitoring studies. However, increased monitoring is often cost-prohibitive and collecting the necessary monitoring data at the required spatial and temporal scale is often just not feasible. Air quality and exposure modeling tools offer an alternative to increased monitoring and can provide estimates of exposure at multiple scales (see Figure 2). For example, air quality models can provide more spatially, temporally, and compositionally refined estimates of ambient concentrations at global, regional, urban, and local scales.

When air quality models are integrated with other data sources and across scales even more opportunities to improve exposure estimates arise. For example, output from air quality models can be used to fill in the spatial and temporal gaps in existing ambient monitoring data. The air quality surfaces that are created by integrating observations and model estimates can then be used to enhance exposure estimates and create exposure surfaces, which, in turn, improve and facilitate stronger epidemiological studies.[9]

Another way air quality models can be used to improve exposure estimates is by combining results from regional-scale air quality models (e.g., CMAQ) and local-scale dispersion models (e.g., AERMOD).[10] The regional air quality model provides a regional background concentration upon which the influence of local stationary and mobile sources can be added using models such as AERMOD. The result is a more spatially refined ambient air quality estimate that may be used to improve exposure assessments.

While air quality models, either alone or in combination, offer opportunities to improve estimates of ambient air concentrations, these modeling tools do not provide estimates of actual human exposure because they do not address the other key exposure factors—air pollutant concentrations in microenvironments and the role of human activities. Human exposure models incorporate these other key exposure factors to generate estimates of actual human exposures.[11] In addition, the integration of air quality and human exposure models provides further opportunities to improve estimates of exposure.[10,12] The resulting estimates of actual human exposures may be used to inform a variety of air quality management activities, including risk assessments and risk management decisions related to the issues identified above

Summary

Exposure provides the critical link between ambient air concentrations and health outcomes. Many of the air quality management issues that we face today involve a number of factors that affect exposure: spatial and temporal variability of ambient concentrations, microenvironmental concentrations, and human activities. As a result, simply equating ambient air concentrations to exposure may not result in the most efficient and effective ways to address these issues. Modeling tools offer tremendous promise for improving exposure estimates needed for air quality management activities. Air quality models have traditionally been used to support implementation of air regulations, while human exposure models have been used mostly to support risk assessments that support development of air regulations. However, these modeling tools, either alone or in combination, have potential to expand beyond their traditional applications to improve exposure assessments in support of all aspects of air quality management. While much progress has been made in addressing the nation's air quality, air quality management issues are becoming increasingly complex and exposure science must play an important role in developing effective policies to address them. **em**

References

1. *Guidelines for Exposure Assessments*; EPA 600Z-92/001; Risk Assessment Forum, U.S. Environmental Protection Agency: Washington, DC, 1992.
2. *Research Priorities for Airborne Particulate Matter IV—Continuing Research Progress*; National Research Council, National Academies Press: Washington, DC, 2004.
3. *Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information, OAQPS Staff Paper*; EPA 452/R-05-005; U.S. Environmental Protection Agency: Washington, DC, 2005.
4. Sarnat, J.A.; Brown, K.W.; Schwartz, J.; Coull, B.A.; Koutrakis P. Ambient Gas Concentrations and Personal Particulate Matter Exposures—Implications for Studying the Health Effects of Particles; *Epidemiol.* **2005**, *16* (3); 385-395.
5. *Air Quality Criteria for Particulate Matter*; EPA 600/P-99/002aF-bF; U.S. Environmental Protection Agency: Washington, DC, 2004.
6. *Review of the National Ambient Air Quality Standards for Ozone: Policy Assessment of Scientific and Technical Information, OAQPS Staff Paper (June 1996)*; EPA-452/R-96-007; U.S. Environmental Protection Agency: Washington, DC, 1996.
7. *Air Quality Criteria for Ozone and Related Photochemical Oxidants (Final)*; EPA/600/R-05/004aF-cF; U.S. Environmental Protection Agency: Washington, DC, 2006.
8. *Air Quality Management in the United States*; National Research Council, National Academies Press: Washington, DC, 2004.
9. Bell, M.L. The Use of Ambient Air Quality Modeling to Estimate Individual and Population Exposure for Human Health Research: A Case Study of Ozone in the Northern Georgia Region of the United States; *Environ. International* **2006**, *32* (5), 586-593.
10. Isakov, V.; Graham, S.; Burke, J.; Özkaynak, H. Linking Air Quality and Exposure Models; *EM* September 2006, 26-29.
11. Özkaynak, H.; Palma, T.; Touma, J.S.; Thurman, J. Modeling Population Exposures to Outdoor Sources of Hazardous Air Pollutants; *J. Expos. Sci. Environ. Epidemiol.* **2008**, *18* (1), 45-58.
12. Georgopoulos P.G.; Wang, S.; Vyas, V.M.; Sun, Q.; Burke, J.M.; Vedantham, R.; McCurdy, T.; Özkaynak H. A Source-to-Dose Assessment of Population Exposures to Fine PM and Ozone in Philadelphia, PA, During a Summer 1999 Episode; *J. Expos. Anal. Environ. Epidemiol.* **2005**, *15*, 439-457