7.6 The Importance of Exposure in Addressing Current and Emerging Air Quality Issues

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Abstract The air quality issues that we face today and will face in the future are becoming increasingly more complex and require an improved understanding of human exposure to be effectively addressed. The objectives of this paper are (1) to discuss how concepts of human exposure and exposure science and should be applied to improve air quality management practices, and (2) to show how air quality modeling tools can be used to improve exposures estimates used for understanding associations between air quality and human health. Data from a large human exposure monitoring study is presented to demonstrate the value of exposure in understanding important air quality issues, such as health effects associated with exposure to components of particulate matter (PM), to PM of different size fractions (coarse and ultrafine), and to air pollution in near roadway environments. Various approaches for improving estimates of exposure via application of air quality modeling are discussed and results from example modeling applications are presented. These air quality modeling approaches include: the integration of regional scale eulerian air quality models with local scale gaussian dispersion models; the fusion of modeled estimates with air quality observations; the integration of air quality and human exposure modeling tools; and the use of exposure factors, such as housing ventilation, to adjust modeled estimates of ambient air quality.

Keywords Air quality, exposure, modeling, particulate mater, toxic air pollutants

1. Introduction

Existing air quality standards and regulations are in place to protect public health and the environment. However, there remain uncertainties regarding whether existing standards/regulations should be adjusted to be more protective or perhaps to more effectively target air quality management activities. For particulate matter (PM) standards, there are questions regarding whether current mass based standards for PM_{10} and $PM_{2.5}$ should be revised to address specific components or sources of PM or different PM size fractions (NRC, 2004a; U.S. EPA, 2005). There are also concerns about potential disproportionate health effects associated with air pollution "hotspots." These "hotspot" concerns are often related to environmental

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justice issues (NRC, 2004b). For these air quality management issues, understanding human exposure is critical. This paper discusses why this is the case, presents data from human exposure monitoring and modeling studies to further highlight the importance of air pollution exposure issues, and discusses how air quality models may be used to improve exposure assessment. While air pollution impacts both humans and ecological resources, this paper focuses on human health outcomes.

2. Exposure and Exposure Science

Although air quality standards to protect public health are most often based on levels of a pollutant in the ambient air, people experience health impacts from the pollutants in the air they breathe, i.e., from their exposure. The United States Environmental Protection Agency defines exposure as contact (of an environmental pollutant) with the exterior of the person (U.S. EPA, 1992). The critical factors to characterize and understand human exposure to air pollution include the following.

- *Spatial and temporal variability of ambient pollutant concentrations* – When ambient air concentrations are relatively homogeneous in space and time, then 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 will more poorly represent human exposure.

- *Concentrations of ambient pollutants in microenvironments* – Micro-environments are locations where people spend their time (e.g., indoors at home, indoors at work/school, in-vehicle, outdoors at home). A person's exposure to ambient air pollution will depend greatly on concentrations of ambient pollutant in micro-environments, which in turn depend upon exposure factors such as proximity to sources, air exchange rates, penetration rates, indoor air chemistry, and indoor decay rates and removal mechanisms.

- *Human Activities* – A person's daily activities play a significant role, if not the most significant role, in characterizing human exposure. Where a person spends their time and how much time he/she spends in each location will impact that person's exposure.

Human 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. Understanding human exposures 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, fate and transport of air pollutants, and ambient air concentrations. Therefore, the field of exposure science also includes aspects of research related to source emission characterization, atmospheric processes, and ambient air measurement and modeling.

3. The Growing Importance of Exposure

Understanding actual human exposures is critical to addressing the current and emerging air quality management issues mentioned in the introduction of this paper. Human exposure is the link between ambient concentrations and health outcomes. 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. However, 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.

3.1. Particulate matter components, size fractions, and sources

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 (NRC, 2004a; U.S. EPA, 2005). Existing standards for $PM_{2.5}$ and PM_{10} are largely based 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, which is reasonable for $PM_{2.5}$ because the variability of $PM_{2.5}$ across many urban areas is relatively homogeneous. 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 $PM_{2.5}$ (U.S. EPA, 2004, 2005). In addition, there are significant uncertainties regarding the microenvironmental concentrations of PM components and PM size fractions (U.S. EPA, 2004). 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.

Related to the issues of PM components and size fractions is the issue of whether PM standards should be targeted at sources of PM that may be disproportionately responsible for observed health impacts. Characteristics of PM emissions vary by source, thus there is the potential that the relative toxicity of PM from different sources may also vary. Exposure will play an important role in addressing this issue as well. One approach to address this issue is to evaluate the inter-city variability of PM characteristics. The composition and characteristics of PM in different urban areas varies because the contributing sources of PM vary (McMurry et al., 2004), therefore studies that evaluate the differential exposures and health impacts across multiple urban areas may provide insights into the issue regarding standards for particular PM sources.

3.2. 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 exposures in "hotspots." In many cases, these issues are centered around environmental justice and toxic air pollutants (NRC, 2004b). An example of such an issue is near roadway exposures and health effects. Exposure assessment will be central to addressing these issues because 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.

4. The Detroit Exposure and Aerosol Research Study

The US Environmental Protection Agency has conducted an exposure study that is generating data to confirm the importance of exposure in addressing the air quality management issues above and to provide insight for future air quality policy decisions. The Detroit Exposure and Aerosol Research Study (DEARS) was designed to describe the relationships between concentrations at a central site and residential/personal concentrations for PM components, PM size fractions, PM from specific sources (mobile and point), and air toxics. To accomplish this, the DEARS included extensive field work conducted over three years and six seasons. The DEARS data collection sites included a central ambient air monitoring site and six exposure measurement areas (EMA) that were selected to evaluate the impact of local sources.

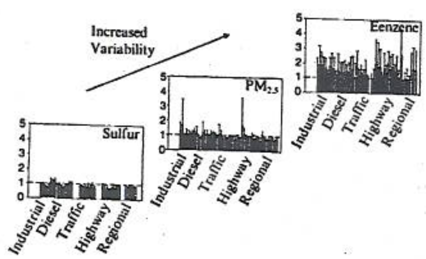

Fig. 1 Ratio of residential outdoor concentrations to central site concentrations for DEARS season 1

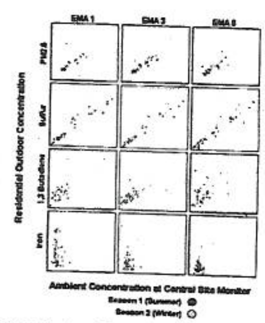

Fig. 2 Relationships between concentrations at residential outdoor sites and the central site for DEARS EMAs

Figures 1 and 2 present data on the spatial variability of pollutants by comparing data collected at the central site to data collected at residential outdoor sites in each EMA. Figure 1 presents the ratios of concentrations at residential outdoor locations to concentrations at the central site for sulfur, $PM_{2.5}$, and benzene. The ratios for sulfur, a PM component, are all very close to 1. The ratios for total $PM_{2.5}$ are also very close to 1, but exhibit a bit more variability than sulfur. The ratios for sulfur and $PM_{2.5}$ confirm the relative spatial homogeneity for these pollutants. However, the ratios for benzene are generally greater than 1, which shows the influence of sources, particularly in industrial and mobile source influenced EMAs. Figure 2 provides additional data to show how spatial variability differs by pollutant. For $PM_{2.5}$, there is a relatively strong relationship between residential outdoor sites and the central site. For sulfur, the correlation is also very strong plus seasonal variation is observed. Again, the results for $PM_{2.5}$ and sulfur are not surprising given the regional nature of these pollutants. However, there is much more variability between the central site and residential outdoor sites for 1,3 butadiene and iron. For 1,3 butadiene, the influence of local sources can be seen particularly at EMA 6, which is impacted by highway sources. For iron, the influence of local sources is even greater, particularly at EMAs 1 and 3.

The DEARS also provides insights into how microenvironmental factors and human activities impact human exposures to various pollutants. Figure 3 compares measurements of various air toxics taken at the central monitoring site, at outdoor residential locations, at indoor residential locations, and personal exposure measurements. The influence of micro-environmental concentrations (including indoor sources) and human activities can be seen as total personal exposure is generally higher and exhibits more variability than indoor, outdoor, and ambient concentrations.

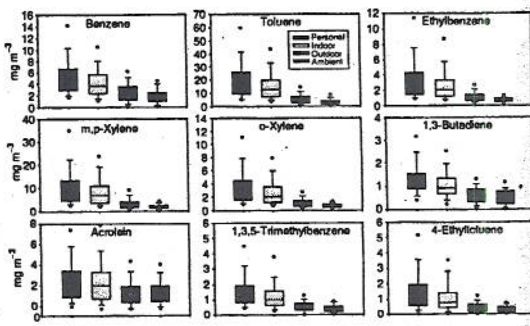

Fig. 3 Comparisons of personal, indoor, outdoor residential and ambient central site measurements for DEARS (seasons 1–4)

5. Improving Exposure Assessment with Air Quality Models

Addressing the air quality management issues above will require improved human exposure assessments. Improved exposure estimates could be obtained through more spatially, temporally, and compositionally refined air quality monitoring and through conducting human exposure monitoring studies. However, increased monitoring is cost prohibitive. Air quality modeling tools offer an alternative to increased monitoring. For example, air quality models can provide more spatially, temporally, and compositionally refined estimates of ambient concentrations. They also can provide scientific insights to improve the understanding and characterization of the atmospheric processes that impact spatial and temporal variability of pollutants.

When air quality models are integrated with each other and with other data sources 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 to improve the estimates of air quality and exposure estimates for health studies (Bell, 2006). Another way air quality models can be used to improve exposure estimates is by combining results from regional scale air quality models, such as CMAQ, and local scale dispersion models, such as AERMOD. Figure 4 demonstrates this concept from a modeling analysis done in New Haven, CT. The regional air quality model provides a regional background concentration upon which the influence of local stationary and mobile sources can be added. The result is a more spatially refined ambient air quality estimate that may be used to improve exposure assessments. Combining air quality modeling output with monitoring data and integrating regional and local scale air quality models provide more spatially and temporally refined estimates of ambient air quality that can be used to improve human exposure estimates. However, while these approaches address the spatial and temporal variability exposure factor, they do not address other exposure factors such as microenvironmental concentrations and human activities. Linking air quality modeling outputs with human exposure models provides an approach to address these exposure factors. Using ambient concentration inputs from air quality models, human exposure models estimate actual human exposures by modeling factors, such as pollutant penetration rates, that impact pollutant concentrations in microenvironments and then integrating human activity data including time spent in each microenvironment. Figure 5 shows results from linking air quality and human exposure models in Philadelphia, PA (Isakov et al., 2006). As shown in Figure 5, while the spatial patterns are similar, the actual human exposures to benzene are greater than ambient concentrations, most likely due to exposures experienced in high exposure microenvironments, such as in-vehicle, at gas stations, or in attached garages.

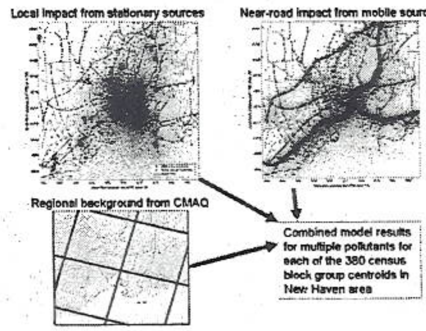

Fig. 4 Approach for combining regional scale and local scale air quality models (New Haven, CT)

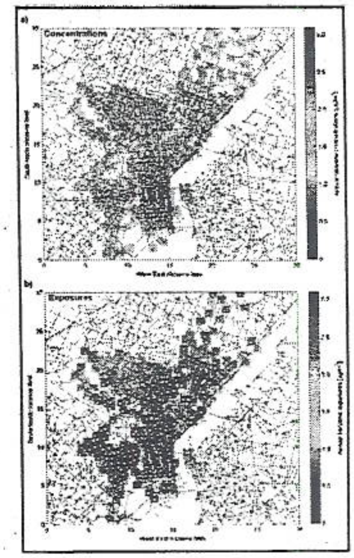

Fig. 5 Results from linking air quality and human exposure models in Philadelphia, Pa (Isakov et al., 2006)

6. Summary and Conclusions

To effectively address the current and emerging air quality management issues that we face today will require an improved understanding of human exposures. This paper provided examples and case studies demonstrating how improved exposure assessment will be an important tool to support environmental policy decisions on whether to revise existing or develop new air quality standards and regulations. Improved exposure assessments can also inform other air quality management activities such developing and evaluating alternative emissions control strategies and evaluating whether air quality regulations have met anticipated goals to protect human health. Air quality modeling tools offer tremendous promise for improving exposure estimates needed for air quality management activities. To date, air quality models have been used sparingly in health studies. However, as air quality modeling approaches become more sophisticated, the opportunities to use air quality models to enhance exposure assessments in health studies will grow and potentially lead to improved air quality policies.

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Discussion

P. Builtjes:

Do you see a future for bio-monitoring, by for example measuring radicals in blood?

T. Watkins:

Yes, I do believe that bio-monitoring holds promise for providing valuable information about human exposures. However, there are currently limited biomarkers routinely available for many air pollutants, particularly for particulate matter. Also, while bio-monitoring information is certainly useful, biomarkers indicate whether an exposure has occurred, but they do provide other important information such the source, route, duration or intensity of exposure. Therefore other tools, including modelling tools, are needed to more fully characterize exposures.