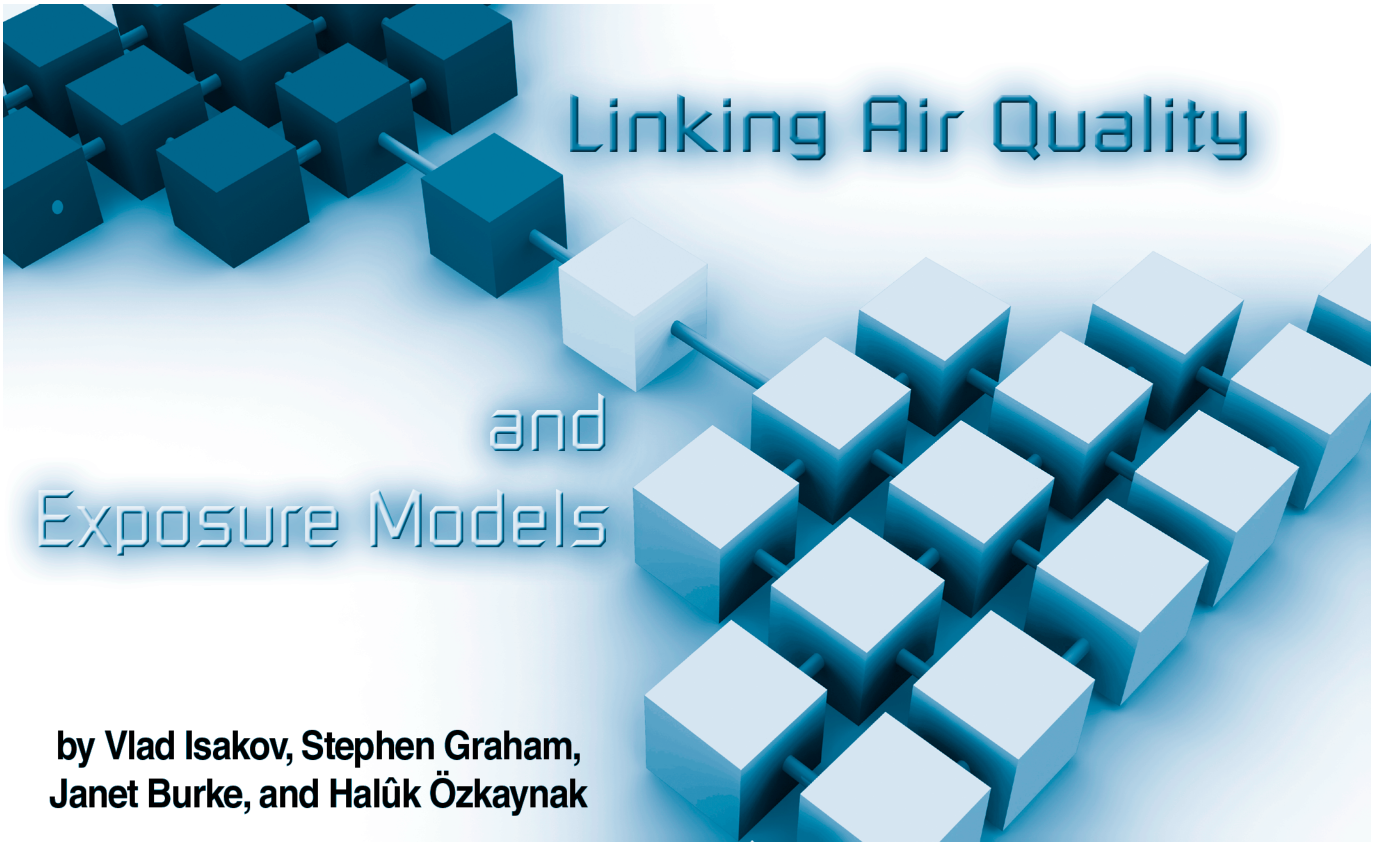

Linking Air Quality and Exposure Models

by Vlad Isakov, Stephen Graham, Janet Burke, and Halûk Özkaynak

In developing a strategy for mitigating undesirable health outcomes, risk managers and health scientists should include an assessment of the extent to which humans are exposed to pollutants. Human exposure assessment involves understanding how individuals or targeted groups will contact environmental chemicals or agents and the inter- and intra-personal variability in their exposure and resultant intake dose. Differences in exposure and intake dose for pollutants are largely due to variations in the concentrations of chemicals where a person is physically located (e.g., microscale—at home, the office, or school; macroscale—urban, suburban, or rural), or due to exposure factors, such as the fundamental physiology associated with activities performed (e.g., breathing rates), and other anthropometric attributes (e.g., age, gender, body weight). An individual's lifestyle and/or life-stage may dictate their proximity to sources of pollutants, such as emissions from automobiles while driving or emissions from household products, as well as the duration and intensity of their daily activities. Thus, human exposure assessments are strongly influenced by the level of detail used to characterize the spatial and temporal variation of pollutant concentrations and how human contact occurs.

Progress has been made in understanding human exposure through exposure measurement programs. Data from exposure studies have also been used to develop population-based exposure models that combine measurements of pollutant concentrations with human activity pattern data and census demographics to simulate actual human exposures. These models can provide estimates of the range of exposures for a population of interest and, if desired, the percent above a level of concern. As monitoring networks are reduced in size and frequency due to their expense, exposure and risk assessments will have to rely more often on air quality model concentrations as input to exposure models. To help identify air pollutant sources of greatest risk to humans, integration of modeling tools is essential to estimating air concentrations from sources and the resultant exposures for a population of interest.

The appropriate combination of human exposure and air quality models for producing scientifically credible estimates of the distribution of exposures will depend on many factors due to the complex nature of environmental transport and fate of chemicals and human contact with air pollutants. Air concentrations may vary significantly for certain pollutants within an urban area based on the source of emission and/or by time of day or season of the year. Human activities also vary in space and time. Depending on the magnitude of the variability of air concentrations and human activities, the relationship between the two may be important to preserve. The level

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of refinement needed in both types of models will also depend on the questions asked, such as those borne out of a screening-level assessment and covering a broad geographic region, those regarding an assessment focused on a discrete location, or those as defined by a specific pollutant. The coupling and appropriate application of these models will improve estimates, demonstrate utility in environmental health accountability programs, assist in the development of risk mitigation strategies, and improve community health or epidemiology studies.

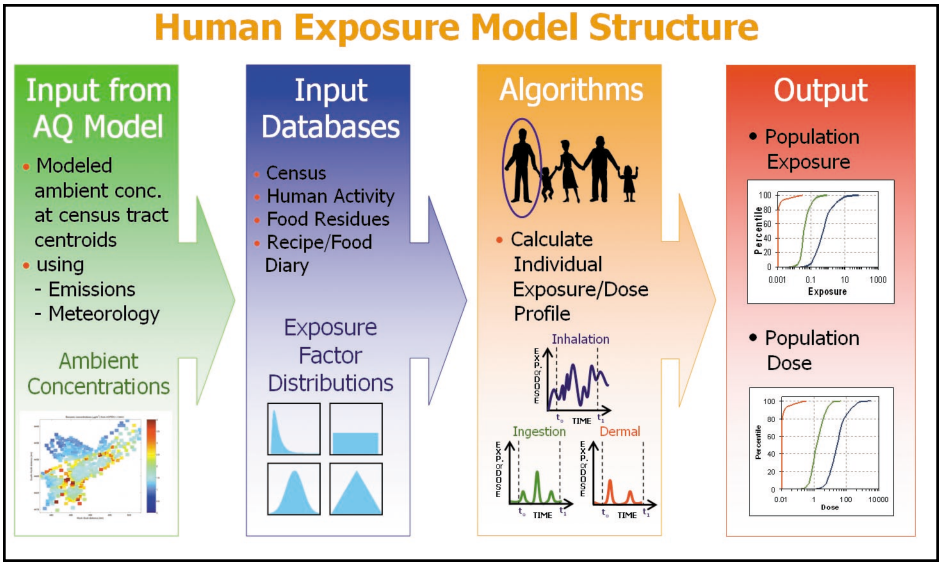

Figure 1. Approach to integrate air quality and human exposure modeling for air pollutants.

AIR QUALITY MODELING

For exposure assessments, air quality modeling should include local-scale features, long-range transport, and photochemistry to provide the best estimates of air concentrations. Generally speaking, there are two major types of air quality models: source-based dispersion models and grid-based chemical transport models. Chemical transport models, such as the Community Multi-scale Air Quality (CMAQ) model,[1] can resolve photochemistry, but not local-level details. CMAQ provides volume-average concentration values for each grid cell in the modeling domain, given stated conditions that can change hourly. Emissions are assumed to be instantaneously well mixed within the cell they are emitted.

While grid-models are the model platform of choice for simulation of chemically reactive airborne pollutants, there are various dispersion models (e.g., AERMOD[2]) that have been developed to simulate the fate of chemically stable airborne pollutants. Not having to incorporate complex atmospheric chemistry in generating output, these dispersion models can provide detailed resolution of the spatial variations in hourly-average concentrations of airborne pollutants. It would be desirable to combine the capabilities of grid-models and dispersion models into one model, but this is still an evolving area of research and development.[3] One option is a hybrid approach,[4] where a regional grid model and a local plume model are run independently. The regional grid model provides the regional background concentrations and urban-scale photochemistry, and the local plume dispersion model provides the air toxics concentrations due to local emission sources. Then, the results of both model simulations are combined to provide the total ambient air toxics concentrations for use in exposure models (see Figure 1). Care is required to avoid double counting of emissions when combining the two simulations.

EXPOSURE MODELING

Air quality models estimate pollutant concentrations for a given time period at a given location. If used for estimating exposure, the general assumption would be that all individuals living in that location are outdoors breathing the ambient concentration level predicted by an air quality dispersion model during the time period. Realistically, most people do not spend their entire day outdoors; a majority of time is spent in indoors (e.g., the home, workplace, school, vehicle), where air concentrations can be quite different than those outdoors due to local sources or decay and deposition processes during and following penetration. Also, the time spent in these locations by individuals or groups of similar individuals is variable from one day to the next.[5,6] Human exposure models have been developed to account for these factors.

The Stochastic Human Exposure and Dose Simulation (SHEDS) model[7] has been developed by the U.S. Environmental Protection Agency's National Exposure Research Laboratory. The general structure of SHEDS includes several input databases, algorithms, and outputs, as shown in Figure 1. SHEDS can estimate sequential exposure and intake dose of a pollutant for the selected population through three principal routes—inhalation, dermal, and dietary—over the course of a specific year. The generation of the time-series involves stochastic processes using numerical Monte-Carlo sampling techniques to characterize the variability within an individual and between individuals across a population. SHEDS is capable of using time-varying ambient concentrations, including hourly, daily, or other time-averaged data.

In estimating inhalation exposures, ambient pollutant concentrations are related to concentrations of pollutants in specific locations (termed "microenvironmental concentrations"). These algorithms typically take the form of proportions, linear regressions, and steady-state mass balance equations. Most of the factors or coefficients in these algorithms are provided in the form of a distribution that retains the inherent variability (and optionally the uncertainty) in these factors. For each simulated individual, a yearlong time series of exposure and intake doses are calculated from the microenvironmental concentration estimates and activity-specific inhalation rates based on the assigned human activity diaries. Daily-averaged exposure and total daily intake dose results for individuals in

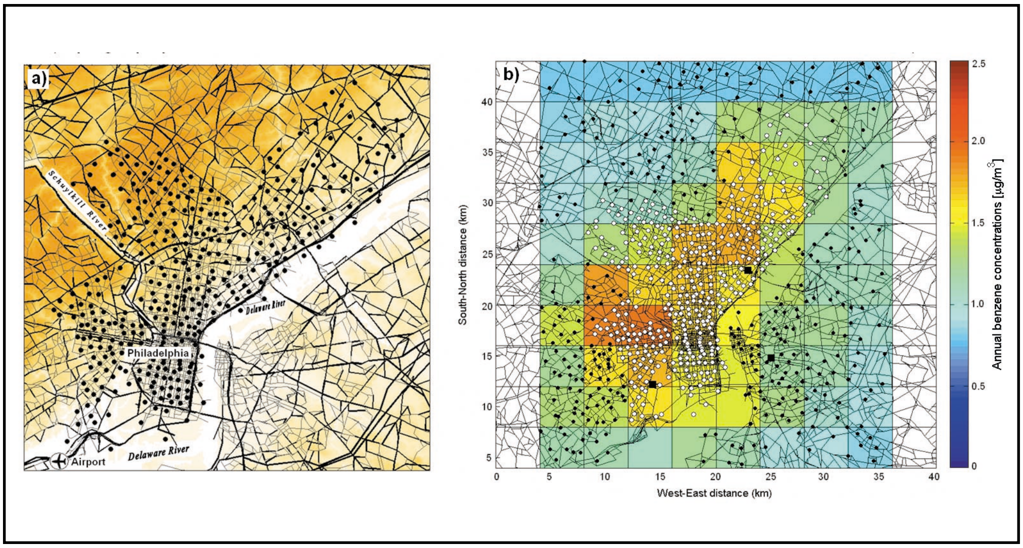

Figure 2. (a) Philadelphia study domain, topography, roads, and census tract centroids, and (b) annual average benzene concentrations [μg/m³] from CMAQ, Philadelphia County, PA.

the simulated population can be combined to produce the estimated population distribution of exposure and dose, which describes the variability in the population over a user-defined broad geographic region or down to a census tract level.

The current model design incorporates advanced exposure algorithms specific to mobile source pollutant exposure scenarios and also considers important sources of the pollutants.[7] For example, in-vehicle exposure and intake dose estimation for the population addresses the spatial and temporal variation encompassed by individuals' commuting patterns, nonwork-related locations visited, and various roadway types traveled that account for variability in daily and monthly traffic density. In addition, estimates of benzene exposures originating from attached garages and emissions from passive cigarette smoke are included as sources to indoor residential exposure and personal exposure, while refueling an automobile is estimated for those performing the activity and for passengers of the vehicle.

INTEGRATED AIR QUALITY/EXPOSURE MODELING IN PHILADELPHIA

To illustrate how air quality models can be used to provide inputs to human exposure models, consider a 100-by-100-km area that includes Philadelphia County and several surrounding counties. Figure 2a displays a roadway network and locations of 380 census tract centroids in Philadelphia County. CMAQ was used to simulate ambient concentrations of several air toxics.[8] Traditionally, CMAQ has been used for criteria pollutant and regional applications to support regulations. In this study, CMAQ results for benzene were used as input to the SHEDS model. The CMAQ modeling system was run for an annual period in a nested mode at 36-, 12-, and 4-km horizontal grid dimensions, using the 1999 National Emission Inventory[9] and meteorological outputs from 2001 using the MM5 meteorological model.[10] The 4-km grid mesh encompasses Philadelphia, PA, and part of New Jersey (see Figure 2b).

Since CMAQ provides average concentrations for grid volumes, they do not reflect the fine-scale details in the concentration pattern that might occur within a grid volume. The number of census tracts in a 4-by-4-km CMAQ grid cell ranges from a few tracts in suburban areas up to 30 tracts in downtown Philadelphia. This suggests that both population density and concentration values will likely vary within a typical CMAQ grid cell, such that if the variations in concentration are not adequately addressed, results of an exposure assessment may be more uncertain. To provide sufficient detail in air quality inputs for exposure modeling, a method that allows CMAQ to provide regional background concentration values and contributions from chemically reactive pollutants was used, and local details in relatively inert pollutants concentrations were provided by a dispersion model.

The results of this hybrid approach is illustrated in Figure 3a. SHEDS was applied to provide annual exposures for a nonsmoking population by accounting for the actual demographic characteristics of persons in the region, and simulating human activities performed and locations visited using the hourly ambient concentrations from the CMAQ-AERMOD hybrid simulation. Figure 3b displays the corresponding annual average exposure concentrations across individuals residing in each Philadelphia County census tract estimated by SHEDS. The spatial pattern in benzene exposures is consistent with the spatial pattern of the ambient concentrations used as input, but indicates that exposures from other sources (e.g., attached garages, refueling) can contribute an additional 25–150% to annual average benzene exposure.

ADVANTAGES AND CHALLENGES OF CONDUCTING INTEGRATED AIR QUALITY/EXPOSURE MODELING

Environmental public health protection requires a good understanding of the types and locations of emissions of pollutants of health concern and the extent and duration of individuals' exposures to these pollutants. Integrated air quality/human exposure modeling provides the means to evaluate the potential health risks from air pollution and the basis to determine optimum risk management strategies, while considering scientific, social, and economic factors. Ideally, emissions control strategies aim not only to reduce the emissions from principal sources of targeted pollutants but also to identify those sources and microenvironments that contribute to greatest portion of personal or population exposures.

Currently, most federal and state air quality implementation plans rely heavily on modeling study results for targeting emissions reductions. However, for protecting the public against adverse health impacts from short-term exposures to reactive outdoor pollutants like ozone, many environmental health agencies advocate exposure mitigation approaches to minimize the health risks (e.g., health advisories on high ozone

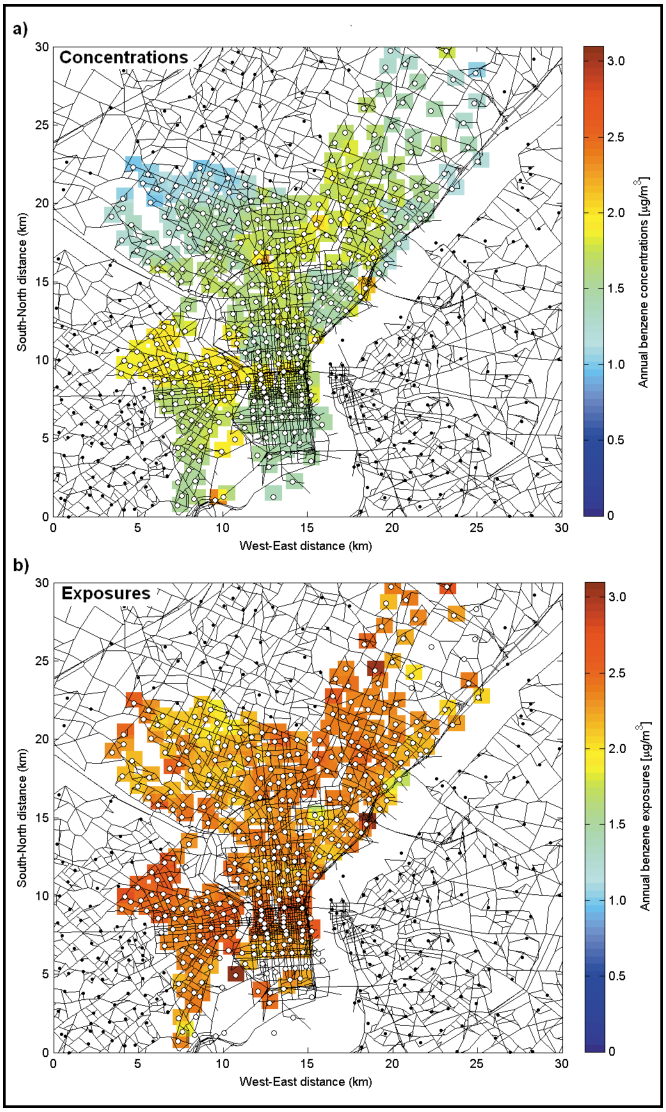

Figure 3. (a) Modeled annual average benzene concentrations and (b) exposures in [µg/m^3] from SHEDS, Philadelphia County, PA.

days recommending asthmatics to limit their activities outdoors or shelter-in-place warnings during a chemical spill event). Thus, an optimum source control program incorporates information from all facets of a combined source-emissions-transport and fate-exposure-health effects modeling assessment. Clearly, such a combined modeling analysis affords many advantages not only for carrying out informed risk management decisions, but also for conducting enhanced air pollution health studies and community-level air accountability studies. Moreover, results from these studies can provide valuable insight into prioritizing future modeling research and data collection activities that improve the limitations of current models, modeling approaches, and their inputs.

Although highly desirable, conducting an integrated air quality/exposure modeling application is not devoid of technical and practical challenges. Both air quality and exposure models require reliable spatially- and temporally-resolved emissions inventory information. Unfortunately, existing emissions inventories, though continually being updated, lack the required specificity for many of the primary and secondary air pollutants of interest. In particular, emissions information on different air toxics or PM species, which is necessary for assessing cumulative health risks from exposures to multiple pollutants, is not yet sufficient for many species. A major limitation of exposure models is the availability of exposure factors information at regional, local, or neighborhood scale, such as indoor air exchange rates, ambient pollutant penetration factors for the different microenvironments, and indoor source strengths. Furthermore, the current exposure models would greatly benefit from collection of multiday time activity diaries from special or vulnerable population groups, such as individuals with preexisting health conditions, genetic susceptibilities, children and aging populations, and individuals living in communities differentially impacted by pollution. Ultimately, with improved emissions, exposure factors, and population mobility/time-activity data, coupled air quality and exposure models for pollutants that are linked with acute and chronic health effects, will provide useful tools necessary for assessing health risks and various risk management options. These models will also serve the ever-growing need to provide more accurate air quality and exposure forecasts, and to quantify the health and economic benefits of emissions reductions programs as part of air accountability studies.

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