Using Models to Enhance Exposure Characterization for Air Pollution Health Studies

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The United States and the United Kingdom are faced with increasing challenges in determining the human health impact of air pollutants emitted locally. Often, these pollutants can be toxic at relatively low doses, are highly reactive, or generate large gradients across space because of the nature or extent of their local sources (e.g. roadways). Thus, typical monitoring strategies may not correctly characterize the exposure of a population to some hazardous pollutants. This article discusses the need for spatially resolving some pollutant concentration estimates across metropolitan areas for use in human health studies and the value of using models to better understand and characterize these exposures. For example, models can be used to help understand pollutant sources (e.g., local versus regional, extent of exposure buffers around sources, influence of meteorology) and they can be used to provide refined estimates across a metropolitan area for health studies and regulatory assessments. This paper presents two examples in Baltimore and in London to demonstrate how models can inform our understanding of exposure to nitrogen oxides. Such evaluations may become increasingly critical as the larger, regional sources of pollution are controlled and we are faced with understanding the health impacts of pollutants that expose populations inequitably across smaller, but more densely populated areas. Furthermore, the exposure and resulting health impacts of air pollution in these densely populated metropolitan areas may be better assessed by characterizing this intra-city spatial variability in combination with the more typical inter-city (or across-city) studies.

Characterizing Exposure in Support of Environmental Health Studies

The United States (US) and the United Kingdom (UK) establish limits for reducing levels of health-threatening air pollution. Although many areas have achieved attainment with these standards, some areas continue to struggle to meet mandated pollutant limits, requiring a better understanding of air pollution at a local-scale. The need for regulatory actions to protect human health is determined through human exposure and health studies that link air quality to health outcomes. These outcomes, in turn, demand differing spatially and temporally resolved data. For example, daily hospital admission counts used in an acute health study may require daily- averaged pollutant data, whereas, a study examining an endpoint such as arrhythmias as recorded by implanted defibrillators may require hourly or even more temporally resolved concentrations (Laden and Nease, this issue). Hence, improving the accuracy of the temporal and spatial variations in ambient concentrations is expected to result in better discernment of a health signal from such studies. The impact of exposure misclassification or exposure prediction errors on the outcome of air pollution epidemiology studies varies depending on the particular study design. In general, at finer spatial inter- or intra-urban scales, there is a greater likelihood that exposure prediction errors will play an important role in the outcome of epidemiologic studies. This is particularly relevant for those pollutants that exhibit strong gradients or are heterogeneous across space. Furthermore, the reactive nature of some locally emitted hazardous air pollutants and health effects at low pollutant concentrations places more demands in characterizing these pollutants at finer temporal and spatial resolutions.

Using Models to Estimate Exposures

In the absence of personal exposure measurements, epidemiology studies have traditionally relied upon alternate surrogates of personal exposures, such as area-wide ambient air pollution levels based on readily available outdoor concentrations. Such studies assume that concentrations at these monitoring sites, or average concentrations over a few monitoring sites, are representative of the complex spatial and temporal patterns of air quality within a large urban area. However, there is increasing evidence that the monitoring network is not capturing the sharp gradients in exposure due to high concentrations near, for example, major roadways (Jerrett et. al. 2005, Sarnat et. al, 2006). In addition, ambient monitoring data are often non-existent or are sparse for many hazardous air pollutants and do not take into consideration the exposure of an individual due to factors such as differing activity patterns, housing infiltration rates or susceptibility.

As a result, alternative approaches that provide greater spatial and temporal resolution in air pollutant concentrations or estimates of actual personal exposure levels are increasingly being evaluated in air pollution epidemiology studies. Thus, an important area of research is evaluating how (and to what extent) air quality models can inform our understanding of pollutant characteristics for health studies. For example, three-dimensional deterministic air quality models, such as the Community Multiscale Air Quality (CMAQ) model (http://www.cmaq-model.org/), can be used to estimate pollutant concentrations across a uniform spatial and temporal scale. Local plume dispersion models such as AERMOD (http://www.epa.gov/scram001/dispersion_prefrec.htm) and the Atmospheric Dispersion Modeling System (ADMS; http://www.cerc.co.uk/environmental-software/ADMS-model.html) are designed to capture local pollutant concentration gradients (e.g., within a few kilometers from the source) and can provide detailed resolution of the spatial variations in hourly-average concentrations. Figure 1 shows an example of how air quality models have been used in the US to provide additional information in characterizing NOx ($NO + NO_2$) in the Baltimore metropolitan area. Only two monitoring sites exist for measuring ambient NOx concentrations in the area, making it difficult to understand the spatial gradients of this pollutant. In this example, models were applied to provide insight into these spatial characteristics. The CMAQ model is used to estimate the regional contribution of NOx (Figure 1.a) and AERMOD is used to estimate the local contribution of NOx (Figure 1.b). The plots reveal that the sources of NOx can be attributed to both regional and local sources (approximately equally), with strong gradients existing along major roadways. Such information can be used in evaluating the impact of emission control actions in the US, particularly for pollutants that are suspected of causing variable exposure depending on the distance from the source (Lobdell et al., 2011).

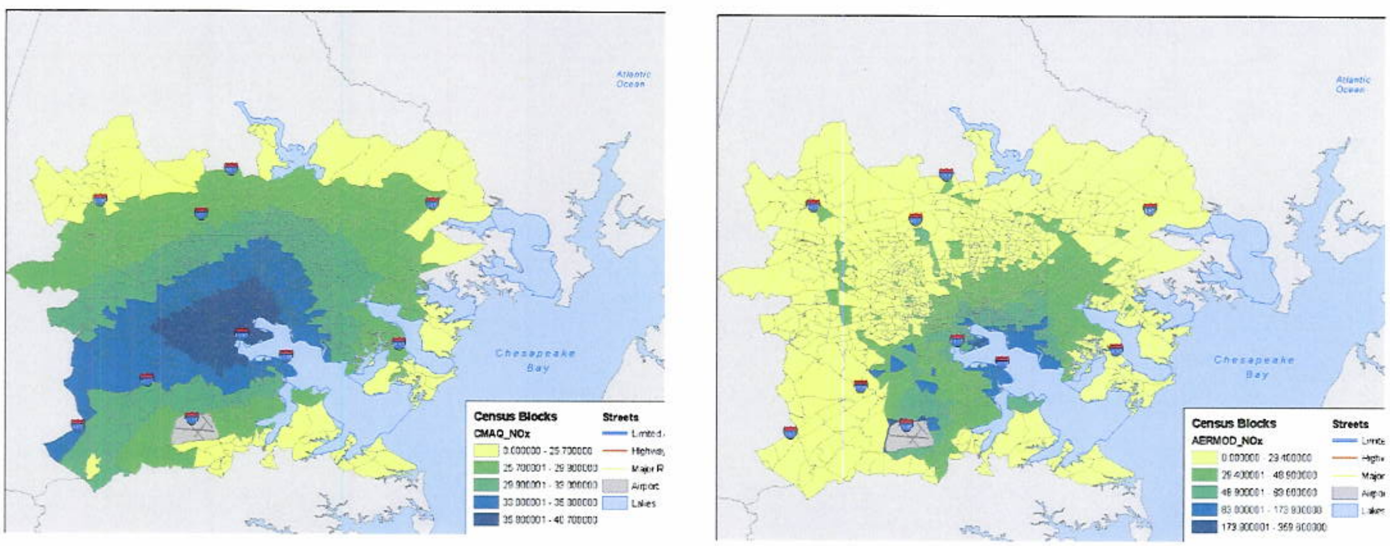

Figure 1. Panel (a) shows estimated regional contribution using CMAQ and panel (b) shows estimated local contribution using AERMOD for ambient 24-hour averaged NOx concentrations for entire 2002 year in Baltimore, Maryland.

Similarly, interest in local street scale concentrations in the UK has been driven by the need to meet European Union (EU) limit values for PM_{10} and NO_2 (EC, 2008). Use of dispersion modeling at this scale is part of air quality decision making in the UK for schemes such as Congestion Charging (Kelly et al., 2011) and more recently for the London Mayor's Air Quality Strategy (GLA, 2010). An example of the model output provided for this purpose is given in Figure 2 and shows the concentrations of annual mean NO_2 ($\mu g\ m^{-3}$) at a spatial scale of 20m x20m. The modeling methods used are described elsewhere (Kelly et al., 2011), as is a recent evaluation of the model, undertaken as part of a UK wide model inter-comparison exercise and organized by the Department for Environment, Food and Rural Affairs (Carslaw, 2011).

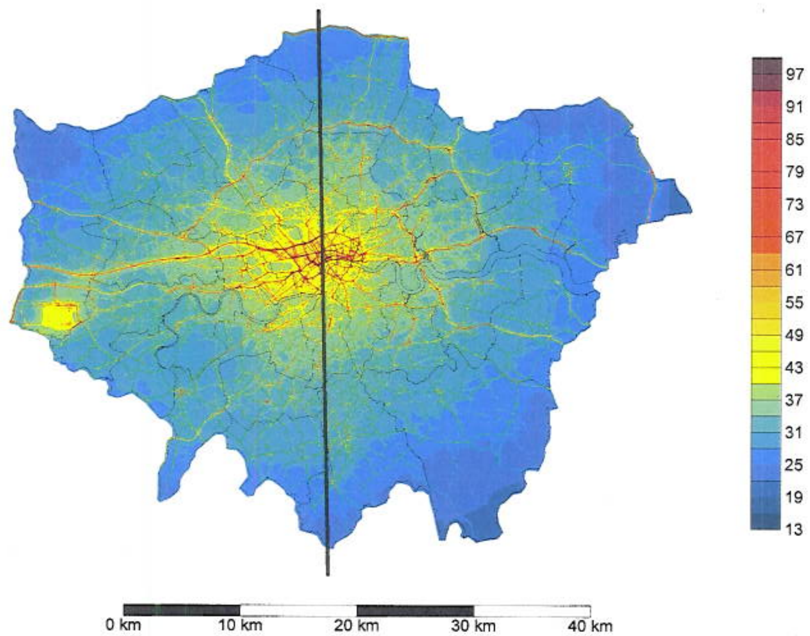

Figure 2. Annual mean NO_2 concentrations ($\mu g\ m^{-3}$) in London for the year 2008.

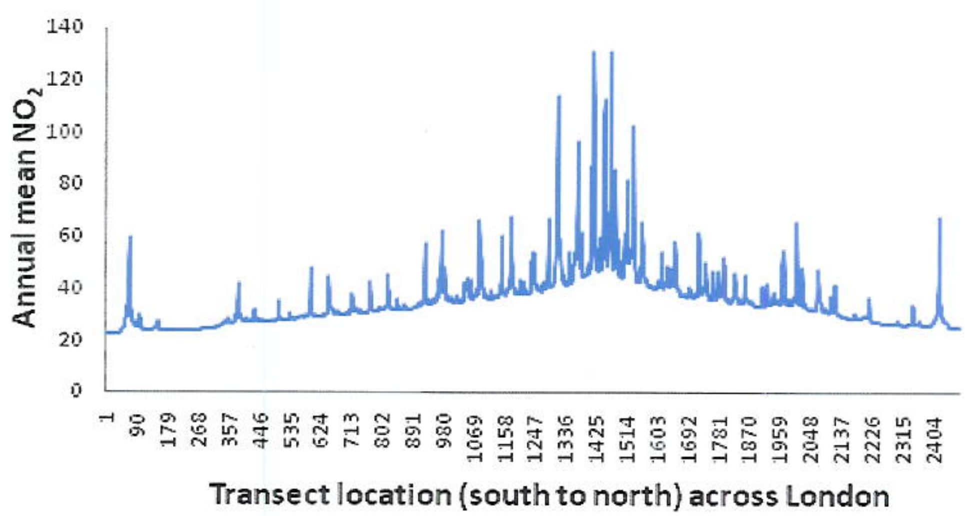

Figure 3. A transect of annual mean NO_2 concentrations ($\mu g\ m^{-3}$) for the year 2008 in London. The transect follows the vertical black line in Figure 2.

It is apparent from Figure 2 that at small spatial scales there are large gradients in concentration and that this is associated with emissions from roads, but also from railways using diesel trains and to the west of the city, from Heathrow airport. The variation in air quality is further demonstrated by plotting the NO_2 concentrations along a slice (vertical black line in Figure 2) in the modeled surface, the results of which are given in Figure 3. The model results show that at scales of 10's of meters, concentrations can range from ~20-40 µg m-3 up to 60 µg m-3 along most major roads in London to beyond 100 µg m-3 in the very centre of the city. Other pollutants, such as PM, also demonstrate a wide variation in concentration.

Implications for Environmental Epidemiology

The question therefore remains whether the analysis of exposure undertaken as part of epidemiological studies and for the development of air quality policy fully reflects variation in air quality concentrations. Furthermore, whether exposure can or should move from the assessment at the postal address of the population (or some other aggregated representation) to encompass the movement of people through space and time as well as in different micro-environments such as in-vehicle, at home/office, walking, cycling etc. The assessment of health impacts at fine spatial resolutions is currently the subject of much debate in the US and in the UK (COMEAP, 2009). Typical assessments have been based upon risk ratios from studies such as the American Cancer Society (ACS) study reported by Pope et al. (2002) in which community-wide estimates of long-term exposure are used and the analysis is based on between city variations. At intra-city scales, these epidemiology study results may not appropriately predict risk, since local-scale variations in air quality occurs on top of a considerable background concentration. The variability within city assessments also reveal interesting spatial and socio-economic connections, indicating that exposure to air pollutants may be driven by many factors, including income, race and proximity to local sources. This issue of variable exposure within cities will become particularly critical as background levels are reduced and areas that are still in non-compliance are struggling to devise mitigation strategies that consider and optimize the exposure of a large, diverse population to multiple pollutants from multiple sources. A possible way forward is to use results from studies that have obtained risk estimates using local variations within an airshed. Examples would be those of Beelen et al, 2008; Willis et al, 2003; Jerrett et al, 2005 to examine exposure within cities. Intra-urban variation in air pollution concentrations have also been used for cohort studies in the UK (Beverland et al 2009; Dadvand et al 2011) although there are opportunities for further development. While addressed at short-term rather than long-term effects, an exploratory project modelling the relationship between background monitoring site concentrations and the population distribution of personal exposure has also been published by Ashmore et al, (2005). Finally, it is important to recognise that pollutants such as particulate matter (PM) can be a complex mixture which is likely to vary in toxicity depending on its physicochemical composition. This means that using a mass of PM for risk assessment may be too simplistic. Should some of the more toxic components of PM prove to be related to specific emission sources such as road transport this would further support the need for more local scale exposure assessments to be undertaken. Without this step change in air quality exposure methods, it may prove difficult to develop optimum policies that provide the maximum benefit for human health.

Disclaimer

Although this paper has been reviewed and approved for publication, it does not necessarily reflect the views and policies of the U.S. Environmental Protection Agency.

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