Topic A10: Public health and exposure studies

INDOOR EXPOSURE TO OUTDOOR POLLUTION IN A TROPICAL ENVIRONMENT

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SUMMARY

Human activity patterns result in indoor environments playing an important role in exposure outdoor air pollution. In tropical climates, building ventilation conditions and occupant preferences may dramatically affect exposure to particulate matter and ozone, as many buildings rely on natural ventilation for cooling at least some portion of the day. We model exposure to particulate matter (PM) and ozone (O_3) in five microenvironments with varying indoor/outdoor PM and O_3 ratios across three regions of Singapore. Results show that geographic variations in outdoor concentrations of PM and O_3 contribute to a factor of two difference in daily exposure across age subgroups while differences between more protective and less protective microenvironments result in a factor of three difference in daily exposure.

INTRODUCTION

Epidemiological studies show that increases in outdoor air pollution are associated with adverse health effects including acute upper respiratory infections, asthma incidence, chronic obstructive pulmonary disease, and overall daily mortality (Sunyer et al., 1991; Bell et al., 2004; Rahman and Adcock, 2006; Salvi, 2007). However, people spend most of their time in indoor microenvironments. As a result, exposure to air pollutants, even those of outdoor origin, can be heavily influenced by conditions in buildings (Weschler, 2006, 2004; Chen et al., 2012). Quantifying the importance of the built environment's impact on exposure to air pollutants is an area of active research in exposure modeling (Özkaynak et al., 2013).

Quantifying exposure to air pollutants in tropical climates presents distinctive challenges. In Singapore, relatively few studies have been conducted of indoor and outdoor exposure to air pollutants. Rapid urbanization of Singapore affects heat fluxes and meteorological parameters relevant for human exposure to outdoor air pollutants, such as the planetary boundary layer height (Li et al., 2013). Furthermore, episodic haze associated with biomass burning in neighboring countries can cause dramatic increases in outdoor air pollution, increasing interest in air pollution and the potential protective benefit of buildings and building environmental systems. Finally, quantifying indoor/outdoor exposure relationships in Singapore is important because a significant fraction of residents (~ 25%) do not own air-conditioners, and because high electricity prices may result in some air-conditioned buildings to be operated in naturally ventilated modes (Singapore Ministry of Trade and Industry, 2013). In light of the known long-term and acute health implications associated with ambient and episodic air pollution, this paper describes the development of a spatially and temporally resolved model of exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and O_3 in five microenvironments in Singapore that can be used to identify opportunities in that country for reducing the public health burden associated with human exposures to outdoor air pollutants.

METHODS

A model of daily human exposure to outdoor air pollutants was created to determine the importance of building operation and daily activities on the exposure of four age-stratified subpopulations to $PM_{2.5}$, PM_{10}, and O_3 in three regions of Singapore. The model employed here estimates exposure as the product of pollutant concentration and time spent in three categories of microenvironment: outdoors, indoors, and transit, as described in Equation 1:

$$Ex_k = \sum_{j=1}^{l} \overline{C}_{k-o,j} \Delta t_j + \sum_{i=1}^{m} \overline{C}_{k-in,i} \Delta t_i + \sum_{h=1}^{n} \overline{C}_{k-trans,h} \Delta t_h \tag{1}$$

Where Ex_k is the exposure of a subpopulation to air pollutant k (μg m^{-3} h), l is the number of time periods spent outdoors (-), $\overline{C}_{k-o,j}$ is the time-averaged outdoor concentration of air pollutant k across time period j (μg m^{-3}), Δt_j is the time spent outdoors during period j (h), m is the number of indoor environments occupied (-), $\overline{C}_{k-in,i}$ is the time-averaged concentration of air pollutant k in indoor environment i (μg m^{-3}), Δt_i is the time spent in indoor environment i (h), $\overline{C}_{k-trans,h}$ is the time-averaged concentration of pollutant k during a period of transit h, and Δt_h is the time spent in transit during period h.

Activity patterns

The microenvironments considered in this investigation were defined using available data of daily activity patterns of Singaporeans. In total, five microenvironments were included: three indoor microenvironments (home, work, and school) one microenvironment reflecting mode of transit (commute) and one microenvironment representing time spent outdoors (outside). Diaries of activity patterns for four age groups (0-5, 5-15, 15-65, 65 and older) were constructed using information from the most recent Singapore census (2005) and other supporting government surveys, with gaps supplemented by the Consolidated Human Activity Database (CHAD) (McCurdy et al., 2000) .

The Singapore census supplied information regarding traveling time to work and school (Singapore Department of Statistics, 2006a) for age groups 5-15, 15-65, and 65 and older and hours worked by residents aged 15 and older (Singapore Department of Statistics, 2006b). Mean values for each age group were input from distributions describing time spent in either commute or at work for each age group subpopulation. Time spent in school is not mandated by the government; however, Singapore guidelines recommend 5 and 6 hours per day for primary and secondary schools, respectively, and an average value of 5.5 hours per day was input into Equation 1 for the school microenvironment (Straughan, 2011). Time spent outdoors in the 0-5 and 5-15 age groups, 3.2 h day^{-1} and 1.2 h day^{-1}, respectively, were taken from investigations of myopia in Singaporean children and teenagers (Dirani et al., 2009; Deng et al., 2010). Time spent in the home was assumed to be equal to the balance of time not spent in other microenvironments and ranged from 12.6 h day^{-1} for the 15-65 age group to

20.8 h day^{-1} for the 0-5 age group. Microenvironment diaries were created to the nearest 15-minute increment with input from the CHAD, and best judgement regarding daily patterns (e.g., a typical work day is assumed to being at 9 am). Future investigations will improve upon the available data sources with a targeted investigation of activity patterns in Singapore.

Exposure concentrations

In addition to activity patterns, Equation 1 requires a value for the pollutant concentration in a specific microenvironment. Estimates of exposure concentrations in outdoor and indoor environments were made from a database of hourly outdoor concentrations of $PM_{2.5}$, PM_{10}, and O_3 and outdoor concentrations multiplied by indoor/outdoor (I/O) ratios taken from literature, respectively. Estimates of outdoor concentrations were taken for three locations in Singapore, described by monitoring station ID: P03, P24, and P27 or central, north, and southwest Singapore, respectively.

Indoor/outdoor (I/O) ratios were defined for two hypothetical scenarios and are shown in Table 1. A low exposure (LowExp) scenario was constructed to simulate a series of daily microenvironments that are more protective of outdoor pollutants. For the LowExp scenario, I/O ratios were taken from estimates in the literature for air-conditioned home and school microenvironments, office microenvironments with MERV12 filters, and commutes in private vehicles. A high exposure scenario (HighExp) was also considered, intended to represent a less protective series of daily microenvironments that correspond to naturally ventilated home and school microenvironments, office microenvironments with MERV6 filters, and a commute with I/O ratios of unity (e.g., walking or traveling by public transit).

Table 1. Indoor/outdoor ratios of $PM_{2.5}$, PM_{10}, and O_3 of outdoor origin under two hypothetical exposure scenarios.

	LowExp Scenario			HighExp Scenario		
Microenvironment	$PM_{2.5}$	PM_{10}	O_3	$PM_{2.5}$	PM_{10}	O_3
Home	0.50[a]	0.38[a]	0.22[b]	0.95[a]	0.80[a]	0.62[b]
Commute	0.82[c]	0.74[c]	0.41[d]	1	1	1
Work	0.20[a]	0.15[a]	0.084[e]	0.72[a]	0.55[a]	0.84[f]
School	0.20[a]	0.15[a]	0.18[g]	0.72[a]	0.55[a]	0.71[g]
Outside	1	1	1	1	1	1

[a]Riley et al. (2002); [b]Zhang and Lioy (1994); [c]Tsai et al. (2008); [d]Hayes (1991); [e]Spengler (1998); [f]Weschler et al. (1989); [g]Gold et al. (1996).

RESULTS AND DISCUSSION

Daily exposure to air pollutants varies across the three regions of Singapore considered as well as across the LowExp and HighExp scenarios, shown in Figure 1. Exposures to $PM_{2.5}$, PM_{10} and O_3 range from 148-266 µg m^{-3} h, 218-340 µg m^{-3} h, and 100-224 µg m^{-3} h, respectively, across both age subpopulations and region in the LowExp scenario and from 297-447 µg m^{-3} h, 466-665 µg m^{-3} h, and 268-559 µg m^{-3} h, respectively, in the HighExp scenario. For comparison, Burke et al. (2001) have estimated median ambient $PM_{2.5}$ exposures from 12 and 24-h integrated outdoor $PM_{2.5}$ concentrations in Philadelphia of 168 µg m^{-3} h (converted to the sum of exposures over the 24 hours each day), in the range values determined in this investigation; inclusion of cooking and smoking as indoor PM sources increased their estimate of daily exposure to 480 μg m^{-3}.

The exposure scenarios remain constant across the three regions included in this investigation. Therefore, differences in exposure across regions are driven by variability in outdoor air pollution concentrations. Southwest Singapore (P27) had the highest ambient concentrations of $PM_{2.5}$ and PM_{10}, but the lowest ambient concentrations of O_3, leading to the higher PM exposures and lower O_3 exposures compared to other regions. In the HighExp scenario, exposures to $PM_{2.5}$ are 45-46% higher, exposures to PM_{10} are 29-30% higher, and exposures to O_3 are 42-44% lower across the age subpopulations in the southwest (P03) region than in the north (P24) region. These differences may reflect the industrial activity of southwest Singapore, where petrochemical operations may lead to direct emissions of PM and emissions of NO that reduce immediate O_3 concentrations but produce higher O_3 concentrations downwind.

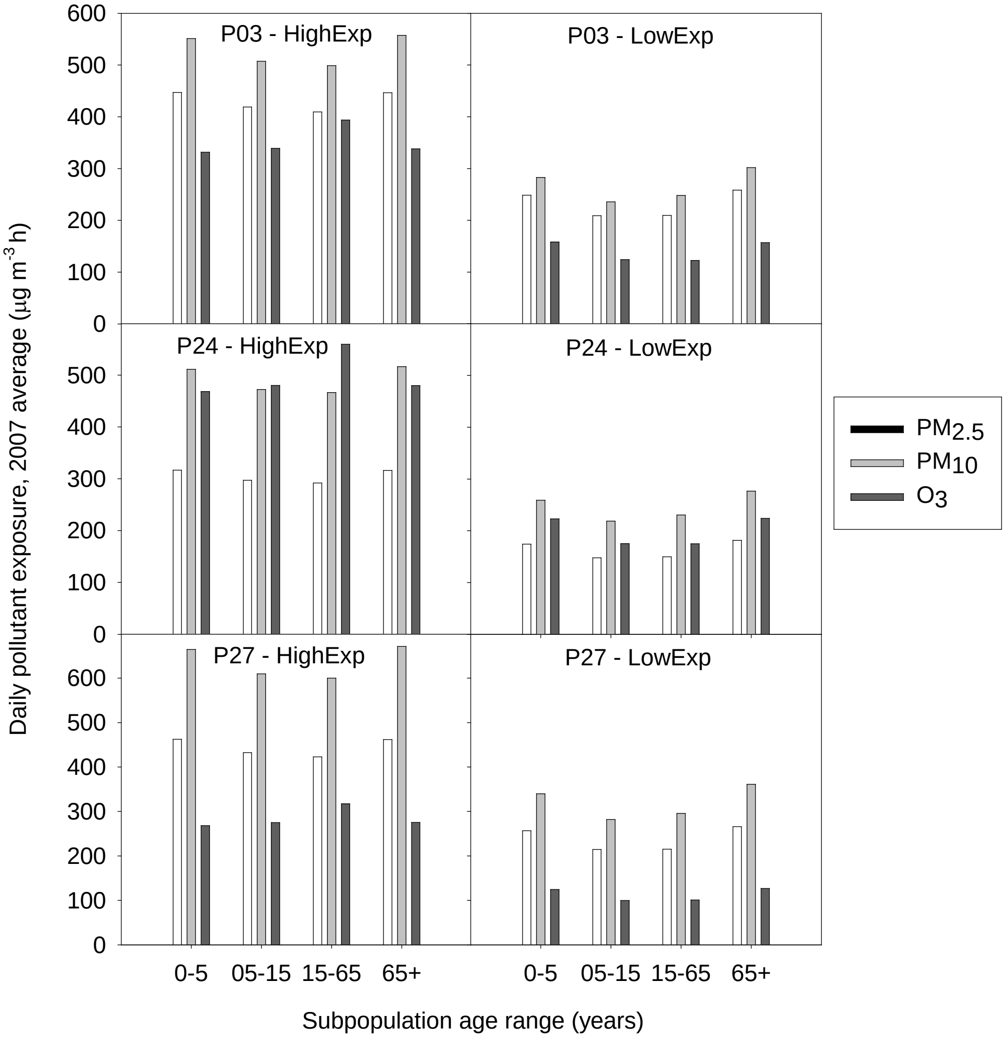

Figure 1. Subpopulation exposures to $PM_{2.5}$, PM_{10}, and O_3 across three regions in Singapore. P03, P24, and P27 refer to outdoor air quality monitoring stations in central, north, and southwest Singapore, respectively.

Across all subpopulations, the LowExp scenario produced a greater percent reduction in exposure to ozone than to particulate matter. Ozone exposures in central, north, and southwest regions are 60%, 59%, and 60% lower, respectively, averaged across the four subpopulations, in the LowExp than in the HighExp scenario while exposures to $PM_{2.5}$ are only 46%, 47%, and 47% lower, respectively. The differences reflect the larger relative reductions in I/O O_3 ratios than for $PM_{2.5}$, particularly for the home, school, and work microenvironments where the assumed presence of air-conditioning and/or mechanical ventilation in the LowExp scenario causes low I/O O_3 ratios for microenvironments with substantial time-activity contributions. Such conditions are seen strongly in the LowExp scenario for the 15-65 age group, where 68%-69% lower O_3 exposures are observed across the three regions as a result of the low I/O ratios in the workplace environment (I/O = 0.084), a benefit not realized by the subpopulations that spend more time in the home (0-5 and 65 and older). This low I/O ratio results in the 15-65 age subpopulation moving from the highest ozone exposure subpopulation in the HighExp scenario to the lowest in the LowExp scenario.

Concentrations of O_3 exhibit a stronger diurnal variation than $PM_{2.5}$ and PM_{10}, because of the prominent influence of photochemical reactions driven by sunlight that trigger O_3 formation. The mid-afternoon ozone peak causes relatively high exposures to the 0-5 age subpopulation, who are assumed to spend outdoor time from 2:00-3:30 PM, whereas the 15-65 age subpopulation is assumed to spend outdoor time from approximately 5:00-7:00 PM when ozone concentrations begin to decrease. Given the presumed susceptibility of the youngest and oldest subpopulations to pollution effects, measures to reduce exposure in these groups could focus on planning time spent outdoors to the early mornings or evening and to reducing ozone concentrations in residences. In pursuit of the latter goal, the prevalence of natural ventilation and split air-conditioning systems in Singapore might encourage development and deployment of passive removal techniques through surface reactions with indoor materials to further reduce indoor-to-outdoor O_3 ratios (Zhang et al., 2013).

In the case of $PM_{2.5}$ and PM_{10}, the profile of daily exposure is similar across the LowExp and HighExp scenarios: subpopulations aged 5-15 and 15-65 have lower exposures than those aged 0-5 and 65 and older under both scenarios. The LowExp scenario results in exposures of 46-47% and 49-50% for $PM_{2.5}$ and PM_{10}, respectively, relative to the HighExp scenario, across the three regions. In general, slightly larger reductions in exposures are observed for PM_{10} than $PM_{2.5}$, a reflection of the greater removal efficiencies for PM_{10} than $PM_{2.5}$ embodied in the indoor/outdoor ratios described in Table 1. In addition to lower absolute exposures, the subpopulations aged 5-15 and 15-65 show greater percent reductions in exposure from the HighExp to LowExp scenario, with reductions of 49-54%, while the subpopulations aged 0-5 and 65 and older show reductions of 42-49%. The greater exposure reductions in 0-5 and 15-65 subpopulations is an illustration of the importance of time-activity patterns of specific subpopulations. The more protective home microenvironments (LowExp scenario) have $PM_{2.5}$ and PM_{10} indoor/outdoor ratios of 0.50 and 0.38, respectively, for $PM_{2.5}$ and PM_{10} while the more protective work and school microenvironments have indoor/outdoor ratios of 0.20 and 0.18, respectively. Since the susceptible subpopulations aged 0-5 and 65 and older spend much more time at home than those aged 5-15 and 15-65, reductions in PM exposure for these subpopulations should focus on reducing I/O PM ratios in the home, particularly for $PM_{2.5}$.

CONCLUSIONS

The exposure model developed here quantifies the exposure of residents to outdoor $PM_{2.5}$, PM_{10}, and O_3 in three regions of Singapore and across two exposure scenarios. Both geography and the hypothetical exposure scenarios contribute to variability in daily exposure, the former resulting in as much as a factor of two difference and the latter as much as a factor of three difference in the total daily exposure. Naturally ventilated spaces drive a large portion of these differences, for example the 10× difference between I/O O_3 ratios in the office microenvironment for the HighExp versus LowExp scenario. For susceptible populations, estimates of activity patterns from available data for the Singapore population indicate that the home is the dominant temporal microenvironment, in broad agreement with surveys of activity patterns in the developed world. Implementing interventions to reduce pollutant concentrations in the residence microenvironment may therefore result in particular benefit for the young and old subpopulations, to reduce both exposure to ambient pollution and also enable preparedness for episodic air pollution like PM exposure during haze events. Future work will incorporate scenarios describing haze events, improve estimates of time-activity patterns, and include indoor sources of PM in estimates of total daily air pollutant exposure.

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