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THE KANSAS CITY, MISSOURI, GROUND LEVEL OZONE (GLO) PROJECT: A COMMUNITY-BASED FIELD EXPERIMENT TO CHARACTERIZE SPATIAL GRADIENTS OF AIR POLLUTION

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1. INTRODUCTION

Ground-level ozone is a secondary air pollutant formed by photochemical reactions involving oxides of nitrogen (NOx) and VOCs, mainly hydrocarbons (Crutzen, 1979). In the presence of solar radiation, nitrogen dioxide (NO_2) dissociates to form nitric oxide (NO) and an oxygen atom (O). Ozone (O_3) is then formed by molecular oxygen (O_2) reacting with the oxygen atom (O). However, when hydrocarbons are present, NO is converted to NO_2, thus leaving little NOx to react with O_3. This reaction leads to a build-up of O_3 in the atmosphere. Sources of NO_2 and VOCs are primarily anthropogenic, generally produced during combustion processes from automobile emissions and industrial activities.

Ground-level ozone is harmful for everyone, especially to people with respiratory problems such as asthma. High levels of ozone are known to increase breathing difficulty for people that suffer from asthma, heart disease and emphysema. Ozone also increases the number of cases of bronchitis in children and senior citizens. Long-term exposure can even cause healthy young adults to experience breathing difficulty especially those that exercise or work for long periods outdoors (Holgate et al. 1999).

Ground level ozone monitoring is routinely carried out in Kansas City from a network of stations operated by the Missouri Department of Natural Resources and the Kansas Department of Health and the Environment. Only one of these stations is located in the urban core, which has the highest population density of residents and where most minorities live. Clearly, the spatial detail of the existing network is insufficient to establish differential exposures across communities in the metro area. Moreover, there are concerns about the potential for disproportionate exposures to air pollution among disadvantaged or racial/ethnic minority populations in urban areas due to the proximity of polluting sources such as high-traffic roads, waste disposal facilities, and industrial point sources. Geographic analyses suggest systematic differences in exposure by community. For instance, indoor levels of carbon monoxide in the Washington, DC, area and nitrogen dioxide in the Los Angeles Basin are higher in central-city areas than in the suburbs (Schwab, 1990; Spengler et al., 1994; Brajer and Hall, 1992).

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Kinney and colleagues also reported results of a study of small-scale spatial variations in particulate matter (PM2.5) and elemental carbon in the Harlem neighborhood of New York City (Kinney et al. 2000). These limited data suggest that ambient concentration differentials can exist in urban areas due to traffic sources.

2. OBJECTIVES

The purpose of this multi-site neighborhood scale air quality sampling pilot study was to characterize the spatial gradients of ground level ozone in Kansas City, Missouri urban core during the 2005 ozone season (April to September). We deployed 20 passive air quality sampling devices (PSDs) at various Kansas City neighborhoods to sample integrated concentrations of ground level ozone during the peak of the ozone season. The project objectives include:

a. To characterize urban air quality and citizen ozone exposure levels at very detailed spatial scales
b. To assess ozone concentration across horizontal gradients to determine concentration levels at detailed spatial scales

Specifically, we address the hypothesis that weekly average ozone concentrations will be higher in the urban core and along transportation corridors, then grade to lower concentrations toward the suburban areas.

PSDs have been widely used to determine cumulative concentrations of air pollutants. The benefits of passive sampling devices to detect ozone concentrations include low operational cost, high correlation results as compared to continuous ozone monitors, ease of use, and deployment in areas where no electricity is available (Krupa and Legge, 2000). In addition, research has shown that when using passive samplers to determine ozone concentrations, measurements are not affected by temperature and humidity, and under ambient conditions, co-pollutant interference is negligible (Koutrakis et al., 1993). The devices are affordable, portable, and provide real-time monitoring of criteria pollutant and air toxic concentrations. The feasibility of using PSDs to characterize urban ozone concentrations was demonstrated in an Environmental Protection Agency (EPA) sponsored study in Dallas, TX (Varns et al., 2001). PSDs have also been used to characterize the ozone distribution around urban areas in Toronto, Canada (Liu et al., 1998).

3. STUDY DESIGN

3.1. Study Area

Twenty sites from within and near the urban core of Kansas City, Missouri, were selected for sampling (Fig. 1). Sampling sites were placed such that there was approximately one per ZIP code area and that the major land use types of high-density residential, low-density residential, and industrial/transportation were represented. We also co-located one sampling site with a continuous monitor maintained by the Kansas Department of Health and Environment (KDHE) in Kansas City, Kansas.

Figure 1: Sampling locations for the 2005 GLO project passive ozone sensors.

The focus of this study is the air quality within the urban core of the metropolitan area. Hence, only one site was located in a truly commercial area, 64120. Two sites were located in suburban (low-density residential) area, 64114 and 64129S. All other locations were either high-density residential or mixed high-density residential plus industrial/commercial/transportation.

Sampling sites are designated according to their ZIP code location. One ZIP code, 64129, is divided into a north and south region due to its size and diverse land use type. The northern half is largely high-density residential interspersed with industrial/commercial, while the southern half was largely suburban. Site classification is based on the National Land Cover Dataset as well as site visits. Only the eastern portions of the large ZIP codes surrounding the Kansas site are included in the study area, so they are displayed with the suffix “E”. Hence, the sampling site co-located with the KDHE continuous monitor is designated 66102E.

The five-county area encompassing the Kansas City Metropolitan area has been classified as a maintenance area for ground-level ozone by the Environmental Protection Agency (EPA) (Mid-America Regional Council, 2005). A network of strategically-placed continuous monitors measure ground level ozone in upwind, downwind, and one urban core locations. The upwind sites are designed to measure the baseline ozone levels, unaffected by the metropolitan air conditions. The downwind sites are located to capture the peak ozone concentration, given the hours-long formation time for ozone. The urban site is designed to measure maximum population exposure. One serious difficulty in siting continuous monitors, especially those in the urban core, is the effect of titration by nitrogen oxides. The EPA recommends that the maximum population exposure monitor location be in a suburb in the urban fringe slightly downwind of the urban area (EPA, 1998). Our network represented a spatial and temporal subset of this more widespread network, but with denser sampling (Fig 2).

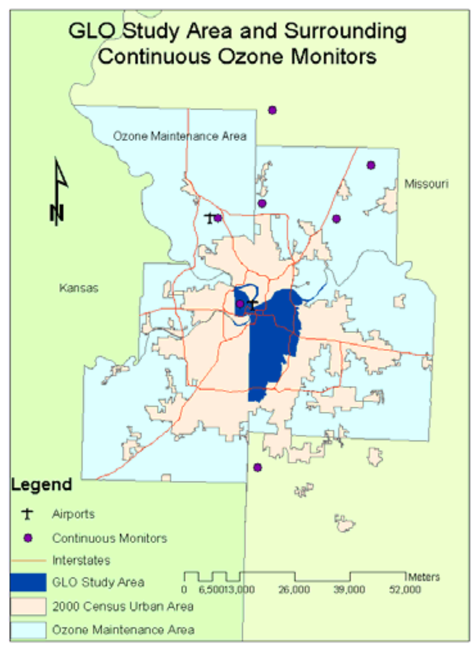

Figure 2: GLO project study area and surrounding continuous ozone monitors. Metropolitan area outline is defined by 2000 Census and includes suburban land use.

3.2. Community Partners

Volunteers were recruited from the study area to monitor ozone sampling stations and collect samples.

Volunteers included individuals from the Kansas City Neighborhood Alliance, the Mid-America Regional Council, the Kansas City Parks and Recreation Department, the Spirit of Hope Church, Horizon Freight, and the University of Missouri – Kansas City (UMKC). Volunteers were given the option of either simply maintaining the site or maintain the site and collecting samples. Over half of the volunteers elected to collect samples. Sampling stations were placed in the volunteers' yards or places of business. After training, these community partners collected their samples at the appointed time and prepared them for pickup at the end of each week. They also permitted researches access to their yards for deployment of new samples at the beginning of each week, and they kept control samples in safe locations.

Response from the collecting volunteers was extremely positive, and they proved to be very reliable in collecting samples in a timely manner, demonstrating the feasibility of a community-based air quality study. A significant advantage of this community-based participatory research model is that it lays the foundation for future work in assessing air-pollution related health disparities among urban vs. suburban communities. Community-based participatory research (CBPR) partnerships are of critical importance in understanding the contributions of physical and social environments to health problems, especially in racially segregated, impoverished urban areas in which health disparities between African Americans and whites persist (Geronimus et al., 1996; McCord and Freeman, 1990). Ethnic minorities of lower socioeconomic status are at a higher risk for lung disease due to air pollution in the community than whites (American Lung Association, 2001). Community participation also ensures that the data collected are relevant to the concerns of the community (Zenk et al., 2005). One successful model of CBPR is the Healthy Environments Partnership (HEP), in which researchers engaged community members in urban Detroit to identify environmental, physical, social, and neighborhood factors which affected cardiovascular health. By partnering with the community to develop an inventory of these factors, the HEP researchers were able to gain important insights into the meanings and relevance of various aspects of the neighborhood environment, which improved both the quality and validity of the inventory (Zenk et al., 2005, Israel et al., 1998). CBPR, conducted rigorously, contributes to both community health and to insight about social inequity (Nyden, 2003), and is practical in that is responsive to the needs of the community, practitioners, and policymakers (Green, 2003, cited by Zenk et al, 2005).

3.3. Sampling protocol

We used PSDs from Ogawa & Co, Inc., Pomano Beach, FL. The PSD is a cylindrical device, 2 cm x 3 cm, which contains two nitrate-coated filter pads. Ozone diffuses into the PSD and oxidizes the nitrite to nitrate on an equimolar basis (Koutrakis et al., 1993). The PSD is reusable, and only the filter pads must be changed.

The PSDs were each contained within a shelter that consists of a 10.14 cm PVC endcap. This shelter not only protects the PSD in case of rain, but also distributes the air contact with the PSD so that it does not receive air from a preferred direction in the case of wind (Koutrakis et al., 1993).

The PSDs were each mounted on a 2 m pole that was then pressed into the ground so that the height of the sampler would approximate the nose and mouth height of the average adult. One exception was site 64108, which was located on the roof of Children's Mercy Hospital so that it could be co-located with instruments for parallel asthma-related studies. The poles were carefully sited in the volunteers' locations to be away from sources of constant exhaust and vertical surfaces. These siting requirements prevent titration of ozone by nitrate or absorption of ozone by surfaces (Harvard School of Public Health, 2001).

The sample period was July 3 – August 18, 2005. Weekly samples were collected for all seven weeks of the study, and daily samples were additionally collected during weeks 4 and 6. The data for the daily samples and for week 7 will be reported in a future publication. On Sunday of each sampling week, researchers deployed the sample. On Thursday, the samples were collected. Researchers picked up samples from the volunteers homes on Friday. Two control samples also were sent to the field each week. These samples were treated identically to the weekly samples except that they were not exposed to the air.

PSD monitor locations were measured using a handheld Global Positioning System (GPS) unit with a Wide-Area Augmentation System (WAAS) enhancement.

4. DATA ANALYSIS

4.1. Laboratory Analysis

Filter pads were removed from the PSDs by researchers and placed in an extract vial for shipment to a laboratory contracted for analysis. There, the samples were extracted with ultrapure Milli-Q water and analyzed via ion chromatography. Each week's control samples showed small amounts of ozone, approximately 7 ppb. This error was most likely due to a combination the natural transition of nitrite to nitrate and brief exposure in the lab during the PSD loading and unloading process. Each week, the amount of ozone from the unexposed control samples was subtracted from the rest of the samples to yield a corrected value.

4.2. GIS Analysis

Maps were constructed using the ArcView Geographic Information System (GIS) software and the Spatial Analyst and 3D Analyst extensions (ESRI). The inverse difference weighted method for surface interpolation method was used. In this method, a value is estimated by averaging the values of sample data points in the vicinity around it. The closer a sample point is to the point being estimated, the more influence, or weight, it has in the process (McCoy et al., 2004). Boundaries and highway features were gathered from the US Census Bureau TIGER/Line files.

4.3. Comparative GLO data
The Mid-America Regional Council (MARC, http://www.marc.org), a partner in this research, receives the hourly ozone monitor data from the regional continuous monitors. Hourly data from the monitor at the co-located site was provided by the Kansas Department of Health and Environment.

4.4. Wind data
Wind data were obtained for the Kansas City Downtown Airport and Kansas City International Airport (KCI) (Figs. 1 and 2). The Downtown airport is situated within a few thousand meters of several of the GLO sites, and the Kansas City International Airport is co-located with one of the continuous monitors to the north of the study area. These wind data were obtained from the National Oceanic and Atmospheric Administration (NOAA). Wind data were plotted WRPlot View (Lakes Environmental Software).

5. RESULTS AND DISCUSSION

5.1. Comparison with continuous monitor
The PSD location 66201E was co-located with a continuous monitor (Figs. 1 and 2). The results of this comparison are shown in Table 1.

Table 1: Comparison of 4-day average ozone readings at co-located site

	Ozone (ppb)	
Week	Continuous monitor	PSD
2	43	41
3	34	31
4	27	26
5	44	45
6	41	12

A PSD sample was not obtained for the co-located site was not obtained for Week 1 of the study. Hourly readings from the continuous monitor were averaged during the time each sample was exposed. With the exception of the sample from Week 6, the PSD samples and the continuous monitor averages are in good agreement. This performance of the PSD's is consistent with previous studies. The exceptionally low value during week six may be due to occlusion of the PSD by a spiderweb, which was noted by the researcher upon sample collection. PSD values tend to be less than the continuous monitor in this case, and excluding the clearly anomalous value the average difference is 1.3 ppb.

5.2. Spatial distribution of ozone and spatial gradients
In all weeks of the study, the central core of the city and northern sites experienced elevated levels of GLO relative to the southern and eastern areas. Sites which were particularly affected by elevated GLO commonly included 64108, 64111, and 64124. These areas correspond to locations at which commercial areas and residential areas are closely juxtaposed. A representative plot of the ozone distribution for a study week may be seen in Figure 3. (See Fig. 1 for site numbers.) During Week 5, depicted in this figure, there were two exceedences of the eight-hour ozone standard (MARC, 2005). One southern site which frequently experienced higher ozone levels than immediately surrounding areas was Site 64132.

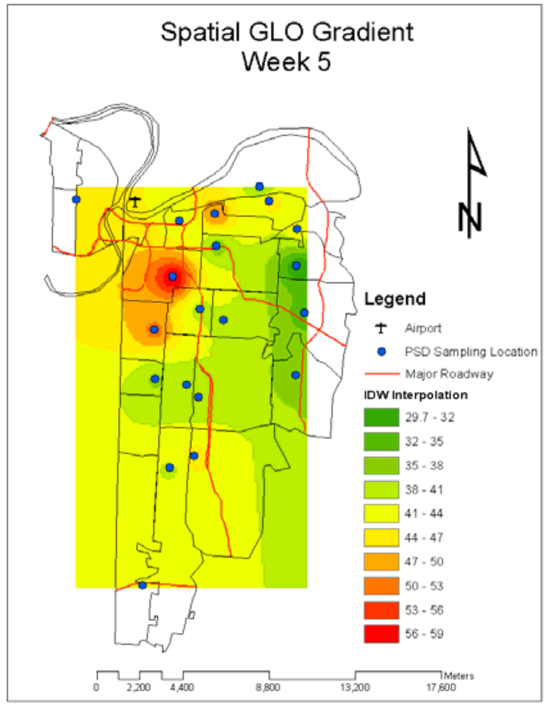

Figure 3: Representative IDW interpolation of spatial distribution of GLO based on PSD data. Week 5 coincided with two eight-hour ozone standard exceedences.

The sites along the eastern border of the study area, 64129N, 64129S, and 64126 typically experienced lower ozone levels relative to other sites. This was also true of Site 64114 to the south. Sites 64129S and 64114 are in suburban locations, while 64129N is largely a commercial district with one high-density neighborhood. Ground-level ozone remained high in the central portion of the city and degrades toward the suburban areas. The high-density neighborhoods in the central portion of the study area experience variable ozone levels with respect to the overall gradient, but are typically not peaks such as that measured in the central area of the city.

These gradients and peaks were consistent whether the overall ozone levels were high or low for a given week. In week 4, the Kansas City area experienced rain throughout the week and so the average ozone concentration for all sites was 26 ppb. Weeks 2, 5, and 6 all experienced exceedences of the 8-hour standard, and these sites had overall sample averages ranging from 36 to 42 ppb for the week. Despite the differences in overall concentration, the same general pattern emerged.

5.3. Comparison with continuous monitor data

The network of continuous monitors demonstrates that the weekly average regional ozone peaks occur outside of the metropolitan area (Fig 4).

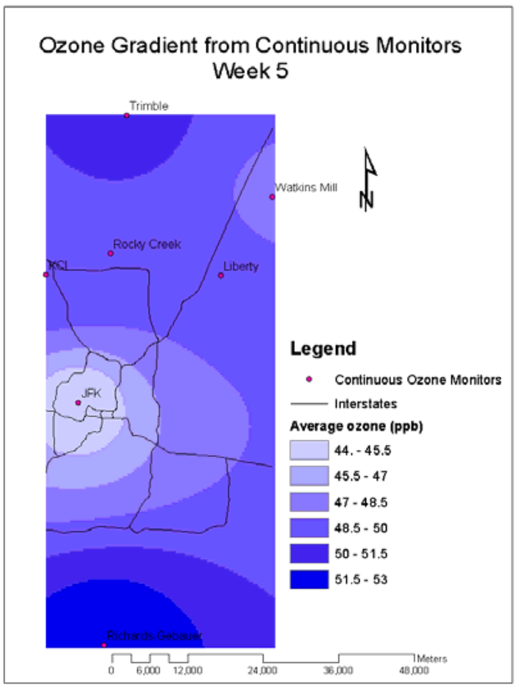

Figure 4: Weekly average ozone concentration gradient from continuous monitors.

In the case of Week 5, the ozone exceedences occurred at the Rocky Creek and the Richards-Gebauer stations. A GLO low actually occurs in the city, which is consistent with the model of ozone forming slowly during transport out of the area in which the precursors are emitted.

To visually compare the differences in the weekly average data, we constructed three-dimensional surfaces of the GLO interpolations. Figure 5 shows the Week 5 data in this form while Figure 6 displays the continuous monitor data for the same period (Note that the horizontal scales in Figures 5 and 6 are not the same).

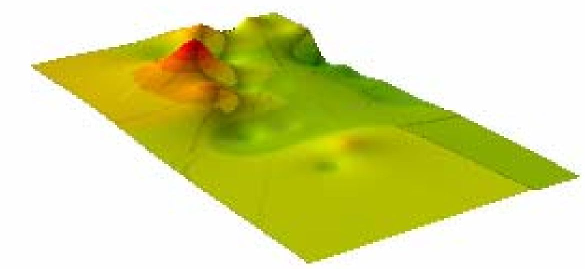

Figure 5: Three-dimensional model of the interpolated surface for the PSD ozone data for Week 5. The contour color scale is the same as Figure 3.

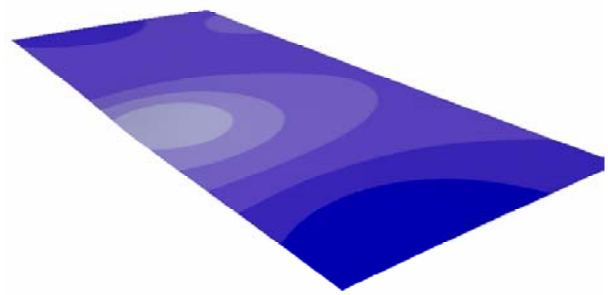

Figure 6: Three-dimensional model of the interpolated surface for the continuous monitor ozone data for Week 5. The contour color scale is the same as in Figure 4.

To compare the two surfaces, we overlayed them. Week 5, as shown in Figure 7, is a typical result.

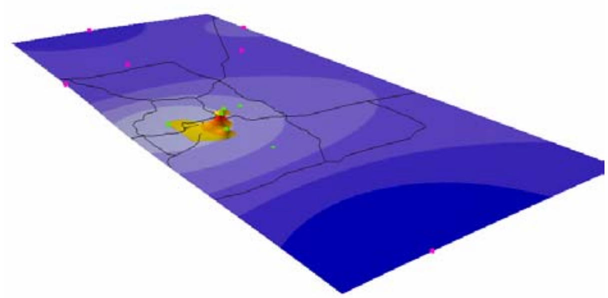

Figure 7: Comparison of interpolated surfaces of PSD and continuous monitor ozone data. PSD data typically shows peaks in the central city area that are not shown in the continuous monitor results. Continuous monitors are shown in pink, visible PSD sites are shown in green.

The peak in the central city sites is clearly visible above the interpolated surface from the continuous monitor sites for all of the study weeks. Central and southern PSD monitor sites are typically slightly below the continuous monitor surface, and the eastern PSD sites are typically distinctly below the continuous monitor surface.

The central city weekly average peak is comparable in magnitude to largest weekly average value outside of the city for Weeks 3, 4, and 6; during these weeks the central city peak values was ± 3 ppb of the value measured outside of the city. For Weeks 1 and 2, the central city ozone peak was 10 and 9 ppb less than the values measured outside of the city, respectively. For week 5, the central city ozone peak was 6 ppb above the value measured outside of the city.

5.4. Wind data

Low average surface wind flow conditions below 5 m/s prevailed during the study period at both sites. For the Downtown airport, the average windspeed was 3.14 m/s and winds were typically from the south-southwest. For KCI, the average windspeed was 3.66 m/s and from the south and southeast. (See Figs. 8 and 9.)

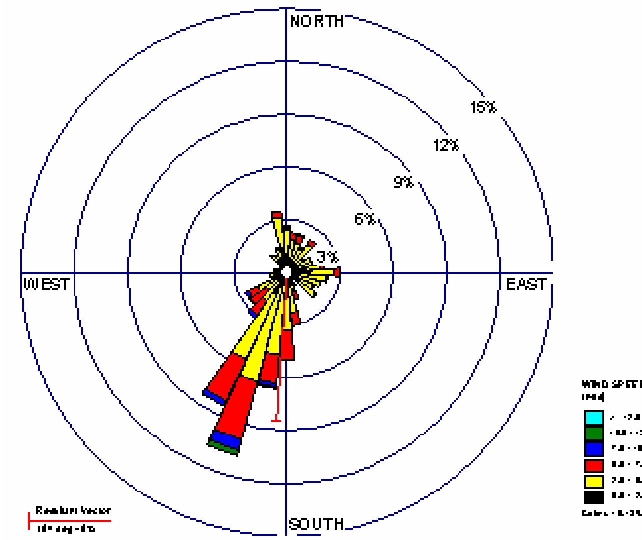

Figure 8: Windrose for Kansas City Downtown Airport. Windspeed color scale is in increments of 2.5 m/s. Yellow is the 2.5 to 5.0 m/s bin.

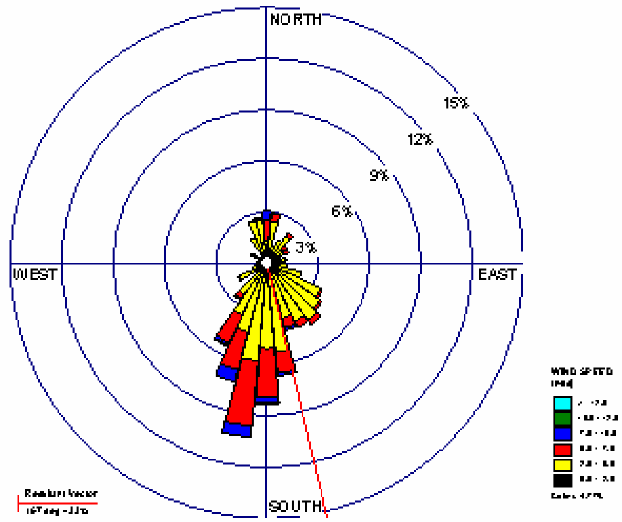

Figure 9: Windrose for KCI airport. Windspeed color scale is in increments of 2.5 m/s.

Both locations experienced low-flow conditions throughout most of the study period; 81.1% of the time for the Downtown site, and 79.4% of the time for the KCI site. One marked difference between the two sites in terms of windspeed was the percentage of calms; the Downtown site experienced calms 15.1% of the time, while the KCI site experienced calms only 4.8% of the time.

5.5. Ozone concentrations in the urban core

There is a persistent peak in ozone concentration over the central city portion of the Kansas City Metropolitan area that is resolved by the high-density PSD network. This is not in conflict with the existing continuous monitor data; rather, these data complement them. The costly nature of continuous monitors virtually prohibits high-density sampling, especially in areas where titration by nitrogen oxides is likely.

The typical model of ozone formation is that peak ozone levels will be reached distant from the area of precursor emission because of the hours-long formation time of ozone. The ozone forms during transport. However, our data demonstrates that a high ozone peak with a much steeper gradient also forms in the area of precursor emission. One possible explanation for this persistent urban core ozone peak is the persistent low-flow surface wind conditions. Not only did the study period experience low-flow conditions about 80% of the time throughout the metropolitan area, but the wind flow data from the Downtown airport vs. KCI demonstrate that the air was calm over three times as frequently. Tall buildings and urban canyons increasingly disrupt airflow toward the center of the city.

6. CONCLUSION

This study characterized spatial gradients of outdoor air quality through a multi-site neighborhood scale air sampling experiment conducted during summer 2005. We developed highly resolved exposure maps based on the detailed air quality observations collected and demonstated that ozone concentration levels were higher in urban core neighborhoods compared to the sorrounding surbuban areas. Implications of these results for the respiratory health of citizens of the Kansas City area are not known and will have to be addressed. We hope that our results provide a starting point for researchers interested in studying the nexus between urban air quality; environmental justice questions implied by disparities in exposure across communities; and the respiratory health of urban residents of Kansas City.

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