AIR POLLUTION RETENTION WITHIN A COMPLEX OF URBAN STREET CANYONS: A TWO-CITY COMPARISON

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1. INTRODUCTION/THEORY

The current study explored spatial and temporal variability in the underlying dynamics of urban air pollutant concentrations that, if uncharacterized, may contribute uncertainty or bias to epidemiological model results. The approach followed that of Richmond-Bryant et al. (2010), which treated urban buildings as a matrix of bluff bodies to determine the retention of air pollution in their wakes. A fuller summary of the bluff body work on air pollutant retention is provided therein. That work was based primarily on bluff body theory developed by Humphries and Vincent (1976a) to derive a functional relationship between a contaminant's nondimensional residence time (H) within a wake and several of the turbulent and mean properties of the local airstream. In Humphries and Vincent (1976a, b, c), Vincent (1977, 1978), and MacLennan and Vincent (1982), the air pollutant was injected directly into the wake of a bluff body, and the decay of its concentration was observed. The characteristic time of contaminant decay (τ) was then computed based on the change in concentration (C) over time (t). Concentration was observed to decay exponentially as $C = C_0 e^{-t/\tau}$, where, C_0 was the concentration at the initial release time. Humphries and Vincent (1976b) theorized that the removal of contaminants from the bluff body wake could occur by 1) turbulent or Brownian diffusion across the wake boundary, or 2) by the vortex shedding motion that occurs in the wake of the bluff body. As such, the size of the bluff body could theoretically affect the rate of concentration decay. The size of a bluff body wake has been shown to be a function of the Reynolds number of the airflow, $Re = UD/v$ where U = freestream wind speed, D = characteristic length scale of the bluff body, and v = kinematic viscosity (Humphries and Vincent, 1976a). Additionally, more recent studies also found that, for multiple obstacles bounding the wake, aspect ratio of the wake was also a predictor of contaminant retention (Fackrell, 1984; Lee and Park, 1994), given that the upstream and downstream obstacles constrain the size of the wake:

$$H = U\tau/D = f(UD/v, k^{0.5}/U, l/D, fD/U, D_B/v, D/W) \quad (1)$$

where k = turbulence kinetic energy, l = eddy length scale, = frequency of vortex shedding, D_B = Brownian diffusion coefficient, and W = width of the space between bluff bodies. For real-world applications, D can be given as the height of a building and W as the street width. H is an important parameter for comparing residence time among buildings because it accounts for D and U, such that a smaller building would have higher H than a tall building with identical τ. In the absence of local sources, the range of H across an urban matrix of street canyons relates to both the spatial and temporal variability of air pollutant concentration in that each H is a nondimensional description of the concentration decay rate in a given street canyon and the range of H varies over space.

The objective of this study was to test the modeling approach for estimating the retention of air pollutants in street canyons. This methodology was first presented in Richmond-Bryant et al. (2010) for an analysis of contaminant retention in downtown Oklahoma City (JU2003). In the current study, tracer gas concentration and meteorological data collected during the Midtown Manhattan 2005 (MID05) Study, along with geographical information system (GIS) data describing the building topography (Burian et al., 2005), were utilized to test if the results from Richmond-Bryant et al. (2010) could be reproduced in another city. The results of this study were also intended to gain insight into the influences of meteorology and urban topography on the spatial and temporal variability of air pollutant concentrations in urban street canyons. The resulting spatial and temporal variability in concentrations can be used to bound estimates of human exposure to air pollution and thus reduce the uncertainty in these estimates.

2. METHODS

2.1 The Midtown Manhattan 2005 (MID05) Study

Data from the MID05 study were obtained in midtown Manhattan, NY during six intensive operating periods (IOP) spanning August 8-24, 2005. The area in which the experiments were conducted is shown in Figure 1. The IOPs were conducted during the hours of 06:00-13:00. Monitoring occurred within a dense urban matrix of buildings and street canyons. Building height ranged from 9-261 m, and the width of the street was 10 m for side streets (running northwest to southeast) and 30 m for avenues (running northeast to southwest). Detailed description of the instruments, sampling methodology, and instrument deployment for MID05 has been provided in Allwine and Flaherty (2007).

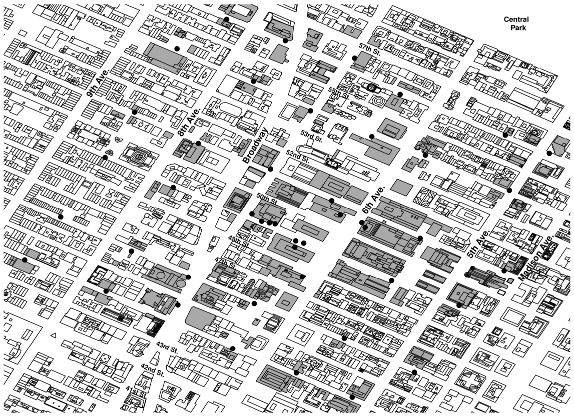

Figure 1. Building layer map of midtown Manhattan. Tracer gas measurement locations are marked with black dots, and buildings included in the models are highlighted in grey. The figure is oriented with north to the top.

Tracer gas experiments for MID05 were conducted in a similar manner to those of JU2003 in Oklahoma City. For each experiment, sulfur hexafluoride (SF_6) tracer gas was delivered to the atmosphere in 30-minute releases. For IOP 1-3, releases occurred at 6:00 and 10:00. For IOP 4-6, releases occurred at 6:00, 8:00, and 10:00. The locations of SF_6 release and the trace gas analyzers (TGAs) varied with IOP depending on the prevailing wind direction and building topography. For MID05, thirty-six programmable integrated gas samplers (PIGS) were used to collect samples of SF_6 in Tedlar® bags that were then brought to a laboratory for analysis using gas chromatography with an electron capture detector (ECD). The PIGS were programmed to capture 30-minute integrated samples. The PIGS were mounted at an elevation of approximately 3.5 m above ground level for MID05.

Meteorological data used for MID05 were obtained using different equipment. Three-dimensional sonic anemometers were used to collect wind data. The sonic anemometers were mounted on 6-foot manifolds placed on five roof tops in proximity of the tracer gas measurements. Wind speed, direction, average and fluctuating wind components, average wind cross products, friction velocity, and turbulence kinetic energy were measured or derived from the data set. These data were averaged over 30 minute periods that matched the tracer gas measurement intervals and were averaged over the five anemometer sites. These data were summarized in an analysis of the mean and turbulent characteristics of the wind in midtown Manhattan by Hanna and Zhou (2009).

2.2 Data analysis

Data analysis followed the methodology developed in Richmond-Bryant et al. (2010) to compute the scaling parameters: computing decay times from the time series of SF_6 concentration data, matching meteorological data to the time period of study, matching upwind building data to the tracer gas sampling site, and performing regression analysis to follow the functional relationships observed in Humphries and Vincent (1976a) and the papers that followed. Much of this analysis was automated using the open source R statistical software package (R Development Core Team, 2011) supplemented with the *rgdal* (Keitt et al., 2010) and *spatstat* (Baddeley and Turner, 2005) libraries. All MID05 data were obtained from Dugway Proving Grounds through secure FTP, while JU2003 data were available to the public via a secure website (https://www.ju2003-slc.org). The repository of data included tracer gas concentration time series; raw and processed meteorological data (Hanna and Zhou, 2009); a geographical database containing building heights, building centroid coordinates; and coordinates of the locations of the PIGS.

For each of the six IOPs, time series data obtained at each PIGS were analyzed. Time series intervals were designated to coordinate with the release times described in Section 3.1. For each concentration decay period, an exponential curve of the form $C = C_0e^{-t/\tau}$ was fit to the data. The concentration decay period was used only if there was an order of magnitude difference between the beginning and ending concentrations. Less difference among the concentrations indicated that the PIGS was not capturing the concentration plume based on the wind direction. Additionally, the data were discarded if the concentration decay curve fit had a coefficient of determination (R^2) value of less than 0.5, which was selected to ensure that time series data that did not exhibit decay were not inadvertently included in the analysis. R^2 was lower than 0.5 one time for the 140 data points meeting the requirement for at least one order of magnitude difference between the first and last concentration data points. Additionally, one outlier for H from the MID05 dataset was removed to improve the normality the dataset.

For each time period over which concentration decay was observed, the 30-minute meteorology data for U and k were averaged then matched to the τ. At the same time, the height of the building upwind of the PIGS was selected using geographic information systems (GIS). An algorithm was developed to select the most proximal upwind building along the wind direction. Because the building centroid defined the location of each building, a 45° tolerance on either side of the wind direction was included in the selection criteria. The tolerance was incorporated into the analysis to avoid selection of a building that was further away but whose centroid was directly upwind of the PIGS. Smaller tolerance values of 5°, 20°, 35°, and 50° were also tested. It was found that the 45° and 50° results produced the buildings that were closest to the PIGS and were comparable with each other. The 45° tolerance was chosen to maintain values within a half quadrant of the wind direction. Additionally, the width of the street, W, in which the PIGS were located was ascertained from the GIS data as well.

The scale model analysis was conducted using the combination of data described. H was computed from τ, U, and D according to equation (1). Re was computed from U and D, and the street canyon aspect ratio was calculated from D and W. Turbulence intensity was calculated as $k^{0.5}/U$. Next, H was graphed as a function of Re, D/W, and $k^{0.5}/U$ for IOPs 1-4 and 6 to assess the relationship between H and these variable groups. Quality of the model was determined based on correlation of H with the other functional groups and validation. R^2 was calculated to assess correlation. The data obtained from IOP 5 were withheld from model training to validate the data. The validation data were plotted along with the fit, and R^2 between the model and the validation data was computed for each function (H vs. Re, H vs. D/W, and H vs. $k^{0.5}/U$).

3. RESULTS AND DISCUSSION

Figure 2 shows the fitted relationship for H vs. Re calculated from the MID05 data. An inverse relationship was fit to the training data with a moderate fit of $R^2 = 0.47$:

$$H = 5 \times 10^7 Re^{-0.814} \quad (2)$$

The R^2 indicates that there is some scatter in the relationship between H and Re, but a relationship is still discernible. Analysis of variance of the linear regression of equation (2) on the field study values of H produced a highly significant model ($p < 0.0001$), indicating that equation (2) was an appropriate fit to the data. Additionally, Figure 2 shows the data used to validate equation (2). The validation data points fit the model with $R^2 = 0.70$. This suggests that the model fit is reasonable for the MID05 experiments.

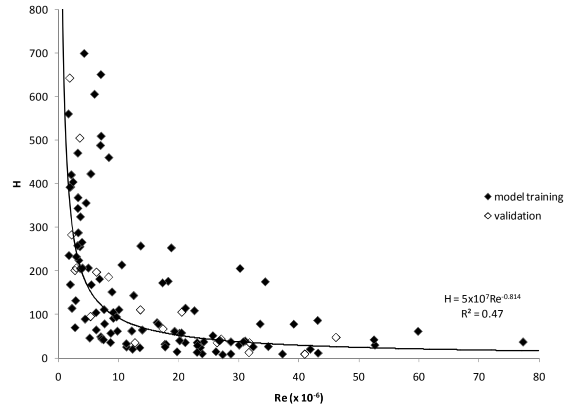

Fig 2. Relationship between H and Re for the MID05 data. The closed symbols show data used to fit the model, and the open symbols show validation data.

Studies examining the relationship between H and Re have had mixed results. The Humphries and Vincent (1976a, 1976b), Gomes et al. (1999), and Gomes et al. (2007) studies found H to be independent of Re, while MacLennan and Vincent (1982), Gomes et al. (1997), and Gomes et al. (2002) observed H to be inversely dependent on Re. Vincent et al.

(1991) also found the curve for H vs. Re to follow an inverse structure for experiments of the retention of contaminants in the wake of a coal shearer. These studies were conducted at Re ~ 10^3-10^4. Wind tunnel studies cannot accommodate Re ~ 10^7 that occur in urban environments. However, the curve fit provided in equation (2) was an inverse power law, similar to that observed for the Joint Urban 2003 study (Richmond-Bryant et al., 2010), where, it was postulated that H increases when airflow separation at the edges of the building becomes turbulent when Re ~ 10^5-10^6 and then decreases towards some asymptotic value. Without data spanning several orders of magnitude of Re, it is impossible to verify this theory.

Figure 3 illustrates the relationship between the nondimensional groups H and D/W for the MID05 data. An inverse relationship was fit to the training data with a moderate fit of $R^2 = 0.48$:

$$H = 296.19(D/W)^{-0.812} \quad (3)$$

The R^2 indicates some scatter in the relationship between H and D/W, but a relationship is still identifiable. Analysis of variance of the linear regression of equation (3) on H produced a highly significant model ($p < 0.0001$), suggesting that equation (3) was a reasonable fit to the data. Additionally, Figure 3 shows the data used to validate equation (3). The validation data points fit the model with $R^2 = 0.31$. This suggests that the model fit is not as strong for equation (3) compared with equation (2) for the MID05 experiments. Hence, the relationship between H and Re appears to be stronger than that for H and D/W.

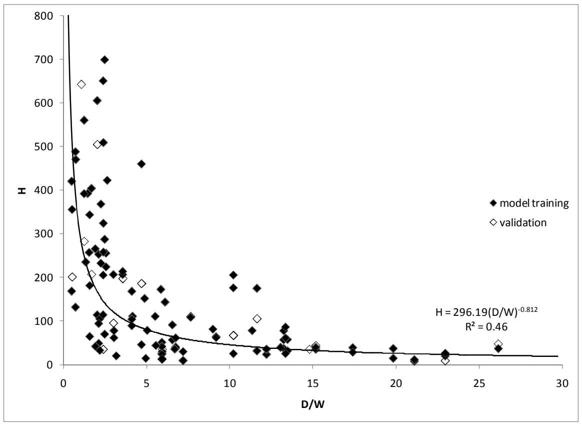

Fig 5. Relationship between H and D/W for the MID05 data. The closed symbols show data used to fit the model, and the open symbols show validation data.

Several issues must be considered before applying these methods to contemporary urban air quality analyses. First, an inert tracer gas was used to represent air pollutant transport from a given source. These controlled releases did not replicate real conditions with sources that vary and pollutants that transform over time and space. Second, the study assumed that boundary layer winds were constant over each decay period, whereas in reality winds can fluctuate substantially over the two-three hour periods in which concentration decay was observed. Third, the method assumed that the upstream building used to define the street canyon height was rectangular, although most buildings have more complex façades that could affect the separation of airflow around them. Additionally, the method only accounted for the building immediately upwind of the tracer gas sampler. Yim et al. (2009) ran computational fluid dynamics simulations and used the results to measure τ in an array of 20 m tall buildings downstream of a row of buildings with height varying from 0 to 80 m. They found that τ increased with increasing upstream building height, from 206 s for 20 m tall upstream buildings to 344 s for 80 m tall upstream buildings with winds perpendicular to the buildings. These results suggest that the zone of recirculation may persist across multiple blocks bounded by the tallest buildings rather than the most proximal buildings. Quantifying the error in H incurred by such approximations is an important next step before applying these scaling methods to the estimation of street canyon level concentrations.

4. CONCLUSION

This study builds upon previous work to illustrate the use of meteorology and building topography for predicting the spatial and temporal variation in contaminant retention within a dense matrix of urban street canyons. This technique is based on fundamental fluid mechanics studies of contaminant retention in the wake of a bluff body. This work thus lays a foundation for developing methods of estimating microscale-level H values based on readily available sources of data. A necessary next step for real-world applicability is to consider the modifications necessary to build analogous models for actual ambient pollutants as opposed to tracer gases, taking processes such as chemical reactivity, adsorption, and deposition into account. Furthermore, the results of the inter-study comparisons suggested that relationships between H and building topography may have underlying site-specific features that would require elucidation prior to generalizing to larger spatial scales. To accommodate these needs, several potential follow up studies should be conducted. Data from live tracer gas experiments, wind tunnel experiments, or CFD simulations should be used to fit models for different locations to assess how the model formulations may vary with setting. Additionally, the modeling technique should be extended to chemically reactive contaminants and to particulate matter. MacLennan and Vincent (1982) developed a theoretical model that included particle Stokes number as a determinant of retention time. Similar analyses may be appropriate for exploring the retention time of ultrafine PM in street canyons. Moreover, inversion of the models for H may potentially be used for concentration prediction. Ultimately, development of this technique to understand microscale variability in urban concentrations may be used for reduction of uncertainty in time series air pollution epidemiological models.

DISCLAIMER

The research and this manuscript have been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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REFERENCES

Allwine, K.J., Flaherty, J.E., 2006. Joint Urban 2003: Study Overview and Instrument Locations. PNNL-15967, Pacific Northwest National Laboratory, Richland, WA.

Allwine, K.J., Flaherty, J.E., 2007. Urban Dispersion Program Overview and MID05 Field Study Summary. PNNL-16696, Pacific Northwest National Laboratory, Richland, WA.

Baddeley, A., Turner, R., 2005. Spatstat: An R package for analyzing spatial point patterns. Journal of Statistical Software 12, 1-42.

Brixey, L.A., Heist, D.K., Richmond-Bryant, J., Bowker, G.E., Perry, S.G., Weiner, R.W., 2009. The effect of a tall tower on flow and dispersion through a modern urban neighborhood. Part 2. Pollutant dispersion. Journal of Environmental Monitoring 11, 2171-2179.

Burian, S., McKinnon, A., Hartman, J., Han, W., 2005. *National Building Statistics Database: New York City*. LA-UR-05-8154, Los Alamos National Laboratory, Los Alamos, NM.

Dominici, F., Zeger, S.L., Samet, J.M., 2000. A measurement error model for time-series studies of air pollution and mortality. Biostatistics 1 157-175.

Dominici, F., Daniels, M., Zeger, S. L., and Samet, J. M., 2002. Air pollution and mortality: Estimating regional and national dose-response relationships. Journal of the American Statistical Association 97, 100–111.

Fackrell, J.E., 1984. Parameters characterising dispersion in the near wake of buildings. Journal of Wind Engineering and Industrial Aerodynamics 16, 97-118.

Fernando, H.J.S., 2010. Fluid dynamics of urban atmospheres in complex terrain. Annual Review of Fluid Mechanics 42, 365-389.

Gomes, M.S.P., Isnard, A.A., Pinto, J.M.C., 2007. Wind tunnel investigation on the retention of air pollutants in three-dimensional recirculation zones in urban areas. Atmospheric Environment 41, 4949-4961.

Gomes, M.S.P., Vincent, J.H., 2002. The effect of inertia on the dispersion of particles in the flow around a two-dimensional flat plate. Chemical Engineering Science 57, 1319-1329.

Gomes, M.S.P., Vincent, J.H., Pui, D.Y.H., 1997. On the retention of inertialess particles in the near wake region of a two-dimensional flat plate placed normal to an aerosol-laden freestream. Aerosol Science and Technology 26, 269–284.

Gomes, M.S.P., Vincent, J.H., Pui, D.Y.H., 1999. The effect of freestream turbulence on the transport of particles in the vicinity of a blunt flow obstacle. Atmospheric Environment 33, 4459–4468.

Hanna, S.R., Zhou, Y., 2009. Space and time variations in turbulence during the Manhattan Midtown 2005 field experiment. Journal of Applied Meteorology and Climatology 48, 2295-2304.

Humphries, W., Vincent, J.H., 1976a. An experimental investigation of the detention of airborne smoke in the wake bubble behind a disk. Journal of Fluid Mechanics 73, 453-464.

Humphries, W., Vincent, J.H., 1976b. Near wake properties of axisymmetric bluff body flows. Applied Scientific Research 32, 649-669.

Keitt, T.H., Bivand, R., Pebesma, E., Rowlingson, B., 2010. Rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 0.6-33. http://CRAN.R-project.org/package=rgdal.

MacLennan, A.S.M., Vincent, J.H., 1982. Transport in the near aerodynamic wakes of flat plates. Journal of Fluid Mechanics 120, 185-197.

Mavroidis, I., Griffiths, R.F., Jones, C.D., Biltoft, C.A., 1999. Experimental investigation of the residence of contaminants in the wake of an obstacle under different stability conditions. Atmospheric Environment 33, 939–949.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Richmond-Bryant, J., Isukapalli, S.S., Vallero, D.A., in press. Air pollution retention within a complex of urban street canyons, Atmospheric Environment (2010), doi: 10.1016/j.atmosenv.2010.11.003.

Sheppard, L., Slaughter, J.C., Schildcrout, J., Liu, L.-J.S., Lumley, T., 2005. Exposure and measurement contributions to estimates of acute air pollution effects. Journal of Exposure Analysis and Environmental Epidemiology 15, 366-376.

U.S. Census Bureau, 2011. American Fact Finder, http://factfinder2.census.gov/faces/nav/jsf/pages/searchresults.xhtml?ref=geo&refresh=t Accessed June 15, 2011.

Vincent, J.H., 1977. Model experiments on the nature of air pollution transport near buildings. Atmospheric Environment 11, 765–774.

Vincent, J.H., Aitken, R.J., Mark, D., Botham, R.A., 1991. Scale model studies of the transport of airborne pollutants on coalfaces. Annals of Occupational Hygiene 35, 359-376.

Yim, S.H.L., Fung, J.C.H., Lau, A.K.H., Kot, S.C., 2009. Air ventilation impacts of the “wall effect” resulting from the alignment of high-rise buildings. Atmospheric Environment 43, 4982-4994.