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Title: **How Do Outdoor Pollutant Concentrations Vary Along the Height of a Tall Building?**

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How Do Outdoor Pollutant Concentrations Vary Along the Height of a Tall Building?

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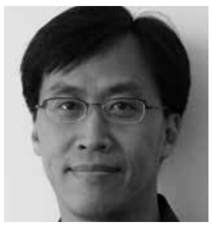

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Abstract

It is generally assumed that vertical pollutant dispersion can reduce exposures to ambient pollutants in tall buildings, as concentrations of some ground-source pollutants are diluted at higher floors. However, no measurements of pollutant concentrations have ever been made specifically along the height of a building that would qualify as a supertall building by CTBUH Height Criteria. This paper summarizes the 2016 CTBUH Research Seed Funding study, conducted during a one-week period in the summer of 2017, which measured the vertical variation in the concentrations of several outdoor pollutants and environmental parameters along the height of an approximately 60-story, 300-meter building in downtown Chicago. Floor height was found to be more strongly correlated with PM_1, $PM_{2.5}$, PM_{10}, CO_2, and O_3 concentrations than with local wind speed and direction.

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Introduction

Elevated outdoor concentrations of airborne pollutants such as particulate matter (PM), ozone (O_3), and nitrogen oxides (NO_x) are associated with increased risks of a variety of health effects (EPA 2009 & 2016). However, because outdoor pollutants can infiltrate and persist indoors where people in industrialized countries spend the majority of their time (Klepeis et al. 2001), much of their exposure to pollutants of outdoor origin often occurs inside buildings (Chen, Xhao, and Weschler 2012a & 2012b; Meng et al. 2005; Weschler 2006). Associations between outdoor pollutant concentrations and adverse health effects are commonly made using large epidemiological studies that rely on stationary ambient measurements with air sampling heights of two to 15 meters above ground (EPA 2012). But what does this mean for occupants of tall buildings, where outdoor air intake heights can be hundreds of meters above ground level?

To the authors' knowledge, no measurements of pollutant concentrations have ever been made specifically along the height of a building that would classify as a tall or supertall building by the CTBUH Height Criteria (CTBUH 2019). Several studies have investigated this vertical variation for a limited number of pollutants along the height of mid-rise buildings, including: a 35-meter building in Boston (Wu et al. 2014); a 40-meter building in China (Li et al. 2005); a 55-meter building in Chile (Villena et al. 2011); a 42- and a 127-meter building in Singapore (Kalaiarasan et al. 2009). These field studies have generally confirmed findings from atmospheric measurements and models, demonstrating that particulate matter concentrations tend to decrease with building height, potentially offering a protective effect at higher floors, while ozone concentrations are likely higher at higher elevations, potentially offering a protective effect at lower floors. However, none have extended beyond 130 meters in height, and the types of pollutant measurements have been limited.

Despite the lack of measurements to date, a few small epidemiology studies have suggested that building height could play an important role in human health, and that the vertical variation in pollutant concentrations might contribute to this effect. For example, a recent study in Switzerland suggested that differences in environmental exposures may have contributed to reductions in all-cause mortality that were associated with increasing residential floor height in buildings (Panczak et al. 2013). Similarly, a study of office buildings in the United States found significantly higher building-related symptoms reported by occupants working on the floors of buildings that had outdoor air intakes less than 60 meters above ground level, which may have been due to greater levels of pollutants from vehicles at air intakes nearer the ground (Mendell et al. 2008).

This work presents results from a pilot study, funded by the Council on Tall Buildings and Urban Habitat (CTBUH) through sponsor Taipei Financial Center Corporation, in which the vertical variation of several outdoor pollutants and environmental parameters were measured along the height of a single tall building in downtown Chicago, from June 22–29, 2017. The aim was to provide novel measurements to quantify the dispersion of ambient pollutant concentrations and environmental parameters along the height of the case study building, and to determine the importance of building height and local meteorological factors in influencing the observed variability in the resulting data. This work has already been published in the Journal Building and Environment (Azimi et al. 2018); here only a brief summary and several excerpts are presented.

"No previous measurements of pollutant concentrations had ever been made specifically along the height of a building that would classify as a 'supertall' building, according to the CTBUH Height Criteria."

Methods

Field measurements

The case study building, which will remain unnamed and whose ownership will not be identified, was approximately 60 stories (300 meters) tall. Several field measurement approaches were discussed with the building engineers and ownership representatives in order to balance equipment costs, accuracy, and practicality, including: (1) multiple instruments measuring simultaneously on multiple floors; or (2) one set of mobile instruments to scan the height of a building, via (a) a pulley system or similar technology to lower and raise an instrument platform or (b) using a drone or other aerial vehicle to lower and raise a (likely much smaller) instrument platform. Both options 2a and 2b were deemed impractical for the purposes of this work, as neither approach would allow for longer-term measurements (i.e., at least one week continuously) but would be limited to short-term measurements (i.e., a few hours). Additionally, neither approach would allow for actual simultaneous measurements, meaning that a true comparison of matched, simultaneous, time-stamped data could never really be made (i.e., only repeated scans of the building height would be achievable). Option 1 was chosen as the most realistic approach from the standpoints of both data quality and practicality.

However, Option 1 also has its own limitations. For example, air quality monitors that are formally designated as Federal Reference Methods (FRM) or Federal Equivalent Methods (FEM) to most accurately measure pollutant concentrations are often at least US$10,000 and thus prohibitively expensive for simultaneous measurements in five locations. Therefore, to be able to establish a finer vertical resolution in matched time-resolved pollutant measurements, a number of more cost-effective air quality monitors on the market were used and calibrated against each other and/or against research-grade FRM/FEM methods in a lab when possible.

Ultimately, several commercially available monitors were selected to measure concentrations of size-resolved particulate matter (PM; 0.3–10 μm), ozone (O_3), nitrogen dioxide (NO_2), carbon dioxide (CO_2), and carbon monoxide (CO), along with temperature and relative humidity in outdoor air along the height of the building. Size-resolved PM number concentrations were also used to estimate PM_1, $PM_{2.5}$, and PM_{10} mass concentrations. Simultaneous measurements were made using multiple sets of instruments placed in the outdoor air intakes on the mechanical systems located on four different floors (i.e., the second, 16th, 29th, and 44th), as well as in an open-air area on the 61st floor located underneath a two-meter-high cooling tower stand. The location of measurements within the outdoor air intakes was upstream of any filtration or mixing processes. Measurements were made within approximately 200 millimeters downstream of a coarse metallic grate located on the exterior facade of the building, through which outdoor air flowed, and approximately three meters upstream from adjustable louvers that were located downstream of the exterior grate. The louvers controlled mixing between outdoor air and return air, and were located two to three meters upstream of a downstream filter bank.

All five sets of instruments were placed in the top drawer in five identical rolling tool carts with uninterruptible power supplies installed in the bottom drawer (see Table 1). The top drawer of each rolling tool cart was modified to include a small exhaust fan on one side and small holes for air intake drilled on the opposite side to continuously draw in sample airflow. A team of researchers distributed the monitoring instruments to be installed on each floor with the help of the

Contained in in five rolling tool carts, deployed for a 24-hour co-location test, positioned on the interior side of an outdoor air intake:
Drawer 1 (top)
MetOne GT-526S OPCs
Aeroqual SM50 OEM ozone monitors
Extech SD800 CO2 monitors
Aeroqual S500 NO2 monitors
LASCAR CO loggers
Onset U12-013 HOBO 2-Channel Temperature/ Relative Humidity data loggers
Small exhaust fan
Air intake holes
Drawer 2 (middle)
Instrument power supplies
Drawer 3 (bottom)
Uninterruptible power supplies (UPS)

Table 1. Equipment used to conduct the experiment.

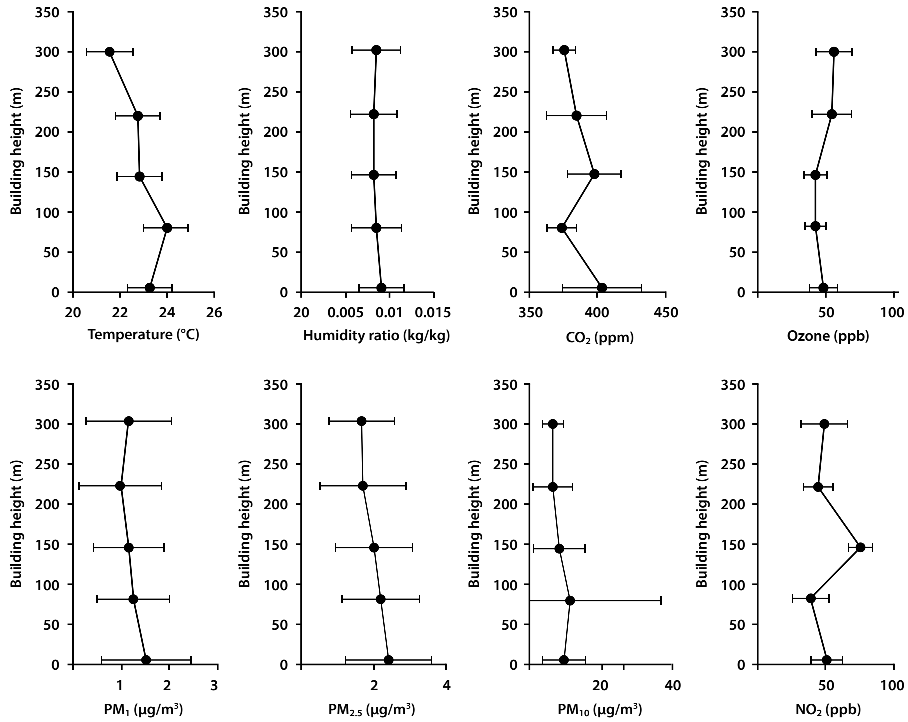

Figure 1. Average (± standard deviation) of the CO_2, O_3, NO_2, PM_1, $PM_{2.5}$, and PM_{10} concentrations and the air temperature and humidity ratios measured (or estimated) during the weeklong field campaign plotted against the approximate corresponding height of the test building.

building's facilities personnel. In the mechanical rooms, the rolling tool carts were placed as close as possible to the exterior grates on the outdoor air intakes, and a box fan was operated continuously to ensure that outdoor air was flowing into the plenum area even if/when the HVAC outdoor air intake happened to shut off for periods of time. For the 61st floor installation, the rolling tool cart was placed underneath a cooling tower stand that was approximately two meters tall and located in an otherwise open area that provided for substantial outdoor airflow to the instrument cart.

All instruments were synchronized to collect data at approximately the same time intervals of either one or two minutes, depending on instrument limitations. In order to launch the other monitors simultaneously, team members were deployed to each floor and communicated via two-way radios to manually initiate data logging on each instrument at the same interval, and at approximately the same time. The result is a set of data that includes synchronized time-stamped data, for which each instrument for each measurement type is synchronized to the other instruments with the same measurement type, while all measurement types are synchronized to within approximately 30 seconds of each other (or closer). The monitors were then left to record data for approximately one week.

Data analysis

Calibration factors were applied to the raw data collected from each instrument during the calibration campaigns. To evaluate the statistical significance of the floor-by-floor comparisons, nonparametric Wilcoxon signed-rank tests were used to make paired comparisons of each simultaneously measured parameter across the five floors. Adjusted p-values that account for the large sample sizes were used to determine statistical significance (i.e., $p = 1 - (1 - 0.05)^{1/n}$, where n = the number of recorded data points for each instrument). Nonparametric Spearman rank correlation coefficients were used to evaluate the statistical significance of comparisons between parameter measurements and floor height and wind speeds and directions from a nearby weather station.

Results

Summary of measurements

The O_3, CO_2, and temperature and relative humidity data loggers successfully collected data for the entire weeklong period, synchronized at one-minute intervals. PM measurements were also successful, collecting at two-minute intervals (limited by onboard data storage capacity). The NO_2 monitors recorded data at one-minute intervals, only for the last ~5.5 days of the measurement campaign, because their internal memory cards were filled, and earlier data points were automatically overwritten. The CO loggers resulted in primarily observations below the detection limit, and thus CO data are excluded.

Comparisons between floors

Figure 1 shows average (± standard deviation) values for all measured parameters over the weeklong monitoring period, plotted versus approximate building height. All differences in measured parameters between floors were statistically significant except for comparisons of (i) $PM_{2.5}$ concentrations measured on the 44th and 61st floors and (ii) humidity ratio measured on the 16th and 61st floors. Below is a summary of results for each measurement type. The second-floor measurements were used as a close-to-ground-level reference for all comparisons.

*Temperature***.** The average temperature was ~2.8% higher on the 16th floor compared to the second floor, but was ~1.7% (i.e., ~0.4°C), ~2.3% (i.e., ~0.5°C), and ~7.6% (i.e., ~1.7°C) lower on the 29th, 44th, and 61st floors compared to the second floor, respectively. The average temperature difference of ~1.7°C between the 61st floor (height of ~300 meters) and the second floor (height of ~5 meters) yields an average temperature lapse rate of about -0.58°C per 100 meters along the height of the building, which is within ~10% of the commonly used Standard Lapse Rate of -6.5°C per 1,000 meters (i.e., -0.65°C per 100 meters) (Ellis and Torcellini 2005; Leung and Weismantle 2008). However, the temperature lapse was not constant across each floor comparison, which suggests that the temperature lapse rate assumption for a building of this size in this urban context may not be linear, and may be influenced by other factors such as surrounding buildings or highly localized meteorological conditions (Tong, Chen, and Malkawi 2017).

Humidity ratio. The average absolute humidity ratios were ~5.2%, ~7.9%, ~8.0%, and ~5.1% lower on the 16th, 29th, 44th, and 61st floors compared to the second floor, respectively. There was no clear linear trend observed between humidity ratio and building height, but the humidity ratio was lower on all floors above ground level.

Particulate matter. The average PM_1 concentration was estimated to be ~18.4%, ~24.8%, ~34.5%, and ~23.7% lower on the 16th, 29th, 44th, and 61st floors compared to the second floor, respectively, suggesting a fairly consistent trend of PM_1 concentrations decreasing with building height (see Figure 2). Similarly, the average PM2.5 concentration was estimated to be ~10.4%, ~18.0%, ~30.3%, and ~31.7% lower on the 16th, 29th, 44th, and 61st floors compared to the second floor, respectively. The trend for both PM_1 and $PM_{2.5}$ was nearly linear from floors 2 through 44, with a deviation in the open-air 61st floor location. The PM_1 and $PM_{2.5}$ concentration dispersion data are reasonably consistent with prior ambient measurements (Chan and Kwok 2000; Li et al. 2005). The average PM_{10} concentration was estimated to be ~12.9%, ~32.4%, and ~31.5% lower on the 29th, 44th, and 61st floors compared to the second floor, respectively, but actually was ~15.8% higher on the 16th floor compared to the second floor (see Figure 3). This inconsistent trend at the lower levels is suggestive of local ground sources with greater dilution occurring at higher elevations. Interestingly, the standard deviation of PM_{10} concentrations was largest on the 16th floor, which means that there were periodically very high PM_{10} concentrations measured on the 16th floor, and suggests an influence from nearby transient PM_{10} sources around this height. Note that the average PM_1, $PM_{2.5}$, and PM_{10} concentrations estimated from number measurements in the second floor outdoor air intake as a near-ground reference were ~1.5 μg/m³, ~2.3 μg/m³, and ~10.6 μg/m³, respectively, which are surprisingly low for an urban environment such as Chicago. However, the average daily $PM_{2.5}$ concentration measured at the nearest ambient regulatory monitor (~9 kilometers away) was only 2.8 μg/m³ during the measurement campaign (EPA 2014). For comparison, the average daily $PM_{2.5}$ concentration for the year 2017 measured at the same regulatory monitor was ~8.6 μg/m³. Although this presents only a limited comparison, it demonstrates that the field campaign happened to occur during a period of relatively low ambient PM concentrations.

Ozone and Oxides. For O_3, only data above the highest measured limit of detection (LOD) for the inexpensive instruments (which was estimated to be ~30 ppb) were used for comparison, as varying LODs make it impossible to compare null values with actual values recorded at concentrations lower than ~30 ppb. The average O_3 concentration above this LOD was ~11.9% and ~11.3% lower on the 16th and 29th floors compared to the second floor, respectively, but ~16.0% and ~18.0% higher on the 44th and 61st floors compared to the second floor, respectively (see Figure 4).

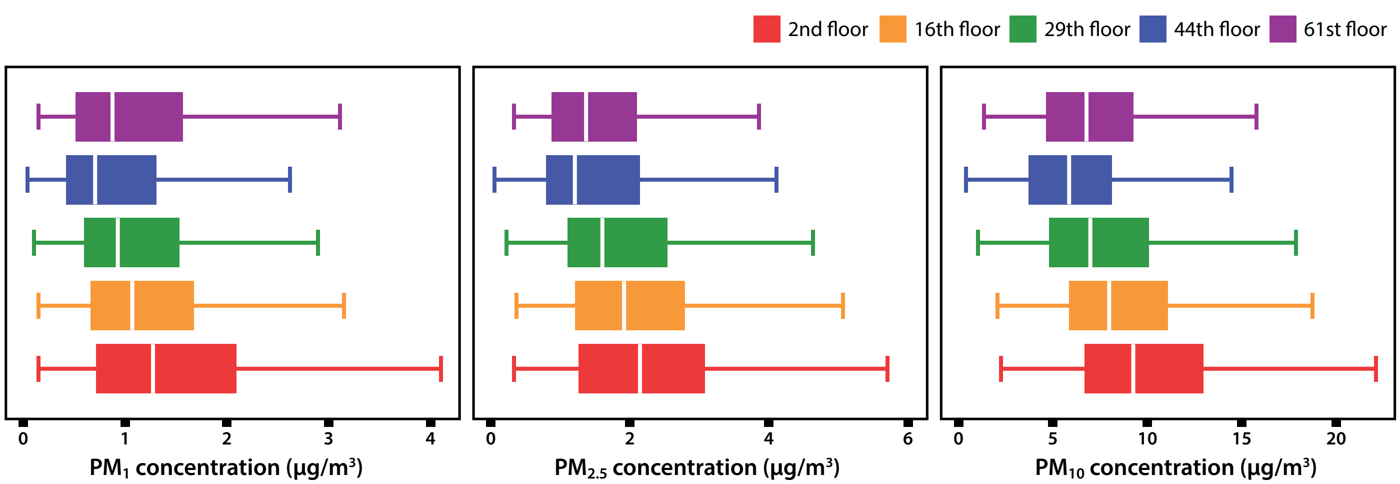

Figure 2. Box plots of estimates of PM_1, $PM_{2.5}$, and PM_{10} mass concentrations made from number concentrations measured on each of the five floors. Outliers are excluded for graphical clarity. The PM mass concentrations are estimates made assuming spherical shape and density = 1.5 g/cm³. No mass below 0.3 μm is counted, so mass concentrations are likely underestimated.

> “Concentrations of carbon dioxide were consistently lower on all floors above the second floor, suggesting dilution or dispersion of ground-level sources at higher floors.”

This inconsistent vertical trend in O_3 concentrations is not unlike the limited data from aircraft measurements, in which concentrations first decrease and then increase with elevation (Zhang and Rao 1999). This may be due to titration of O_3 by NO from ground-level tailpipe emission sources, which might not reach the higher elevations or might be diluted and/or reacted away by the time air masses reached higher elevations. The average NO_2 concentration was ~25.3% lower on the 16th floor, ~47.0% higher on the 29th floor, ~15.1% lower on the 44th floor, and ~5.3% lower on the 61st floor, each compared to the second floor. The average CO_2 concentration was ~7.6%, ~1.5%, ~4.9%, and ~6.9% lower on the 16th, 29th, 44th, and 61st floors compared to the second floor, respectively. These relative differences correspond to average absolute differences of ~30 ppm, ~6 ppm, ~20 ppm, and ~28 ppm, respectively. There was no consistent linear trend in average CO_2 concentrations across all elevations, although once again, concentrations were consistently lower on all floors above the second floor, suggesting dilution or dispersion of ground-level sources at higher floors.

Potential Drivers of Variations in the Measured Data

To investigate other potential meteorological drivers of the observed variations in measured parameters on each floor, data for wind speed and wind direction from the same time period as the field measurements were obtained from a nearby weather station (Weather Underground 2017). These data were typically reported at five-minute intervals, which were then summarized as hourly averages for analysis. The most prevalent wind direction was ~200° to ~250° (i.e., predominantly from the southwest), which would be expected to transport traffic-related pollutants from the heavily trafficked I-90/94 and I-290 highways toward the building located in downtown Chicago.

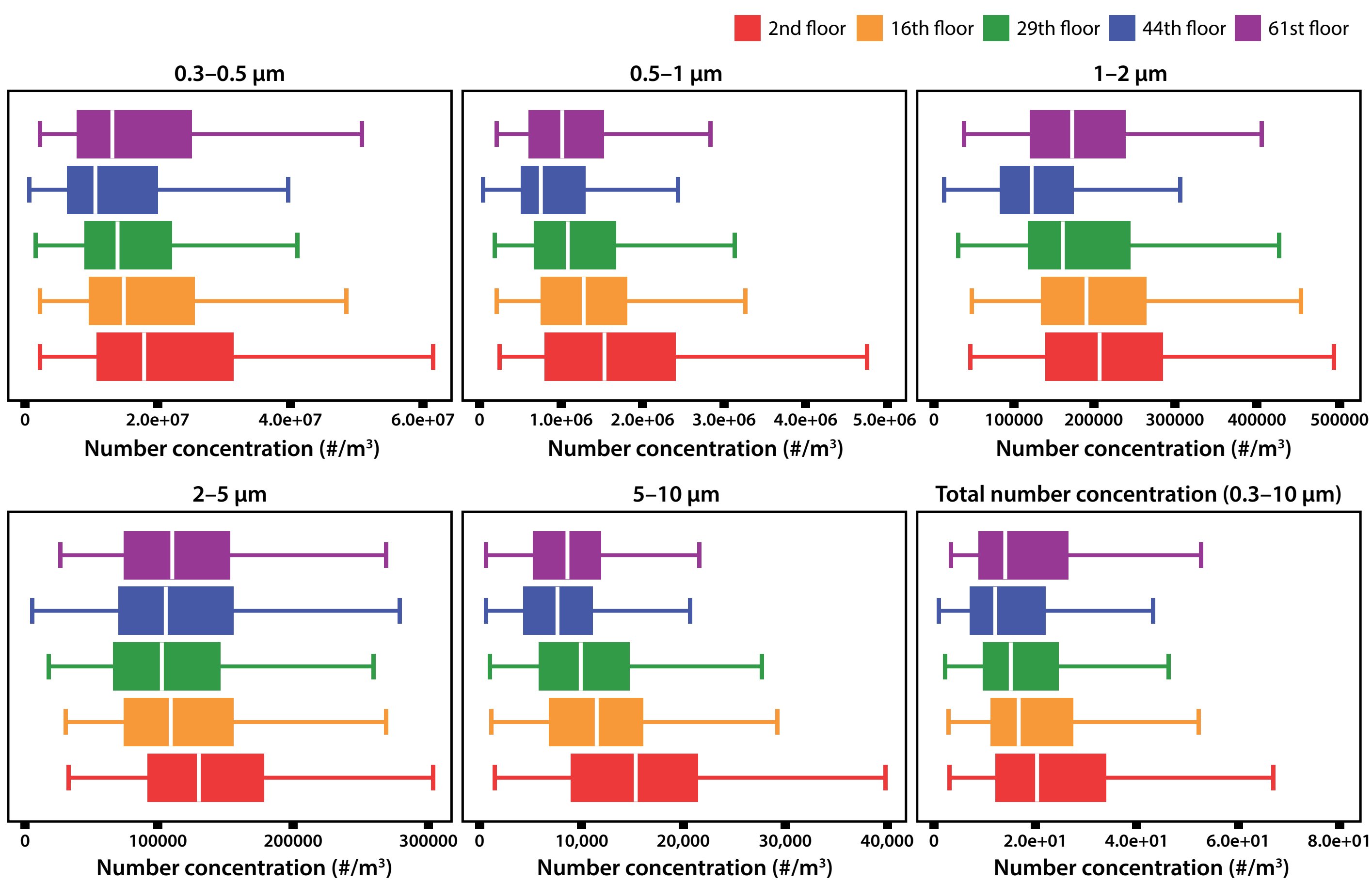

Figure 3. Box plots of size-resolved particle number concentration data measured on each of the five floors. Bins include: 0.3–0.5 µm, 0.5–1 µm, 1–2 µm, 2–5 µm, 5–10 µm, and total number concentrations (0.3–10 µm). Outliers are excluded for graphical clarity.

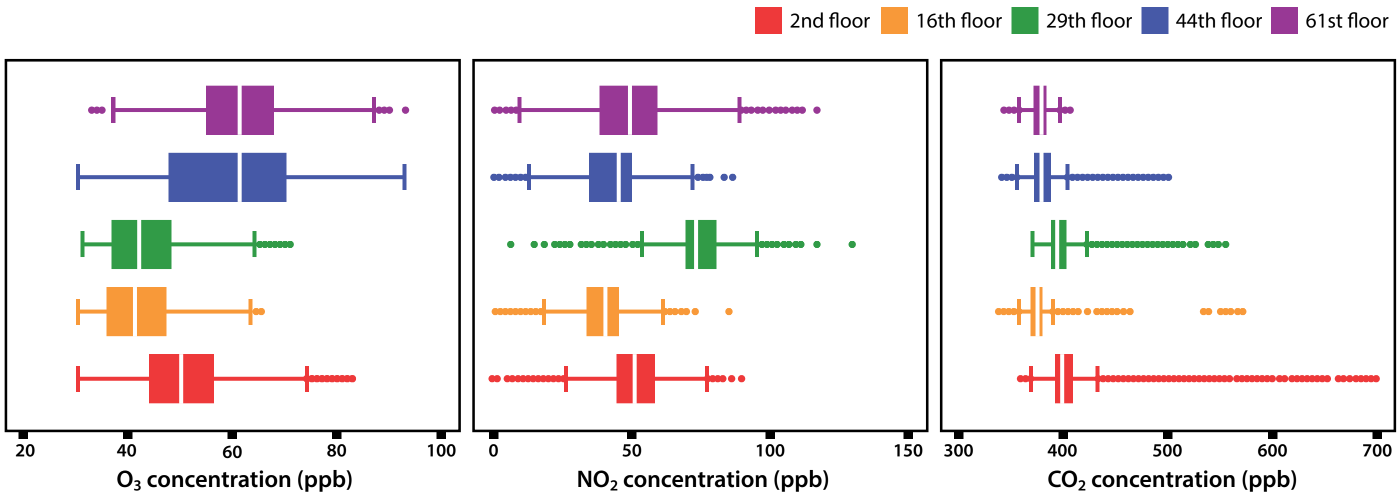

Figure 4. Box plots of ozone (O_3), nitrogen dioxide (NO_2), and carbon dioxide (CO_2) concentration data measured on each of the five floors.

Lake Michigan is to the east of the measurement site. There was minimal rainfall during the sampling period, with ~1.2 centimeters falling between 6:30 am and 11:00 p.m. on June 23 and another ~0.4 centimeters falling between 12:30 p.m. and midnight on June 28.

Spearman rank correlation coefficients were calculated using hourly averages of each measured parameter as the dependent variable and building height, hourly average wind speed, and hourly average wind direction as independent variables (see Table 2). The variable that was most strongly correlated with most of the measured pollutant concentrations was floor height, with the highest Spearman rank correlation coefficients for hourly average PM_1, $PM_{2.5}$, PM_{10}, O_3, and CO_2 concentrations. Spearman rank correlation coefficients were negative for all of these pollutants, suggesting a decreasing trend in concentration with building height, except O_3, which showed an increasing trend in concentration with building height. Moreover, each of these comparisons with building height was statistically significant ($p < 0.0001$), but relatively weak. The comparison between NO_2 concentrations and building height was not significant; however, wind direction was positively correlated with measured NO_2 concentrations, which suggests NO_2 concentrations were higher when the prevailing wind direction was from the southwest (supporting the hypothesized transport of vehicular NO_2 emissions). Building height was also significantly correlated with temperature and humidity ratio, but wind direction was more strongly correlated with both parameters. Wind speed showed the strongest association with temperature, but was weakest for humidity ratio.

Overall, these pilot-study data add valuable contributions to the existing limited numbers of experimental investigations and numerous modeling and wind tunnel investigations on pollutant dispersion and local environmental conditions in urban environments within the context of tall buildings. In general, the average values of most measured parameters tended to decrease with building height, albeit with some exceptions. The magnitude of measured differences among floors was statistically significant but typically small for most parameters (i.e., less than 10% for temperature, relative humidity, humidity ratio, and CO_2) but larger for others (i.e., up to a maximum decrease of ~32%, with averages consistently decreasing with floor height, for PM_1 and $PM_{2.5}$ concentrations). Variations in other parameters such as PM_{10}, O_3, and NO_2 concentrations were less consistent and varied in magnitude. Statistical analyses demonstrate that the majority of floor-by-floor comparisons shown here are robust to the inclusion of other local meteorological factors, and although prevailing environmental conditions in the area had an influence on some of the observed variations in the measured parameters, building height had the strongest correlations with all but one measured pollutant (NO_2) and was also strongly correlated with temperature and humidity ratio.

Conclusions

These pilot data suggest several implications for the design and operation of tall buildings. First, the dry bulb temperature lapse rate of a building can deviate from the linear Standard Lapse Rate assumption during some periods, which may need to be accounted for in HVAC design and energy simulation. Second, concentrations of some ambient pollutants or constituents, especially PM, and, to a lesser extent, CO_2, showed strong signatures of ground-level emissions that become dispersed or diluted at higher floors, which may need to be accounted for in designing and operating ventilation and particle filtration systems. Third, concentrations of O_3 were highest at the highest elevations of the building, which may also need to be considered in the design and operation of ventilation and gas-phase filtration systems. Given some of the relatively large magnitudes of differences in measured values observed herein, additional measurements should be made in other tall and supertall buildings, in other climate zones and geographic regions, to better understand how and why pollutant concentrations vary with elevation at scales that are relevant to occupants of these building types. ■

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	Spearman rank correlation coefficients (p-value)		
Parameter	**Floor Height**	**Wind Direction**	**Speed**
Temperature	-0.186 (<0.0001)	-0.202 (<0.0001)	0.248 (<0.0001)
Humidity Ratio	-0.120 (0.0006)	-0.191 (<0.0001)	0.060 (0.084)
PM_1	-0.195 (<0.0001)	-0.174 (<0.0001)	-0.065 (0.062)
$PM_{2.5}$	-0.195 (<0.0001)	-0.174 (<0.0001)	-0.065 (0.062)
PM_{10}	-0.275 (<0.0001)	-0.220 (<0.0001)	-0.082 (0.019)
CO_2	-0.358 (<0.0001)	0.086 (0.013)	-0.143 (<0.0001)
O_3	0.362 (<0.0001)	-0.144 (0.0001)	0.025 (0.490)
NO_2	-0.004 (0.914)	0.179 (<0.0001)	0.038 (0.325)

Table 2. Spearman rank correlation coefficients and significance testing between measured (or estimated) parameters and floor height, wind direction, and wind speed.

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References

AZIMI, P., ZHAO, H., FAZLI, T., ZHAO, D., FARAMARZI, A., LEUNG, L. & STEPHENS, B. 2018. "Pilot Study of the Vertical Variations in Outdoor Pollutant Concentrations And Environmental Conditions along the Height of A Tall Building." ***Building and Environment*** 138: 124–34. DOI: 10.1016/j.buildenv.2018.04.031.

CHAN, L. & KWOK, W. 2000. "Vertical Dispersion of Suspended Particulates in Urban Area of Hong Kong." ***Atmospheric Environment*** 34(26): 4403–12. DOI: 10.1016/S1352-2310(00)00181-3.

CHEN, C., ZHAO, B. & WESCHLER, C. J. 2012a. "Assessing the Influence of Indoor Exposure to 'Outdoor Ozone' on the Relationship between Ozone and Short-term Mortality in US. Communities." ***Environmental Health Perspectives*** 120(2): 235–40. DOI: 10.1289/ehp.1103970.

CHEN, C., ZHAO, B. & WESCHLER , C. J. 2012b. "Indoor Exposure to 'Outdoor PM_{10}.'" ***Epidemiology*** 23(6): 870–78. DOI: 10.1097/EDE.0b013e31826b800e.

COUNCIL ON TALL BUILDINGS AND URBAN HABITAT (CTBUH). 2019. "CTBUH Height Criteria." Accessed October 2018. http://www.ctbuh.org/TallBuildings/HeightStatistics/Criteria/tabid/446/language/en-US/Default.aspx.

ELLIS, P & TORCELLINI, P. 2005. "Simulating Tall Buildings Using EnergyPlus." In ***Proceedings of Ninth International Building Performance Simulation Association (IBPSA) Conference,*** Montréal, August 15–18, 2005: 279–86. Toronto: IBPSA**.**

KALAIARASAN, M., BALASUBRAMANIAN, R., CHEONG, K. W. D. & THAMA, K. W. 2009."Traffic-Generated Airborne Particles in Naturally Ventilated Multi-Storey Residential Buildings of Singapore: Vertical Distribution and Potential Health Risks." ***Building and Environment*** 44(7): 1493–500. DOI: 10.1016/j.buildenv.2008.07.012.

KLEPEIS, N. E., NELSON, W. C., OTT, W. R., ROBINSON, J. P., TSANG, A. M., SWITZER, P., BEHAR, J. V., HERN, S. C. & ENGELMANN, W. H. 2001. "The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants." ***Journal of Exposure Analysis and Environmental Epidemiology*** 11(3): 231–52. DOI: 10.1038/sj.jea.7500165.

LEUNG, L. & WEISMANTLE, P. 2008. "Sky-Sourced Sustainability: How Super Tall Buildings can Benefit from Height." In ***CTBUH 8th World Congress Proceedings Dubai,*** Dubai, March 3–5. 2008: Chicago: CTBUH.

LI, C., FU, J., SHENG, G., BI, X., HAO, Y., WANG, X. & MAI, B. 2005. "Vertical Distribution of PAHs in the Indoor and Outdoor PM2.5 In Guangzhou, China." ***Building and Environment*** 40(3): 329–41. DOI: 10.1016/j.buildenv.2004.05.015.

MENDELL, M. J., LEI-GOMEZ, Q., MIRER, A. G., SEPPÄNEN, O. & BRUNNER, G. 2008. "Risk Factors in Heating, Ventilating, and Air-Conditioning Systems for Occupant Symptoms in US Office Buildings: The US EPA Base Study." ***Indoor Air*** 18(4): 301–16. DOI: 10.1111/j.1600-0668.2008.00531.x.

MENG, Q. Y., TURPIN, B. J., KORN, L., WEISEL, C. P., MORANDI, M., COLOME, S., ZHANG, J. J., STOCK, T., SPEKTOR, D., WINER, A., ZHANG, L., LEE, J. H., GIOVANETTI, R., CUI, W., KWON, J., ALIMOKHTARI, S., SHENDELL, D., JONES, J., FARRAR, C. & MABERTI, S. 2005. "Influence of Ambient (Outdoor) Sources on Residential Indoor and Personal PM2.5 Concentrations: Analyses of RIOPA Data." ***Journal of Exposure Analysis and Environmental Epidemiology*** 15(1): 17–28. DOI: 10.1038/sj.jea.7500378.

PANCZAK, R., GALOBARDES, B., SPOERRI, A., ZWAHLEN, M. & EGGER, M. 2013. "High Life in The Sky? Mortality by Floor of Residence in Switzerland." ***European Journal of Epidemiology*** 28(6): 453–62. DOI: 10.1007/s10654-013-9809-8.

TONG, Z., CHEN, Y. & MALKAWI, A. 2017. "Estimating Natural Ventilation Potential for High-Rise Buildings Considering Boundary Layer Meteorology." ***Applied Energy*** 193: 276–86. DOI: 10.1016/j.apenergy.2017.02.041.

US ENVIRONMENTAL PROTECTION AGENCY (EPA). 2009. ***Integrated Science Assessment for Particulate Matter.*** Research Triangle Park: EPA.

US ENVIRONMENTAL PROTECTION AGENCY (EPA). 2012. "Probe and Monitoring Path Siting Criteria for Ambient Air Quality Monitoring." In ***Code of Federal Regulations*** 40 CFR Chapter 1, Part 58, Appendix E: 294–302. Research Triangle Park: EPA.

US ENVIRONMENTAL PROTECTION AGENCY (EPA). 2014. "Air Data: Air Quality Data Collected at Outdoor Monitors Across the US." Accessed January 13, 2014. http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm.

US ENVIRONMENTAL PROTECTION AGENCY (EPA). 2016. ***Integrated Science Assessment for Oxides of Nitrogen – Health Criteria.*** Research Triangle Park: EPA.

VILLENA, G., KLEFFMANN, J., KURTENBACH, R., WIESEN, P., LISSI, E., RUBIO, M. A., CROXATTO, G. & RAPPENGLÜCK, B. 2011. "Vertical Gradients of HONO, NOx and O_3 in Santiago de Chile." ***Atmospheric Environment*** 45(23): 3867–73. DOI: 10.1016/j.atmosenv.2011.01.073.

WEATHER UNDERGROUND. 2017. "PWS Data: West Loop KILCHICA403." https://www.wunderground.com/personal-weather-station/dashboard?ID=KILCHICA403.

WESCHLER, C. J. 2006. "Ozone's Impact on Public Health: Contributions from Indoor Exposures to Ozone and Products of Ozone-Initiated Chemistry." ***Environmental Health Perspectives*** 114(10): 1489–96. DOI: 10.1289/ehp.9256.

WU, C. D., MACNAUGHTON, P., MELLY, S., LANE, K., ADAMKIEWICZ, G., DURANT, J. L., BRUGGE, D. & SPENGLER, J. D. 2014. "Mapping the Vertical Distribution of Population and Particulate Air Pollution in A Near-Highway Urban Neighborhood: Implications for Exposure Assessment." ***Journal of Exposure Science and Environmental Epidemiology*** 24(3): 297–304. DOI: 10.1038/jes.2013.64.

ZHANG, J. & RAO, S. T. 1999. "The Role of Vertical Mixing in the Temporal Evolution of Ground-Level Ozone Concentrations." ***Journal of Applied Meteorology*** 38(12): 1674–91. DOI: 10.1175/1520-0450(1999)038<1674:TROVMI>2.0.CO;2.