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Pilot study of the vertical variations in outdoor pollutant concentrations and environmental conditions along the height of a tall building

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A B S T R A C T

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, we are aware of very few measurements of airborne pollutant concentrations that have been made specifically along the height of tall buildings. Therefore, we conducted a pilot study to measure the vertical variation in the concentrations of several outdoor pollutants and environmental parameters along the height of a ∼60-story (∼300 m) building in downtown Chicago, IL during a one-week period in the summer of 2017. Simultaneous measurements of concentrations of size-resolved particulate matter 0.3–10 μm (which were also used to estimate PM_1, $PM_{2.5}$, and PM_{10} mass concentrations), ozone (O_3), nitrogen dioxide (NO_2), carbon dioxide (CO_2), and carbon monoxide (CO), as well as temperature and relative humidity, were made using multiple sets of instrumentation installed in the outdoor air intakes of the mechanical systems upstream of any filtration or mixing processes on the 2nd, 16th, 29th, and 44th floors and in an open-air area on the 61st floor. The average PM_1 and $PM_{2.5}$ concentrations estimated on the top two floors were more than 30% lower than on the 2nd floor. Temperature, humidity ratio, and CO_2 concentrations decreased with height, O_3 concentrations increased with height, and NO_2 concentrations were less consistent. Most of the differences between floors were statistically significant. Floor height was more strongly correlated with PM_1, $PM_{2.5}$, PM_{10}, CO_2, and O_3 concentrations than with local wind speed and direction.

1. Introduction

Elevated outdoor concentrations of airborne pollutants such as particulate matter, ozone, and oxides of nitrogen have been consistently associated with increased risks of respiratory symptoms, mortality, and lung cancer [1–7]. Concentrations of many of these pollutants have increased in many urban environments globally in recent years [8–10]. Associations between outdoor pollutant concentrations and adverse health effects are typically made in large epidemiological studies using stationary ambient measurements with inlet heights of ∼2–∼15 m [11]. However, because outdoor pollutants can infiltrate and persist indoors where Americans spend the majority of their time [12], much of their exposure to pollutants of outdoor origin often occurs inside buildings [13–20]. Indoor exposures to outdoor pollutants are a function of several key factors including outdoor air ventilation rates, envelope pollutant penetration efficiency, HVAC filtration efficiency, indoor pollutant deposition rates, and, importantly, outdoor pollutant concentrations at the source of ventilation air [21]. While previous research has assessed many of these parameters in smaller residential and commercial buildings [22,23], very few measurements have ever been made in tall buildings where inlet heights for outdoor air can be hundreds of meters above ground level.

Most previous studies on vertical pollutant dispersion or the vertical distribution of other environmental parameters in urban street canyons have relied on computational fluid dynamics (CFD) simulations [24–26] or wind tunnel experiments [27–29]. There have been very few field measurements of the vertical dispersion of outdoor pollutants specifically along the height of tall buildings. As an example, one recent study of a mid-rise (i.e., ∼22 stories, or ∼55 m tall) building in Chile showed that outdoor ozone concentrations were found to increase with height [30]. Measured outdoor ozone concentrations were approximately 10–15% higher on the 21st story (53 m above ground level) than on the 3rd story (6 m above ground level). These measurements suggest that occupants of the higher floors in this building may be exposed to

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higher indoor concentrations of outdoor ozone, depending on detailed ventilation system characteristics such as ventilation rates and the location of the outdoor air intakes.

Other limited previous experimental research, while not necessarily sampling in and around tall buildings, has shown that outdoor pollutant concentrations can vary greatly with elevation within the range of height of many tall buildings [31]. Perhaps most relevant to tall (i.e., < 300 m) and super-tall (i.e., > 300 m) buildings [32], aircraft measurements have shown that the vertical variation in outdoor ozone concentrations may be even greater at higher elevations. For example, one study showed that the highest outdoor ozone concentrations during nighttime periods were observed above 200 m (note that 200 m roughly corresponds to ~55 stories with typical floor height) [33]. This variation was more scattered during mornings and afternoons, but still suggested an overall similar pattern. These data suggest that occupants on the highest floors of tall or super-tall buildings may be subjected to more than twice the outdoor ozone concentrations than someone in the bottom third floors of the same building, depending on a number of detailed HVAC system characteristics. Vertical variations in outdoor ozone concentrations tend to vary with the height of the atmospheric boundary layer [34], which can vary highly between rural and urban environments and can vary diurnally [35,36]. There is also strong experimental evidence from ambient monitoring that outdoor particulate matter concentrations often decrease with building height [37,38], potentially offering a protective effect at higher floors. However, very few measurements of the vertical variation in outdoor pollutant concentrations exist, particularly along the height of tall buildings in urban environments.

Despite the lack of measurements to date, a study in Switzerland recently 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 [39]. Similarly, a study of office buildings in the U.S. found significantly higher building-related symptoms reported by occupants working on the floors of buildings that had outdoor air intakes less than 60 m above ground level, which may have been due to greater levels of pollutants from vehicles at air intakes nearer the ground level [40]. The need to better understand pollutant exposures in tall buildings is growing, as there are now a total of over 1300 buildings taller than 200 m in the world, with 144 (11% of the total) being completed in 2017 alone [41]. To begin to fill this knowledge gap, here we report results from a pilot study in which we measured the vertical variation of several outdoor pollutants and environmental parameters along the height of a single tall building in downtown Chicago, IL, USA. The aim is to quantify the dispersion of ambient pollutant concentrations and environmental parameters measured along the height of the test building and to determine the importance of building height and local meteorological factors in influencing the observed variability in the resulting data.

2. Material and methods

A single tall building in Chicago, IL, USA, was recruited for measurements. The building, which will remain unnamed and whose ownership will not be identified, was approximately 60 stories (~300 m) tall. Time-resolved measurements were conducted over one weeklong period from June 22, 2017 to June 29, 2017 to monitor concentrations of size-resolved particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), and temperature and relative humidity along the height of the tall building. To best represent outdoor air coming into the building, 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 2nd, 16th, 29th, and 44th floors), as well as in an open-air area on the 61st floor located underneath a ~2 m high metal rack on which a cooling tower was located. The location of measurements within the outdoor air intakes was upstream of any filtration or mixing processes. Measurements were made within approximately 0.2 m downstream of a coarse metallic grate located on the exterior facade of the building through which outdoor air flowed, and approximately 3 m 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 2–3 m upstream of a downstream filter bank. A photo of the measurement location in one outdoor air intake is shown in the SI (Fig. S1).

2.1. Instrumentation

The following sections describe the instruments that were used to measure pollutant concentrations and environmental conditions in the five sampling locations along the vertical height of the test building.

2.1.1. Particulate matter (PM)

MetOne GT-526S optical particle counters (OPCs) were used to measure size-resolved optical particle concentrations for particles from 0.3 to 10+ µm in optical diameter in 6 size bins: 0.3–0.5 µm, 0.5–1 µm, 1–2 µm, 2–5 µm, 5–10 µm, and 10+ µm [42]. We primarily used estimates of PM mass concentrations rather than number concentrations for the analyses herein because of their greater, or at least better known, implications for human health. However, we also show the measured size-resolved particle number concentrations in the results section and in the SI.

To estimate integral PM mass concentrations, the mass concentration of particles in each size bin smaller than 10 µm was estimated by assuming spherical particles with diameter equal to the geometric mean diameter of each size bin and uniform density of 1.5 g/cm^3 for all particle sizes [43,44]. The mass concentration of PM_1, $PM_{2.5}$, and PM_{10} was then estimated by adding the mass of particles in the size bins associated with each fraction, as shown in Equations (1)–(3) [45–47]. The assumption for uniform particle density is taken from existing literature sources and may not be accurate for the Chicago area [48–50]. Further, this approach does not account for any mass below 0.3 µm, which will greatly underestimate total number concentrations and may also underestimate PM mass concentrations [51]. However, for the purposes of this study (i.e., to explore the pattern of pollutant concentrations measured along the height of the test building), only repeatable, not absolutely accurate, PM measurements are required on each floor.

$$C_{PM1} = \left(\frac{1}{6}\pi d_{0.3-0.5}^3 \rho N_{0.3-0.5} + \frac{1}{6}\pi d_{0.5-1.0}^3 \rho N_{0.5-1.0}\right) \times 10^{-6} \tag{1}$$

$$C_{PM2.5} = \left(\frac{1}{6}\pi d_{0.3-0.5}^3 \rho N_{0.3-0.5} + \frac{1}{6}\pi d_{0.5-1.0}^3 \rho N_{0.5-1.0} + \frac{1}{6}\pi d_{1.0-2.0}^3 \rho N_{1.0-2.0} + \frac{1}{6}\pi d_{2.0-2.5}^3 \rho N_{2.0-5.0} \times \frac{\log 2.5 - \log 2.0}{\log 5.0 - \log 2.0}\right) \times 10^{-6} \tag{2}$$

$$C_{PM10} = \left(\frac{1}{6}\pi d_{0.3-0.5}^3 \rho N_{0.3-0.5} + \frac{1}{6}\pi d_{0.5-1.0}^3 \rho N_{0.5-1.0} + \frac{1}{6}\pi d_{1.0-2.0}^3 \rho N_{1.0-2.0} + \frac{1}{6}\pi d_{2.0-5.0}^3 \rho N_{2.0-5.0} + \frac{1}{6}\pi d_{5.0-10}^3 \rho N_{5.0-10}\right) \times 10^{-6} \tag{3}$$

where C_{PM1}, $C_{PM2.5}$, and C_{PM10} are the mass concentrations of PM_1, $PM_{2.5}$, PM_{10}, respectively (µg/m^3); $d_{i\text{-}j}$ is the geometric mean of particle diameter sizes from i to j (µm); ρ is the assumed particle density (1.5 g/cm^3); and N_i is the particle number concentration measured in size range i (#/m^3). To estimate $PM_{2.5}$ mass concentrations, we used a log-basis differential method to estimate the mass concentration in the 2–2.5 µm size range based on measurements in the 2–5 µm size bin. The number concentration in a virtual size bin of 2–2.5 µm was estimated by multiplying the number concentration of the default 2–5 µm size bin by the ratio of the logarithmic difference of the virtual 2–2.5 µm and actual 2–5 µm size bins (i.e., (log2.5 − log2)/(log5 − log2)).