Investigating How Occupancy and Ventilation Mode Influence the Dynamics of Indoor Air Pollutants in an Office Environment

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ABSTRACT

Indoor air quality (IAQ) in office environments is important for the well-being of office workers. Poor IAQ can adversely affect human health and reduce occupant cognitive function and productivity. Indoor air includes a complex mixture of gases, such as volatile organic compounds (VOCs), O_3, and CO_2, along with airborne particulate matter (aerosols). VOCs can be released from exhaled breath, personal care products, building materials, and furnishings. O_3 is a highly reactive gas that plays an important role in driving the oxidative capacity of indoor environments. Aerosols can be emitted indoors or delivered from outdoors via the HVAC system. Understanding how people and the operational mode of HVAC systems affect IAQ is essential to determine appropriate ventilation rates for office buildings.

An intensive four-week field measurement campaign was conducted during winter 2019 in an occupied office and its HVAC system to investigate how occupancy and ventilation mode shape the composition and chemistry of indoor air. The office is part of a living laboratory facility, which are four reconfigurable, side-by-side large open-plan office spaces. An integrated building automation system is used for real-time monitoring and precise control of the HVAC system. The fraction of outdoor air varied from 0 to 100% and occupancy was tracked via chair-embedded thermocouples. State-of-the-art analytical and aerosol instrumentation was used to characterize the composition of indoor and outdoor air in real time, including VOCs, O_3, CO_2, and aerosols from 1 nm to 10 μm. Time-resolved concentrations of VOCs were monitored via proton transfer reaction time-of-flight mass spectrometry (PTR-TOF-MS). A multi-point sampling system was built to sample VOCs, O_3, and CO_2 at eight locations throughout the air handling unit. Size distributions of aerosols were also sampled upstream and downstream the HVAC filter bank to explore the in-situ efficiency of the filters.

Preliminary results suggest that occupancy and the fractional amount of outdoor air play a significant role in influencing the concentrations of VOCs, O_3, CO_2, and aerosols. Each species exhibited spatiotemporal variations in concentrations throughout the HVAC system. Human-associated emissions (exhaled breath, personal care products) were found to be the dominant source for numerous VOCs in the office. O_3 oxidation of monoterpenes initiated the formation of nano-sized particles, while O_3 oxidation of human skin oils produced VOCs such as 6-MHO and 4-OPA. In general, increasing the amount of outdoor air reduced concentrations of indoor-generated VOCs and CO_2, while increasing levels of O_3 and aerosols.

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INTRODUCTION

Indoor air quality is important for human health and well-being as Americans spend 90% of their time indoors (Klepeis et al., 2001). Poor indoor air quality in office environments can reduce cognitive function and productivity of office workers (Allen et al., 2016). Indoor air pollutants, including volatile organic compounds (VOCs), ozone (O_3), and particulate matter (aerosols), can adversely impact human health. Indoor concentrations of many VOCs are typically higher than those outdoors (Brown, 2002). Indoor VOCs can be emitted from building materials, furnishings, people (e.g. exhaled breath, skin secretions) (Fenske & Paulson, 1999), personal care products (Coggon et al., 2018), and cleaning products (Nazaroff & Weschler, 2004). The primary source of O_3 in the indoor environment is the transport of outdoor O_3 indoors via ventilation and infiltration. O_3 is a highly reactive gas and an important oxidant in the indoor environment. O_3 can oxidize certain VOCs and react with human skin oils on the surfaces of skin, clothing, and furnishings to produce an array of reaction products (Wisthaler & Weschler, 2010). In an office setting, indoor aerosols can be emitted directly due to human activities (e.g. dust resuspension), via O_3 reactions with VOCs, from appliances (laser and 3D printers), and transported from outdoors through ventilation and infiltration.

VOCs, O_3, and aerosols are important participants in indoor chemistry. The predominant sources of these pollutants in office air are occupancy and ventilation. Mechanical ventilation delivers outdoor air into indoor environments and dilutes indoor pollutants when outdoor concentrations are low (e.g. for CO_2). Conversely, ventilation can transport outdoor pollutants indoors. Occupancy plays a significant role in indoor chemistry. Studies have shown that people can be one of the primary sources of indoor VOCs and that occupancy plays an important role in indoor ozone chemistry (Weschler, 2016). However, indoor chemistry has been seldom investigated from the perspective of building science. It is important to understand how both occupancy and HVAC system operational modes affect indoor air quality. Doing so can inform selection of appropriate ventilation strategies for varying levels of occupancy and outdoor air pollution.

METHODS

Site Description

To investigate how occupancy and ventilation mode impact the composition and chemistry of indoor air, an intensive one-month field campaign was conducted from 02/14/2019 to 03/18/2019 in an occupied office and its HVAC system (Figure 1). The office is part of a living laboratory facility, which are four reconfigurable, side-by side open-plan office spaces, each with a maximum occupancy of 20 and a volume of 477 m^3. The HVAC system is equipped with a MERV-8 pre-filter and MERV-14 filter. A building automation system, along with hundreds of sensors, was applied to achieve real-time monitoring and precise control of the HVAC system. The sensors monitor dry-bulb temperature, relative humidity, volumetric airflow rates, damper positions, and fan speeds at different locations throughout the HVAC system. Such data provides a detailed airflow profile for the entire system. Damper positions and supply and return fan speeds were changed throughout the campaign to adjust the supply airflow rate and the ratio of recirculation to total supply air (recirculation ratio = recirculation airflow rate/total supply airflow rate). Occupancy was monitored via chair-embedded thermocouples.

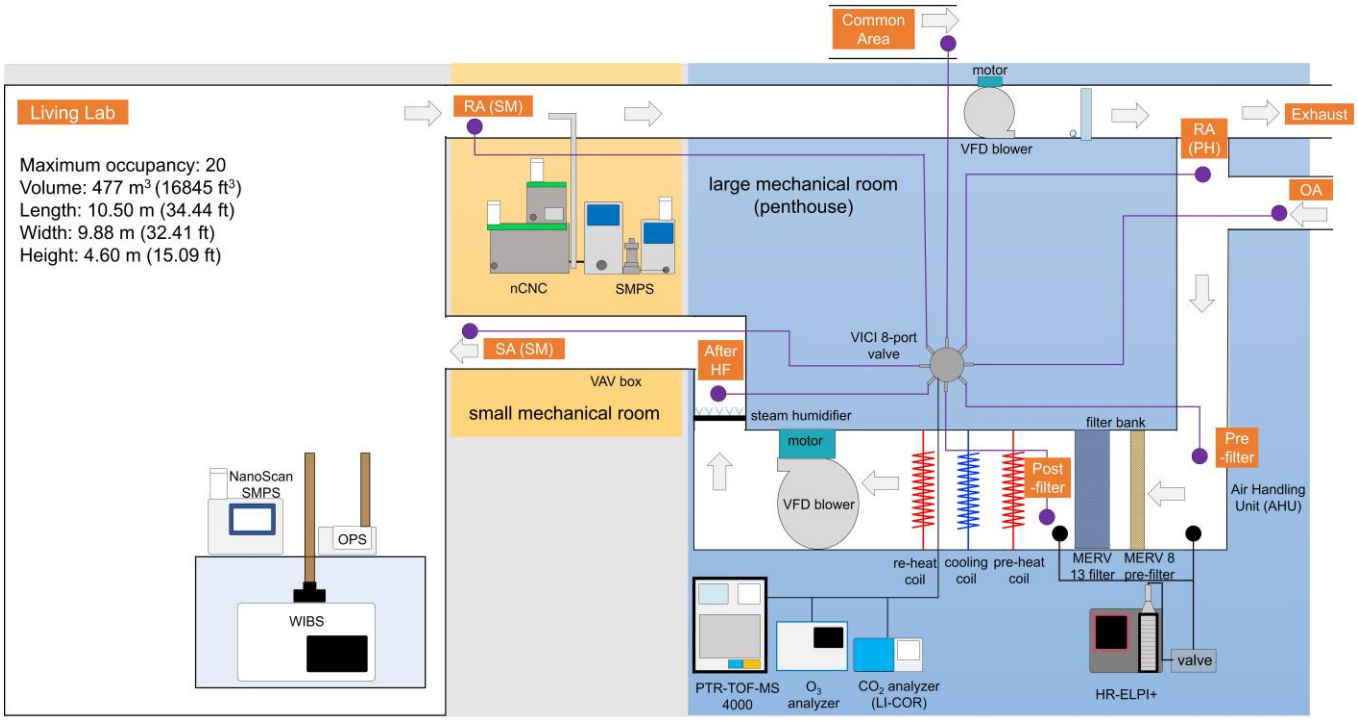

Figure 1 Schematic of experimental setup in the living lab office and associated HVAC system.

Measurements and Instrumentation

The composition of indoor and outdoor air, including VOCs, O_3, CO_2, and aerosols from 1 nm to 20 μm were characterized in real time by the aerosol and trace gas instrumentation listed in Tables 1 and 2. Proton transfer reaction time-of-flight mass spectrometry (PTR-TOF-MS) can provide high time-resolution characterization of various VOCs. VOCs related to indoor activities are listed in Table 3, along with their potential indoor sources. As shown in Figure 1, an automated multi-point sampling system was built with an 8-port valve to sample VOCs, O_3, and CO_2 at eight different locations through the HVAC system, including: outdoor air (*OA*), pre-filter, post-filter, supply air post-humidifier (*After HF*), supply air at the variable air volume (VAV) box (*SA (SM)*), return air immediately after the register (*RA (SM)*), return air immediately before mixing with outdoor air (*RA (PH)*), and the common area exterior to the office. The sampling system was used to determine how the office occupants and HVAC system components, including filters, heating exchangers, and blowers, would affect the levels of these compounds. The HR-ELPI+ was used to sample aerosol size distributions upstream and downstream of the HVAC filter bank in a 4-minute cycle via a three-way valve system: 2 minutes upstream and 2 minutes downstream. The in-situ time- and size-resolved removal efficiency of the HVAC filter bank was evaluated by comparing the difference in the aerosol size distributions upstream and downstream the filter.

Table 1 List of aerosol instrumentation

Instrument	Size Range Measured
nano Condensation Nucleus Counter (nCNC)	1-3 nm
Scanning Mobility Particle Sizer (SMPS)	3-60 nm
NanoScan Scanning Mobility Particle Sizer (NanoScan SMPS)	10-420 nm
Optical Particle Sizer (OPS)	300-10,000 nm
Wideband Integrated Bioaerosol Sensor (WIBS)	500-20,000 nm
High Resolution Electrical Low Pressure Impactor (HR-ELPI+)	6-10,000 nm

Table 2 List of trace gas instrumentation

Instrument	Species Measured
Proton transfer reaction time-of-flight mass spectrometry (PTR-TOF-MS)	VOCs
Photometric ozone analyzer	O_3
CO_2 analyzer	CO_2

Table 3 Selected list of VOCs measured by PTR-TOF-MS

Compound	Source
Methanol	Human metabolic activity
Acetone	
Acetic acid	
Isoprene	
4-oxopentanal (4-OPA)	O_3 oxidation products of human skin oil
6-methyl-5-hepten-2-one (6-MHO)	
Decanal	
Benzene	Glues, adhesives, cleaning products
Monoterpenes	Personal care products, cleaning products, citrus fruits
decamethylcyclopentasiloxane (D5)	Personal care products

Experimental Protocol

To explore the spatial and temporal trends in concentrations of VOCs, O_3, CO_2, and aerosols, as well as the influence of occupants on indoor chemistry, the valve system was scheduled to sample for two days in a spatial sequence and one day in temporal sequence. During the spatial sequence, the valve ran a 30-minute cycle which sampled at all eight locations in turns. The spatial sequence helps to understand how the components of the HVAC systems affect the concentration of these species. During the temporal sequence, the valve was only switched among three locations: supply air, return air, and outdoor air, in order to better monitor the temporal trends.

Manipulations, such as peeling mandarins, applying perfume, brewing coffee, and cleaning the room, were made every several days to explore how specific activities would impact the levels of various pollutants and the nucleation of nano-sized particles. During the other days, the impact of general occupancy levels and typical occupant activities on indoor air quality was studied. In addition, different recirculation airflow ratios, ranging from 0 to 100% (outdoor air ratio (OA %) ranging from 100% to 0), were applied throughout the campaign to investigate how ventilation modes shape indoor air pollutant dynamics and the in-situ performance of the HVAC filter bank.

RESULTS

Spatiotemporal Distribution of VOCs in Office HVAC System

Preliminary results demonstrate that humans are a prominent source of VOCs in the occupied office and concentrations of human-associated VOCs exhibit diurnal variations driven by occupancy. Figure 2 shows an example diurnal trend in concentrations of four VOCs as measured with the PTR-TOF-MS at 8 locations in the HVAC system while running with 50% recirculation air (isoprene, D5, monoterpenes and 6-MHO). VOCs related to human metabolic activity (e.g. methanol: ~25 ppb; acetone: ~10 ppb, isoprene: ~1.5-2 ppb) typically reached peak concentrations in mid-afternoon when occupancy reached its maximum, following a similar trend as CO_2. VOCs related to personal care products present daily maxima in the morning (e.g. D5: ~0.2 to 2 ppb) and then decay throughout the day. Concentrations of several VOCs, including formaldehyde and benzene, were nearly constant throughout the day, indicating that the main sources of these compounds were building materials and furnishings. 6-MHO, a reaction product of O_3 oxidation of human skin oil, reached peak concentrations of ~0.3-0.5 ppb in mid-afternoon, also following the trend of occupancy level indicated by CO_2 concentrations.

The ratio of indoor to outdoor concentrations (I/O ratios) exhibited variations among the many VOCs detected, ranging from ~1 for benzene to > 10 for isoprene and > 20 for 6-MHO and decanal (Figure 3). The high I/O ratios demonstrate the importance of indoor VOC sources in contributing to office air chemistry. In general, outdoor air was not a significant source of VOCs in the office and exhibited the lowest concentrations among the 8 sampling locations in the HVAC system. The I/O ratio peaked at mid-afternoon, further demonstrating the importance of human-associated emissions in contributing to the VOC mass in the office. Spatial variations in VOC concentrations throughout the HVAC system were observed for all VOCs. Concentrations of some VOCs were found to decrease by ~5 to 20% across the HVAC filter bank, suggesting VOC removal via partitioning to deposited particles captured by the filter media. Such a process may represent a meaningful loss mechanism for certain compounds.

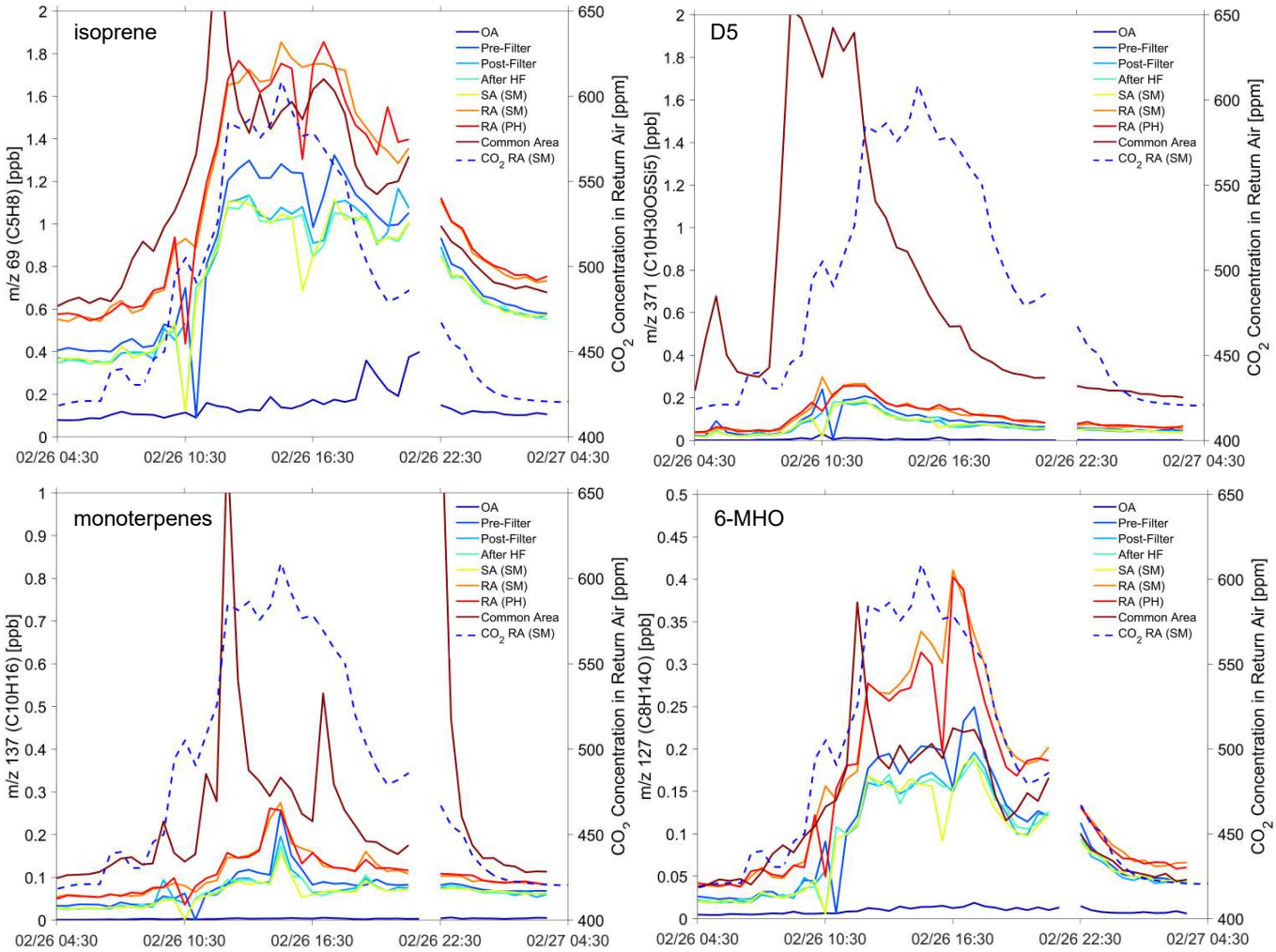

Figure 2 Diurnal trend in concentrations of selected VOCs at 8 locations in HVAC system at 50% recirculation air ratio.

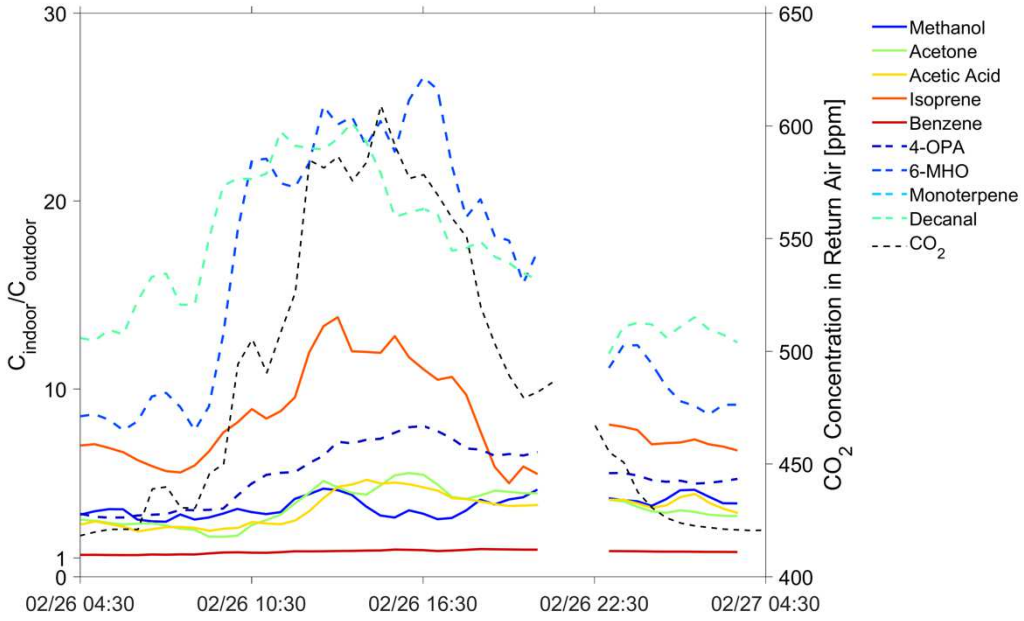

Figure 3 Diurnal trend in the ratio of indoor to outdoor concentrations of selected VOCs at 50% recirculation air ratio.

Spatiotemporal Distribution of Ozone in Office HVAC System

Prominent spatial variations in O_3 concentrations were observed throughout the HVAC system. Figure 4 illustrates the spatiotemporal distribution of O_3 under different ventilation modes. The spatial distribution of O_3 at 8 different locations through the HVAC system reveals how different components of the HVAC system can affect O_3 concentrations. When the recirculation ratio was 50% and 100%, O_3 concentrations dropped significantly from outdoor air to mixed air (pre-filter) due to the dilution of the outdoor air. O_3 deposition to the surfaces of the HVAC filter bank, heat exchangers, and humidifier was not significant in all three scenarios. However, the O_3 level dropped slightly from the return air immediately after the register to the return air immediately before mixing with outdoor air, demonstrating that there was O_3 deposition to the ventilation ducts. A significant reduction in O_3 concentrations was observed between the supply air and return air, demonstrating that indoor surfaces are an important O_3 sink. O_3 concentrations dropped by ~10 ppb from supply to return when recirculation was 50% and 100%. O_3 reduction in the office was not sensitive to the occupancy level as it was relatively constant throughout the day. This indicates that the primary sink of O_3 in the office was O_3 deposition to building surfaces and organic films on those surfaces.

The recirculation ratio is closely related to the I/O ratio for O_3 as it determines how much outdoor O_3 can be delivered to the indoor environment. As the recirculation ratio increases from 0% to 50% to 100%, the average I/O ratios decreased from 0.70 to 0.46 to 0.15, respectively. When the recirculation ratio was higher, the indoor O_3 concentration was less influenced by outdoor O_3 levels and the drop of O_3 across the room was also lower.

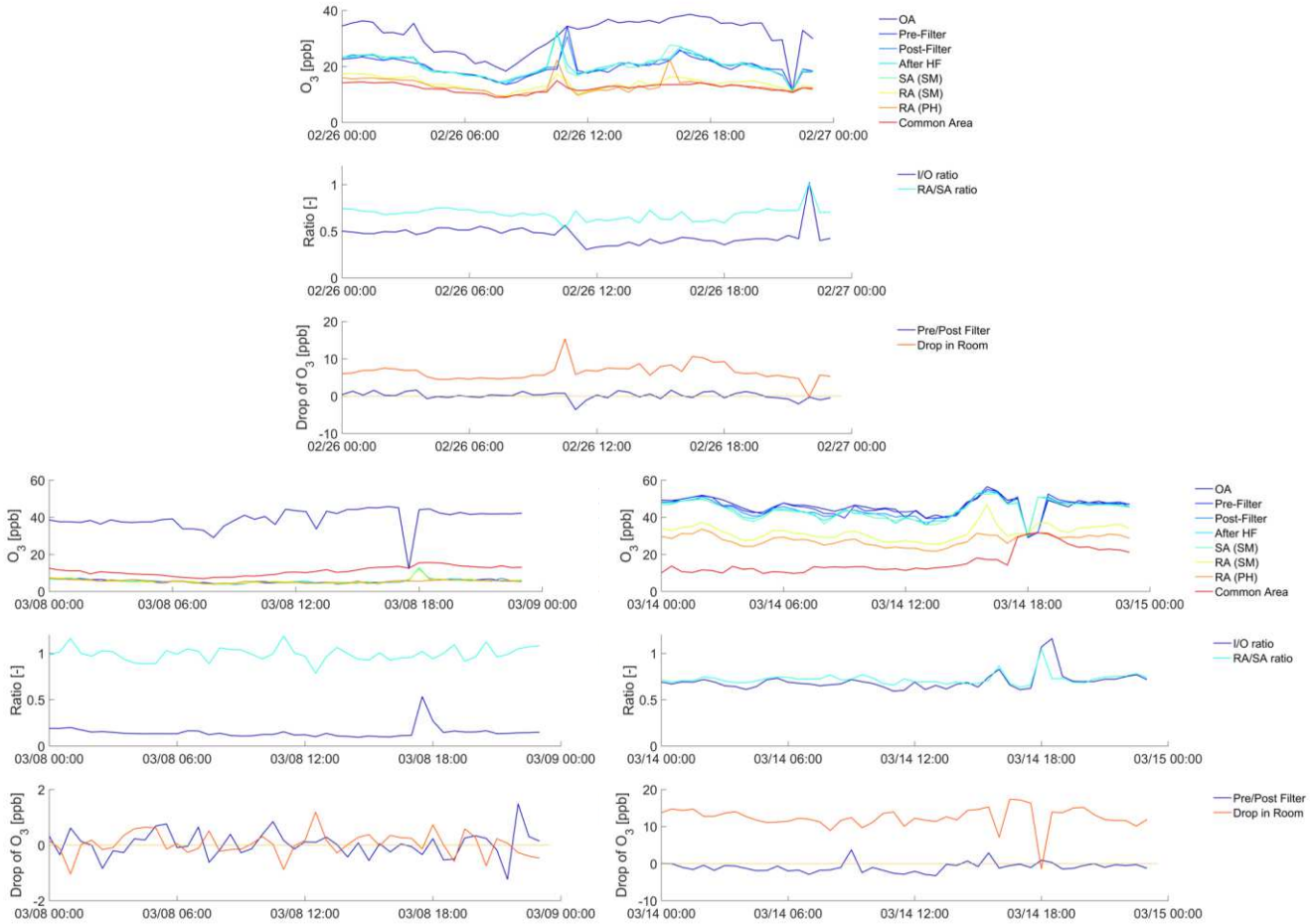

Figure 4 Spatiotemporal distribution of O_3 concentrations through the HVAC system at: 50% recirculation air ratio (OA % = 50%) (top), 100% recirculation air ratio (OA % = 0) (bottom-left), and 0% recirculation air ratio (OA% =100%) (bottom-right).

Ultrafine Particle Number Concentrations in Office

As shown in Figure 5, the number concentration of ultrafine particles (UFPs, particles with diameter smaller than 100 nm) in the office was relatively low as compared to other indoor environments (e.g. residences), due to particle removal by the HVAC filter bank and no indoor combustion or cooking sources. The UFP concentration fluctuated from 400 cm^{-3} to over 2,000 cm^{-3} throughout the day. Previous research in typical residences shows that average UFP concentrations were often above 5,000 cm^{-3}, sometimes exceeding 20,000 cm^{-3} (Bhangar et al., 2011; Bekö et al., 2013). The UFP concentration was often higher during the day compared to the evening. At around 08:00, the rise of UFP concentrations could be due to the transport of outdoor particles (e.g. from traffic) indoors via ventilation. The UFP concentration fluctuated during the remainder of the day.

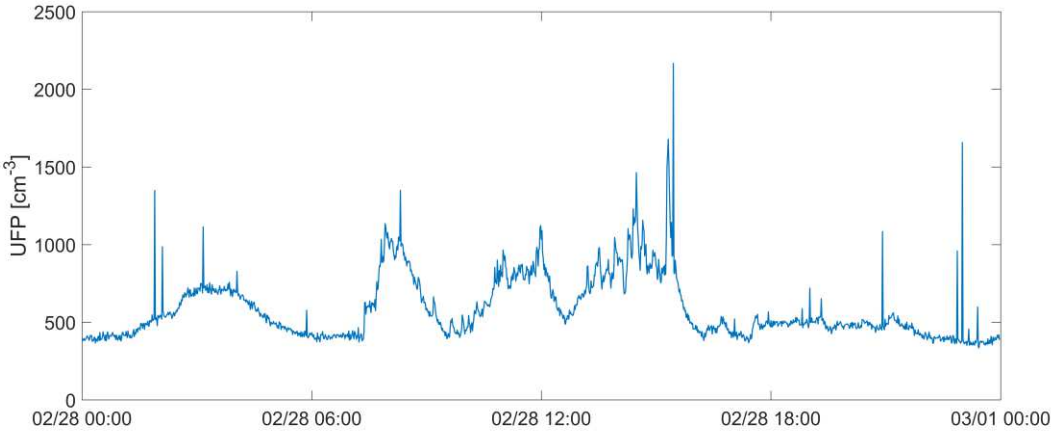

Figure 5 Diurnal trend in ultrafine particle number concentrations at 50% recirculation ratio.

In Situ Time- and Size-Resolved Particle Removal Efficiency of Office HVAC Filter Bank

The in-situ time- and size-resolved particle removal efficiency of the HVAC filter bank is shown in Figure 6(a). The particle removal efficiency of the HVAC filter bank was the lowest in the particle size range of 100-1000 nm. The HVAC filter bank more efficiently removes smaller particles (< 25 nm) due to diffusion, and larger particles (> 1,000 nm) due to inertial impaction and interception. It can be observed that when the pre-filter particle number concentration was higher, more particles can be removed. When the particle number concentration was higher, there were often a larger portion of particles below 100 nm. Therefore, a greater fraction of particles could be captured by the filter and the size-integrated filtration efficiency can be higher. As for the total number of particles from 6 nm to 10,000 nm, the filter bank had an averaged filtration efficiency of 52% (Figure 6(b)).

Figure 6(c) shows the ultrafine particle removal efficiency of the HVAC filter bank. Overall, the filtration efficiency of UFPs was slightly higher than that of total particles, with an average value at 59%., due to more efficient removal of particles below 100 nm. Azimi et al. (2014) reported a mean value of 100% outdoor air UFP removal efficiency at 73% for a MERV 14 filter, which is higher than the results of our study. One possible explanation is that their study evaluated the performance of filter with 100% outdoor air, the particle concentration of which can be higher than in our study, with a 50% recirculation air ratio. On the other hand, the MERV 14 filter was installed for a longer time in this study and the filter was already loaded with some particles, which can also affect the filtration efficiency.

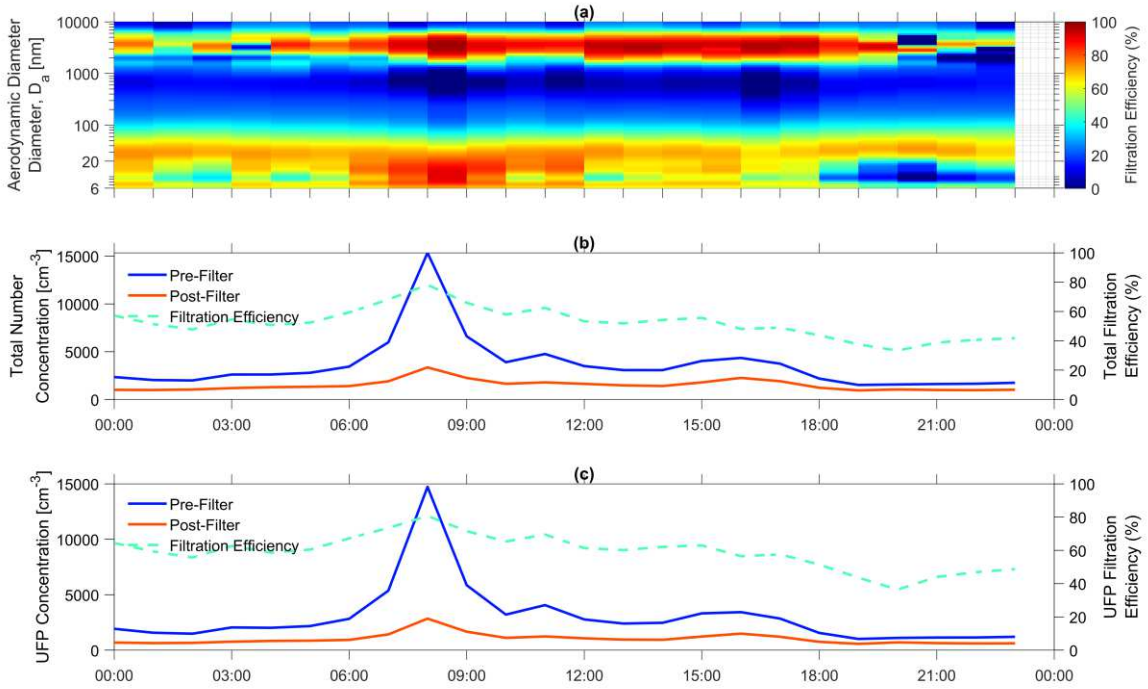

Figure 6 In-situ particle removal efficiency of the HVAC filter bank at 50% recirculation ratio. (a) size-resolved particle removal efficiency; (b) total particle removal efficiency; (c) ultrafine particle removal efficiency.

CONCLUSIONS

This one-month measurement campaign demonstrated that occupancy and ventilation can significantly influence indoor concentrations of VOCs, O_3, CO_2, and aerosols in an office. Our preliminary analysis shows that occupancy is strongly related to the production of numerous VOCs, including isoprene, acetone, D5, and 6-MHO, among others. Human-associated emissions, such as exhaled breath and personal care products, were found to be the primary source of these VOCs in the office. Oxidation of these VOCs is an important step towards new particle formation and O_3 is a major oxidant of VOCs. O_3 concentrations exhibited spatiotemporal variations throughout the HVAC system, especially among outdoor air, return air, mixed air, and supply air. O_3 deposition on indoor surfaces contributed most to the loss of O_3. Occupancy levels did not significantly affect O_3 concentrations in this office environment, however, O_3 oxidation of human skin oils produced VOCs, such as 6-MHO and 4-OPA. Thus, occupancy is still important for indoor O_3 chemistry. The ventilation mode is also critical for indoor O_3 levels. When the recirculation ratio was high, indoor O_3 was less influenced by outdoor air and the O_3 loss in the office was lower. Ultrafine particle concentrations in the office were relatively low as compared with other indoor environments, due to the filtration by a filter bank with the UFP removal efficiency of 59% and the absence of combustion source, but the potential impact of ozonolysis of VOCs should not be overlooked. Overall, preliminary results of this study showed how occupancy and ventilation could affect indoor pollutants levels and indoor chemistry. Additional analysis will focus on characterizing and quantifying the production and loss mechanisms of these indoor pollutants to better evaluate the contribution of ventilation and occupancy to indoor chemistry, along with new particle formation events.

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