Field Code Changed
Field Code Changed
Field Code Changed

Supporting Information

Ozone, electrostatic precipitators, and particle number concentrations: correlations observed in a real office during working hours

Jianbang Xiang [1, 2], Charles J. Weschler [1, 2, 3], Jinhan Mo [1, 2, *], Drew Day [4], Junfeng (Jim) Zhang [4, 5], Yinping Zhang [1, 2]

[1] Department of Building Science, Tsinghua University, Beijing 100084, China

[2] Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Beijing 100084, China

[3] Environmental and Occupational Health Sciences Institute, Rutgers University, Piscataway, NJ 08854, United States

[4] Global Health Institute and the Nicholas School of Environment, Duke University, Durham, NC 27708, United States

[5] Duke Kunshan University, Kunshan, Jiangsu 215316, China

Corresponding Author

[*]E-mail: mojinhan@tsinghua.edu.cn; Tel: 86-10-62779994; Fax: 86-10-62773461; Address: Department of Building Science, Tsinghua University, Beijing 100084, China.

This supporting information (9 pages) includes 7 tables and 4 figures.

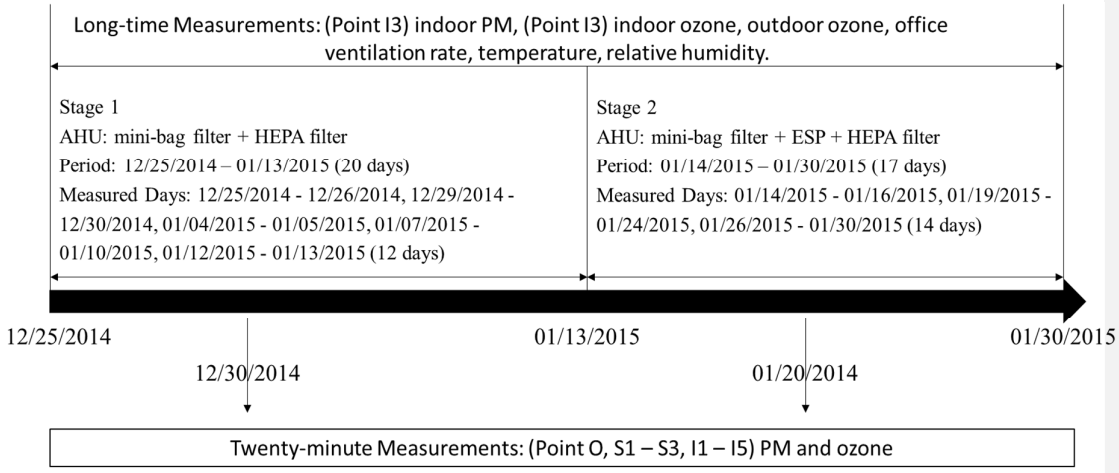

Figure S1 Timeline for the investigation

Calibration of ozone and PM monitors

The monitor (2B Tech., Model 205) has been approved as a US EPA Federal Equivalent Method.[1] The ozone monitor was calibrated using an ozone calibration source (2B Tech., Model 306). We also made zero-point calibrations, using an ozone adsorption tube, every day before the measurements. Additionally, we did three single-point comparisons between outdoor levels at the office location and corresponding levels at the nearby government monitoring station (Figure S2). As shown in the figure, the agreement between the values measured at the office location and those measured at the closest ambient monitoring station was reasonable.

The PM monitor (TSI CPC 3007) was calibrated at the factory before it was delivered. We did zero-point calibration with a dedicated "HEPA zero filter" prior to these studies.

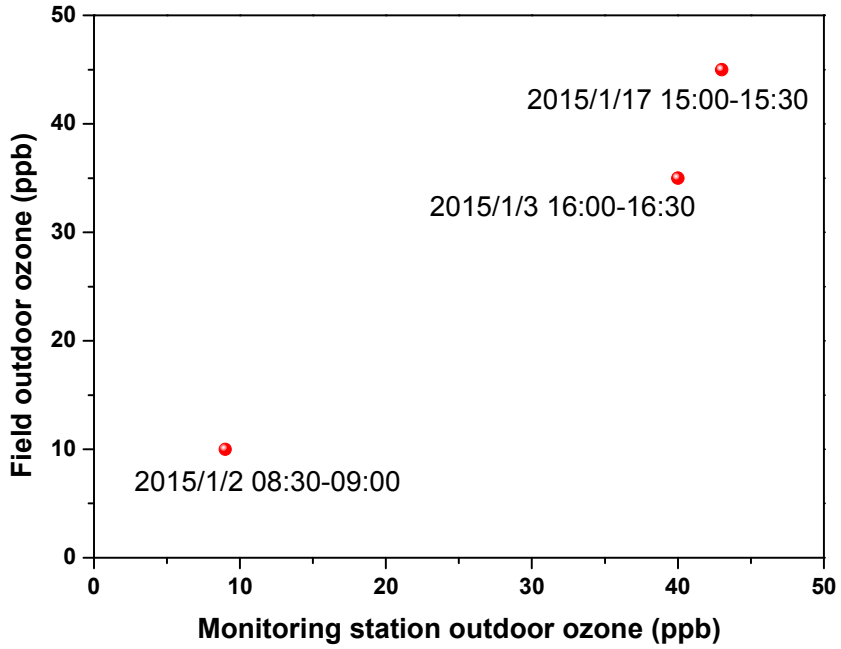

Figure S2. Comparison between field outdoor ozone and monitoring station outdoor ozone

Table S1 PM and ozone concentrations at different measuring points on typical days: (a) Stage 1 – no ESP (b) Stage 2 – with an ESP (S1-3 represent different locations in supply air, I1-5 represent different locations in indoor air and the intake for the supply air (O), which was regarded as outdoor air.) Office was occupied during measurements.

Measuring point	Test 1 (10:00-10:20, Dec. 30, 2014, without ESP		Test 2 (15:30-15:50, Jan. 20, 2015, with ESP	
	Ozone (ppb)	PM (particles/cm^3)	Ozone (ppb)	PM (particles/cm^3)
O	20.0	10000	15.0	12000
S1	15.8	3	25.5	2
S2	15.5	20	25.3	30
S3	15.1	100	25.0	115
I1	3.8	33000	5.2	63000
I2	3.5	32000	5.0	62000
I3	4.1	30000	5.6	60000
I4	3.1	35000	5.1	65000
I5	2.9	34000	5.1	64000

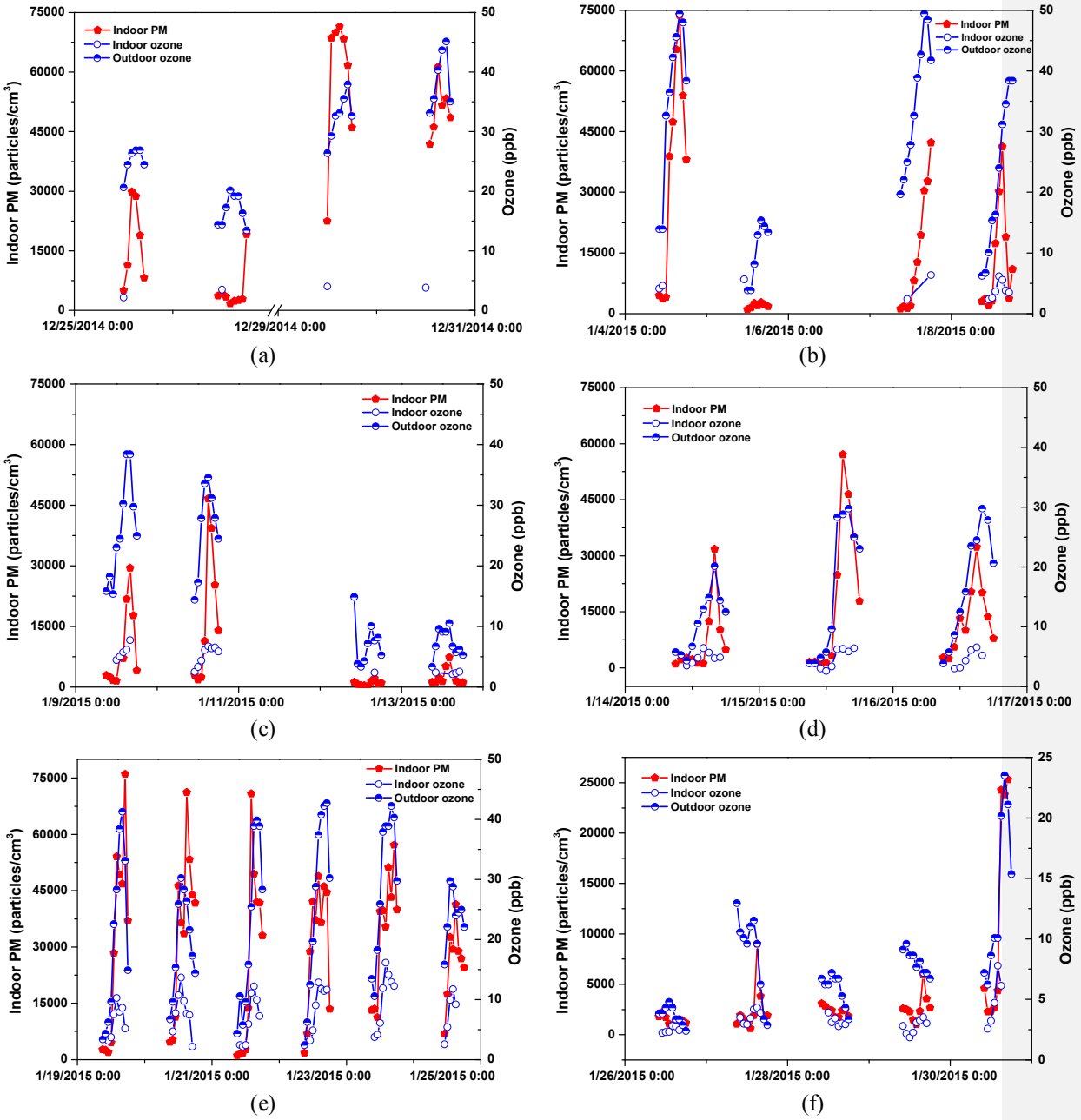

Figure S3 Hourly temporal variation of indoor PM, and indoor and outdoor ozone concentrations for all measuring days: (a)-(c) Stage 1 – no ESP; (d)-(f) Stage 2 – with an ESP

Table S2 Correlation coefficient ρ (Spearman) among indoor PM, outdoor and indoor ozone

Stage 1	outdoor ozone	indoor ozone	indoor PM
outdoor ozone	1.00	0.70	0.78
indoor ozone		1.00	0.70
indoor PM			1.00
Stage 2			
outdoor ozone	1.00	0.84	0.84
indoor ozone		1.00	0.77
indoor PM			1.00

$p < 0.0005$

Table S3 Results for key parameters

Parameter	Calculation and/or result
γ_{filt}	$= \left[1 - \left(\frac{15.8}{20}\right)\right] \approx 0.2$
V_{room}	= 960 m^3
A_{room}	= 1040 m^2
$A_{room\_effective}$	= 1920 m^2
Q_{supply}	= (960 ± 19) m^3/h
λ_v	= (1 ± 0.02) h^{-1}
k_d	= (2.8 ± 0.2) h^{-1}
v_d (ozone's deposition velocity to room surfaces)	= $k_d \times V_{room} / A_{room\_effective}$ = 0.04 ± 0.01 cm s^{-1}
k_h	= (0.6 ± 0.5) h^{-1}
v_h (ozone's deposition velocity to human surfaces)	= $k_h \times V_{room} / A_{human} = k_h \times V_{room} / (1.7\times80)$= 0.12 ± 0.10 cm s^{-1}
R (conversion factor)	= 500 ppb mg^{-1} m^3
ε (12:00-14:00, derived from ozone mass balance model)	= (24.7 ± 18.3) mg h^{-1}
ε (working hours, derived from ozone mass balance model)	= (23.1 ± 9.8) mg h^{-1}
ε (supply air ozone model)	= $(C_{supply}(t)-(1-\gamma_{filt})\times C_{out}(t))\times Q_{supply}/(R\times(1-\gamma_{filt}/2))$ = (25.5-15×(1-0.2))×960/(500 ×(1-0.2/2)) = 28.8 mg h^{-1}
α (supply air ozone increase due to ESP operation)	= $\varepsilon\times(1-\gamma_{filt}/2)\times R/Q_{supply}$ = 28.8× (1-0.2/2)×500/960 ppb = 13.5 ppb
β (indoor air ozone increase due to ESP operation)	=$\varepsilon\times(1-\gamma_{filt}/2)\times R/((\lambda_v+k_d+k_h)\times V_{room})$=28.8×(1-0.2/2)×500 /((1+2.8+0.6) ×960) ppb = 3 ppb
indoor PM number concentration increase due to ESP operation	= 2000×13.5 particles/cm^3 = 27000 particles/cm^3

Table S4 Calculations of k_d

Time	outdoor ozone (ppb)	indoor ozone (ppb)	k_d (h^{-1})
1/8/2015 13:00*	17.0	3.8	2.6
1/9/2015 13:00*	25.5	5.2	2.9
	mean ± std. (k_d): 2.8 ±0.2 (h^{-1})		

* Close to steady-state conditions since the outdoor ozone varied by less than 1.5 ppb during the previous two hours.

Table S5 Calculations of k_h

Time	outdoor ozone (ppb)	indoor ozone (ppb)	k_h (h^{-1})
12/29/2014 12:00*	27.5	4.2	1.5
1/9/2015 16:00*	40.0	8.1	0.2
1/10/2015 11:00*	15.0	2.6	0.8
1/10/2015 12:00*	18.0	3.5	0.4
1/10/2015 15:00*	36.0	7.0	0.3
	mean ± std. (k_h): 0.6 ±0.5 (h^{-1})		

* Close to steady-state conditions since the outdoor ozone varied by less than 3.5 ppb during the previous two hours.

Table S6 Calculations of ε during 12:00-14:00

Time	Outdoor ozone (ppb)	Indoor ozone (ppb)	ε (10^{-6} kg h^{-1})
1/14/2015 14:00*	13.5	6.7	31.2
1/20/2015 14:00*	29.5	10.2	32.0
1/23/2015 14:00*	40.5	16.8	67.1
1/24/2015 14:00*	30.0	12.2	47.8
1/26/2015 13:00*	5.0	2.4	11.1
1/26/2015 14:00*	4.5	2.9	16.1
1/27/2015 13:00*	11.5	3.6	9.4
1/27/2015 14:00*	12.0	4.4	14.9
1/28/2015 13:00*	7.5	3.2	13.5
1/28/2015 14:00*	7.0	3.6	17.0
1/29/2015 13:00*	9.0	2.4	37.7
1/29/2015 14:00*	8.0	3.2	12.5
1/30/2015 13:00*	10.5	4.9	21.9
1/30/2015 14:00*	10.5	8.1	47.8
	mean ± std. (ε): (24.7 ±18.3) mg h^{-1}		

* Close to steady-state conditions since the outdoor ozone varied by less than 2.5 ppb during the previous two hours.

Table S7 Calculations of ε during working hours

Time	Outdoor ozone (ppb)	Indoor ozone (ppb)	ε (10^{-6} kg h^{-1})
1/14/2015 11:00*	4.5	3.7	26.6
1/15/2015 12:00*	5.0	3.2	15.2
1/15/2015 16:00*	31.0	6.1	4.3
1/16/2015 15:00*	25.5	6.8	20.7
1/19/2015 10:00*	4.5	4.0	29.9
1/19/2015 11:00*	6.5	3.3	19.7
1/20/2015 15:00*	27.5	8.0	28.0
1/21/2015 16:00*	41.5	10.4	26.5
1/22/2015 16:00*	44.0	11.9	36.7
1/22/2015 17:00*	44.5	12.1	38.1
1/23/2015 17:00*	42.0	12.7	48.1
1/26/2015 12:00*	4.5	2.4	14.9
1/26/2015 15:00*	3.5	2.9	21.1
1/26/2015 16:00*	3.5	2.6	18.2
1/26/2015 17:00*	3.0	3.2	25.0
1/27/2015 11:00*	10.5	3.1	11.4
1/27/2015 12:00*	10.0	3.1	11.6
1/27/2015 15:00*	10.0	4.5	25.3
1/28/2015 12:00*	6.5	4.1	27.3
1/28/2015 17:00*	4.5	3.1	21.0
1/29/2015 16:00*	7.5	3.7	21.7
1/29/2015 17:00*	7.5	3.2	16.8
mean ± std. (ε): (23.1 ±9.8) mg h^{-1}			

* Close to steady-state conditions since the outdoor ozone varied by less than 2 ppb during the previous two hours.

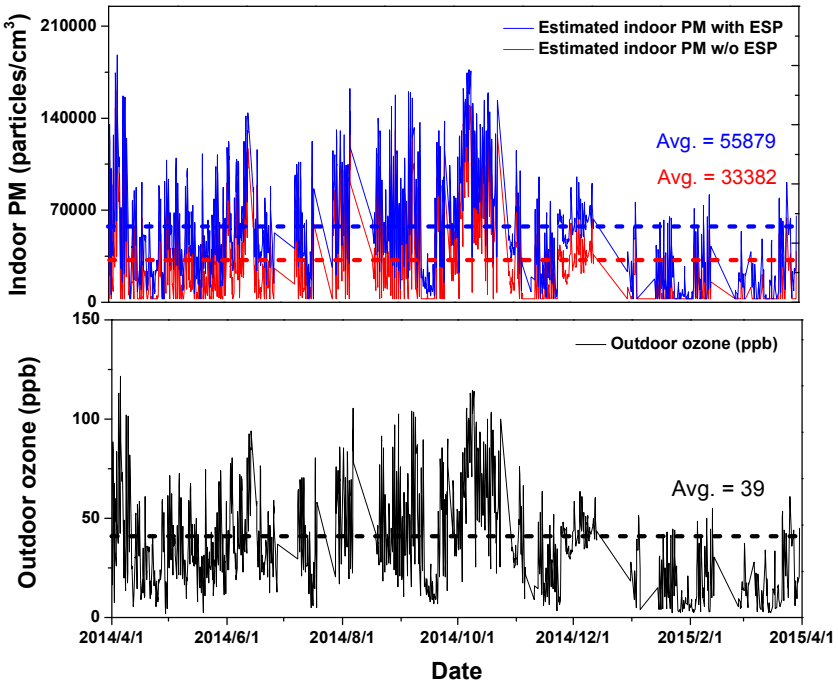

Figure S4 Hourly outdoor ozone concentrations and estimated hourly indoor PM with and without ESP operation during working hours from April 1, 2014 to March 31, 2015 in Changsha (data from the National Air Pollution Monitoring System which was certified by the Ministry of Environmental Protection of China; real-time data is available at http://106.37.208.233:20035/)

Calculation of ESP contributions to indoor PM

Based on the linear fitting shown in Figure 5, indoor PM number concentrations (particles/cm^3) can be determined as:

$$C_{PM}(t)=\begin{cases}2600 & C_{s\_ozone}(t)\le 18\,ppb\\ 2000\left(C_{s\_ozone}(t)-18\right)+2600 & C_{s\_ozone}(t)>18\,ppb\end{cases} \quad (S1)$$

where $C_{PM}(t)$ is indoor PM number concentration at time t [particles/cm^3], and $C_{s\_ozone}(t)$ is supply air ozone concentration at time t [ppb].

Based on Equation (6), the supply air ozone concentration can be determined as:

$$C_{s\_ozone}(t)=\begin{cases}0.8\times C_{o\_ozone}(t) & \textbf{with ESP absent}\\ 0.8\times C_{o\_ozone}(t)+13.5 & \textbf{with ESP present}\end{cases} \quad (S2)$$

where $C_{o\_ozone}(t)$ is the outdoor ozone concentration at time t [ppb].

Based on Equations (S1) and (S2), and the outdoor ozone concentrations obtained from the

National Air Pollution Monitoring System, which was certified by the Ministry of Environmental Protection of China, the mean hourly indoor PM number concentrations during working hours (08:00-12:00, 14:00-18:00) from April 1, 2014 to March 31, 2015 in Changsha with and without the ESP operating are estimated be 55880 and 33380 particles/cm^3, respectively. Thus, the mean hourly indoor PM number concentration contributed by ESP operation is around 22000 particles/cm^3 over the 12-month period.

References:

1. U.S. EPA, Automated equivalent method: EQOA-0410-190. In 2010; Vol. 75, pp 22126-22127.