Mitigation of fine particulate matter exposures in schools

Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches

Workshop on Mitigation of Indoor Exposure to Fine Particulate Matter

National Academies of Science and Engineering

Dr. Elliott T. Gall, Ph.D.

Assistant Professor

Department of Mechanical and Materials Engineering

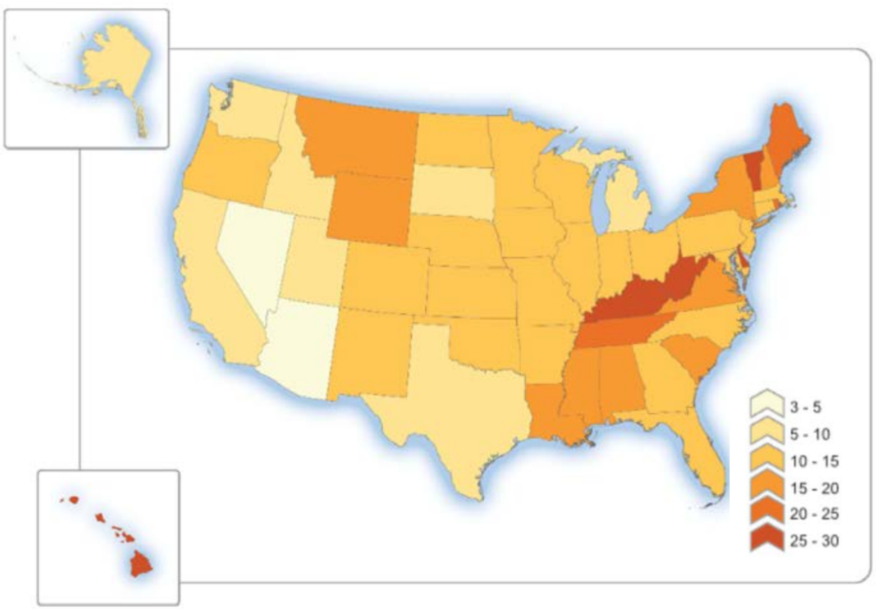
Healthy Buildings Research Lab

Portland State University

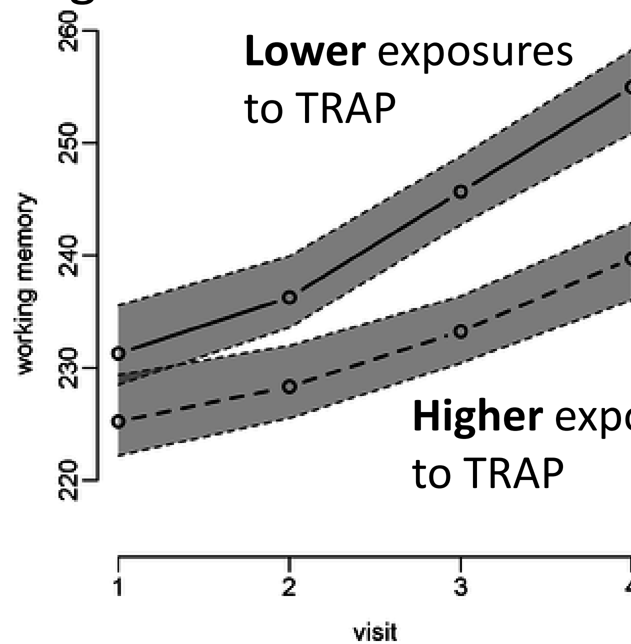
Air pollution and near-roadway schools

Schools are critical environment for susceptible population:
- 15% of schools (6.4 million children) < 250 m distance from major roadway[1]
- Schools with higher % Hispanic, Black, Asian students have disparate exposure[2,3]

Traffic-related air pollution (TRAP) affects student health and cognition:
- e.g., increased asthma diagnosis[4]
- Decreased working memory scores, other cognitive markers[5]



% of students attending a school within 250 m of major roadway[1]



BREATHE study in Spain: 2,715 children and 10,112 tests from 39 schools.

[1]Kingsley et al. 2014, JESEE 24:253-259; [2]Grineski and Collins, 2018 Env. Res. 161:580-587, [3]Gaffron and Niemeier 2015 Int. J. Environ. Res. Public Health (2) 2009-2021. [4]HEI, 2010 Traffic-related air pollution: A critical review of the Literature on Emissions, Exposure, and Health Effects; [5]Sunyer et al., 2015. PLOSone, March 2015: 1-24.

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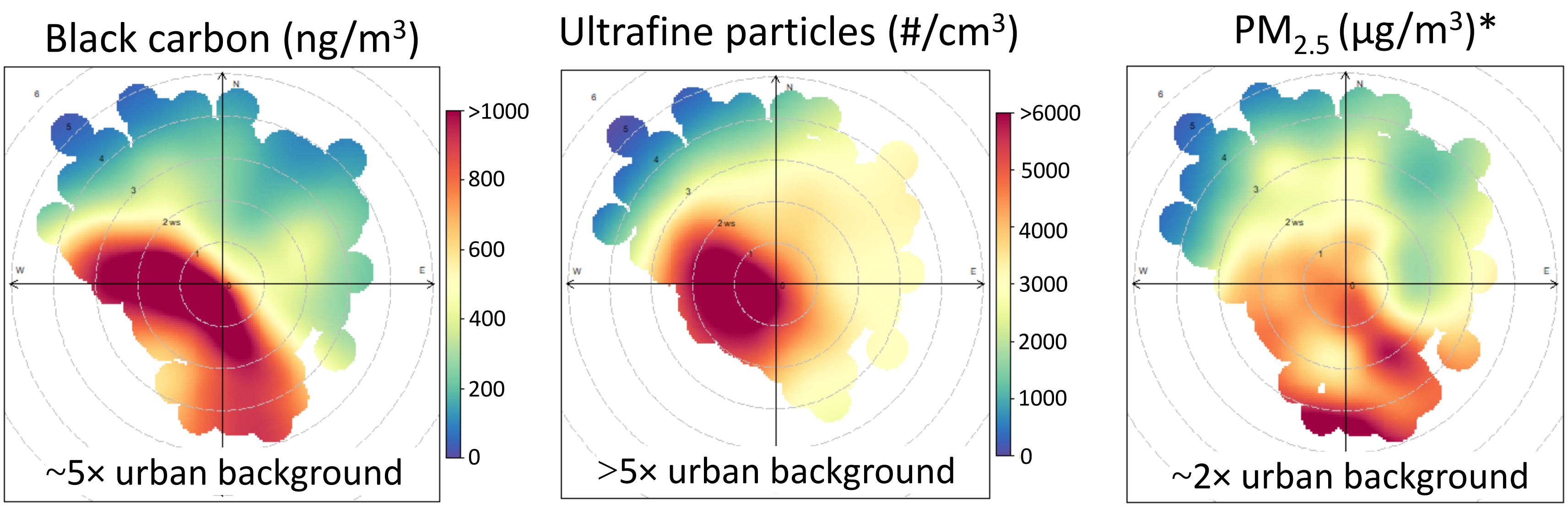
Air pollution in near-roadway schools

Near-roadway middle school **Harriet Tubman Middle School (HTMS)** in Portland, OR, USA; site of field study.

Challenges for near-roadway schools[1]:

- Elevated air pollution levels
  - Temporally and spatially variant
  - Meteorology is important
- TRAP constituents elevated, $PM_{2.5}$ less so
  - Health impacts greater for TRAP than $PM_{2.5}$[2]
  - Standards (ASHRAE 62.1)↑ filtration if NAAQS exceeded
- Indoor + site outdoors contribute to student exposure



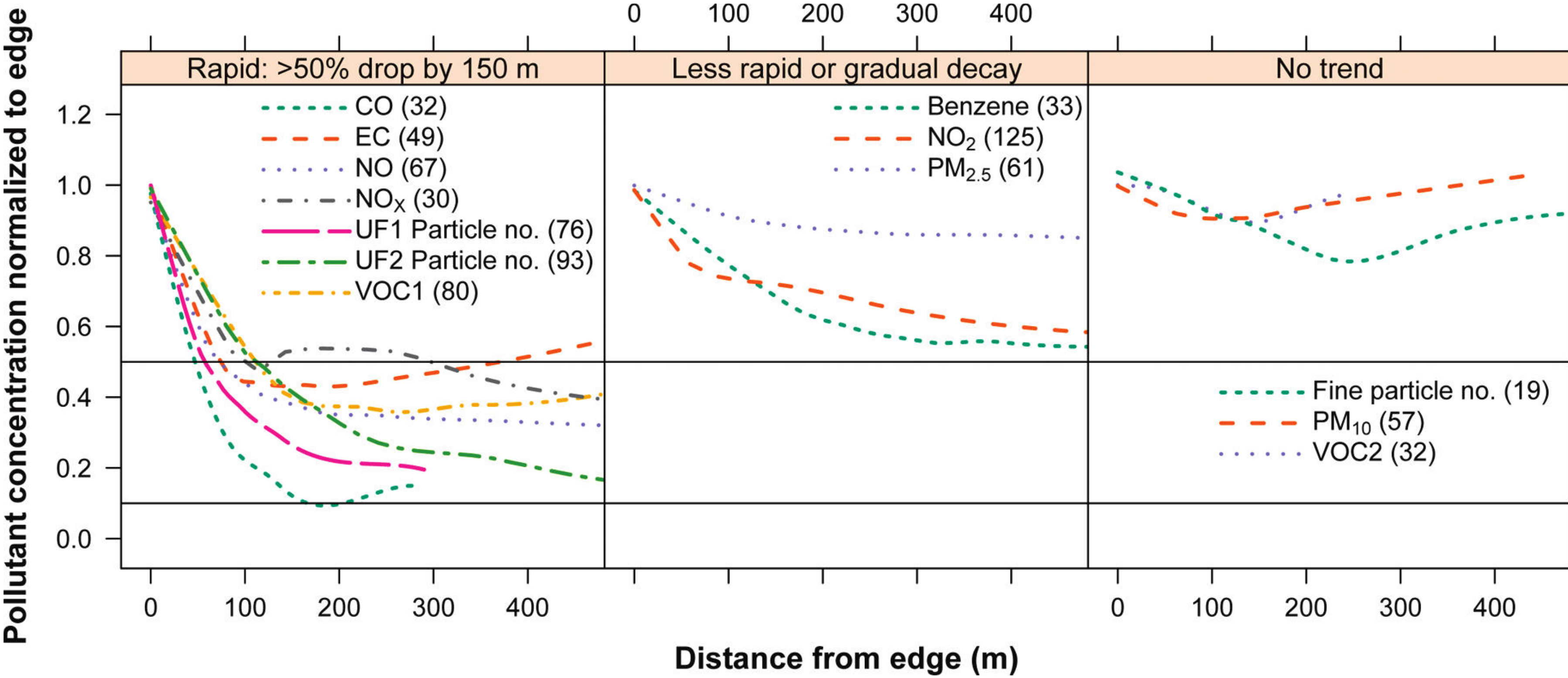
Polar plots from Spring 2019 campaign at HTMS

*w/ ρ = 1 g/cm³

[1] Gall and George, 2018, ASHRAE Journal: IEQ applications, 80-83; [2]Janssen et al. 2011 EHP 119(12):1003369;

Strong spatial gradients for TRAP

- TRAP elevated above urban background within zone of ~200-500 m[1]
- Zone may be 1000s of meters during nighttime[2]



Opportunity: leverage spatial gradient to reduce exposure

[1]Karner et al. 2010 *Environ. Sci. Technol.* 44, 5334-5344. [2]Fruin et al; *Atm. Env..* 2009, 43, 2541-2549

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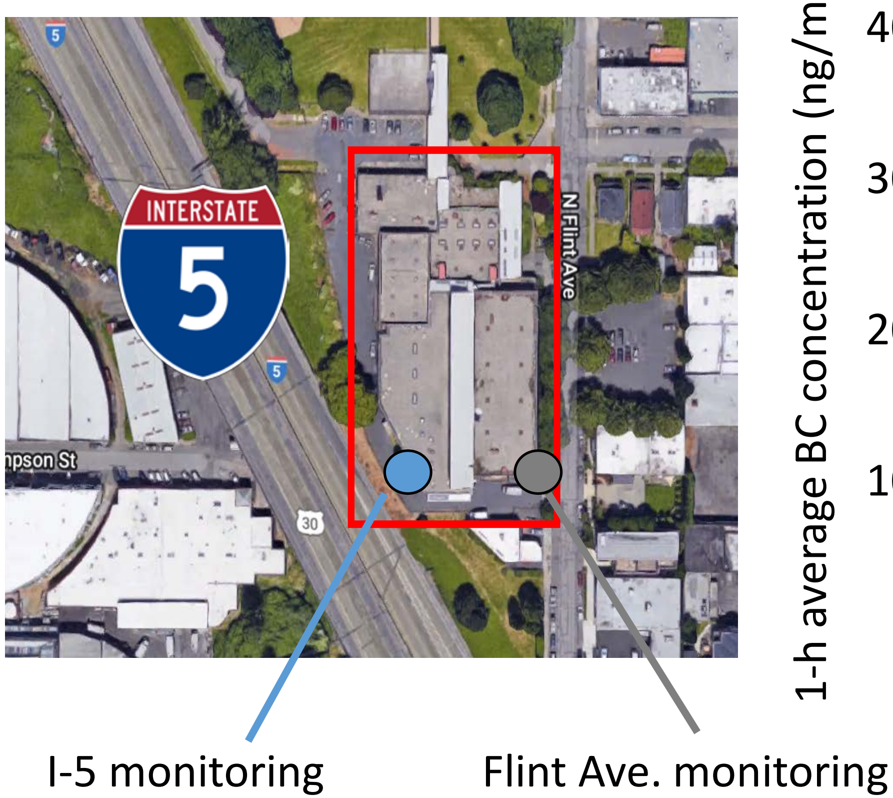
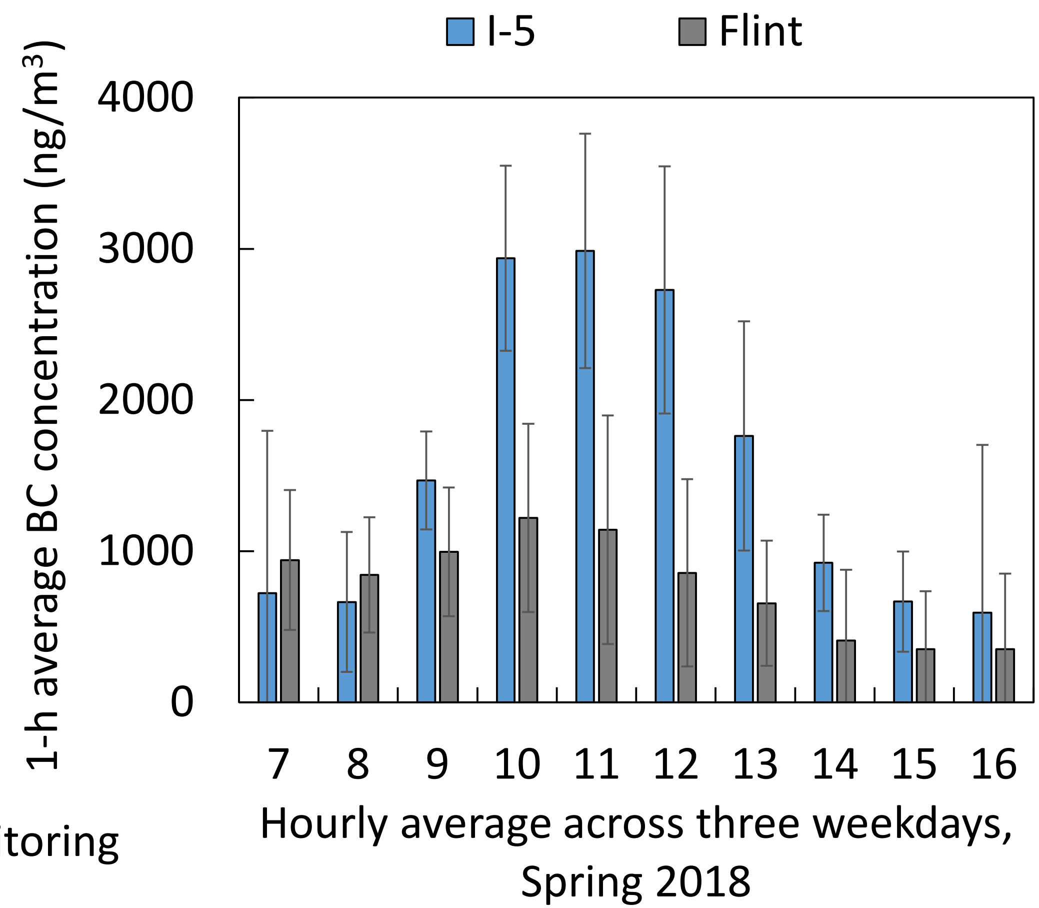
Siting outdoor air intake

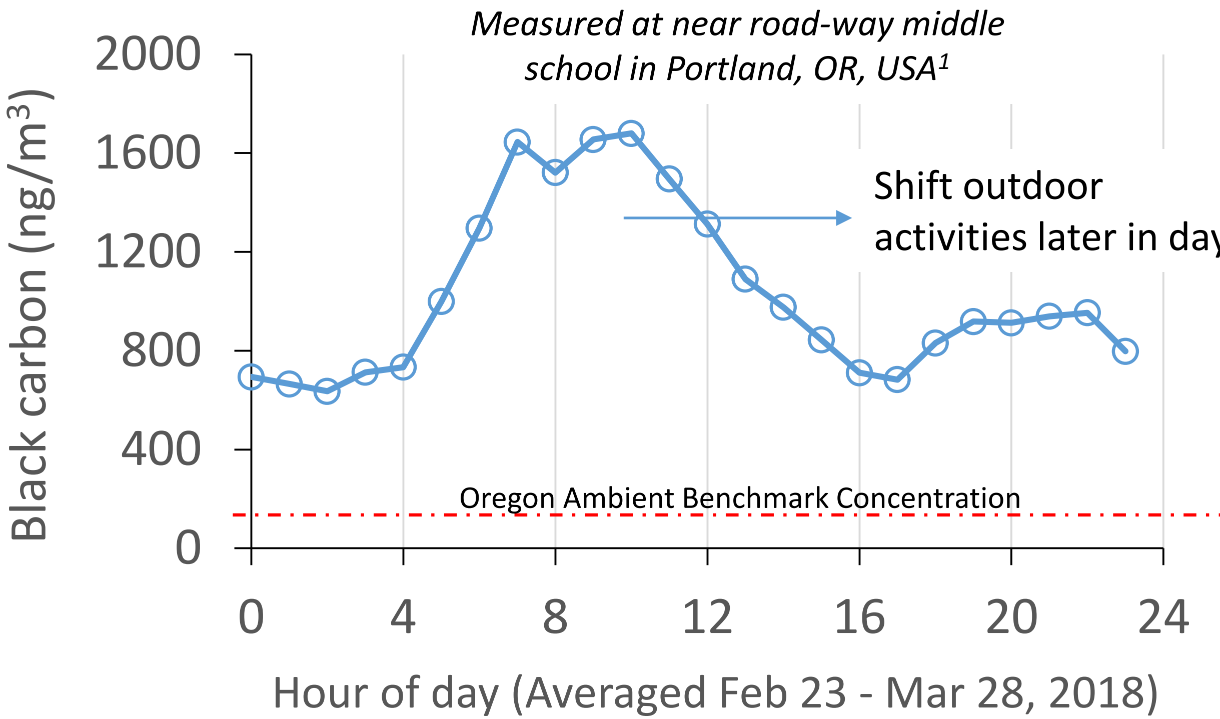




- Monitoring of black carbon on two faces of Harriet Tubman Middle School[1]
  - At peak periods, ↑ distance is equivalent to a ~MERV8 filter
  - Benefit is realized without energy input (due to mixing and dilution of TRAP)

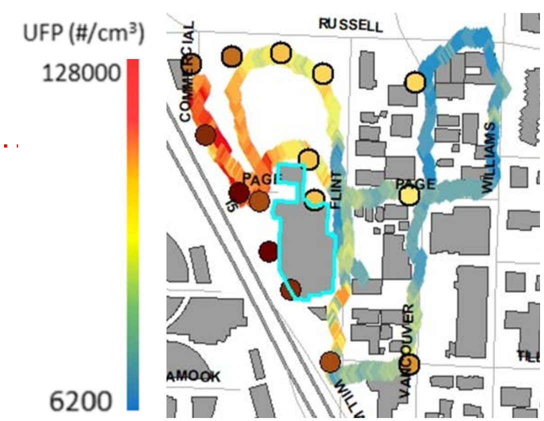
[1]Laguerre et al., 2020, ES&T 54(19):11798-11808

Leverage diurnal trends in TRAP



TRAP generally peak between 7 and 9 AM due to rush hour traffic[2]

And shift location:



Monitoring of UFP and NO_2 at near-roadway school[1]

Alter timing of ventilation system[3]

- Test of four schools in Ottawa, ON
    1. Outdoor air ventilation from 5:30 – 6:30 AM
    2. Recirculation only until school starts at 8 or 9 AM

→ Significant reductions in UFP, VOCs for schools starting at 9 AM

[1]Laguerre et al., 2020, ES&T 54(19):11798-11808; [2] Touma et al. J Air Waste Manage, 56, 1716–1725.
[3]MacNeill et al. 2015, Indoor Air 26(5): 687-701

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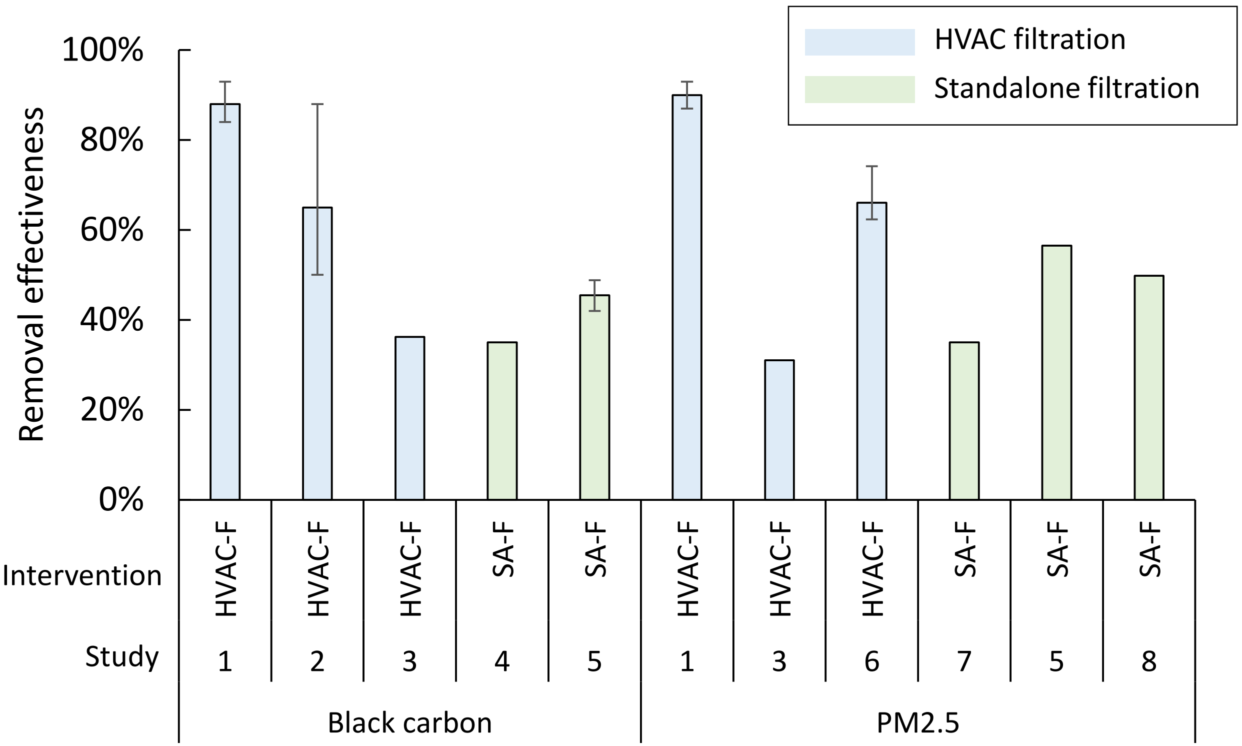
Active approaches: air-cleaning

Air cleaning effectiveness for PM in **occupied** schools

- Filtration *can be* effective, but results are variable
- Eight studies of occupied schools w/ air cleaning intervention[1-8]
  - o Most common: Filtration in HVAC system (HVAC-F), standalone (SA-F) filtration

Removal effectiveness
$$= 1 - \frac{C_{controlled}}{C_{uncontrolled}}$$



[1]Polidori et al. 2013, Indoor Air 23(3): 185-195; [2]McCarthy et al. 2012 Indoor Air 23:196-207; [3]van der Zee et al. 2017 Indoor Air 27(2): 291-302; [4]Scheepers et al. 2015 Environ Sci Processes Impacts 17:316-325 ; [5] Jhun et al. 2017 J Allergy Clin. Immun. 5(1): 159-159e.3; [6] Gao et al. 2019 Env. Res 197 Part A, 108749; [7]Park et al. 2020 Build. Environ 167:106437; [8]Smythe, A. 2018 Master's Thesis, Harvard University

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At near-roadway school in Portland, OR

Pre-renovation

Post-renovation

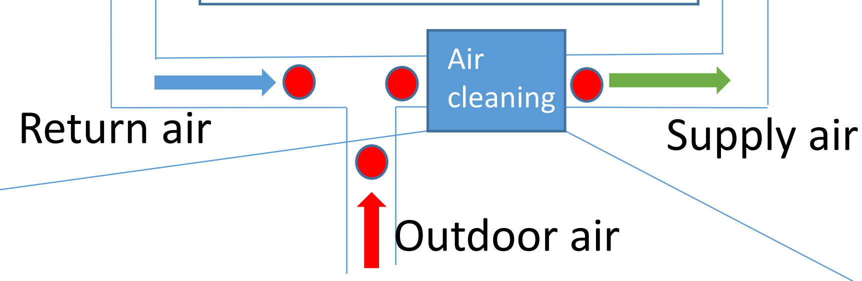
● Air monitoring locations[1]

Middle School

N = ~500 students

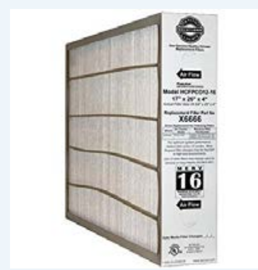
V = 36,800 m^3

λ_{oa} = ~0.9 h^{-1}; λ_{sa} = ~2 h^{-1}



MERV8 pre-filter

protect lifespan of downstream high efficiency filter + AC downstream



MERV16 filter

effective across broad range of particles, <10 nm – 10+ µm

Functionalized carbon

VOC and NO_2 removal, large mass required, ↑cost

[1]See Laguerre et al., 2020, ES&T 54(19):11798-11808 for description of monitoring activities

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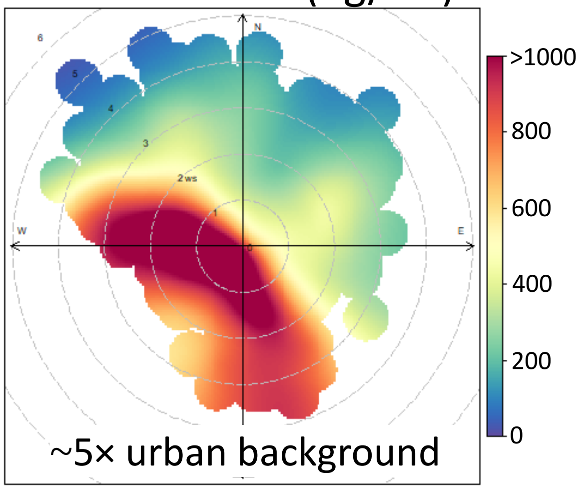
Address TRAP in ventilation air

- Minimum goal for near-roadway school:
  - o TRAP in ventilation air = to urban background w/ standard filtration

Black carbon (ng/m^3)[1,2]



Set black carbon source in school ventilation air so that:

If near-roadway (NR) = If in urban background (BG)

$$[(1-\eta)\lambda_{OA}C]_{NR} = [(1-\eta)\lambda_{OA}C]_{BG}$$

$$\eta_{NR} = 1 - \frac{C_{BG}}{C_{NR}}(1-\eta_{BG})$$

$$\eta_{NR} = 1 - \frac{1}{5}(1-0.2)$$

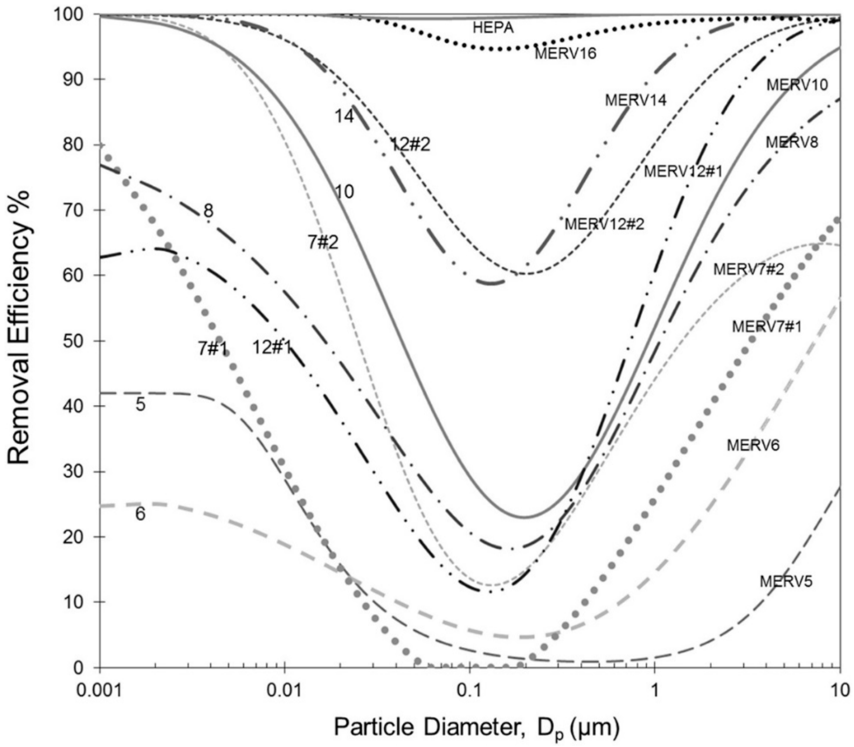
$\boldsymbol{\eta \geq 84\%}$ **required** to make BC outdoor source similar to that of urban background w/ typical filter (at near-roadway school in Portland, OR USA[1,2])

η = black carbon removal efficiency (-)
λ_{OA}= outdoor air exchange rate (h^{-1}), = 0.85 h^{-1}
C= black carbon outdoor air concentration ($\frac{ng}{m^3}$)

[1]Laguerre et al., 2020, ES&T 54(19):11798-11808; [2]Gall et al. 2018 Indoor and outdoor air quality at Harriet Tubman Middle School and the design of mitigation measures: Phase I report

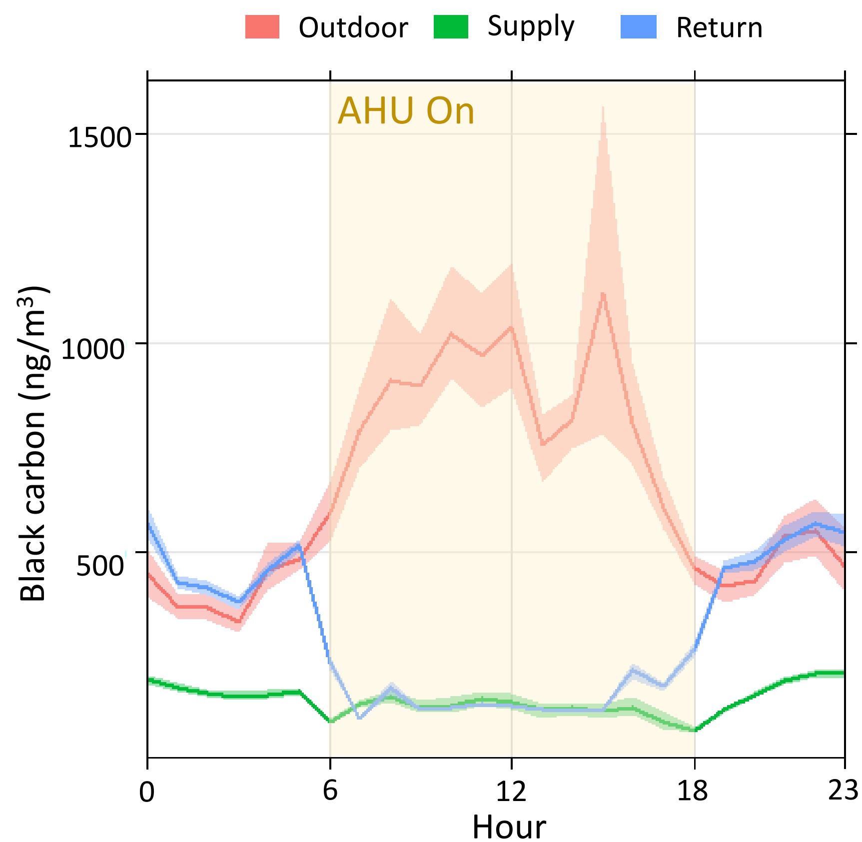
Efficacy of high-efficiency air cleaning

Predictions of size-resolved removal efficiency vs. MERV rating[1,2]



>84% removal efficiency of fine particulate matter achievable, f(MERV, d_p)

1-week at near-roadway middle school[3], w/ MERV 8 + 16



Blue line: Indoor BC levels avg. 150 ng/m^3 w/ air cleaning; **effectiveness of ~85%**

[1]Azimi et al. Atm. Env. 98:337-47; [2]Hecker, R.; Hofacre, K. C. Development of Performance Data for Common Building Air Cleaning Devices Report No. EPA/600/R-08/013; U.S. EPA; [3]Laguerre et al., 2020, ES&T 54(19):11798-11808

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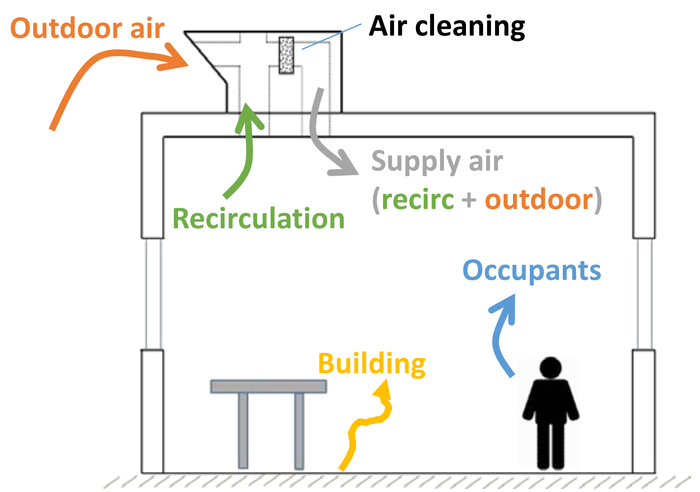
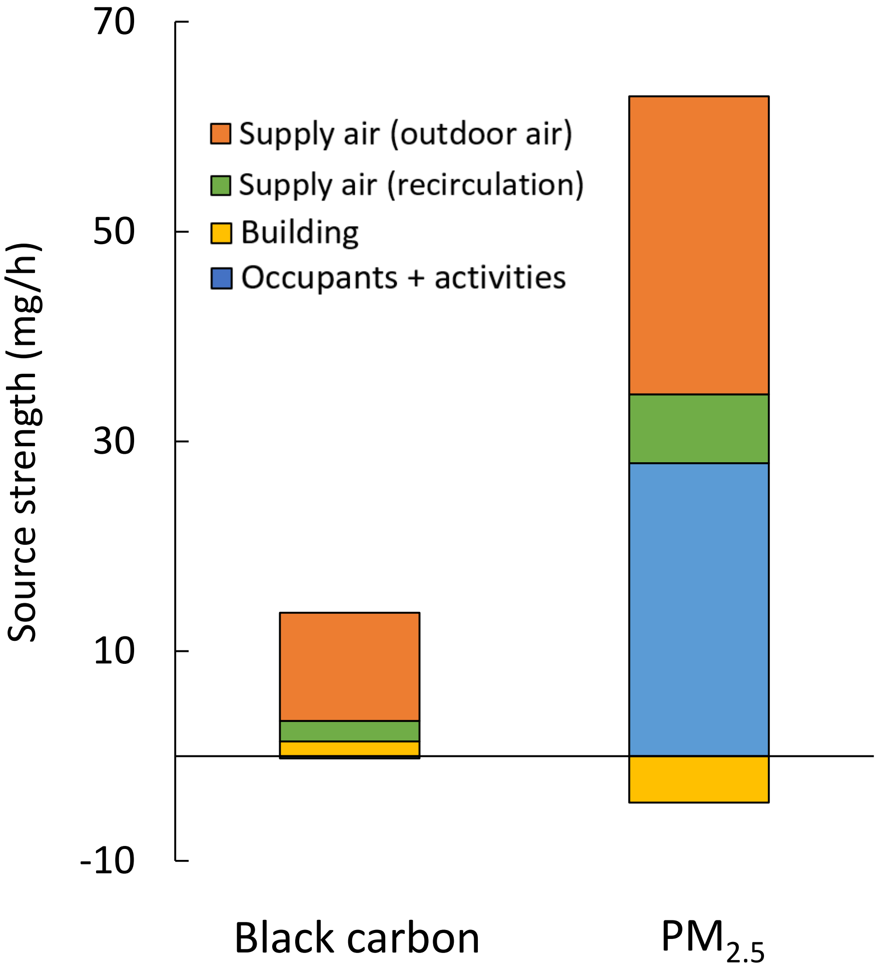
Indoor sources of fine PM in schools

Occupants and their activities generate fine particulate matter



- Indoor sources important for $PM_{2.5}$
  - o $PM_{2.5}$ indoor emission at HTMS: $\sim 70 \frac{\mu g}{h\ person}$ (preliminary calculation)
- For black carbon:
  - o No source from occupants + activities
  - o Net source from building implies some BC penetrates envelope and persists

Preliminary source apportionment of fine particulate matter at HTMS[1]:



[1]method based on as shown in Tang et al., 2016, Environmental Science & Technology 50(23): 12686-12694

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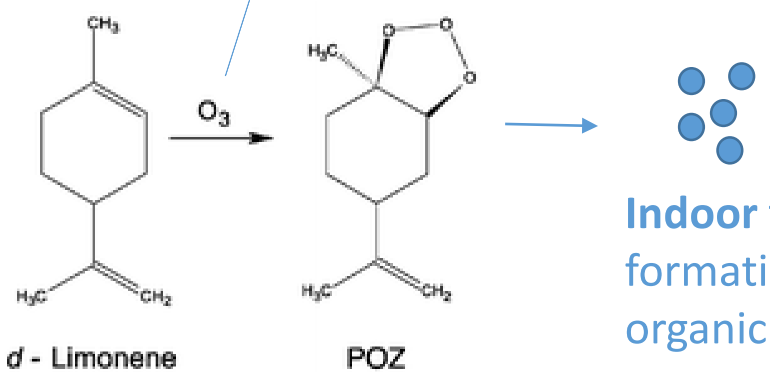
Indoor VOC chemistry → particles

- Some volatile organic compounds of indoor origin are reactive
  - Limonene is the dominant indoor terpene[1]
  - Limonene has high aerosol formation potential[2]
  - Ozone – monoterpene chemistry occurs on time-scale relevant to indoor air[3]
  - Contributes to ultrafine and accumulation mode PM; possible health impact[4]

Monoterpenes: compounds with molecular formula $C_{10}H_{16}$.[1] Over 1000 different compounds

Ozone enters from outside



Limonene, a monoterpene, with indoor sources

Indoor fine particle formation as secondary organic aerosol (SOA)

[1]Weisel et al. 2005 Health Eff. Inst., 109– 127; [2]Youseffi and Waring, 2014, Environmental Science & Technology 48(14): 7899-7908; [3]Wainman et al. (2000): EHP 108:1139-1145 [4]Tuet et al., 2017, *ACP* 17, 11423 - 11440

Air-cleaning alters indoor chemistry

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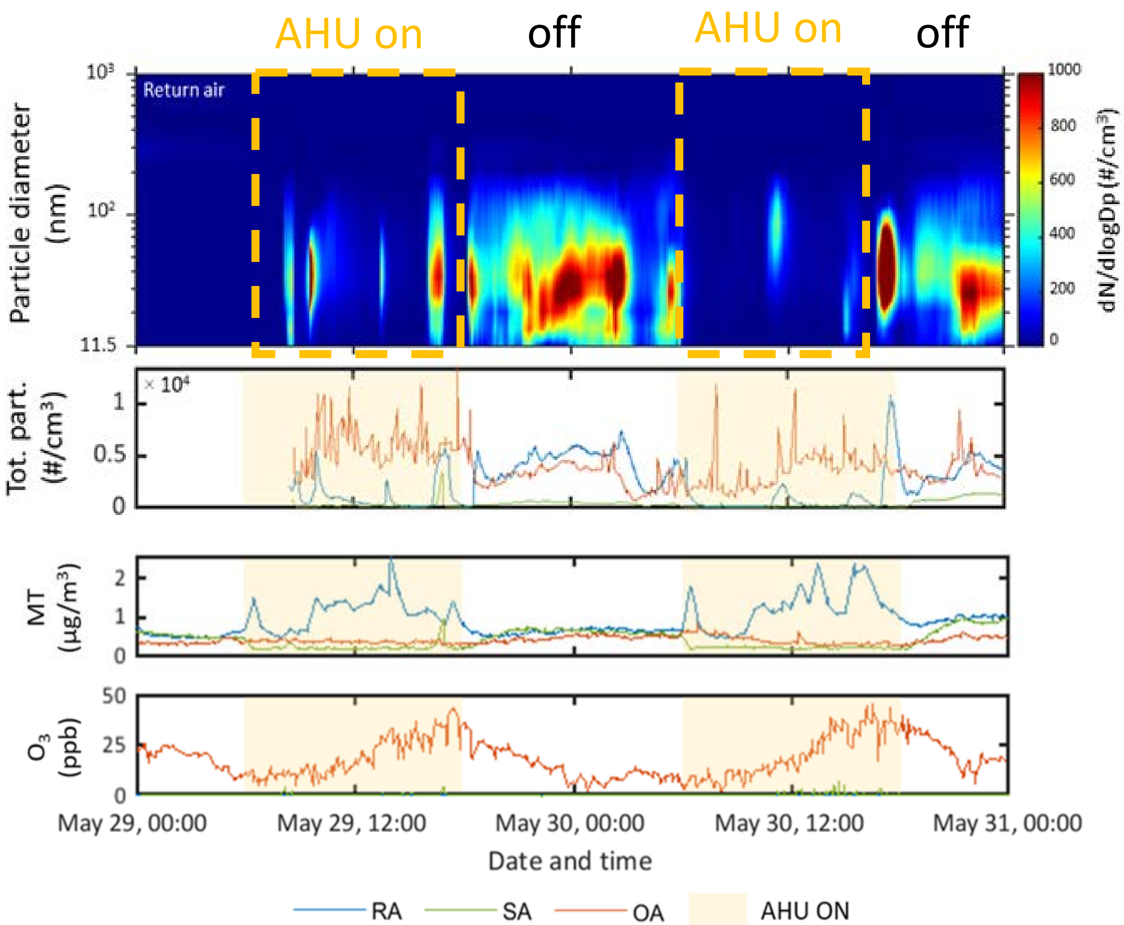
Carbon scrubber appears to reduce indoor secondary organic aerosol formation[1]

AHU on → air cleaning → low indoor O_3 and lower monoterpene → **lower SOA formation**

AHU off → no air cleaning → higher O_3 and higher monoterpene **→ higher SOA formation**

81% reduction in SOA source strength Δ = 3-5 mg/h



[1]Laguerre et al., 2020, ES&T 54(19):11798-11808

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Fine PM in near-roadway schools

Opportunities to reduce fine particle exposures in near-roadway schools:

1. ↑ distance from outdoor sources
2. Alter timing of activities
3. Air-cleaning
4. Address indoor sources
5. Quench indoor chemistry via air-cleaning and/or source reduction

Research and resource needs for schools:

1. Data on efficacy of installed interventions
2. Lower energy + maintenance methods for ventilation, air-cleaning
3. Research on PM source strengths in schools
4. Health impact of exposures to PM of indoor origin

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Acknowledgements

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- Dr. Linda George, Portland State University
- Brett Stinson, Portland State University

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Supporting slides

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Traffic related air pollution

Vehicles emit products of incomplete combustion:

select TRAP constituents:

Particle-phase
- Black carbon
- Ultrafine particles, <100 nm

Gas-phase
- Carbon monoxide
- Oxides of nitrogen (NO/NO_2)
- Volatile organics (e.g., BTEX)

TRAP: Traffic-related air pollution

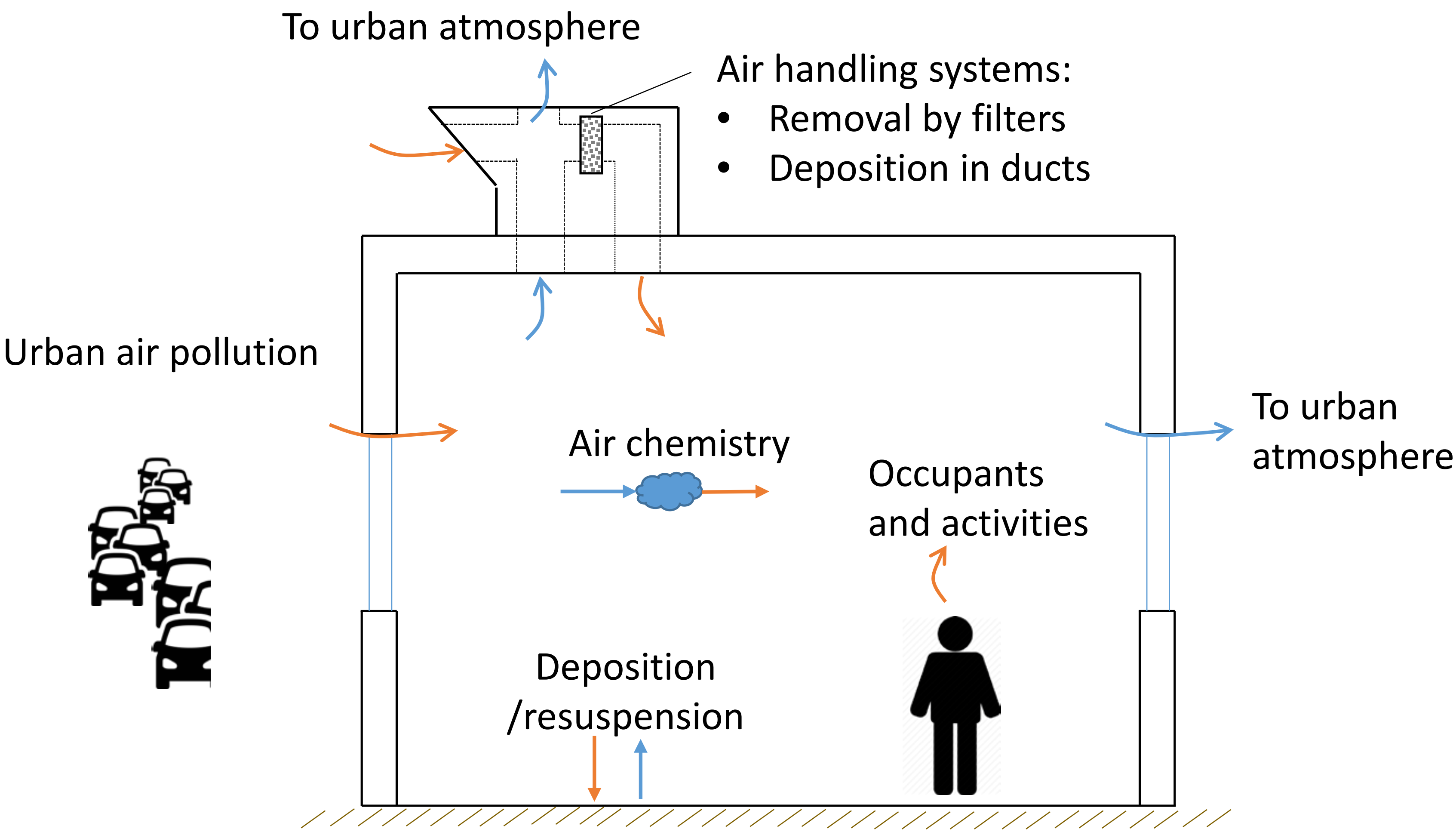
Black carbon (BC): carbonaceous product of incomplete combustion[1]

Black carbon is a substantial fraction of:

i) $PM_{2.5}$ in traffic environments[2] ii) vehicle PM emission factor[3]

[1]Shrestha et al. 2010, Sustainability 2:294-320; [2]Bond et al. 2013 J. Geophs. Res. 109: D14203; [3]Krecl et al. 2018, Atm. Env. 186:229-240

Indoor particle dynamics



$$\frac{dC_{fp}}{dt} = S - LC_{fp}$$

To apply mass conservation principles, we require parameterization of sources (**S**, μg m^{-3} h^{-1}) and losses (**L**, h^{-1}) to indoor control volume

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Humans are major source of VOCs

"…building's occupants, simply by being present, significantly change the air chemistry inside…"

https://www.pnas.org/content/117/37/22619

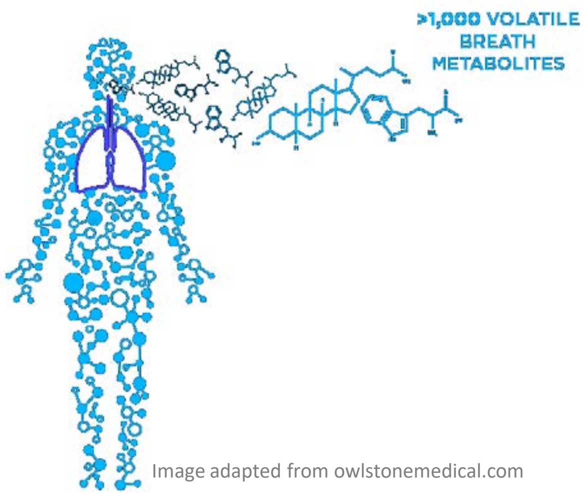
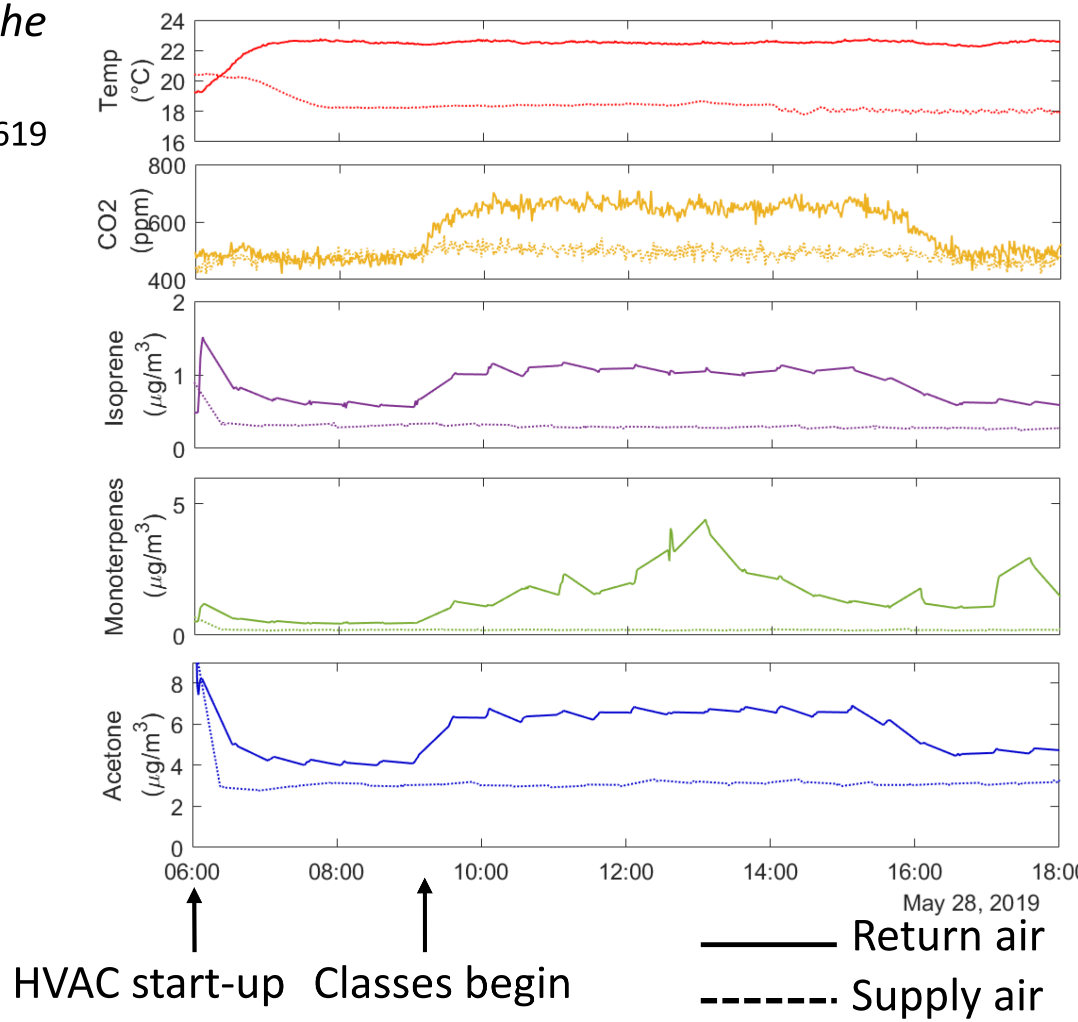


Image adapted from owlstonemedical.com

Humans emit VOCs that:

- degrade perceptions of indoor air
- engage in chemistry and become harmful to health

CO_2 and VOCs in Harriet Tubman Middle School



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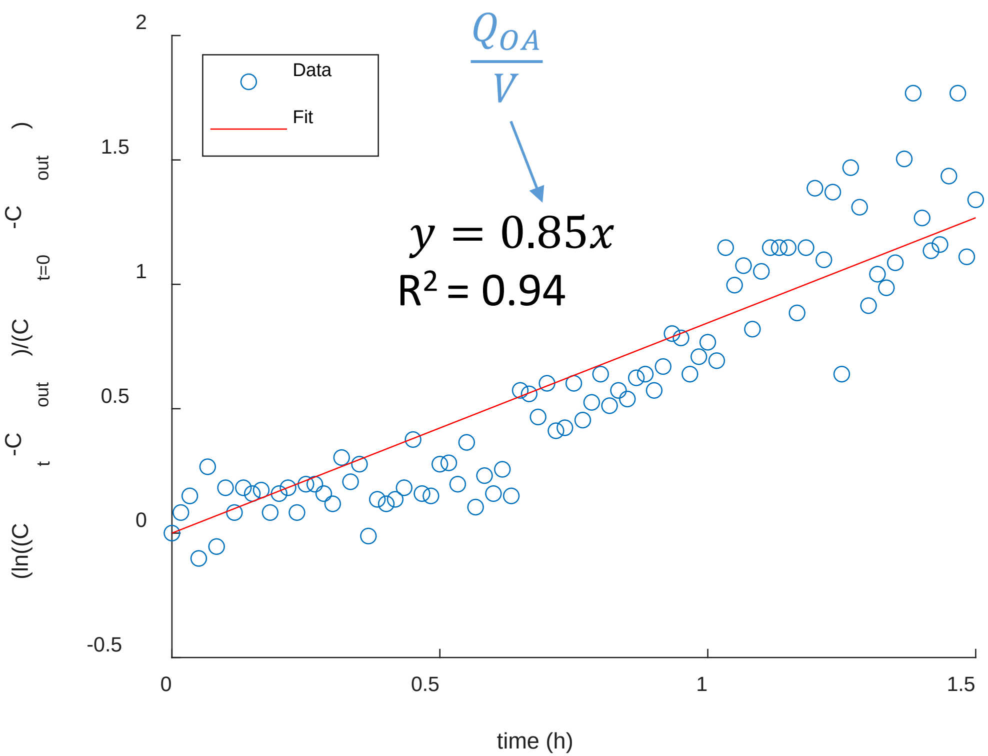
Ventilation and occupancy

1 Analyze CO_2 decay occurring at end of day post occupancy, air handler operating



2 Use steady-state period to estimate # of students*

CO_2 above ambient is due to humans:

$$N = \frac{(C_{CO2,RA} - C_{CO2,OA})Q_{OA}}{EF_{CO_2}}$$

$$\boldsymbol{N = 447\ people}$$

Compares well with school district records: 515 people

*Assumes Q_{OA} from end of day applies to stable occupancy period

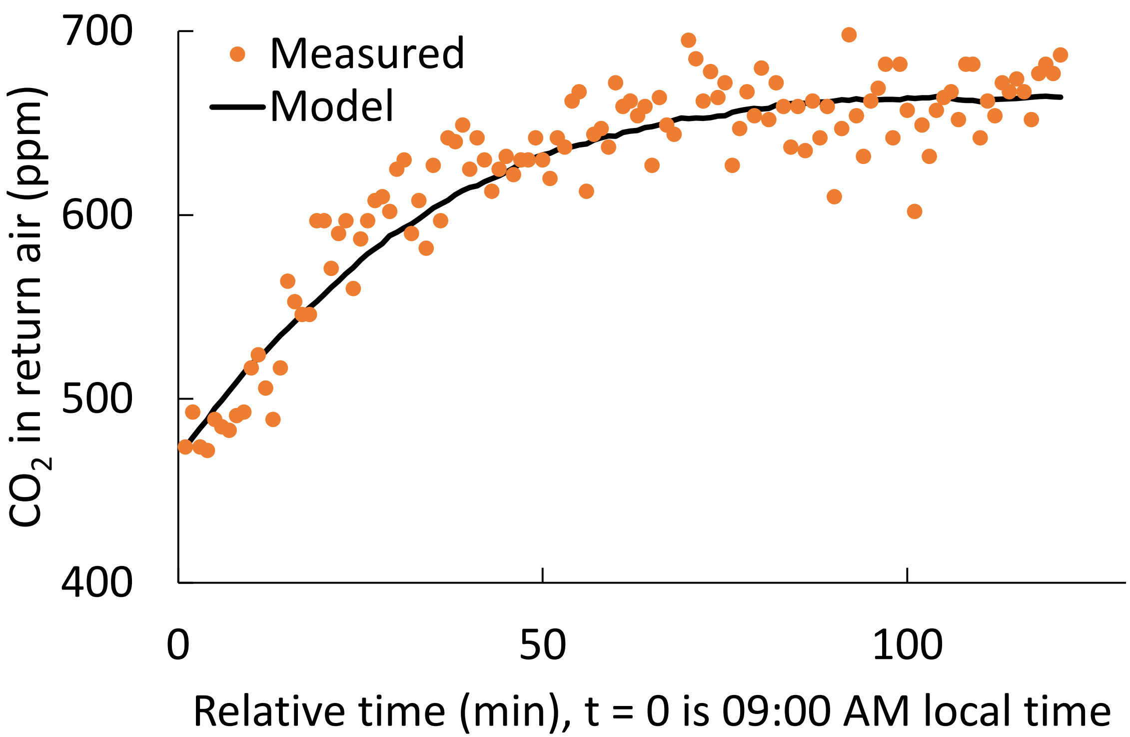
*CO_2 emission factor is weighted average of students aged 11-16 (weighted equally for males, females) and staff from Persily et al.[1]

[1]Persily, A., and L. de Jonge. 2017. "Carbon Dioxide Generation Rates for Building Occupants." Indoor Air 27 (5): 868–79. https://doi.org/10.1111/ina.12383.

Estimating school airflows

3 Analyze accumulation period determine λ

$$\frac{dC}{dt} = \frac{Q_{SA}}{V} C_{CO2,SA}(t) - \frac{Q_{SA}}{V} C_{CO2,RA}(t) + \frac{EF \times N}{V}$$



1. Discretize
2. Solve for best fit Q_{SA} by minimizing residuals (SSE)

Q_{SA} = 43,000 ft³/min

Consistent w/ mechanical contractor's estimate 40,000 – 65,000 ft³/min and Q_{SA} from steady-state flow balance on AHU

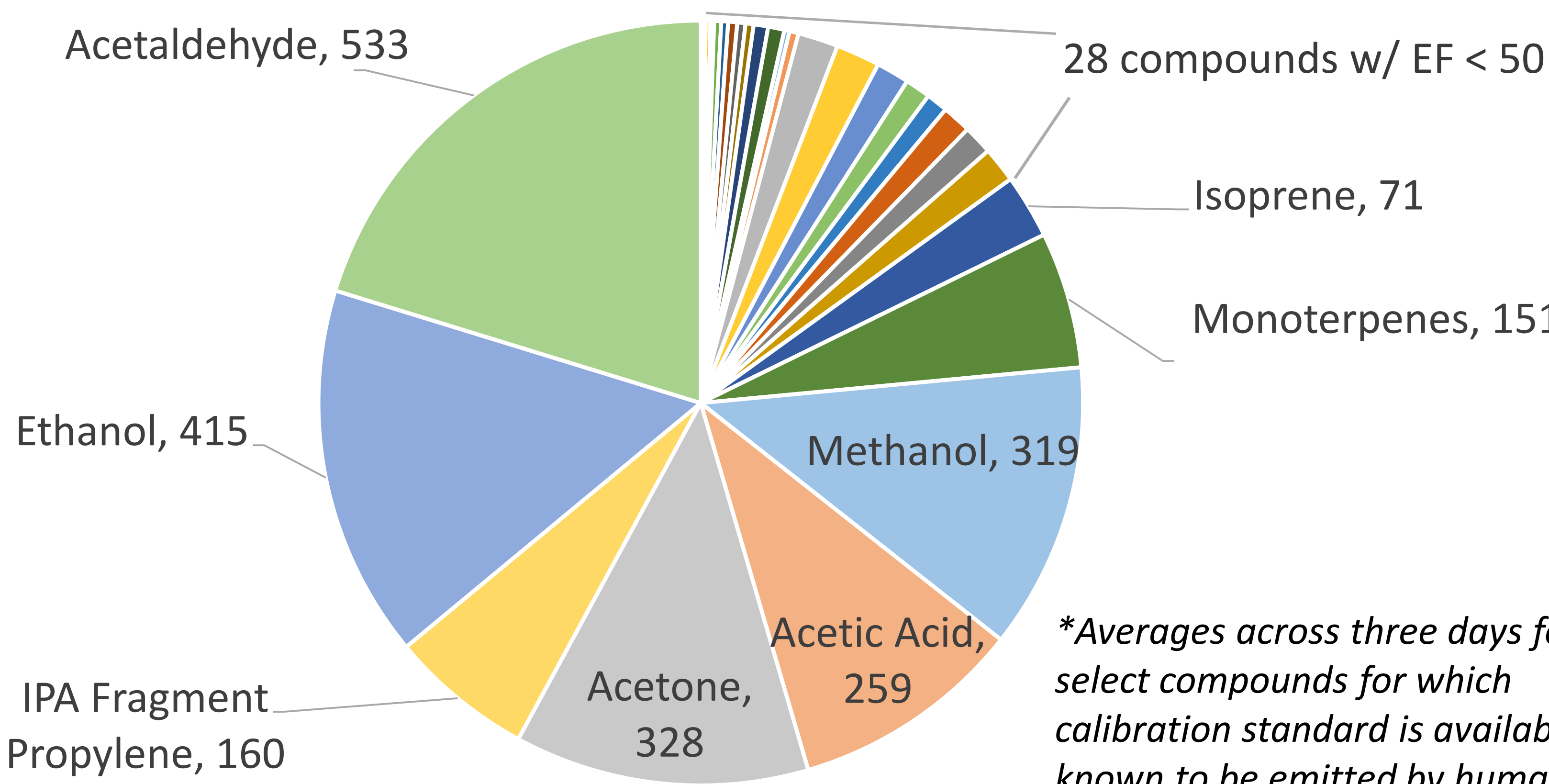
Method may be useful for buildings that are occupied, access to air handler only

Emission factors

$$EF = \frac{\left(\frac{M_{emitted}}{\Delta t}\right)_{occuppied} - \left(\frac{M_{emitted}}{\Delta t}\right)_{vacant}}{\#\ of\ people}$$

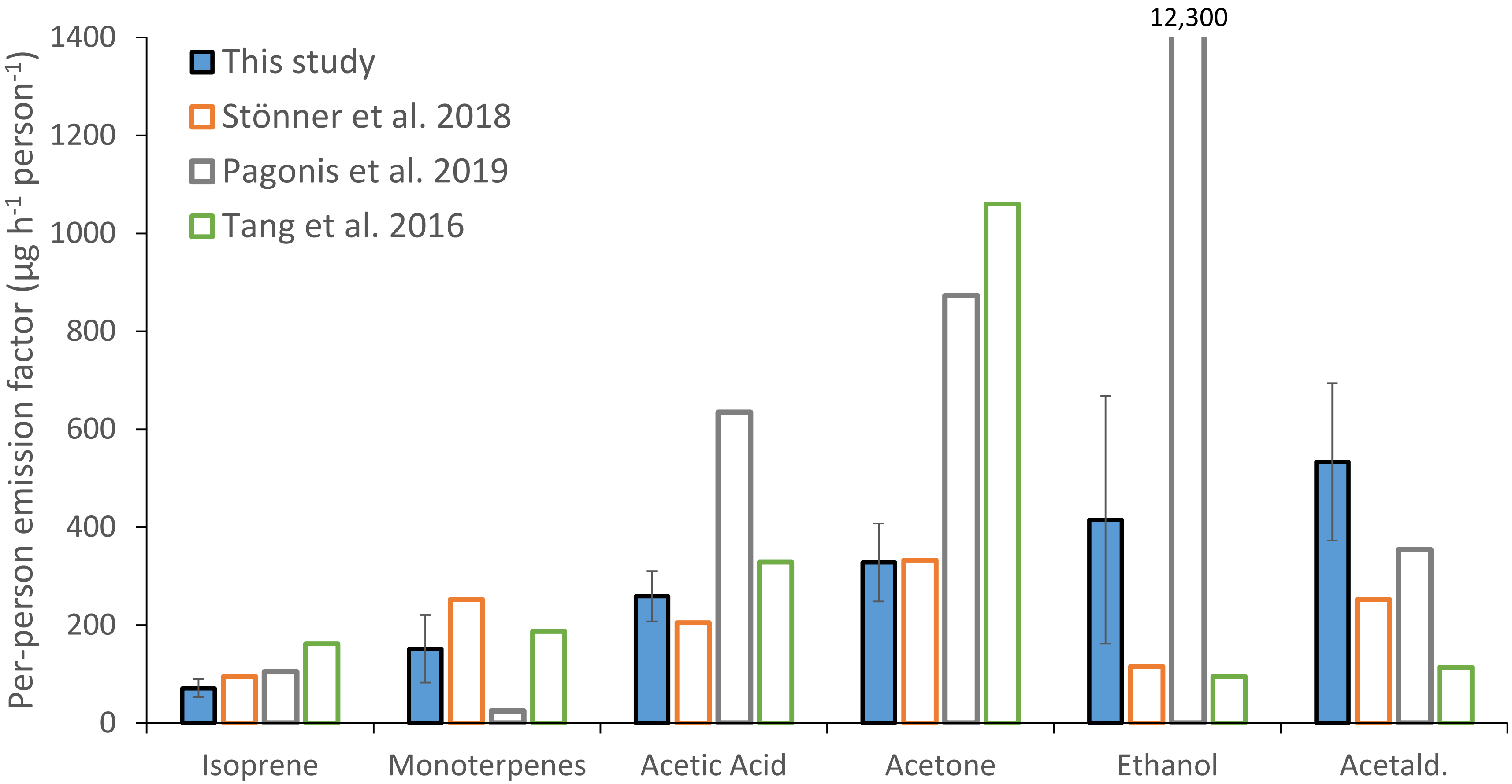
- Monday: Federal holiday as control
- Tues, Wed, Friday: all met criteria for analysis of flows, occupancy calcs

Per-person emission factors* (µg h^{-1} $person^{-1}$)



*Averages across three days for select compounds for which calibration standard is available or known to be emitted by humans

EFs are scarce, esp. for K-12 schools



[1]Stönner al., 2018, Indoor Air 28(1):164-172, [2]Pagonis et al. 2019 Environmental Science & Technology 53(9): 4794-4802, [3]Tang et al., 2016, Environmental Science & Technology 50(23): 12686-12694

Fate of indoor emissions

- Chemistry & partitioning[1] to surfaces
- Emissions outdoors?
  - Monoterpenes are well studied in outdoor air
  - Limonene emission factor (area): school vs. plants

5800 m² area

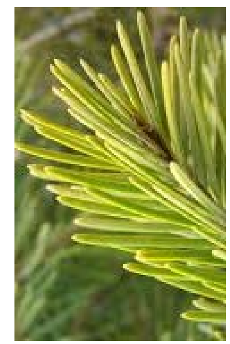
Area emission factor

$$= \frac{92{,}000\ \mu g\ h^{-1}}{5800\ m^2}$$

$$= \mathbf{16\ \mu g\ m^{-2}\ h^{-1}}$$

for a middle school campus

Needle leaf[2]: 99 $\frac{\mu g}{m^2\ h}$



Broadleaf[2]: 41 $\frac{\mu g}{m^2\ h}$

Delosperma (sedum)[3]: 5 $\frac{\mu g}{m^2\ h}$

In cities, large building footprints.

- Indoor emissions can be released outdoors and affect urban + regional air quality!

[1]Wang et al. 2020 Science Advances 6(8):eaay8973 [2]Sakulyanontvittaya et al. 2008, ES&T 42(5):1623-1629; [3]Research in progress at PSU

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Characterizing indoor emission rates

Supply air → **School** → Return air

V = 36,800 m^3

λ_{SA} = 0.8 h^{-1}

occupants = ~500

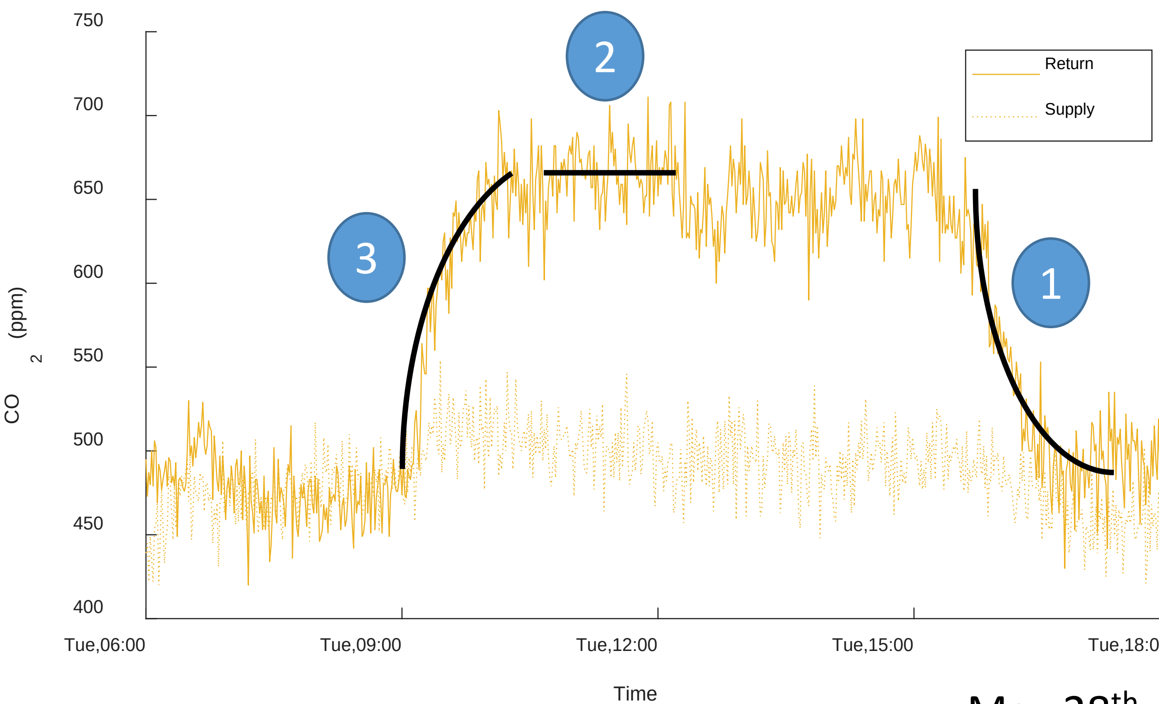
Mass, M, of compound emitted into school[1]

$$M = \lambda_{SA} V \int_{t_0}^{t_1} \left(C_{return} - C_{supply}\right) dt + V \int_{t_0}^{t_1} dC_{return}$$

Flowrate to building (SA = supply air) is unknown

- Could not perform intentional tracer decay
- Developing method for λ_{SA} from analysis of:

1. λ_{OA} (outdoor air) via "natural" decay
2. Use λ_{OA} w/ steady-state to estimate # of students
3. Use # students and the CO_2 emission rate to determine λ_{SA}



May 28th, 2019

[1]method based on as shown in Tang et al., 2016, Environmental Science & Technology 50(23): 12686-12694

Indoor VOC dynamics at HTMS

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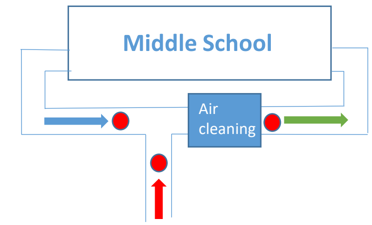
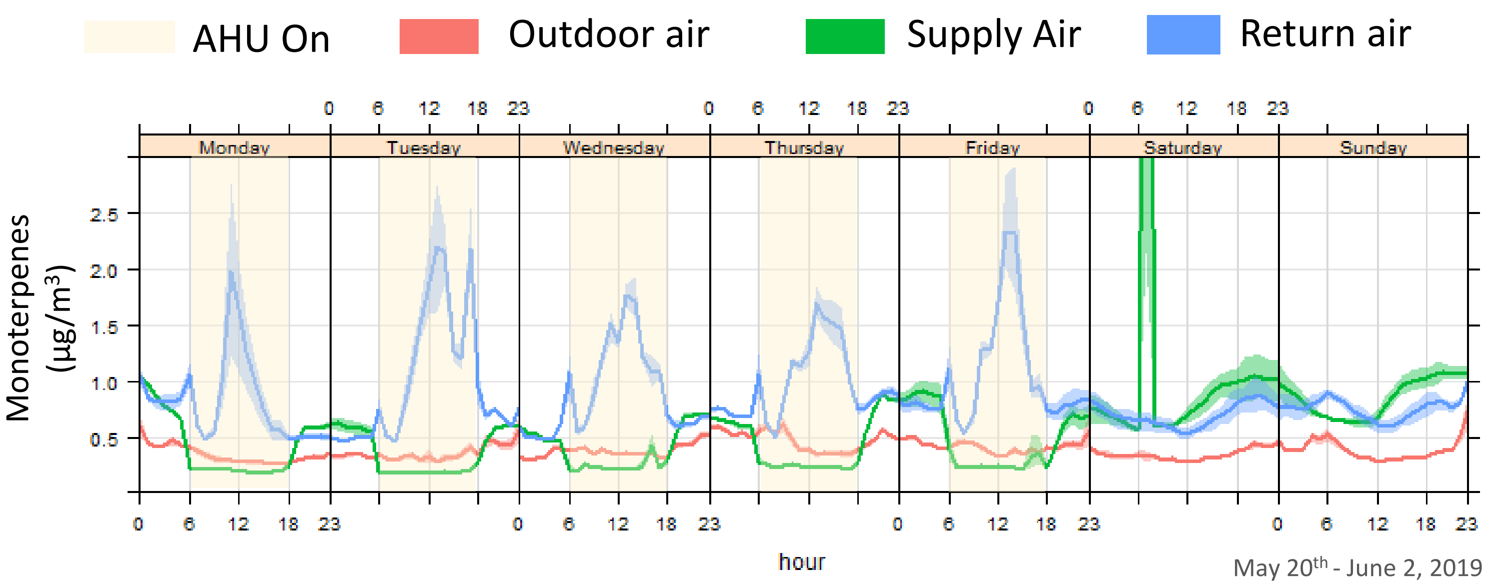
VOC monitoring at HTMS shows:

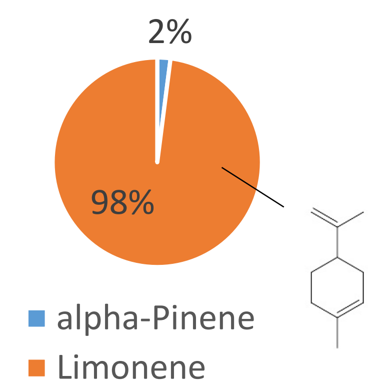
- Indoor VOC concentrations are dynamic
- Humans are an important source of monoterpenes to the space
- Most of the indoor monoterpene signal likely limonene

PTR-MS, sampling manifold to three locations in AHU



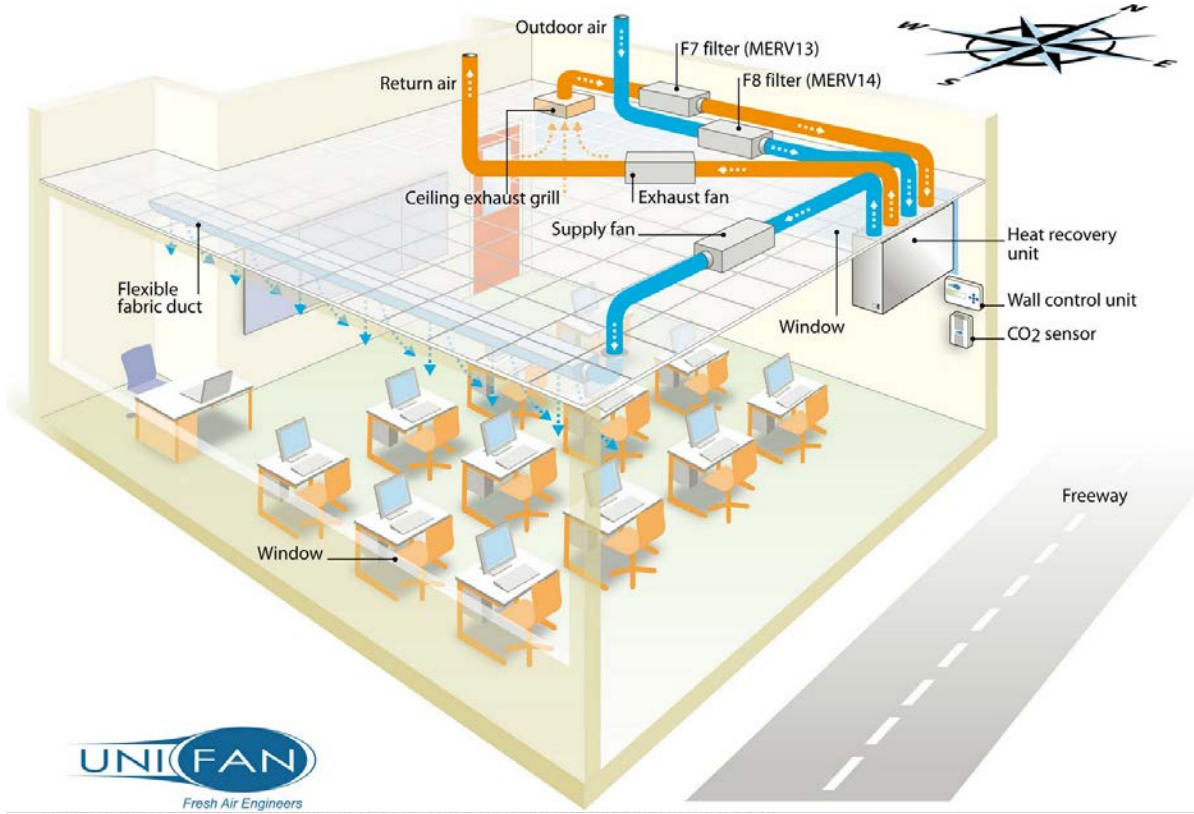


From TD-GC-MS analysis of return air on May 29th, 2019, of 1.9 μg/m^3 measured:



[1]Seigler, D.S. 1998, Plant Secondary Metabolism, Chp. 19 Pages 324-352

Air cleaning efficacy in occupied schools



Air-cleaning and ventilation (MERV13/14) system implemented in near-roadway school in Amsterdam[1]

- Reduced I/O ratio of BC by, on average, 36%
- Authors suggest high infiltration, recommend locating schools far from freeways

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Additive air "cleaners"

Bipolar Ionization/Corona Discharge/ Needlepoint Ionization and Other Ion or Reactive Oxygen Air Cleaners

ASHRAE: Convincing scientifically-rigorous, peer-reviewed studies do not currently exist on this emerging technology; manufacturer data should be carefully considered.[1] **May range from "ineffective" to "very effective"[2]**

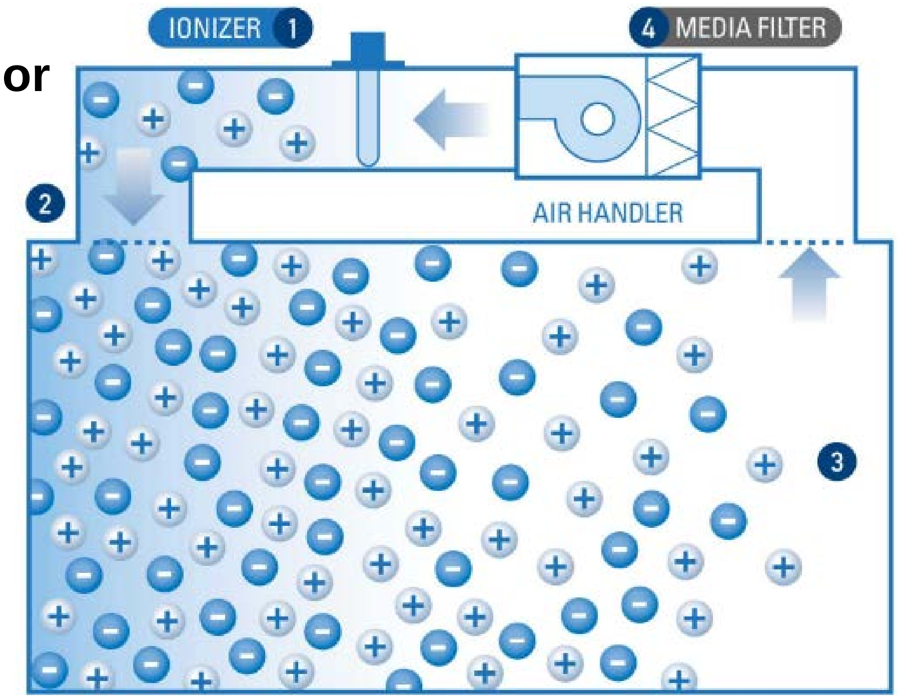


Image: ASHRAE

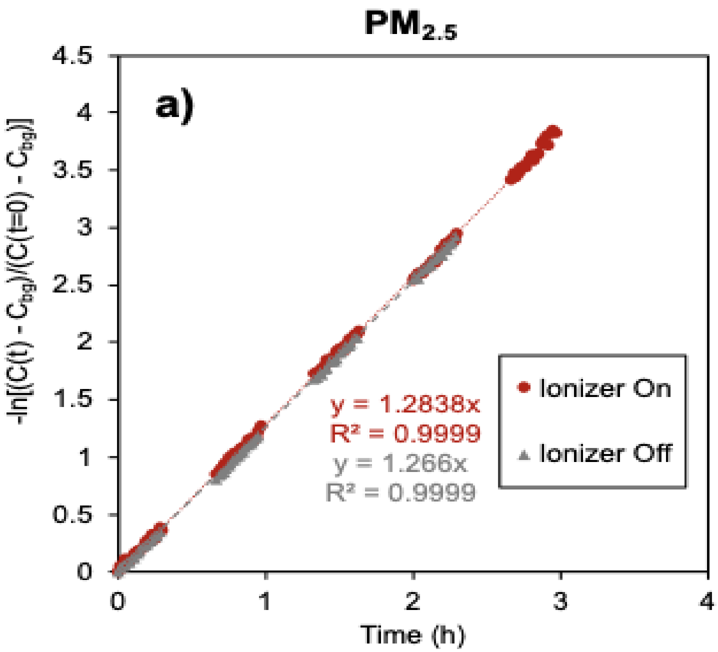
Recent peer-reviewed studies:

- Negative ions (~60,000 /cm^3) decreased $PM_{2.5}$, did not reduce markers of oxidative stress. "…downsides do not support the use of [negative ions] as a health-based mitigation strategy …"[3]
- Ionizer use in Beijing classrooms (~13,000 /cm^3) may have positively impacted respiratory health at the expensive of negative effects on cardiac health.[4]

[1]https://www.ashrae.org/technical-resources/filtration-disinfection; [2]ASHRAE, 2018. ASHRAE Position Document on Filtration and Air Cleaning. [3]Liu et al. 2020 Indoor Air, https://doi.org/10.1111/ina.12728 [4]Dong et al. 2019, Env. Poll. 254: 113054

Effects in the space

Particles: little to no effect on loss rates



Loss rates (1/h):

	Ionizer off	Ionizer on
PM2.5	1.27	1.28
SMPS (10-150 nm)	1.31	1.45
OPS (0.3 – 10 µm)	1.16	1.13

VOCs: some removed, some formed

Analyte	% Change in I/O Ratio[1]
Formaldehyde	+2%
Acetaldehyde	+13%
Acetone	+73%
Butyraldehyde	+28%
Toluene	+15%
1,2-Dichloroethane	< -42%
Ethylbenzene	< -64%
m,p-Xylene	< -78%
Dichlorodifluoromethane	< -17%
Summed TOC[2]	-19%

[1] values with < indicate measured value inside the chamber was below MDL

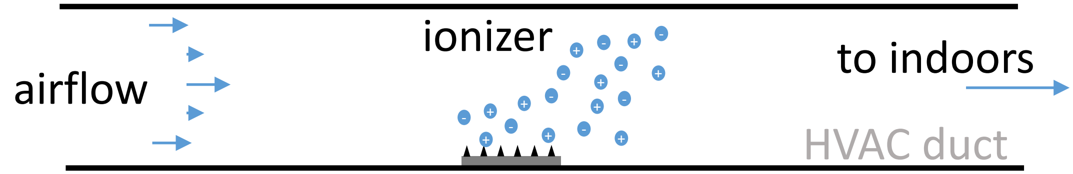
Experiments and results by IIT, led by Dr. Brent Stephens w/ his team

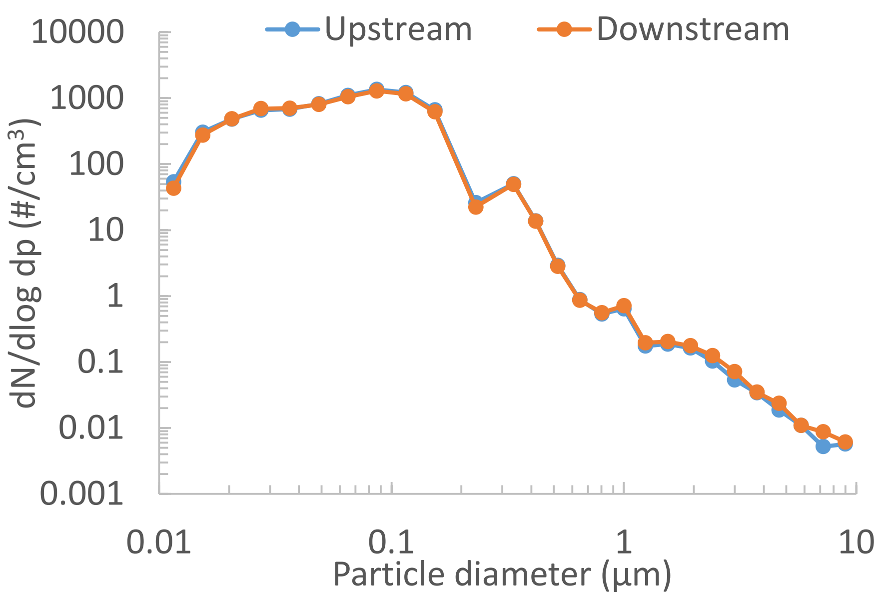
Zeng et al. 2021, Building and Environment, doi:10.1016/j.buildenv.2021.107750

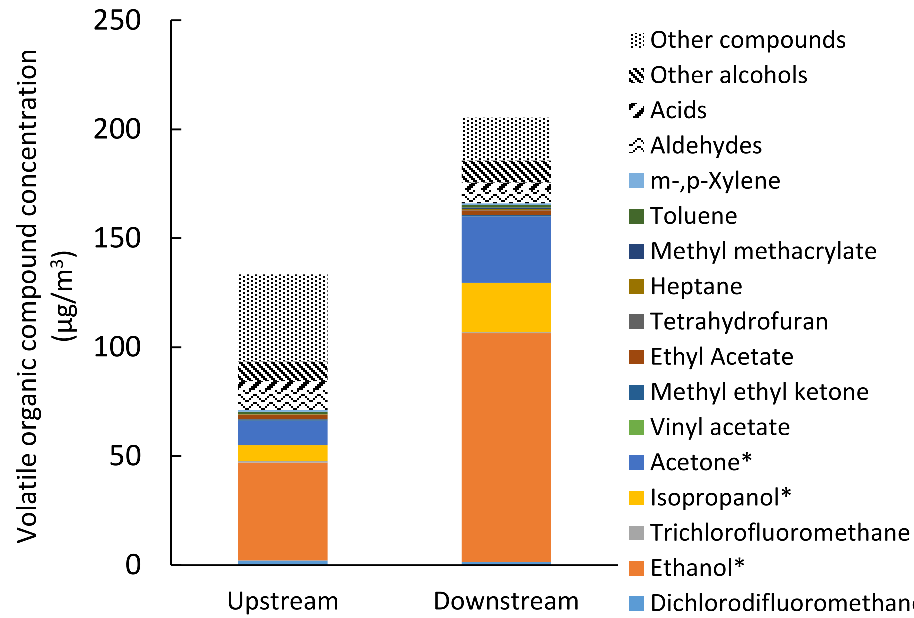
Effects in the duct

Possible claims:

- ↑ removal by filtration if ionizer upstream filter
- ↑ particle deposition in duct







**extrapolated beyond calibration curve*

Field measurement results:

- Measurements in office building with NPBI operating, averaged over 1 h
- Ozone levels were similar upstream and downstream
- No evidence of agglomeration, VOC byproducts generated

Zeng et al. 2021, Building and Environment, doi:10.1016/j.buildenv.2021.107750