Testing of a Low-Cost Sensor and Sampling Platform Alongside Reference Instruments in a Home Kitchen

Session 4C: Indoor Sensing for Air Quality Control and Ventilation Applications
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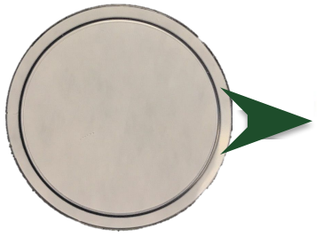
MECHANICAL ENGINEERING
COLORADO STATE UNIVERSITY

Tools for characterizing indoor air pollution

Physical samples

PM



Mettler-Toledo

ThermoFisher Scientific

VOCs

MilliporeSigma

Markes International

ThermoFisher Scientific

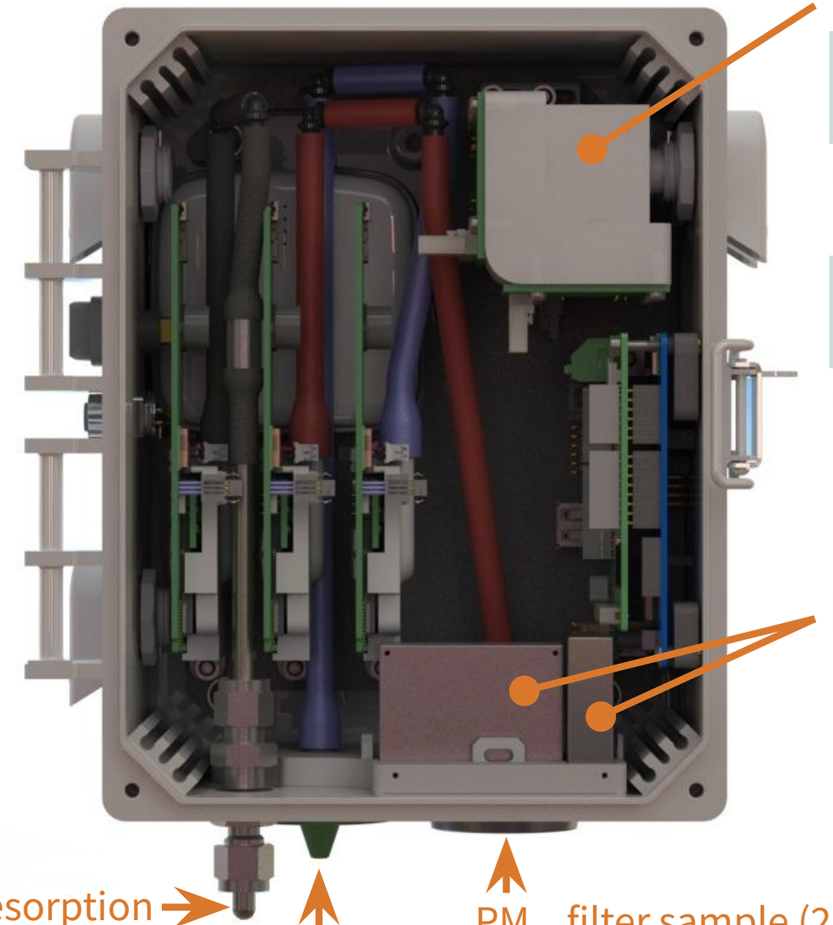
Low-cost sensors

Plantower

Sensirion

Alphasense

Low-Cost Sensor and Sampling Platform



Gas Sensors

CO_2	Sensirion SCD30 (NDIR)
CO	Alphasense B series (Electrochemical)
NO_2	Alphasense B series (Electrochemical)
O_3	Alphasense B series (Electrochemical)

Real-time PM sensors
Plantower PMS5003
Sensirion SPS30

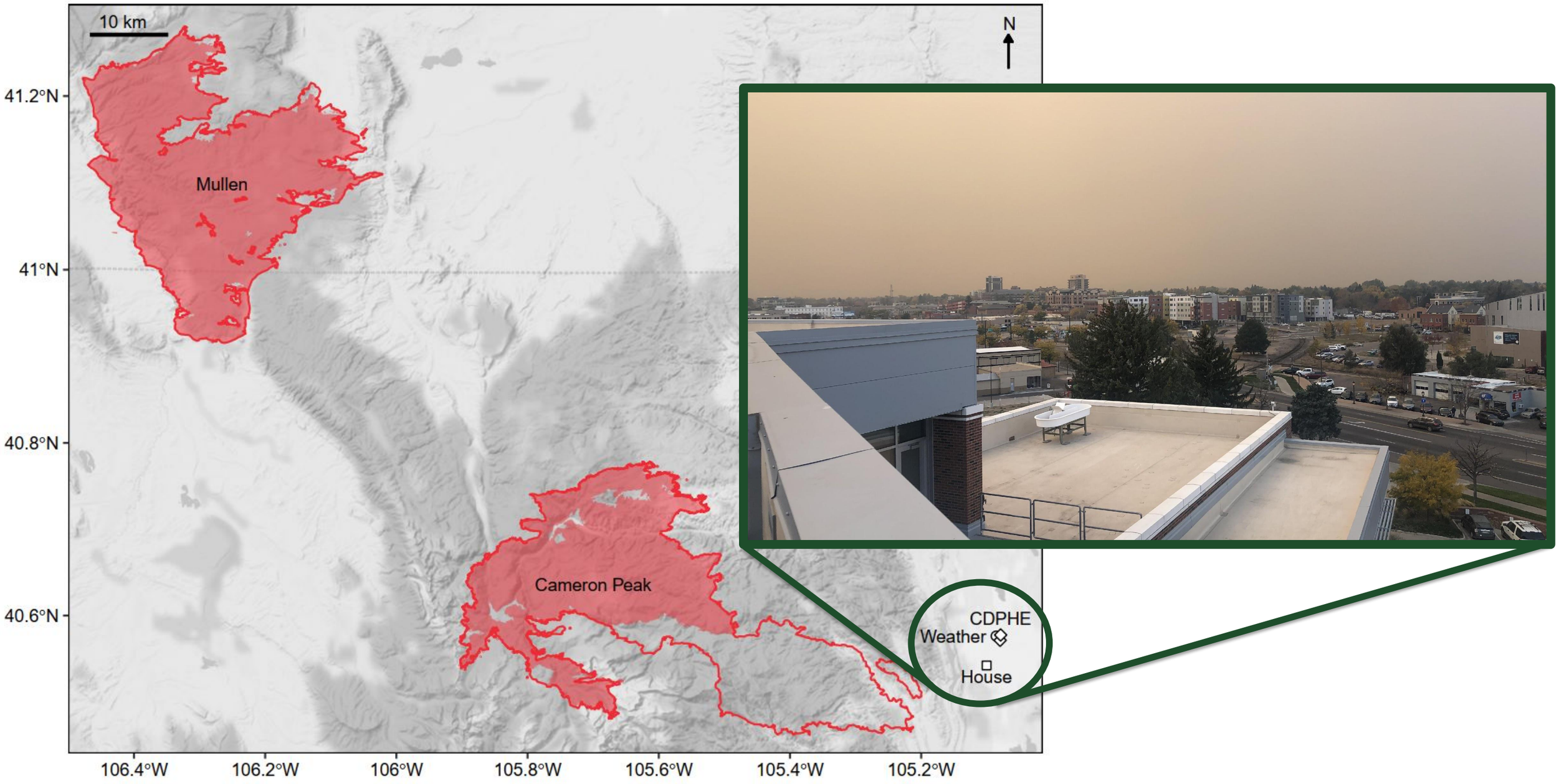
Thermal desorption tube sample (0.03 L min^{-1})

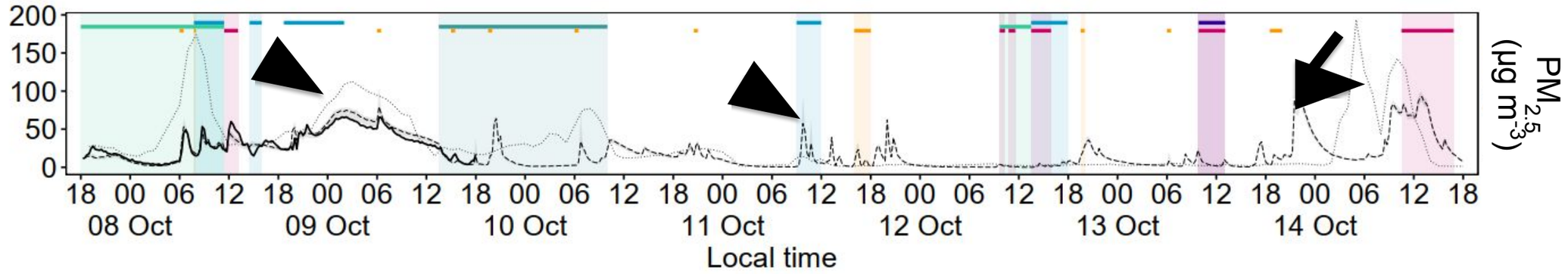
$PM_{2.5}$ filter sample (2 L min^{-1})

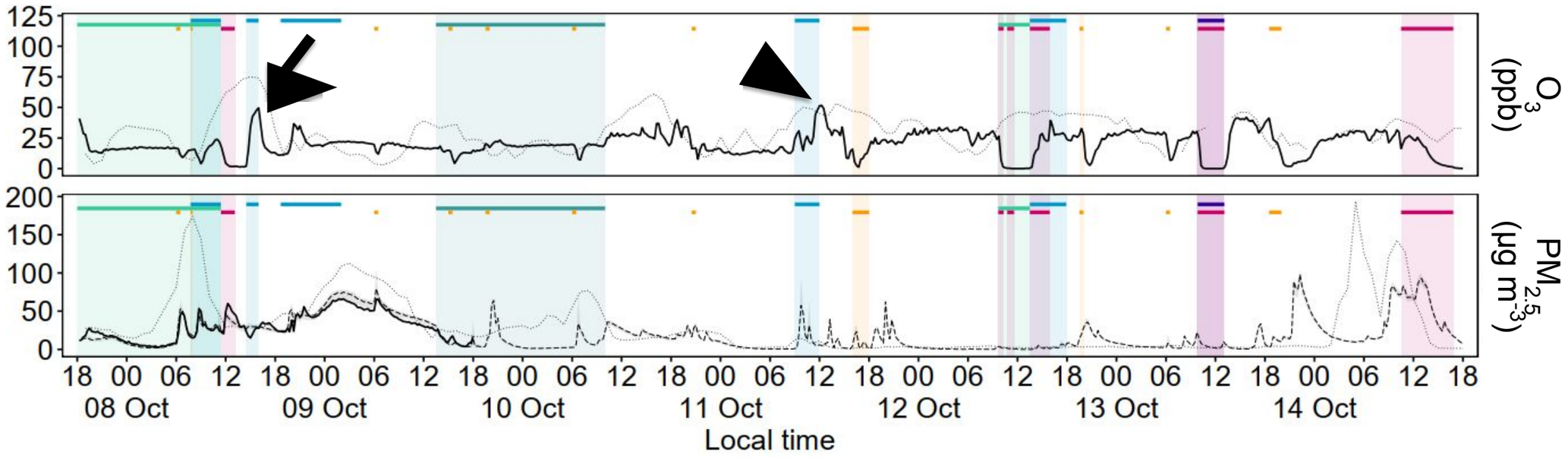
PM_{10} filter sample (2 L min^{-1})

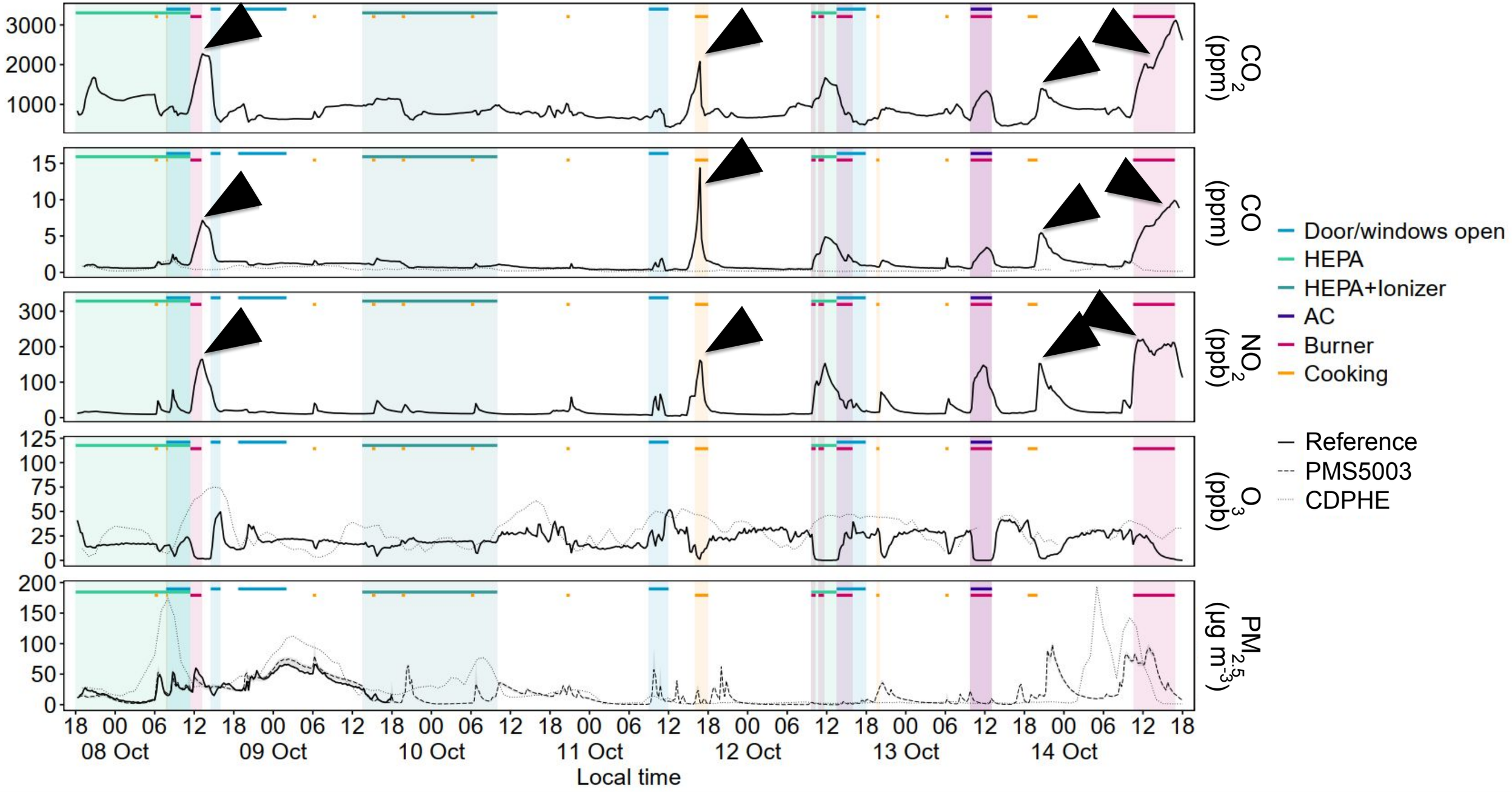
Instruments Installed in Kitchen

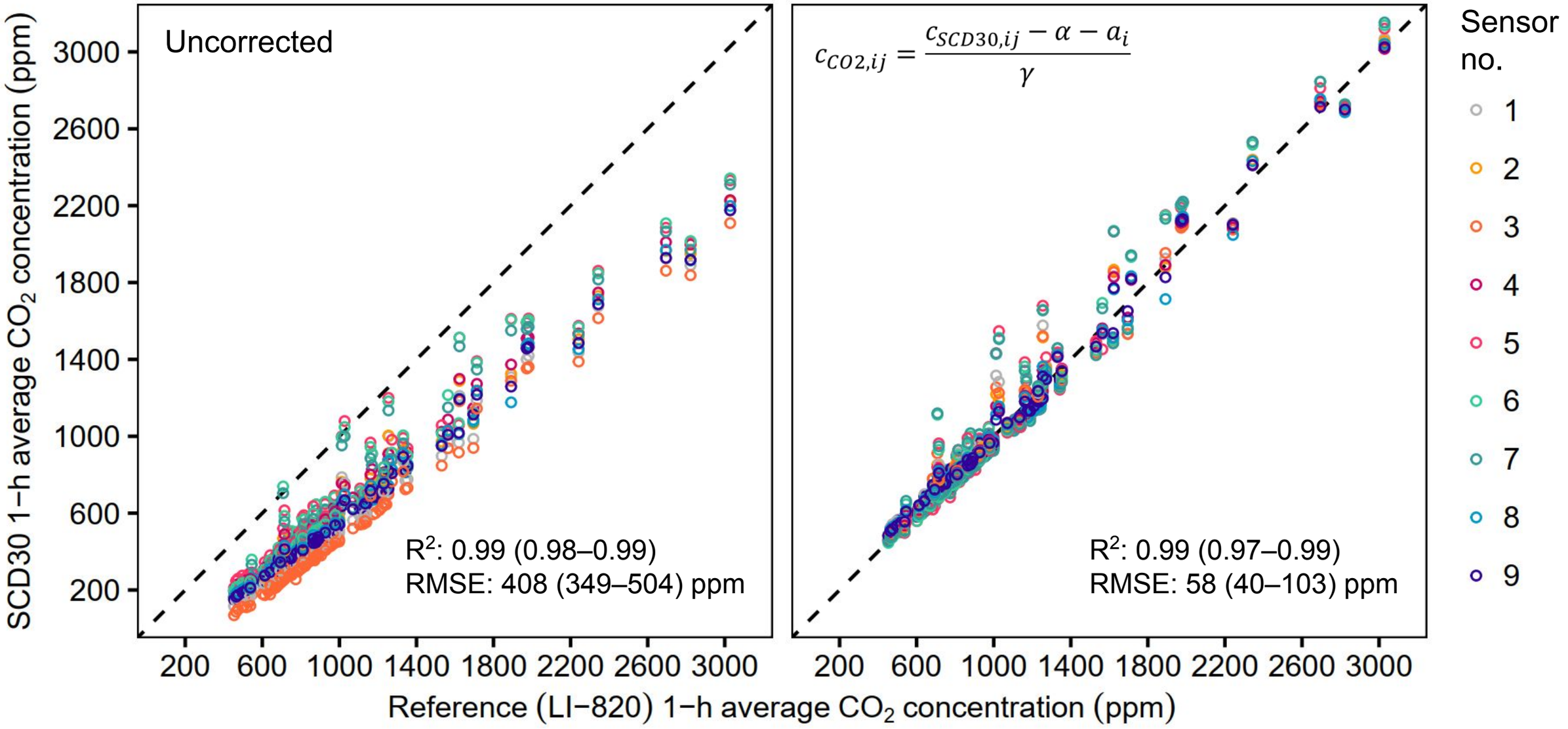
Reference Instruments	
CO_2	LI-COR LI-820 (NDIR)
CO	TSI Q-Trak (Electrochemical)
NO_2	Thermo 42C (Chemiluminescence)
O_3	Thermo 49C (UV Photometric)
$PM_{2.5}$	Thermo TEOM 1405


10 km
N
Mullen
Cameron Peak
CDPHE
Weather
House
41.2°N
41°N
40.8°N
40.6°N
106.4°W
106.2°W
106°W
105.8°W
105.6°W
105.4°W
105.2°W


Door/windows open
HEPA
HEPA+Ionizer
AC
Burner
Cooking
Reference
PMS5003
CDPHE
200
150
100
50
0
18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18
08 Oct
09 Oct
10 Oct
11 Oct
12 Oct
13 Oct
14 Oct
Local time
PM2.5 (μg m-3)


Door/windows open
HEPA
HEPA+Ionizer
AC
Burner
Cooking
Reference
PMS5003
CDPHE
125
100
75
50
25
0
O_3 (ppb)
200
150
100
50
0
$PM_{2.5}$ ($\mu g\ m^{-3}$)
18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18
08 Oct
09 Oct
10 Oct
11 Oct
12 Oct
13 Oct
14 Oct
Local time


3000
2000
1000
CO_2 (ppm)
15
10
5
0
CO (ppm)
300
200
100
0
NO_2 (ppb)
125
100
75
50
25
0
O_3 (ppb)
200
150
100
50
0
$PM_{2.5}$ ($\mu g\ m^{-3}$)
18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18 00 06 12 18
08 Oct
09 Oct
10 Oct
11 Oct
12 Oct
13 Oct
14 Oct
Local time
Door/windows open
HEPA
HEPA+Ionizer
AC
Burner
Cooking
Reference
PMS5003
CDPHE


Uncorrected
$c_{CO2,ij} = \frac{c_{SCD30,ij} - \alpha - a_i}{\gamma}$
SCD30 1−h average CO_2 concentration (ppm)
Reference (LI−820) 1−h average CO_2 concentration (ppm)
200
600
1000
1400
1800
2200
2600
3000
R^2: 0.99 (0.98–0.99)
RMSE: 408 (349–504) ppm
R^2: 0.99 (0.97–0.99)
RMSE: 58 (40–103) ppm
Sensor no.
1
2
3
4
5
6
7
8
9

Electrochemical gas sensor calibration

Sensor manufacturer-supplied calibration models

(1)

(2)

(3)

(4)

$$c_{ij} = \frac{WE_{c,ij}}{r_{T,ij} s_i}$$

WE = working electrode
AE = auxiliary electrode

Electrochemical gas sensor calibration

Sensor manufacturer-supplied calibration models

(1)

(2)

(3)

(4)

$$c_{ij} = \frac{WE_{c,ij}}{r_{T,ij} s_i}$$

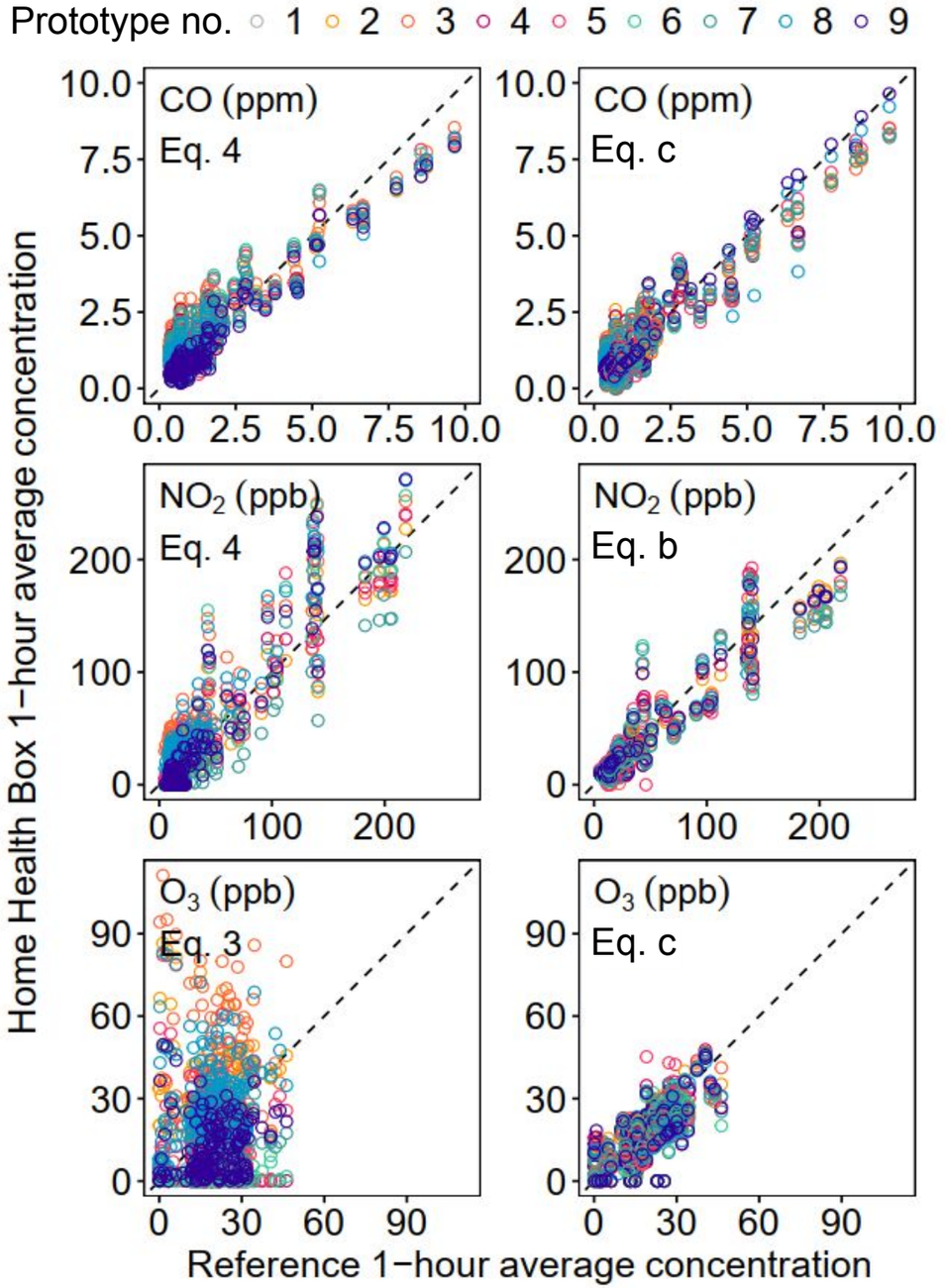
WE = working electrode
AE = auxiliary electrode

Empirical calibration models

(a)

(b)

(c)

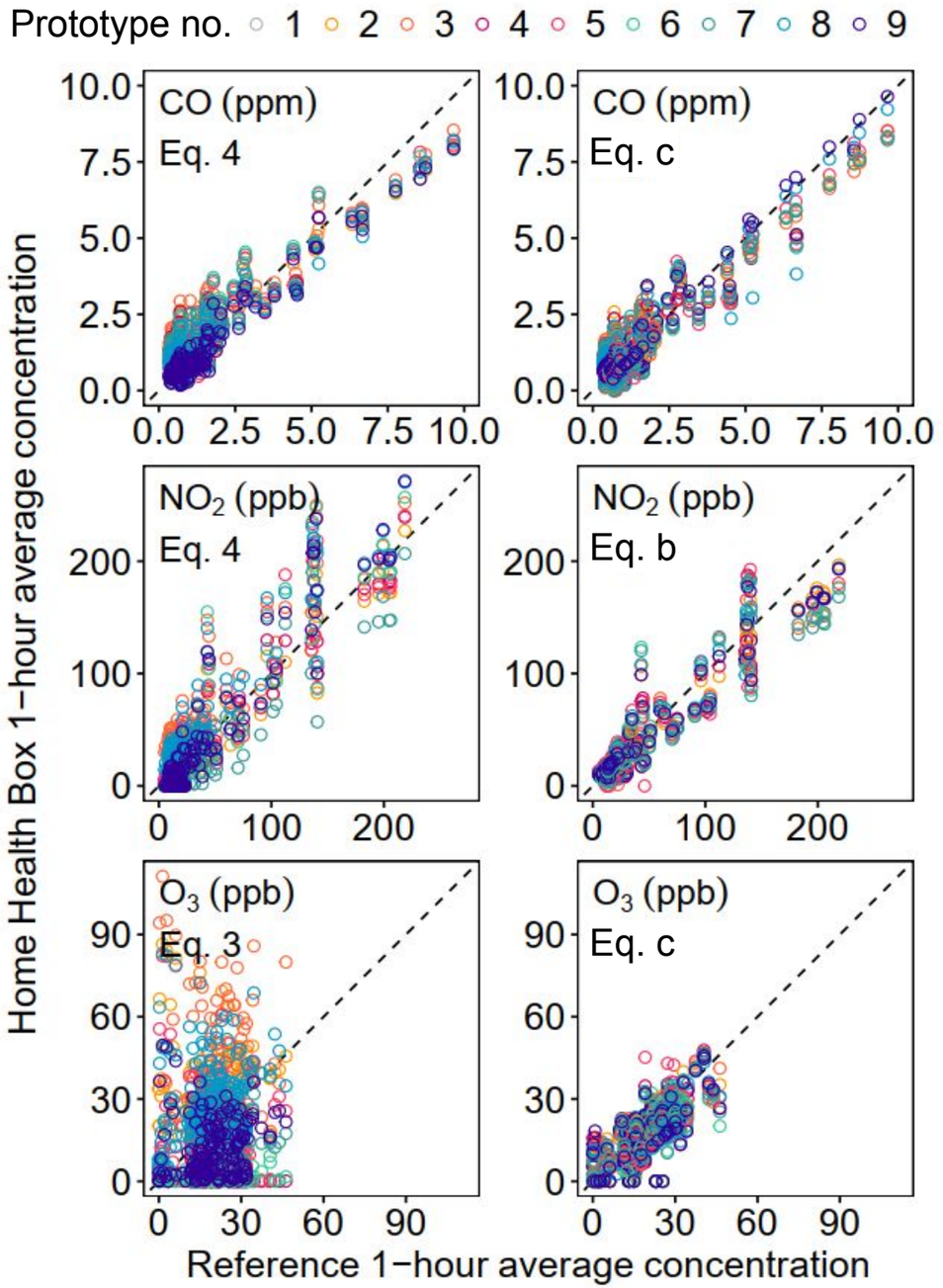

Prototype no. 1 2 3 4 5 6 7 8 9
CO (ppm)
Eq. 4
CO (ppm)
Eq. c
NO2 (ppb)
Eq. 4
NO2 (ppb)
Eq. b
O3 (ppb)
Eq. 3
O3 (ppb)
Eq. c
Home Health Box 1−hour average concentration
Reference 1−hour average concentration

Best-performing **sensor manufacturer-supplied** calibration models:

$$WE_{c,ij} = \left(WE_{u,ij} - WE_{e,i}\right) - WE_{0,i} - k''_{T,ij}$$

$$WE_{c,ij} = \left(WE_{u,ij} - WE_{e,i}\right) - WE_{0,i} - k''_{T,ij}$$

$$WE_{c,ij} = \left(WE_{u,ij} - WE_{e,i}\right) - \left(WE_{0,i} - AE_{0,i}\right) - k'_{T,ij}\left(AE_{u,ij} - AE_{e,i}\right)$$

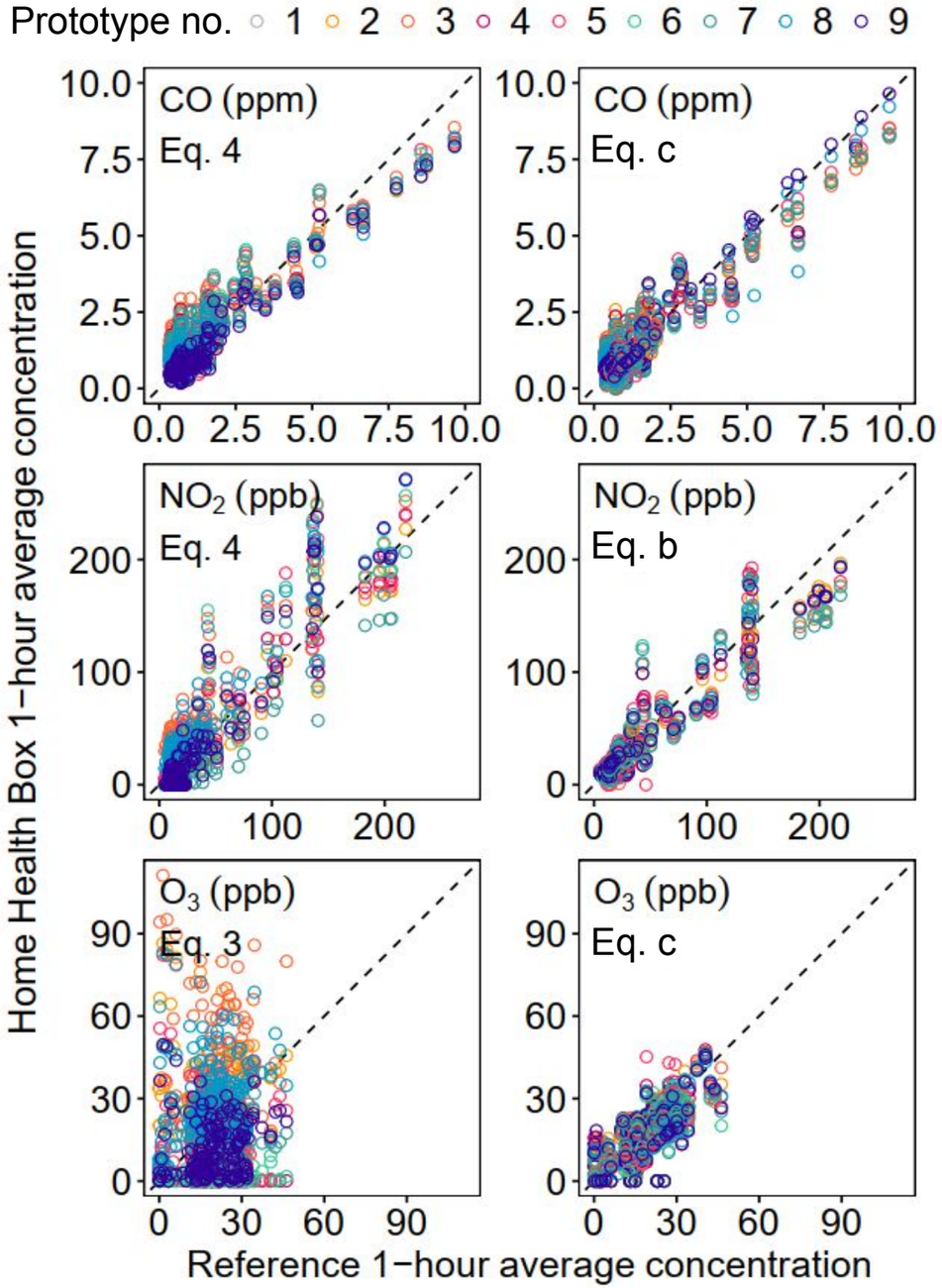


Best-performing **sensor manufacturer-supplied** calibration models:

$$WE_{c,ij} = (WE_{u,ij} - WE_{e,i}) - WE_{0,i} - k''_{T,ij}$$

$$WE_{c,ij} = (WE_{u,ij} - WE_{e,i}) - WE_{0,i} - k''_{T,ij}$$

$$WE_{c,ij} = (WE_{u,ij} - WE_{e,i}) - (WE_{0,i} - AE_{0,i}) - k'_{T,ij}(AE_{u,ij} - AE_{e,i})$$



Best-performing **empirical** calibration models:

$$c_j = \alpha + a_i + (\beta + b_i)(WE_{u,ij} - WE_{e,i}) + \gamma_{RH} RH_{ij} + \epsilon_{ij}$$

$$c_j = \alpha + a_i + (\beta + b_i)(WE_{u,ij} - WE_{e,i}) + \gamma_T T_{ij} + \epsilon_{ij}$$

$$c_j = \alpha + a_i + (\beta + b_i)(WE_{u,ij} - WE_{e,i}) + \gamma_{RH} RH_{ij} + \epsilon_{ij}$$

Comparison to air quality guidelines

Pollutant	Averaging period (h)	Range for each classification			Highest average measured		Classification	
		Low	Elevated	High	Reference	HHB	Reference	HHB
CO_2 (ppm)	8	< 1200 (ASHRAE, >700 ppm above outdoor CO_2)	1200 – 5000	> 5000 (NIOSH TWA REL)	2198	1597 (1494, 1745)	Elevated	Elevated
CO (ppm)	8	< 2 (90^{th} %ile of annual 2^{nd}-highest in U.S., 2016)	2 – 9	> 9 (EPA NAAQS, 8-h average)	6	6 (6, 6)	Elevated	Elevated
CO (ppm)	1	< 6 (WHO indoor 24-h guideline)	6 – 35	> 35 (EPA NAAQS, 1-h average)	10	8 (8, 9)	Elevated	Elevated
NO_2 (ppb)	1	< 53 (EPA NAAQS, annual average)	53 – 100	> 100 (EPA NAAQS, 1-h average)	219	246 (211, 271)	High	High
O_3 (ppb)	8	< 20 (NRC 90-day continuous exposure limit)	20 – 70	> 70 (EPA NAAQS, 8-h average)	31	59 (2, 74)	Elevated	Elevated

Source	N	Mean (μg m^{-3})	Range (μg m^{-3})	RSD (%)
Filter	9	19.4	17.2 – 20.8	6.1
PMS5003	9	33.4	26.0 – 38.5	10.5
SPS30	5	19.4	16.4 – 19.2	6.8