AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Laboratory Evaluation Report for

Atmotube Pro

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Revision History

Version	Date	Note
1	12/23/2025	VOC lab testing results added; $PM_{1/2.5}$ results from 2020 lab testing now presented in new visual format

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The laboratory evaluation was conducted in an AQ-SPEC environmental chamber with simulated pollutant and interferent concentrations that were generated from nebulizer solutions, dust dispensers, and/or gas dilution calibrators. Generated environments may not be able to fully replicate the conditions that may be experienced under ambient settings. The sensor assembly, installation, and use can also impact the reliability of the products evaluated by the AQ-SPEC program.

South Coast AQMD makes no claim, warranty, or guarantee that these devices will or will not work when operated by other users for their specific applications.

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Report Role	Name	Date Completed
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Approved by	Wilton Mui, Ph.D. (VOC)	12/23/2025 (VOC)
Revision by	Wilton Mui, Ph.D. and Michelle Kuang, Ph.D. (Version 1)	12/23/2025

Table of Contents

Section 1: Background

Three **Atmotube Pro** sensors (units IDs: B21A, 3A25, 73CD) were evaluated in an AQ-SPEC environmental chamber under controlled temperatures, humidities, and volatile organic compound (VOC) concentrations.

This report also incorporates earlier published results from three **Atmotube Pro** sensors (units IDs: E7E0, 05AB, 6C77) that were evaluated in an AQ-SPEC environmental chamber under controlled temperatures, humidities, and potassium chloride particle concentrations.

Atmotube Pro

Thermo 55i

GRIMM EDM 180

Section 2: Manufacturer Specs (VOC)

Parameter	Sensor: Atmotube Pro (raw sensor is Sensirion SGPC3)	Reference Instrument*: Thermo 55i
Pollutant	Total VOC (hereinafter referred to as "VOC")	CH_4 and non-methane hydrocarbons
Cost	$162 (at time of 2025 testing)	~$25,000
Weight	0.21 pounds	50 pounds
Dimensions (LxWxD)	3.4 x 2 x 0.9 inches	23 x 16.75 x 8.62 inches
Power	5 VDC	115 - 240 VAC
Battery	Yes (2000 mAh)	No
Data transmission	Bluetooth	Ethernet, serial, analog output
Internal memory	Yes (10 days)	Yes (>20,000 total records)
Operating temperature range	-40 to 185 degrees F (raw sensor)	59 to 95 degrees F
Operating RH range	10 to 95% (noncondensing; raw sensor)	N/A
Product website	https://atmotube.com/atmotube-pro	https://www.thermofisher.com/order/catalog/product/55I
Operating principle	Metal Oxide	Flame Ionization Detection
Time resolution	1 minute	70 seconds
Concentration range	0 – 60 ppm	0 – 50 ppm

*There is also an Agilent 6890N GC-FID that is used as a supplemental VOC reference instrument; additional results with the GC-FID can be found at the end of the report.

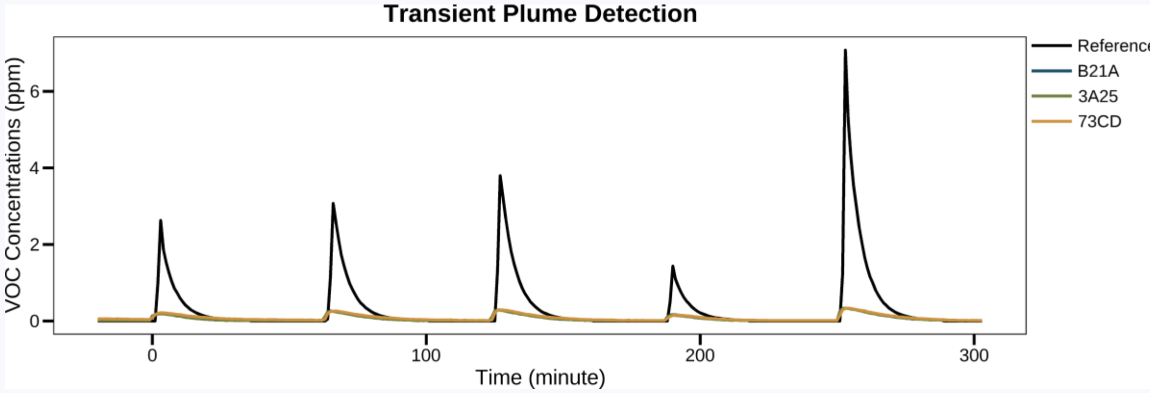
Section 2: Manufacturer Specs ($PM_{1/2.5}$)

Parameter	Sensor: Atmotube Pro (raw sensor is Sensirion SPS30)	Reference Instrument: GRIMM EDM 180
Pollutant	$PM_{1.0}$, $PM_{2.5}$, PM_{10}	$PM_{1.0}$, $PM_{2.5}$ (FEM), PM_{10}
Cost	$189 (at time of testing in 2020)	~$25,000
Weight	0.21 pounds	39.7 pounds
Dimensions (LxWxD)	3.4 x 2 x 0.9 inches	19 x 14.3 x 10.5 inches
Power	5 VDC	115 - 240 VAC
Battery	Yes (2000 mAh)	No
Data transmission	Bluetooth	USB, Ethernet, serial
Internal memory	Yes (10 days)	Yes (~3 days for 1-minute time resolution)
Operating temperature range	-40 to 185 degrees F (raw sensor)	39 to 104 degrees F
Operating RH range	10 to 95% (noncondensing; raw sensor)	<95% (noncondensing)
Product website	https://atmotube.com/atmotube-pro	https://www.durag.com/en/product-filter-837.htm?productID=EDM%20180
Operating principle	Optical light scattering	Optical light scattering
Time resolution	1 minute	1 minute (as configured)
Concentration range	0 – 1,000 µg/m³	0.1 – 1,500 µg/m³

Section 3: VOC

Section 3.1: Transient Plume Detection

Atmotube Pro vs Thermo 55i Reference



Interpretation:

- The Atmotube Pro sensors responded to 100% of the VOC peaks.
- The Atmotube Pro sensors detected the peaks at nearly the same time as the Thermo 55i reference; the apparent difference is due to different sampling times of the sensors vs. the Thermo 55i reference instrument.

Section 3: VOC

Section 3.2: Initial Concentration Ramp

Section 3.2.1: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC, low conc. ramp	100%	100%	100%
VOC, high conc. ramp	100%	100%	100%

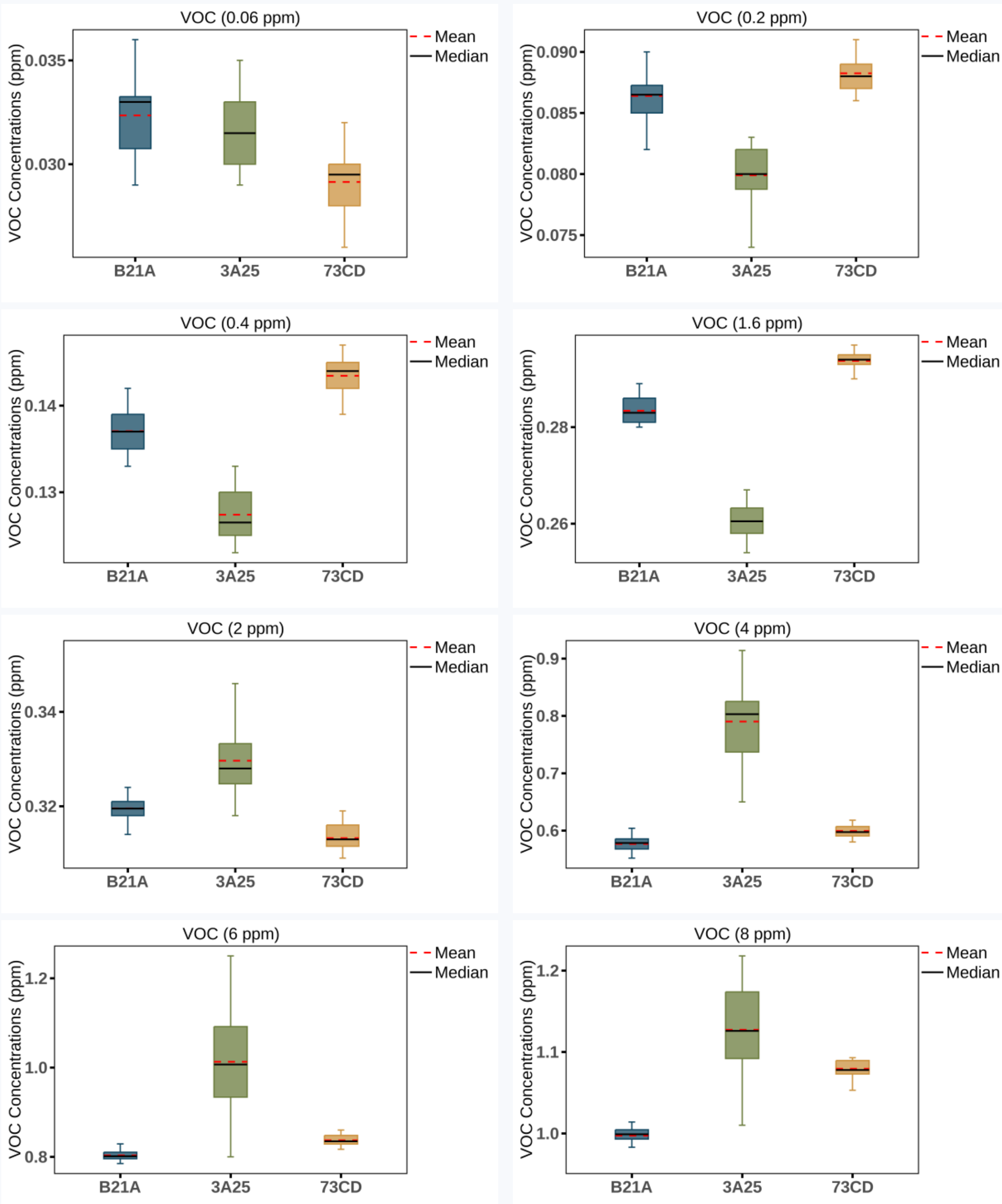
Section 3.2.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

Test VOC Concentration (ppm)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
0.06	0.002	5.35
0.20	0.004	5.17
0.40	0.008	5.94
1.60	0.017	6.09
2.00	0.008	2.58
4.00	0.117	17.89
6.00	0.113	12.73
8.00	0.066	6.16

Section 3: VOC

Section 3.2.2: Intra-Model Variability – Box Plots



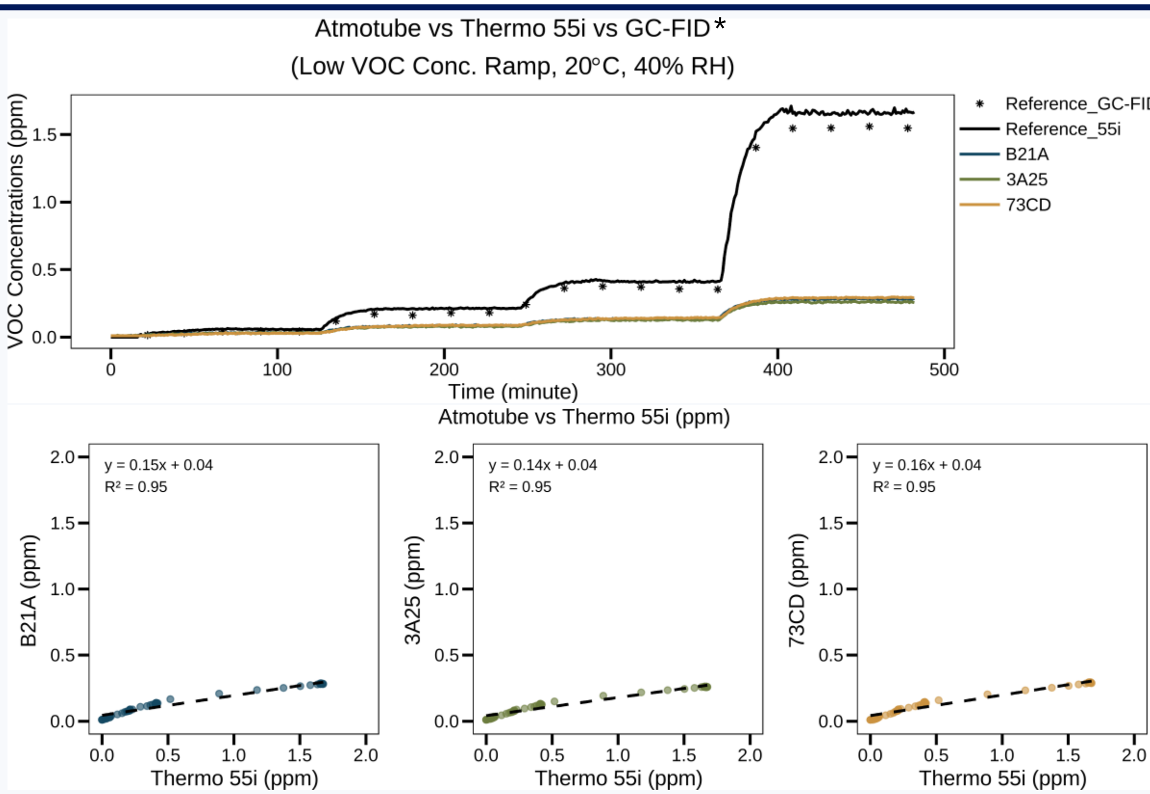
Section 3: VOC

Section 3.2.3: Linearity (R^2) – Low Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
VOC, low conc. ramp	5-minute	0.95 ± 0.00



Interpretation:

- The Atmotube Pro sensors showed very strong correlation with the corresponding Thermo 55i reference instrument (R^2 = 0.95), at 5-minute averaging, for a VOC mixture containing equal concentrations of 1,3 butadiene, benzene, ethane and tetrachloroethylene, from 0.06 to 1.6 ppm (low concentration ramp), at 20°C and 40% RH.

*There is also an Agilent 6890N GC-FID that is used as a supplemental VOC reference instrument; additional results with the GC-FID can be found at the end of the report.

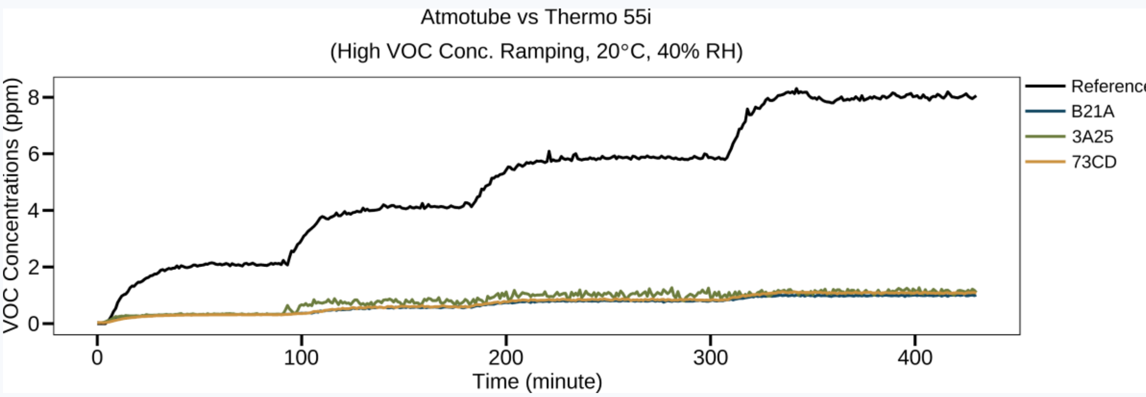
Section 3: VOC

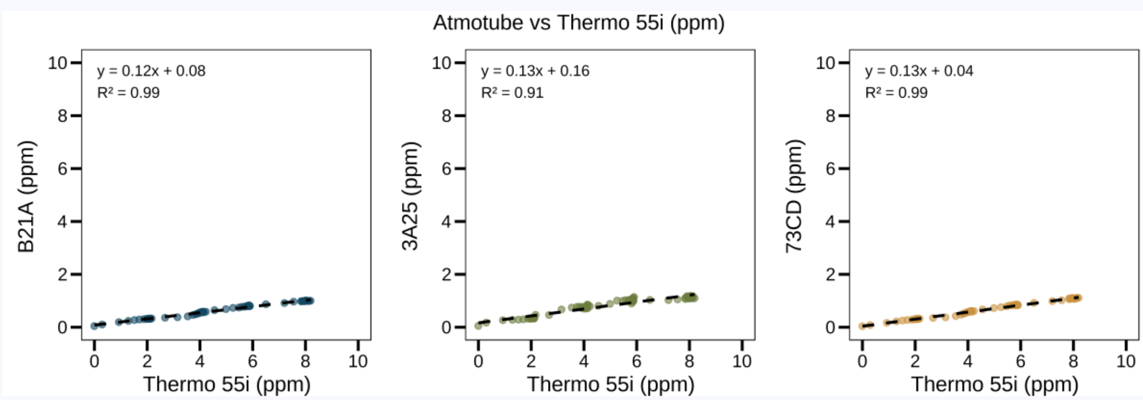
Section 3.2.3: Linearity (R^2) – High Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
VOC, high conc. ramp	5-minute	0.96 ± 0.05





Interpretation:

- The Atmotube Pro sensors showed very strong correlation with the corresponding Thermo 55i reference instrument ($R^2 > 0.91$) at 5-minute averaging, for a VOC mixture containing equal concentrations of 1,3 butadiene, benzene, ethane and tetrachloroethylene, from 2 to 8 ppm (high concentration ramp), at 20°C, 40% RH.

Section 3: VOC

Section 3.3: Effect of Temperature and Humidity

Section 3.3.1: Normal and Extreme Conditions

Section 3.3.1.1: Data Recovery

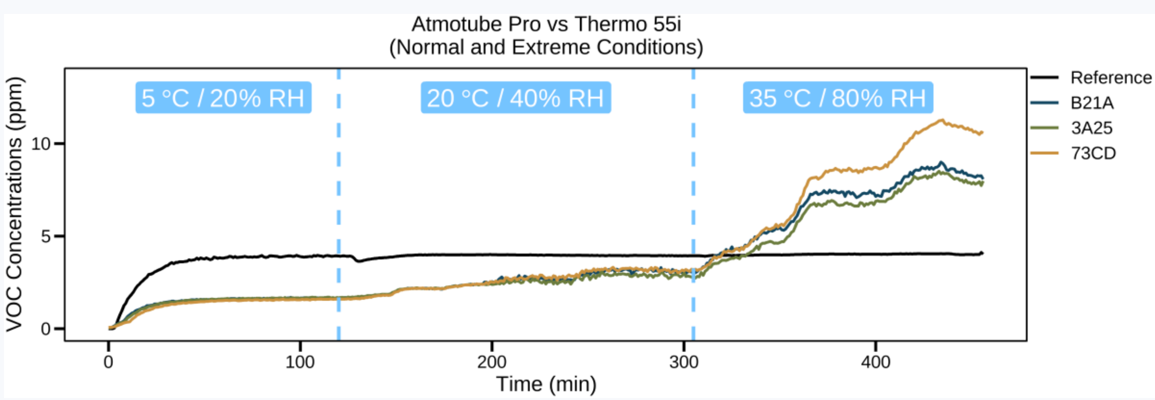
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.3.1.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

Condition	T (°C)	RH (%)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
Cold/dry	5	20	0.05	2.76
Baseline	20	40	0.23	7.64
Hot/humid	35	80	1.51	16.61



Interpretation:

- The Atmotube Pro sensors showed an increase in VOC concentrations as T/RH increased from 5°C/20% RH to 20°C/40% RH, and then a larger increase in mean VOC concentrations as T/RH was further increased to 35°C/80% RH, relative to the Thermo 55i reference instrument.
- The Atmotube Pro sensors' VOC concentrations increased by ~380-580% at 35°C/80% RH as compared to the concentrations reported at 5°C/20% RH.

Section 3: VOC

Section 3.3.2: RH interference

Section 3.3.2.1: Data Recovery

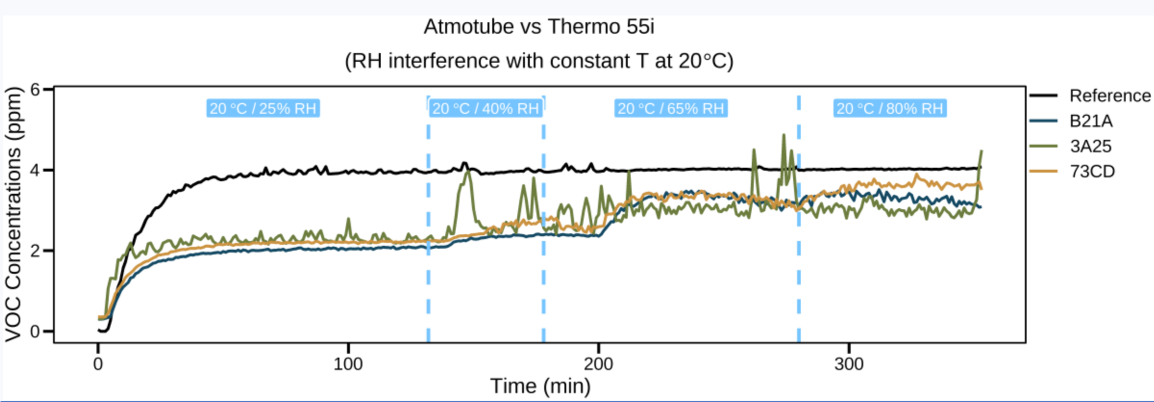
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.3.2.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

RH (%) (T constant at 20° C)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
25	0.10	4.68
40	0.21	8.22
65	0.20	6.14
80	0.28	8.33



Interpretation:

- The Atmotube Pro sensors' VOC concentrations increased by ~18 to 51% as RH increased from 25% to 80%.

Section 3: VOC

Section 3.3.3: T interference at constant RH

Section 3.3.3.1: Data Recovery

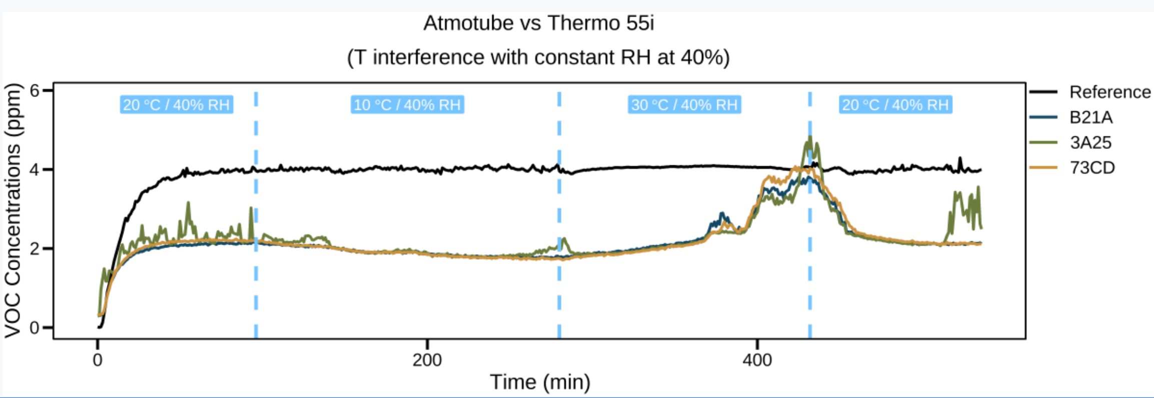
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.3.3.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

T (°C) (RH constant at 40%)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
20	0.10	4.55
10	0.10	5.66
30	0.15	4.03
10	0.51	20.97



Interpretation:

- A T change at constant RH appeared to cause sensor response to move in the same direction, i.e., the sensors' VOC reading increased when temperature increased and vice versa, after steady-state T and RH conditions were realized. The sensors showed a large concentration increase as T increased to 30°C, followed by a concentration decrease as T decreased to 20°C.

Section 3.3.4: T interference at constant absolute humidity (AH)

Section 3.3.4.1: Data Recovery

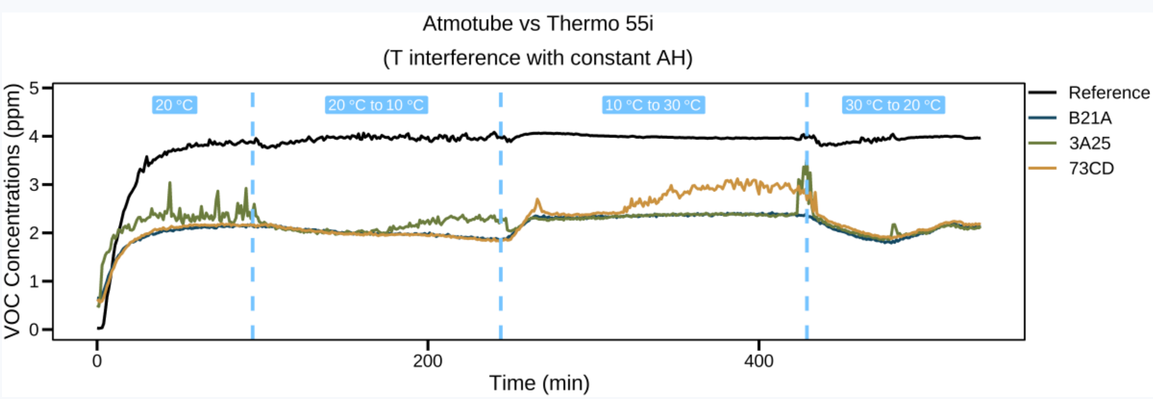
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.3.4.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

T (°C) (AH constant at 0.007 kg/m^3)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
20	0.13	6.01
10	0.24	12.07
30	0.27	10.20
10	0.04	1.92



Interpretation:

- A temperature change at constant AH appeared to cause sensor response to move in the same direction, i.e., the sensors' VOC reading increased when temperature increases and vice versa, after steady-state T and AH conditions were realized.

Section 3: VOC

Section 3.4: Effect of Gaseous Interferents

Section 3.4.1: Ozone Interference

Section 3.4.1.1: Data Recovery

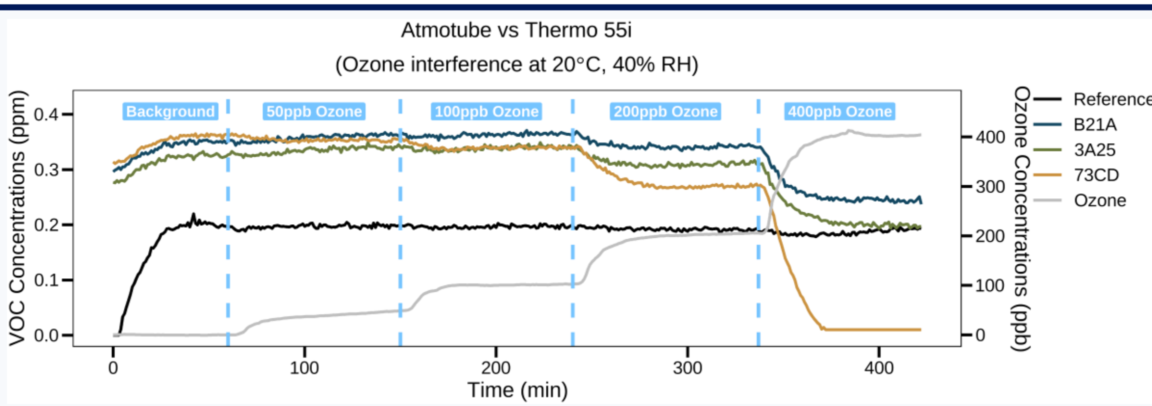
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.4.1.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

O_3 (ppb) (At constant 0.2 ppm of VOC)	Absolute intra-model variability (ppm of VOC)	Relative intra-model variability (%)
background	0.02	5.36
50	0.01	3.14
100	0.01	4.01
200	0.04	11.83
400	0.12	82.21



Interpretation:

- The VOC concentrations measured by the Atmotube sensors did not appear sensitive to O_3 concentrations up to 100 ppb.
- The VOC concentrations measured by the Atmotube Pro sensors decreased as O_3 increased from background to ~400 ppb. Unit 73CD's VOC concentration dropped to ~0 ppm when O_3 levels were at 400 ppb.

Section 3: VOC

Section 3.4.2: CO Interference

Section 3.4.2.1: Data Recovery

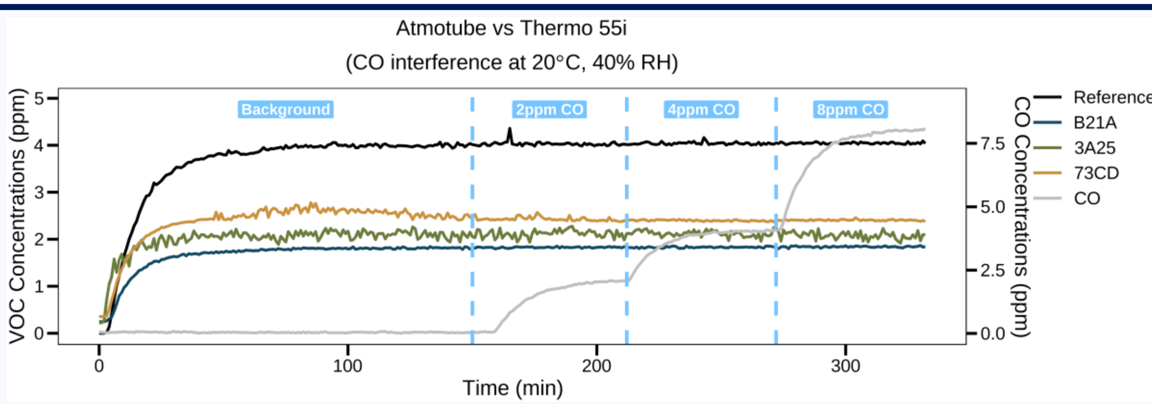
Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.4.2.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

CO (ppm) (At constant 4 ppm of VOC)	Absolute intra-model variability (ppm of VOC)	Relative intra-model variability (%)
background	0.33	15.65
2	0.29	13.64
4	0.28	13.27
8	0.28	13.43



Interpretation:

- CO had negligible effect on the VOC concentrations measured by the Thermo 55i reference instrument and the Atmotube Pro sensors as CO increased from background to ~8 ppm.

Section 3: VOC

Section 3.4.3: CO_2 Interference

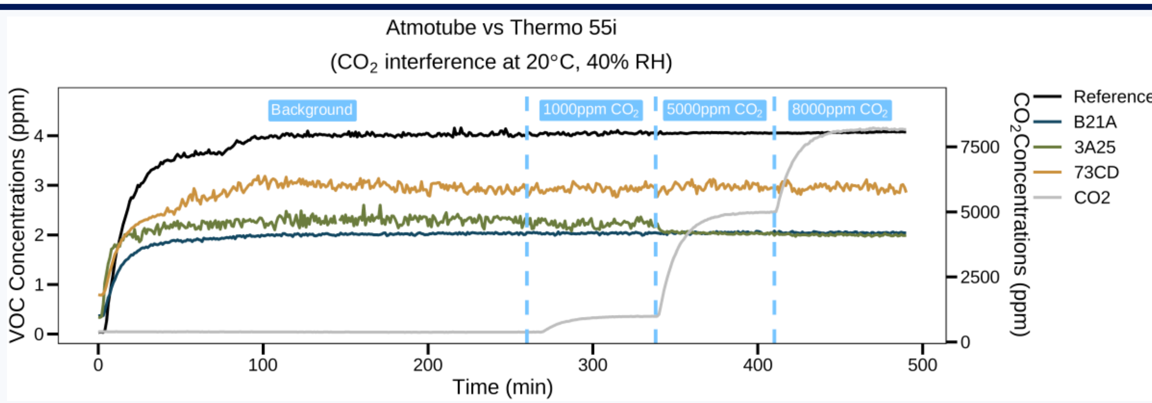
Section 3.4.3.1: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

Section 3.4.3.2: Intra-Model Variability

CO_2 (ppm) (At constant 4 ppm of VOC)	Absolute intra-model variability (ppm of VOC)	Relative intra-model variability (%)
background	0.45	18.66
2	0.48	20.00
4	0.54	23.04
8	0.52	22.47



Interpretation:

- CO_2 had minimal effect on the VOC concentrations measured by the Thermo 55i reference instrument and the Atmotube Pro as CO_2 increased from a background value of ~380 ppm to ~8000 ppm. Unit 3A25 showed a decrease in VOC concentrations at CO_2 concentrations > 5000 ppm.

Section 3: VOC

Section 3.5: Outdoor Simulation

Section 3.5.1: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC	100%	100%	100%

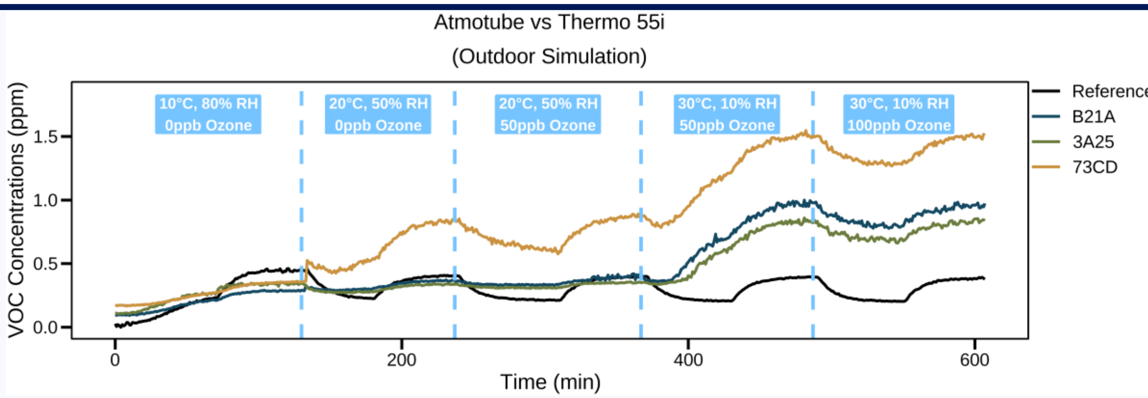
Section 3.5.2: Intra-Model Variability

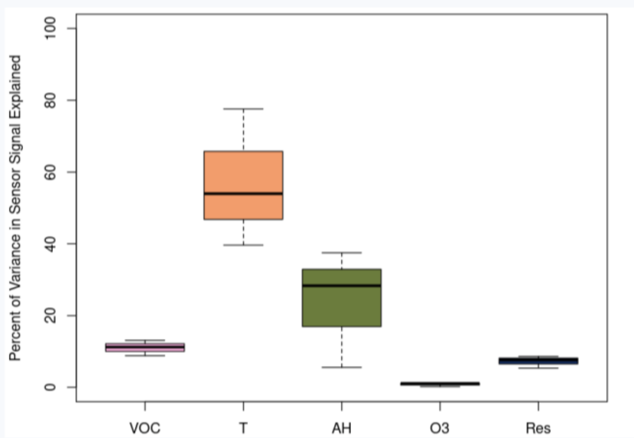
Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

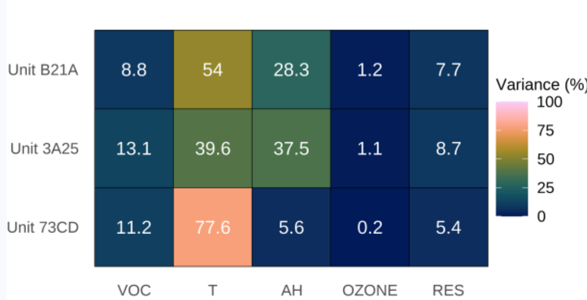
Step	VOC (ppm)	T (°C)	RH (%)	O_3 (ppb)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
1	0.2	10	80	0	0.03	13.68
2	0.4	10	80	0	0.04	11.11
3	0.2	20	50	0	0.12	33.08
4	0.4	20	50	0	0.28	54.03
5	0.2	20	50	50	0.17	40.66
6	0.4	20	50	50	0.28	52.75
7	0.2	30	10	50	0.31	39.51
8	0.4	30	10	50	0.36	32.26
9	0.2	30	10	100	0.32	34.51
10	0.4	30	10	100	0.36	32.39

Section 3: VOC

Section 3.5.3: ANOVA Statistical Test







Interpretation:

- **Temperature** explained ~ 40-78% of the Atmotube Pro sensors' VOC readings, followed by **AH** (~ 6-38%), followed by **VOC** (~ 9-13%), while **Ozone** (of up to 100 ppb O_3) explained a small percentage (<2%) of the variance.

Notes:

- "VOC" is the Thermo 55i reference VOC monitor reading
- "AH" is the absolute humidity and is used instead of RH in ANOVA due to multicollinearity between RH and T
- "RES" is the residual, or variance that is not explained by the other variables

Section 3: VOC

Section 3.6: Final Concentration Ramp

Section 3.6.1: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit B21A	Unit 3A25	Unit 73CD
VOC, low conc. ramp	100%	100%	100%
VOC, high conc. ramp	100%	100%	100%

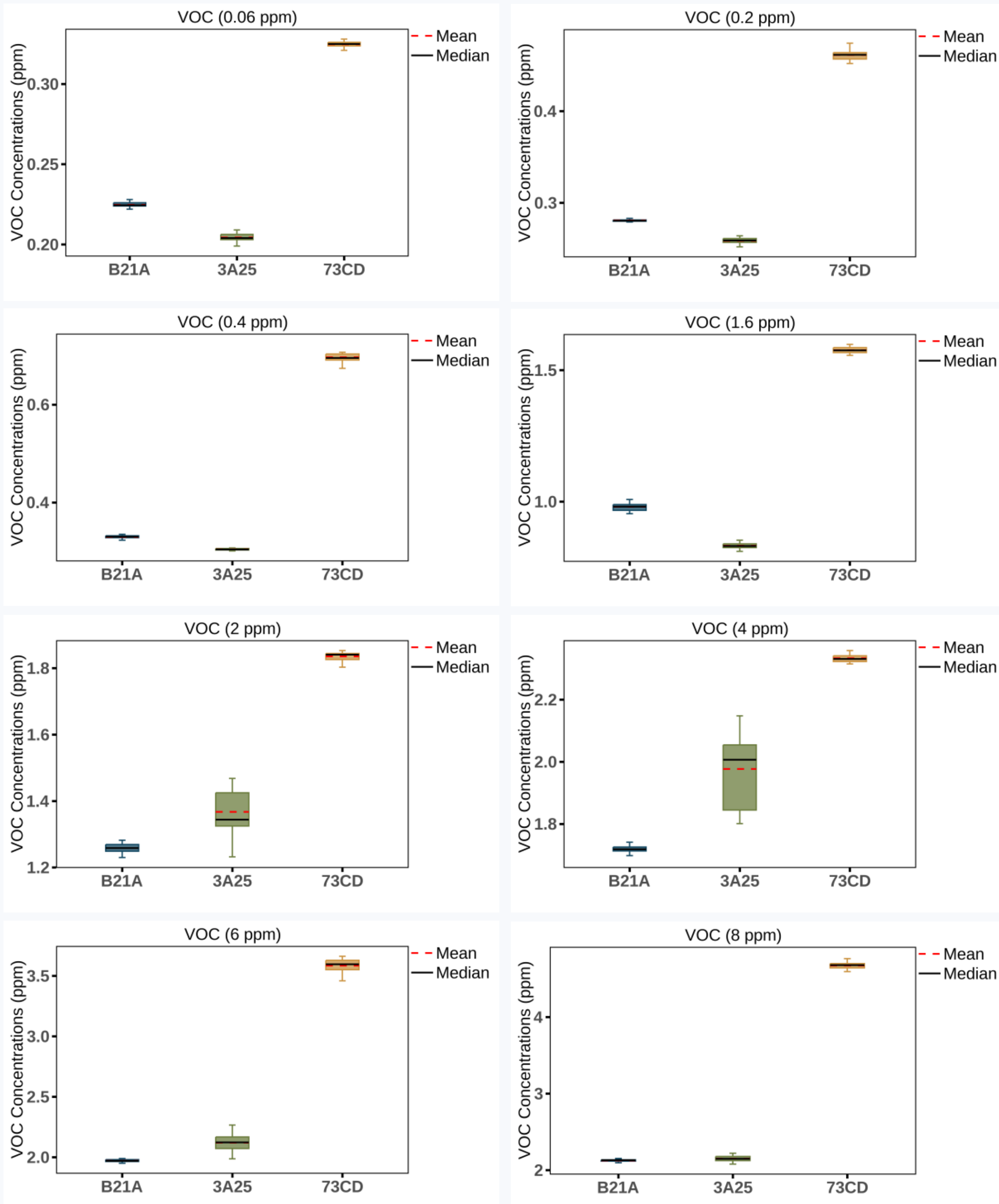
Section 3.6.2: Intra-Model Variability

Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

Test VOC Concentration (ppm)	Absolute intra-model variability (ppm)	Relative intra-model variability (%)
0.06	0.06	25.66
0.2	0.11	33.31
0.4	0.22	49.54
1.6	0.39	34.84
2	0.31	20.61
4	0.31	15.36
6	0.89	34.86
8	1.46	49.02

Section 3: VOC

Section 3.6.2: Intra-Model Variability – Box Plots



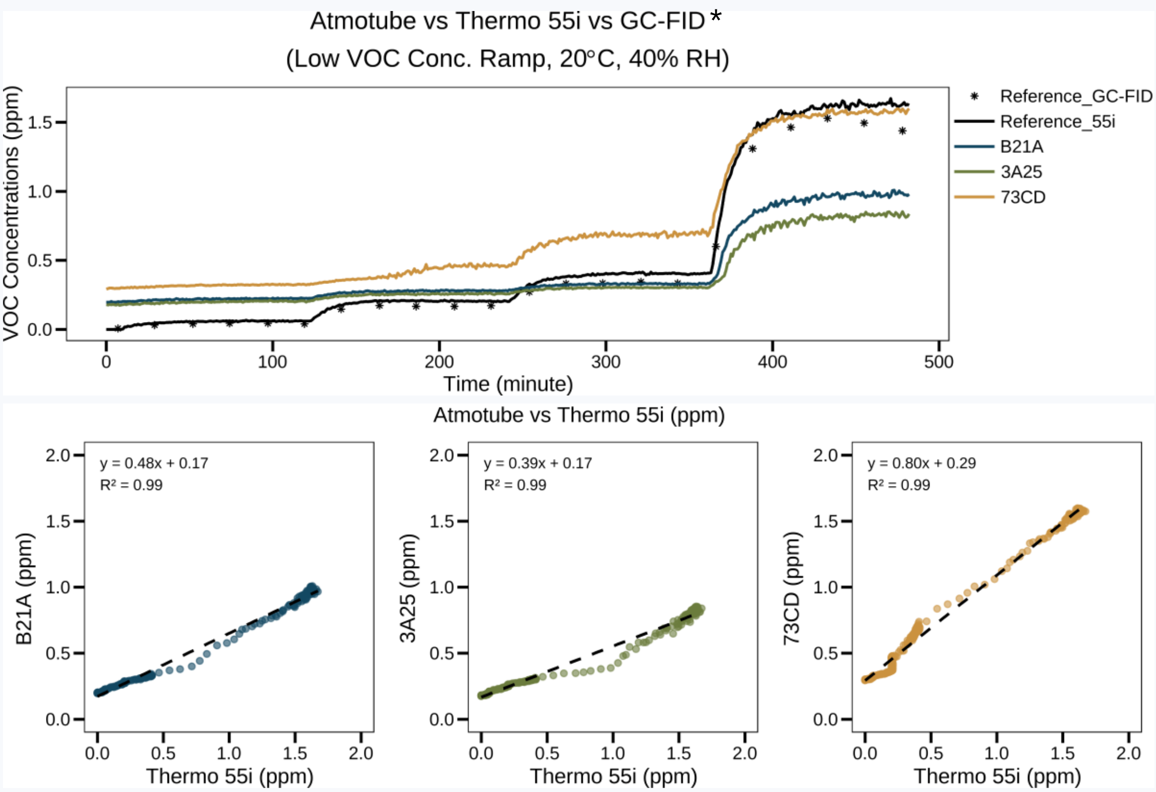
Section 3: VOC

Section 3.6.4: Linearity (R^2) – Low Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
VOC, low conc. ramp	5-minute	0.99 ± 0.00



Interpretation:

- The Atmotube Pro sensors showed very strong correlation with the corresponding Thermo 55i reference instrument (R^2 = 0.99), for a VOC mixture containing equal concentrations of 1,3 butadiene, benzene, ethane and tetrachloroethylene, from 0.06 to 1.6 ppm (low concentration ramp), at 20°C and 40% RH.

*There is also an Agilent 6890N GC-FID that is used as a supplemental VOC reference instrument; additional results with the GC-FID can be found at the end of the report.

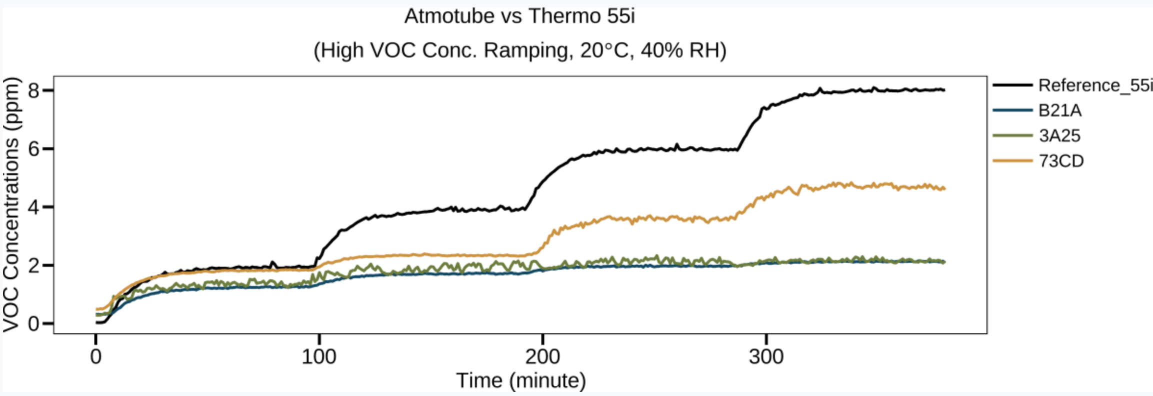
Section 3: VOC

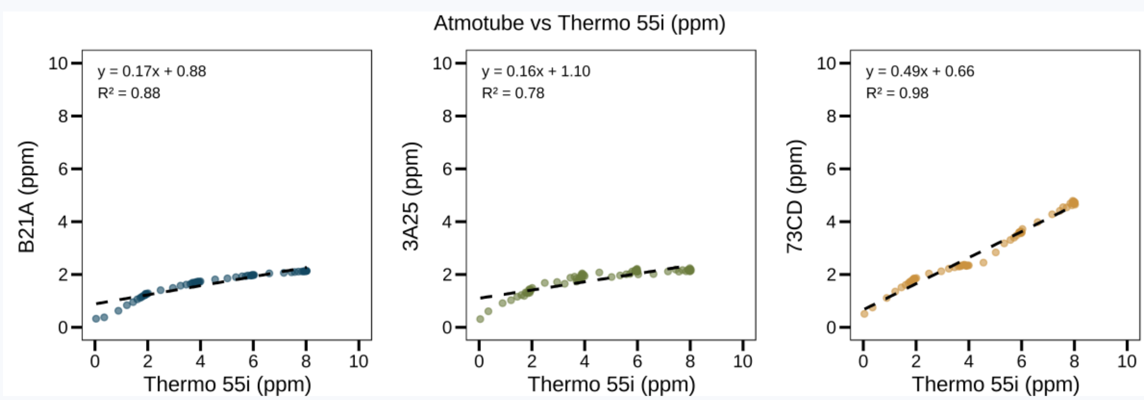
Section 3.6.4: Linearity (R^2) – High Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
VOC, high conc. ramp	5-minute	0.88 ± 0.10





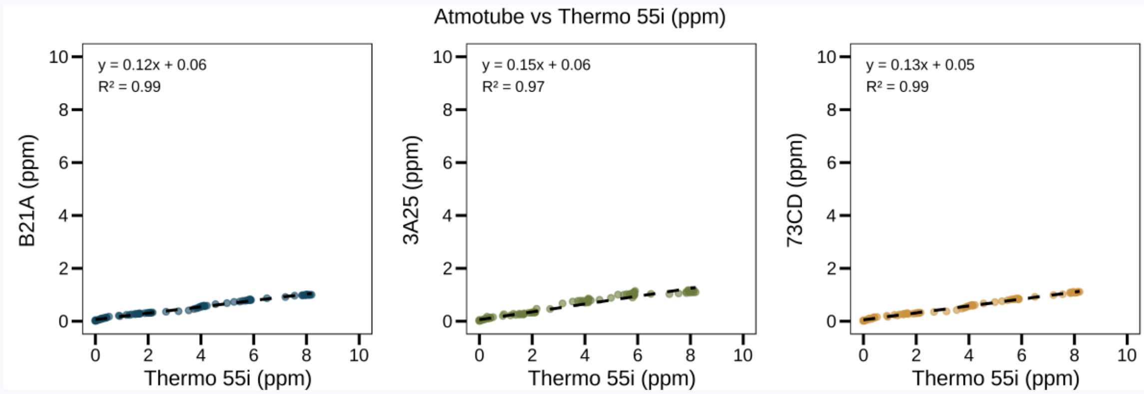
Interpretation:

- The Atmotube Pro sensors showed strong to very strong correlation with the corresponding Thermo 55i reference instrument (0.78 < R^2 < 0.99) at 5-minute averaging, for a VOC mixture containing equal concentrations of 1,3 butadiene, benzene, ethane and tetrachloroethylene, from 2 to 8 ppm (high concentration ramp), at 20°C, 40% RH.

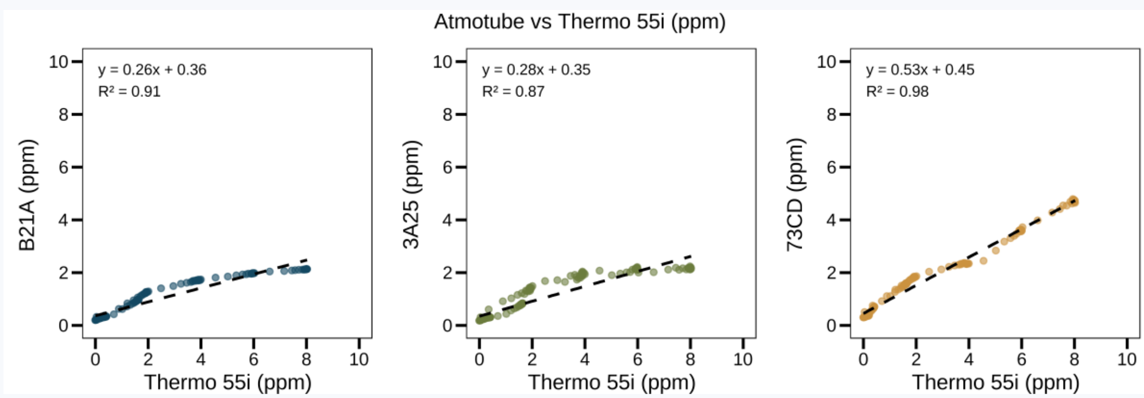
Section 3: VOC

Section 3.6.5: Short-Term Sensor Response Change

Initial Concentration Ramp



Final Concentration Ramp



Interpretation:

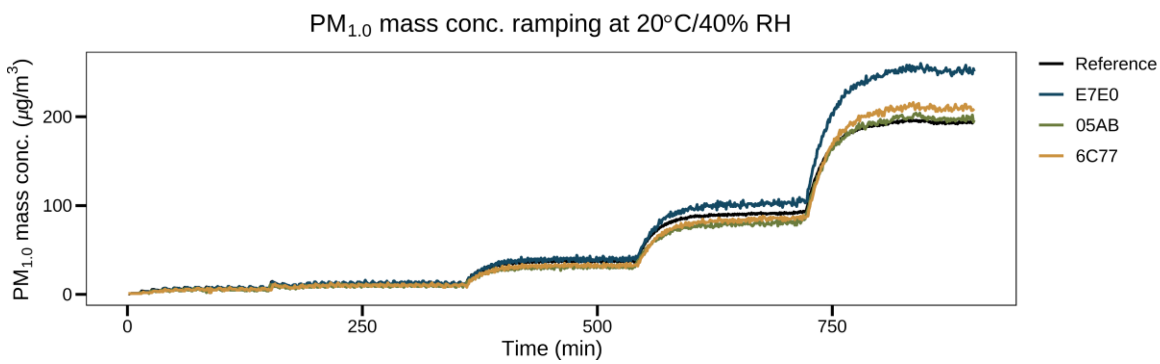
- Short-term sensor response change is characterized as the change in reference-sensor regression between the initial and final concentration ramping experiments
- Combining data from both low and high concentration ramps of the VOC blend, the slope of the final concentration ramp was higher, suggesting that the Atmotube Pro sensors on average became more sensitive to unit changes in VOC concentrations compared to the initial concentration ramp, especially for Unit 73CD.

Section 4: $PM_{1.0}$

Section 4.1: Concentration Ramp

Section 4.1.2: Data Overview

Timeseries of $PM_{1.0}$ Concentration Ramp



Section 4.1.3: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

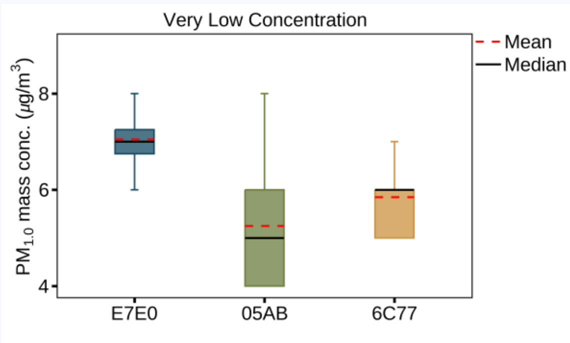
Parameter	Unit E7E0	Unit 05AB	Unit 6C77
$PM_{1.0}$	100%	100%	100%

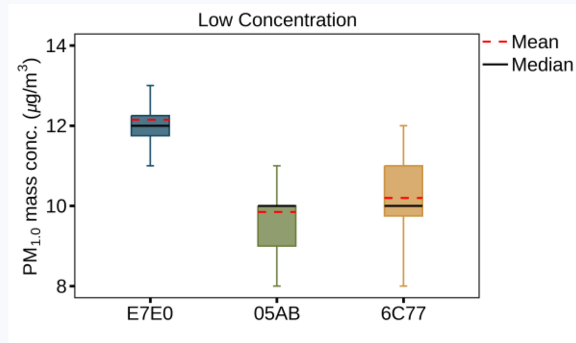
Section 4.1.4: Intra-Model Variability

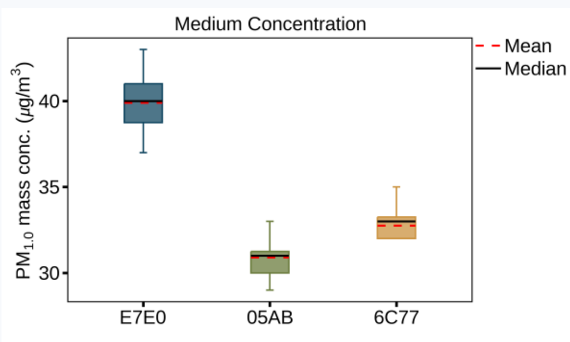
Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

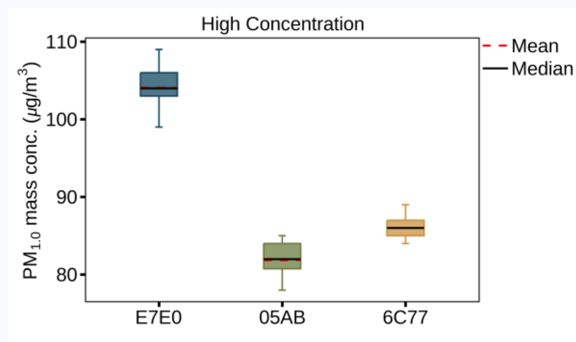
$PM_{1.0}$ Concentration (µg/m³)	Absolute intra-model variability (µg/m³)	Relative intra-model variability (%)
Very Low (7.2)	0.92	15.15
Low (12.0)	1.24	11.55
Medium (37.8)	4.75	13.77
High (92.1)	11.83	13.05
Very High (193.5)	28.55	12.99

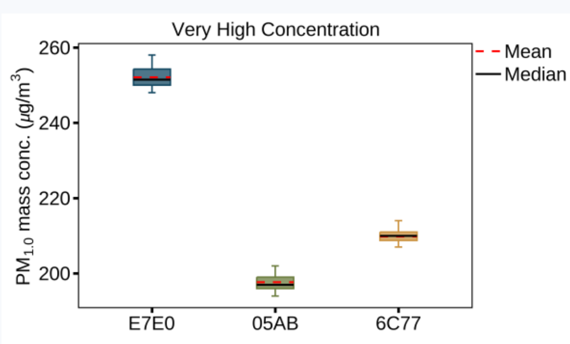
Section 4.1.4: Intra-Model Variability – Box Plots











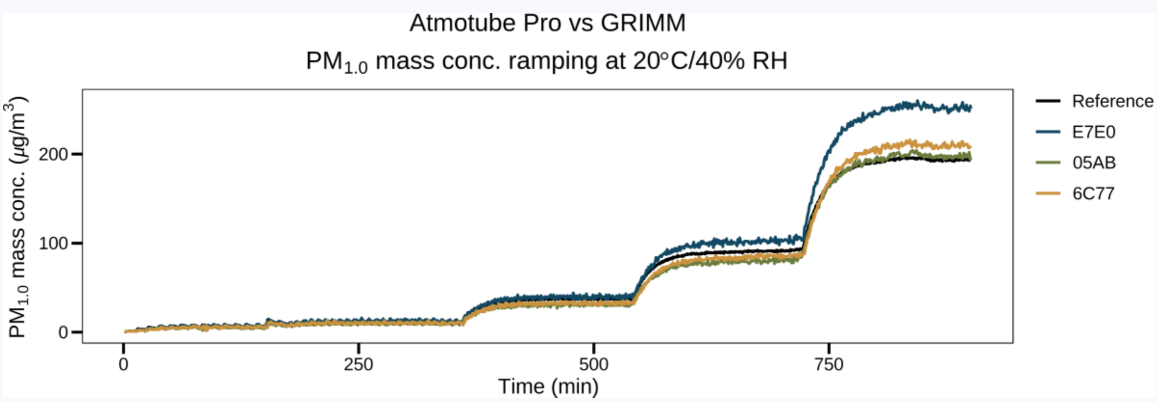
Section 4: $PM_{1.0}$

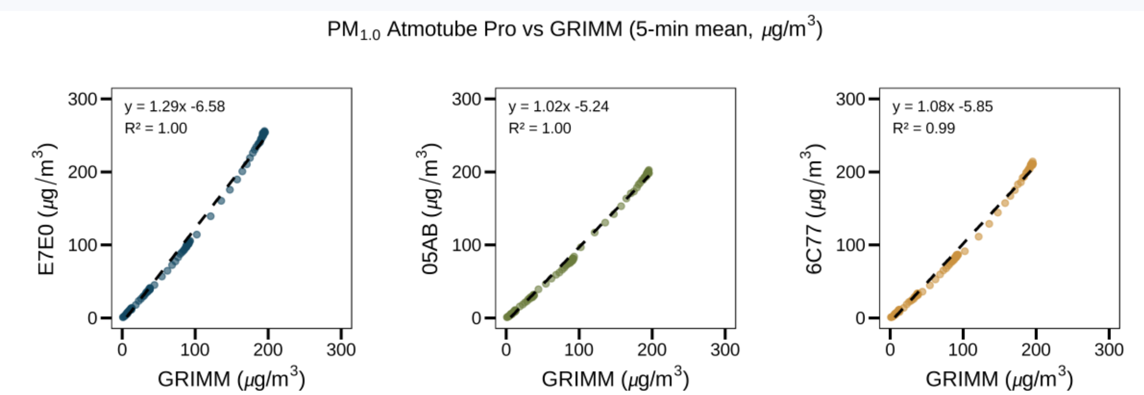
Section 4.1.5: Linearity (R^2)

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and GRIMM across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
$PM_{1.0}$	5-minute	1.00 ± 0.01



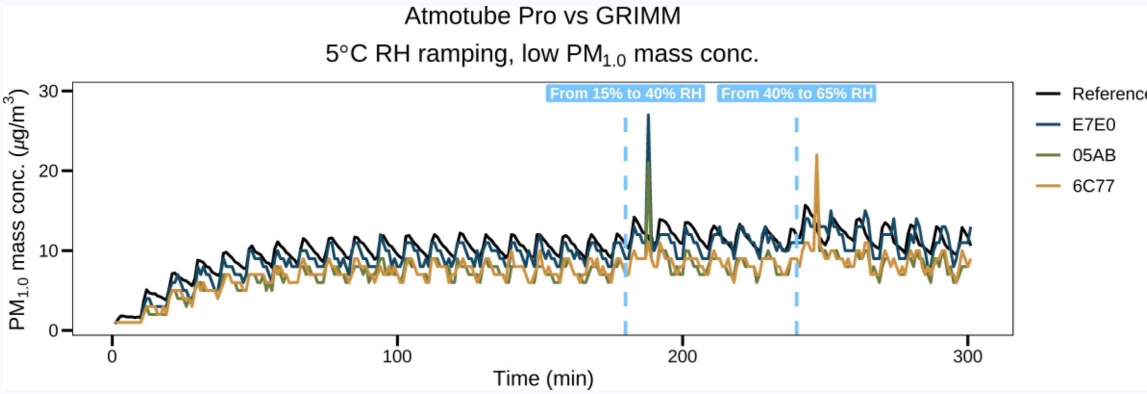


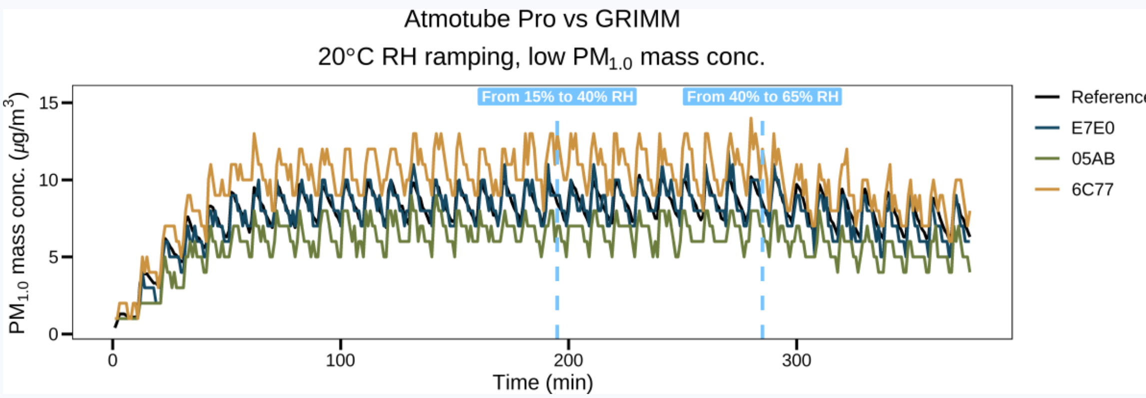
Interpretation:
- The Atmotube Pro sensors showed very strong correlation with the corresponding GRIMM data ($R^2 > 0.99$) at 5-minute averaging, for potassium chloride particles.

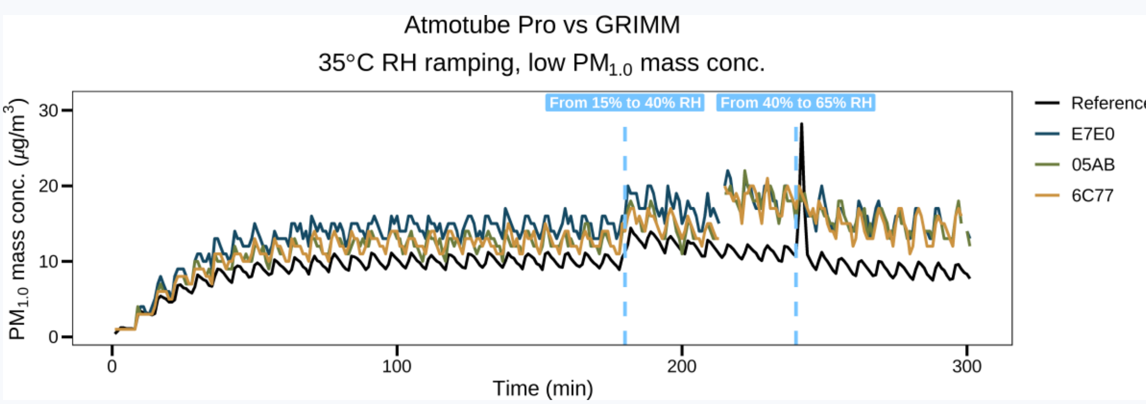
Section 4: $PM_{1.0}$

Section 4.2: Climate Susceptibility

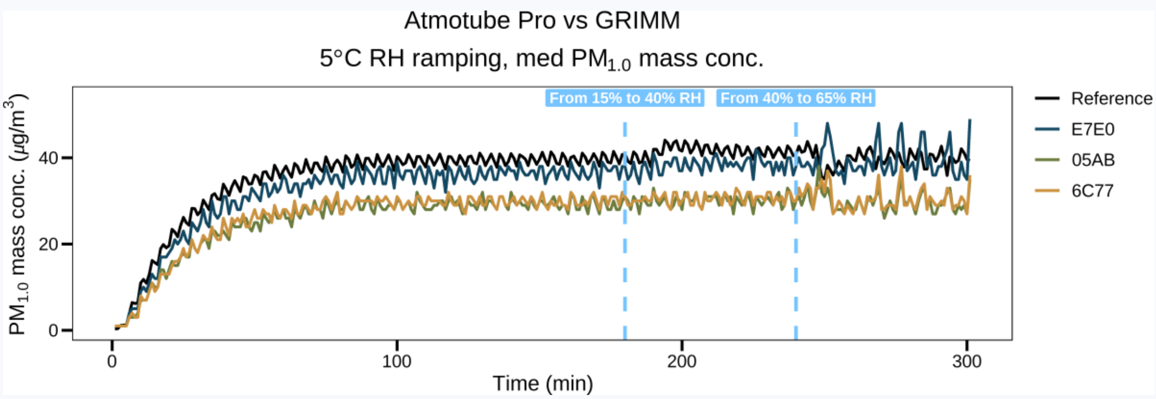
Section 4.2.1: Low Concentrations

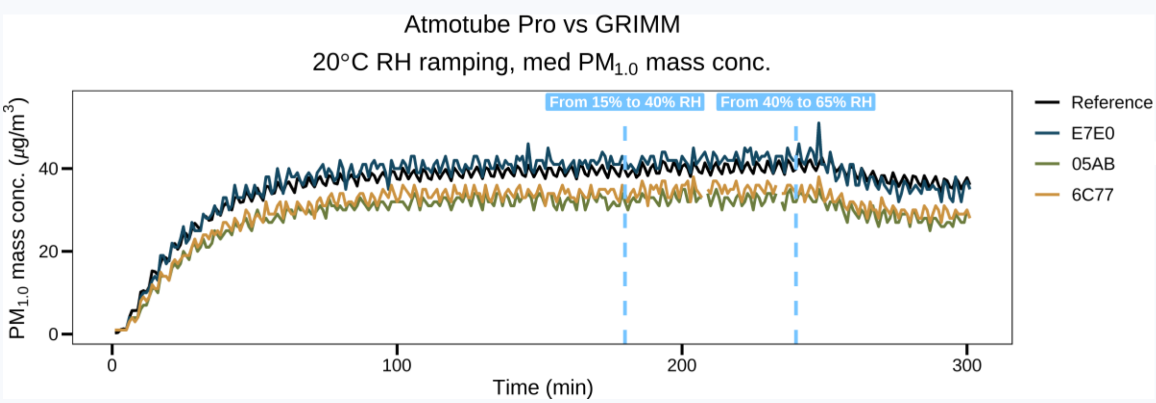


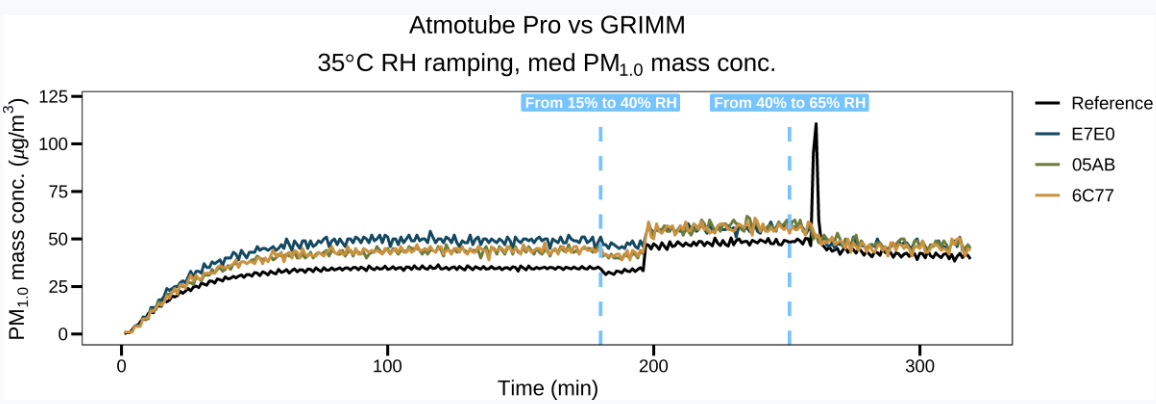




Section 4.2.2: Medium Concentrations

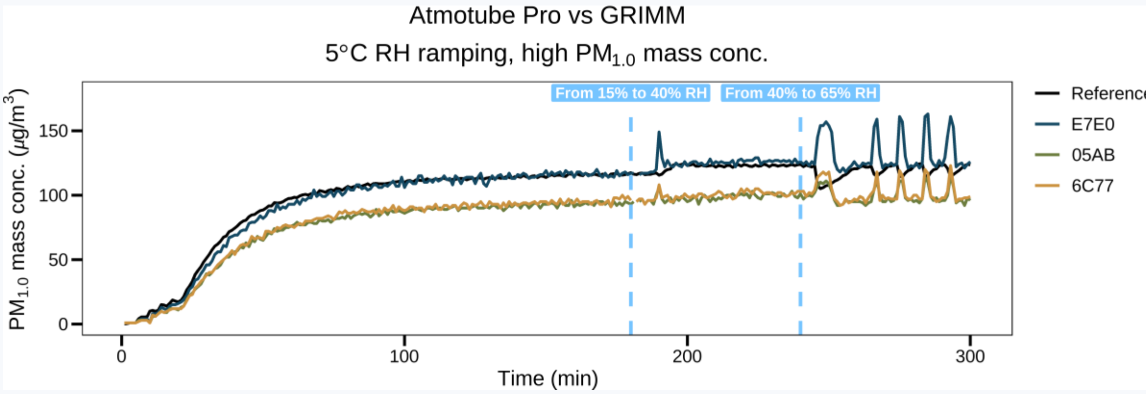


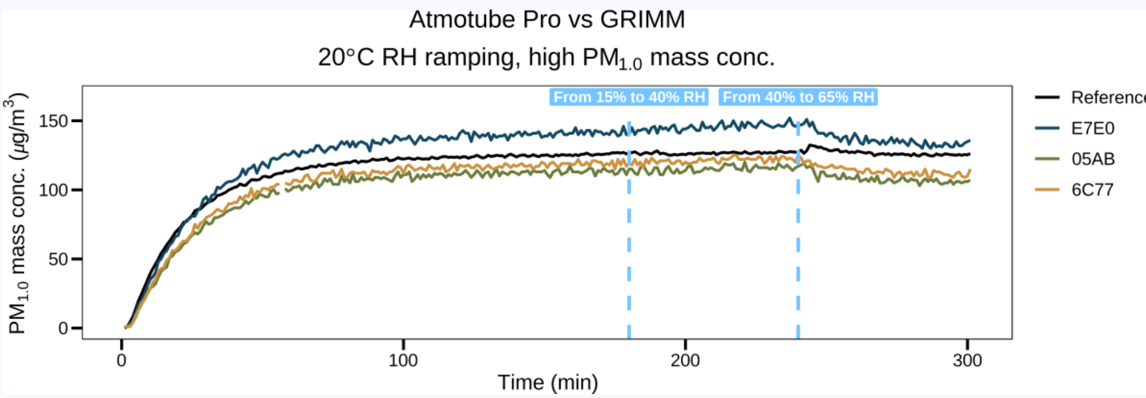


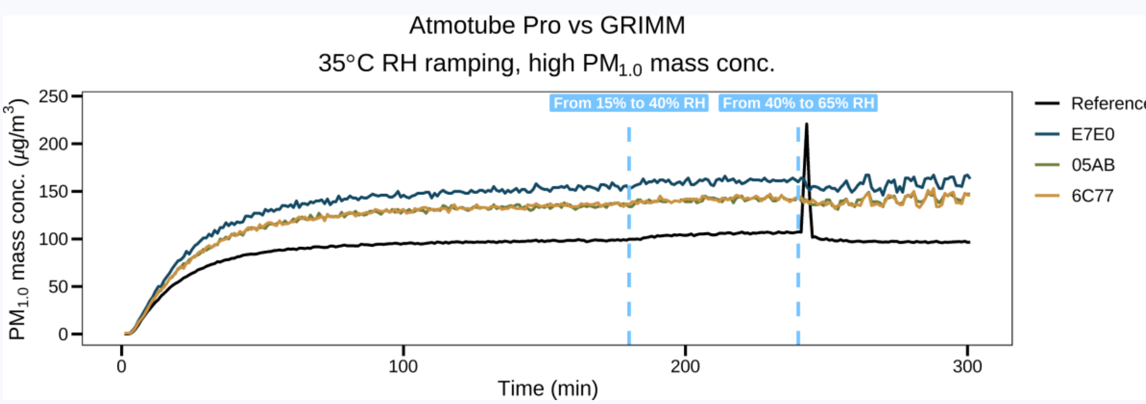


Section 4: $PM_{1.0}$

Section 4.2.3: High Concentrations



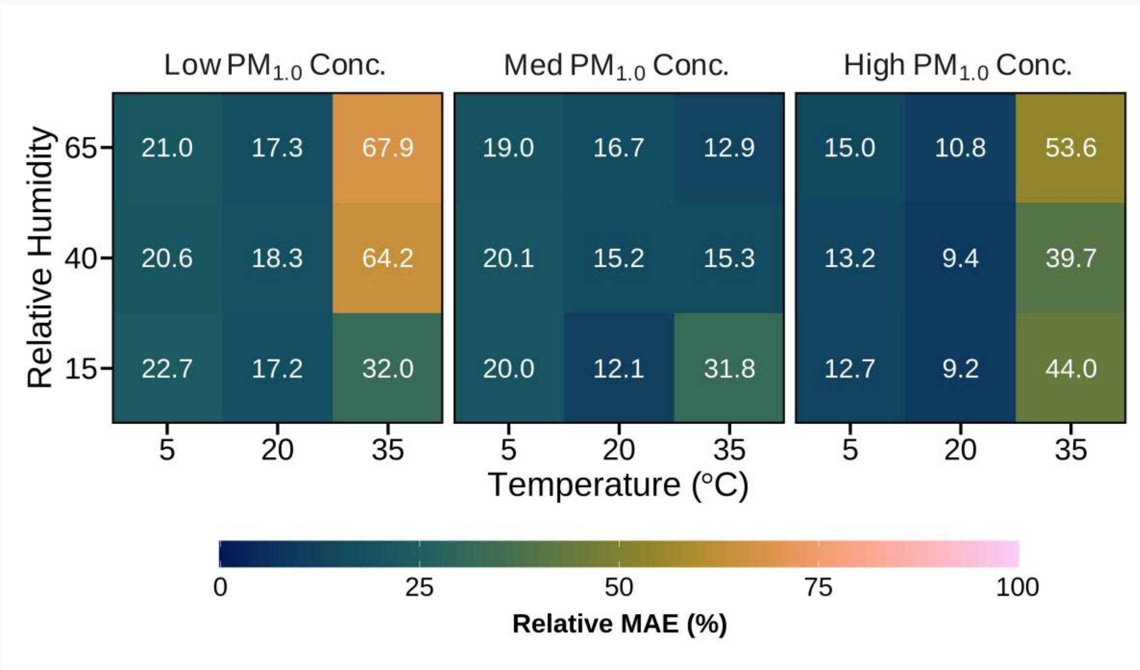




Section 4: $PM_{1.0}$

Section 4.2.4: Relative Mean Absolute Error

Relative MAE: effect of $PM_{1.0}$ concentration, temperature and RH



Interpretation:

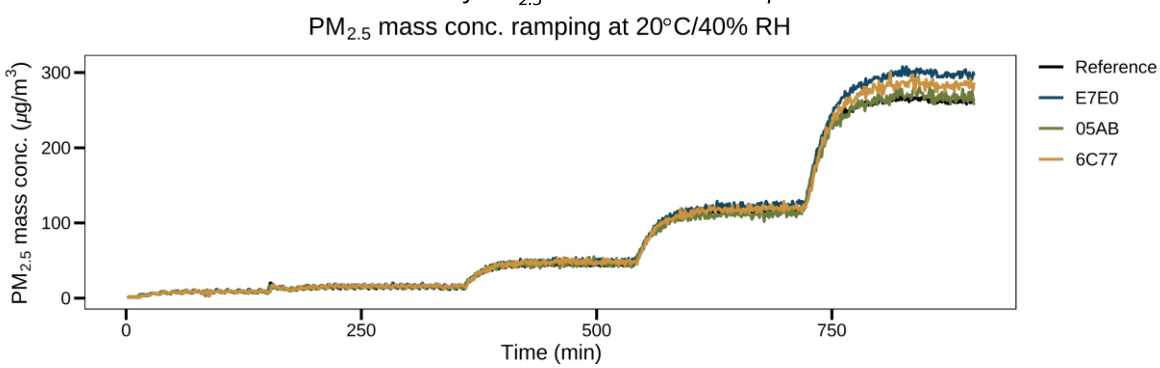
- The Atmotube Pro sensors generally showed higher relative MAE values at 35°C for potassium chloride particles. At the Low and High PM_1 concentrations, higher relative MAE values were observed at higher RH conditions.

Section 5: $PM_{2.5}$

Section 5.1: Concentration Ramp

Section 5.1.1: Data Overview

Timeseries of $PM_{2.5}$ Concentration Ramp



Section 5.1.2: Data Recovery

Basic QA/QC procedures such as removal of duplicate records was performed. Nulls, negatives, out of instrument bounds as specified by the manufacturer, and values flagged as invalid by the sensor were considered invalid. Data recovery was calculated as the percent of valid readings through the entire evaluation.

Parameter	Unit E7E0	Unit 05AB	Unit 6C77
$PM_{2.5}$	100%	100%	100%

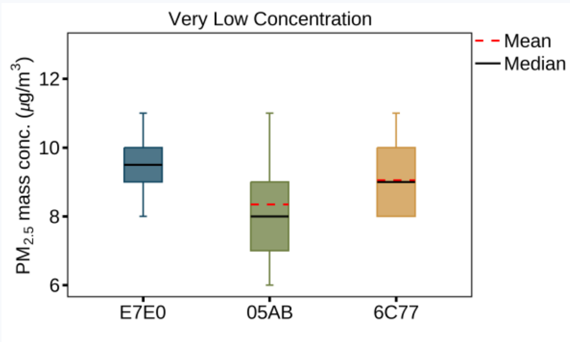
Section 5.1.3: Intra-Model Variability

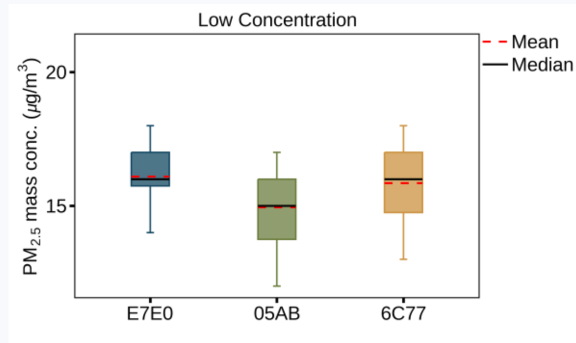
Absolute intra-model variability was calculated as the standard deviation of the mean values of the sensors. Relative intra-model variability was calculated as the absolute intra-model variability divided by the sensor grand mean. Calculations were performed using 20 measurements from each steady-state period.

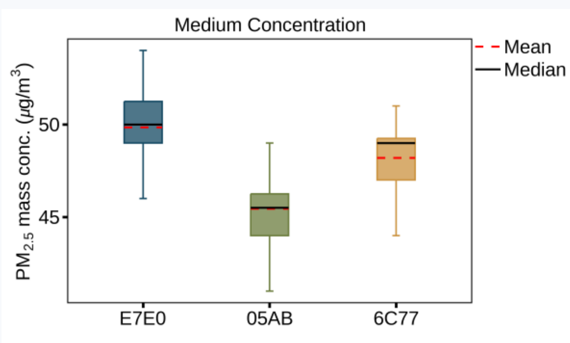
$PM_{2.5}$ Concentration (µg/m³)	Absolute intra-model variability (µg/m³)	Relative intra-model variability (%)
Very Low (8.4)	0.58	6.46
Low (13.7)	0.60	3.87
Medium (45.3)	2.22	4.65
High (117.7)	5.30	4.42
Very High (261.5)	15.31	5.41

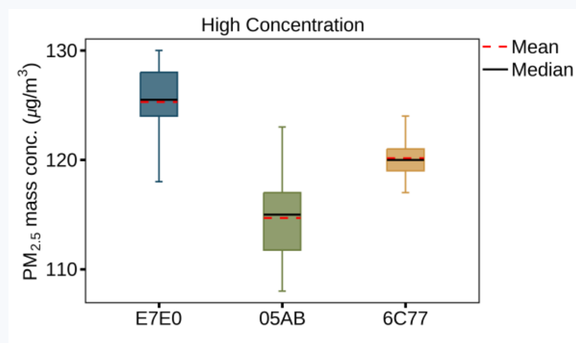
Section 5: $PM_{2.5}$

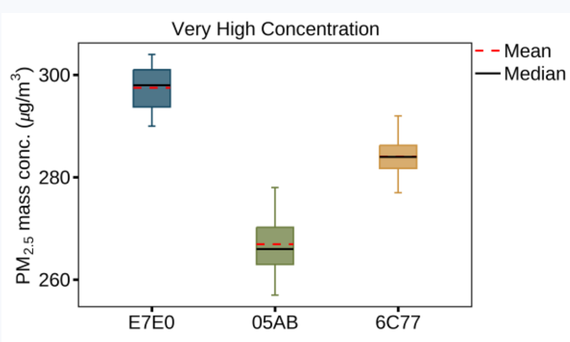
Section 5.1.3: Intra-Model Variability











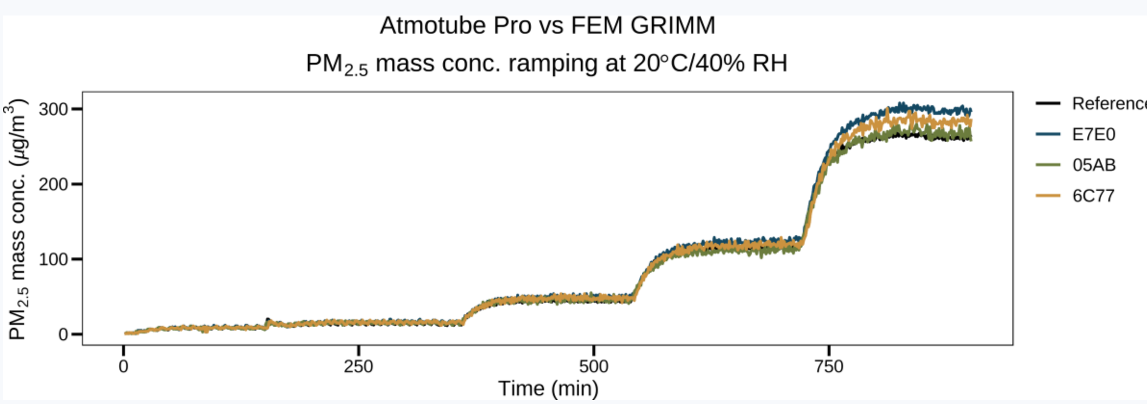
Section 5: $PM_{2.5}$

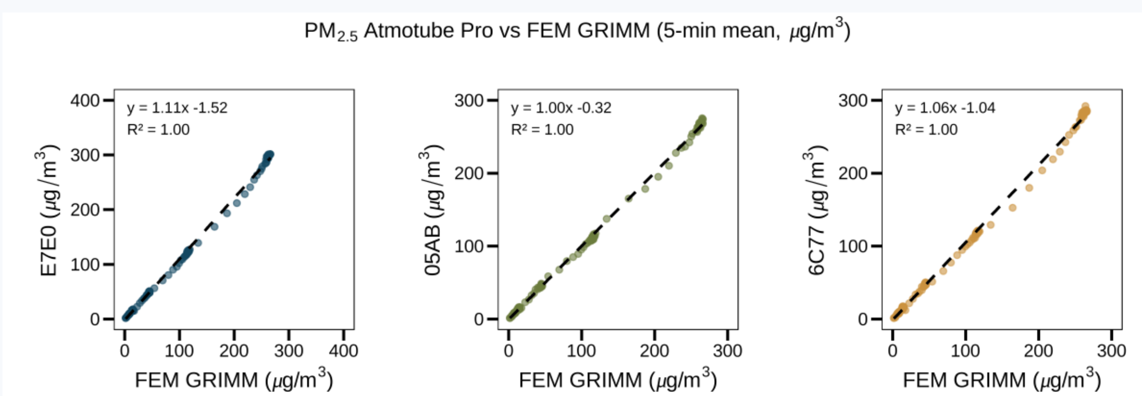
Section 5.1.4: Linearity (R^2)

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and FEM GRIMM across all units tested.

Parameter	Time Resolution	Atmotube Pro (mean ± SD)
$PM_{2.5}$	5-minute	1.00 ± 0.00



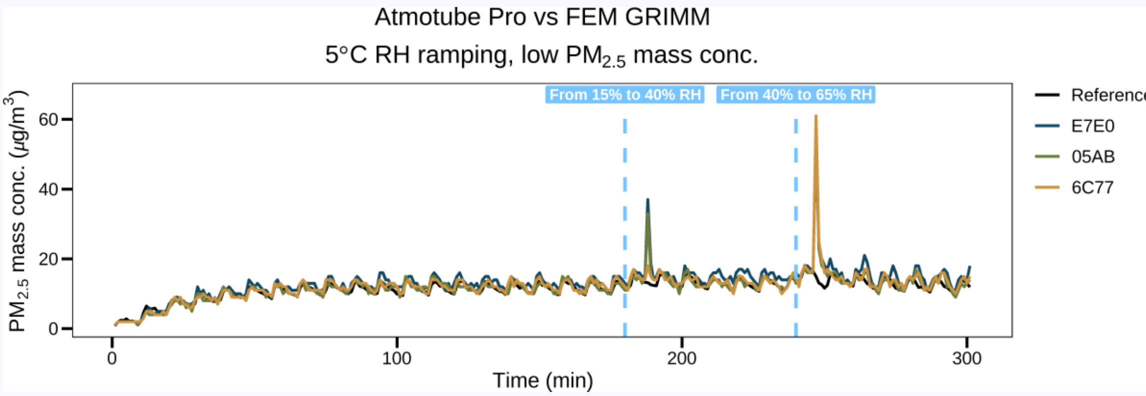


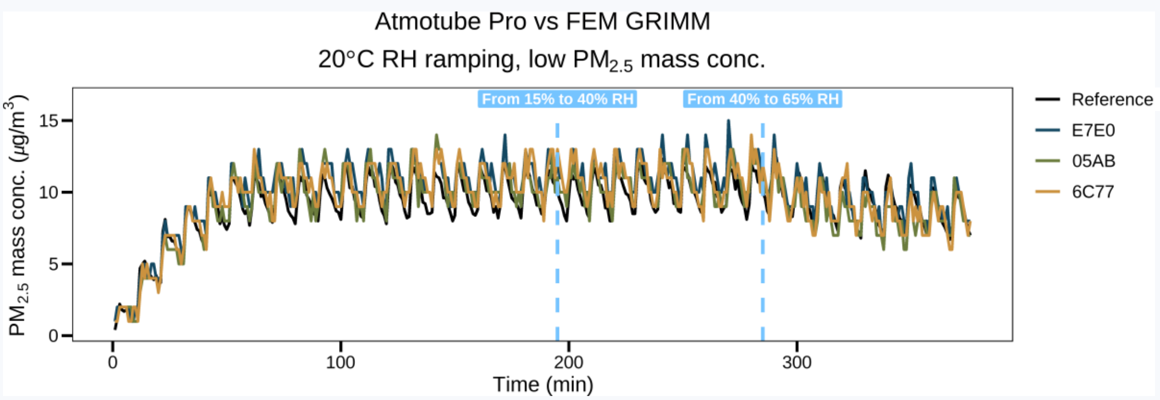
Interpretation:
- The Atmotube Pro sensors showed very strong correlation with the corresponding FEM GRIMM data (R^2 = 1) at 5-minute averaging, for potassium chloride particles.

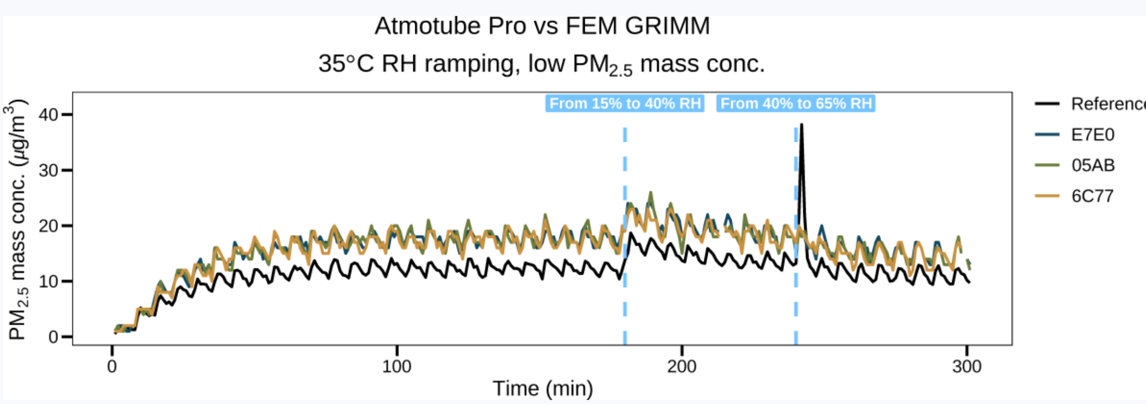
Section 5: $PM_{2.5}$

Section 5.2: Climate Susceptibility

Section 5.2.1: Low Concentrations

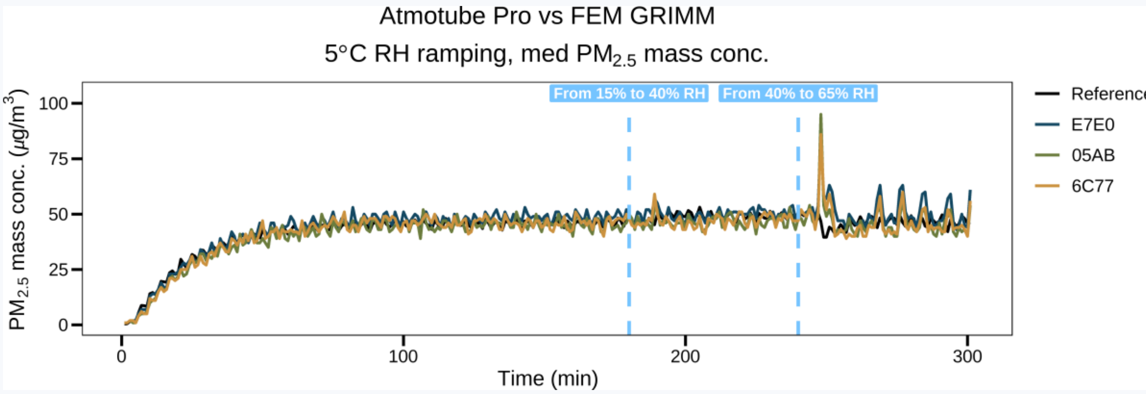


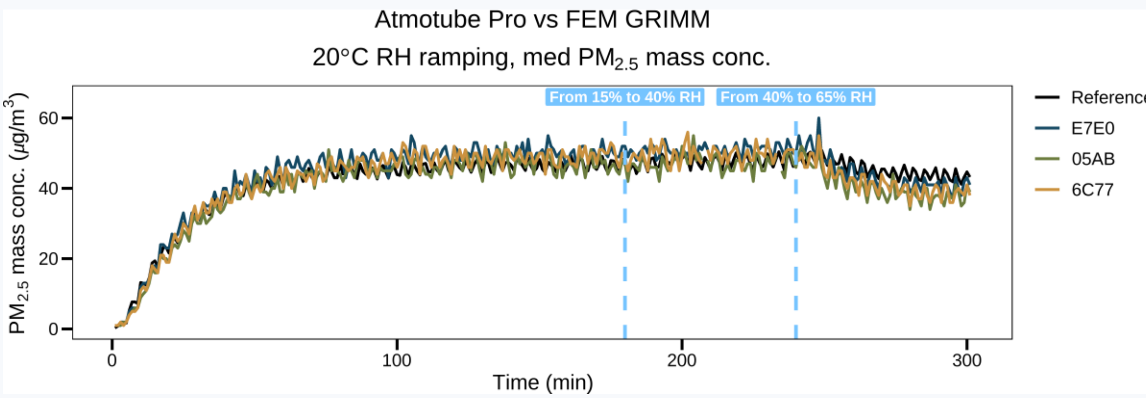


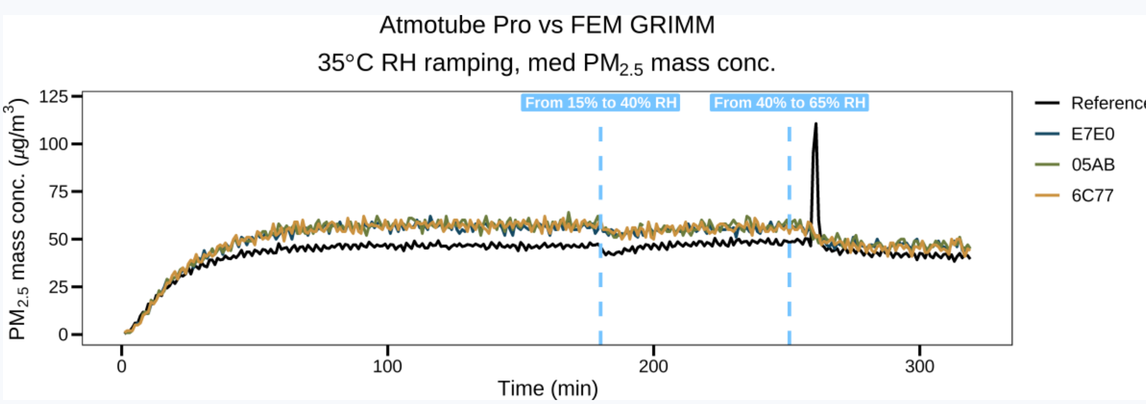


Section 5: $PM_{2.5}$

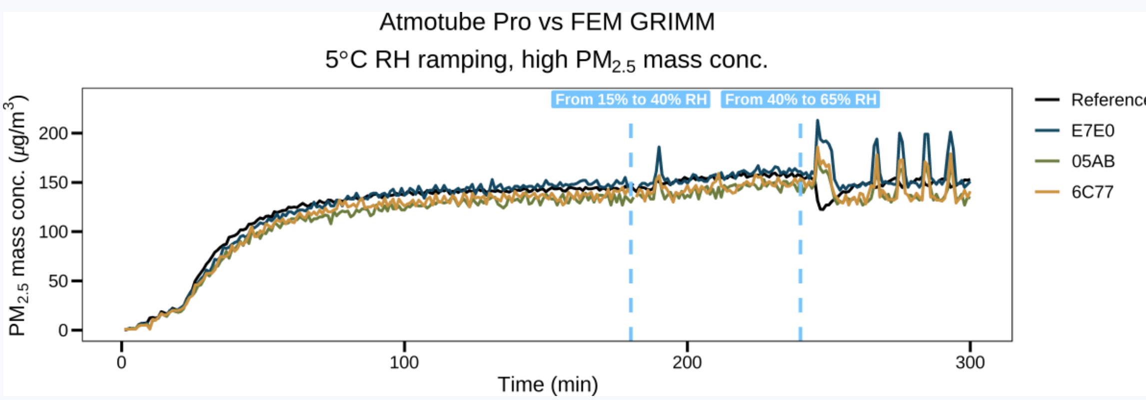
Section 5.2.2: Medium Concentrations

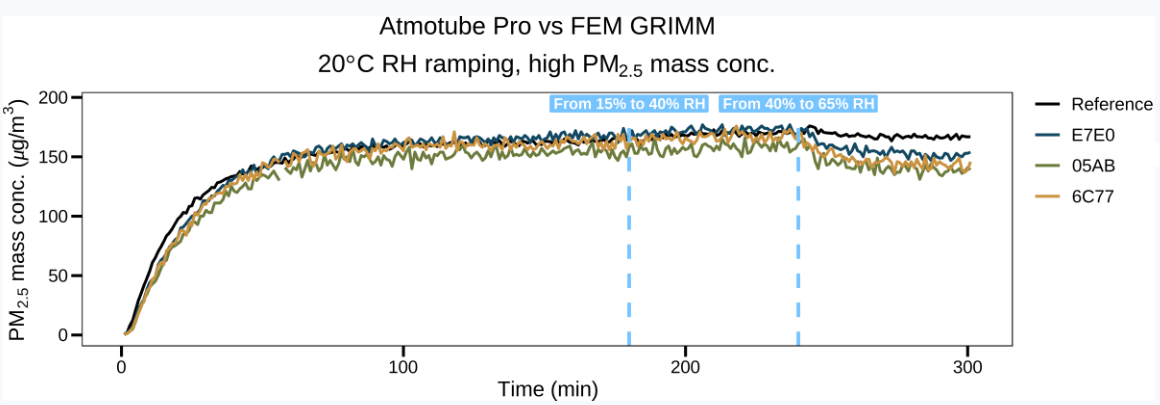


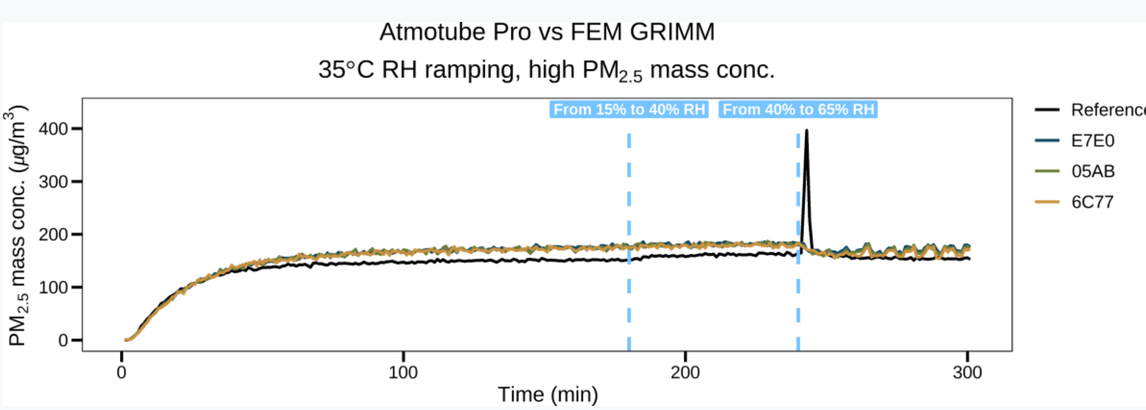




Section 5.2.3: High Concentrations



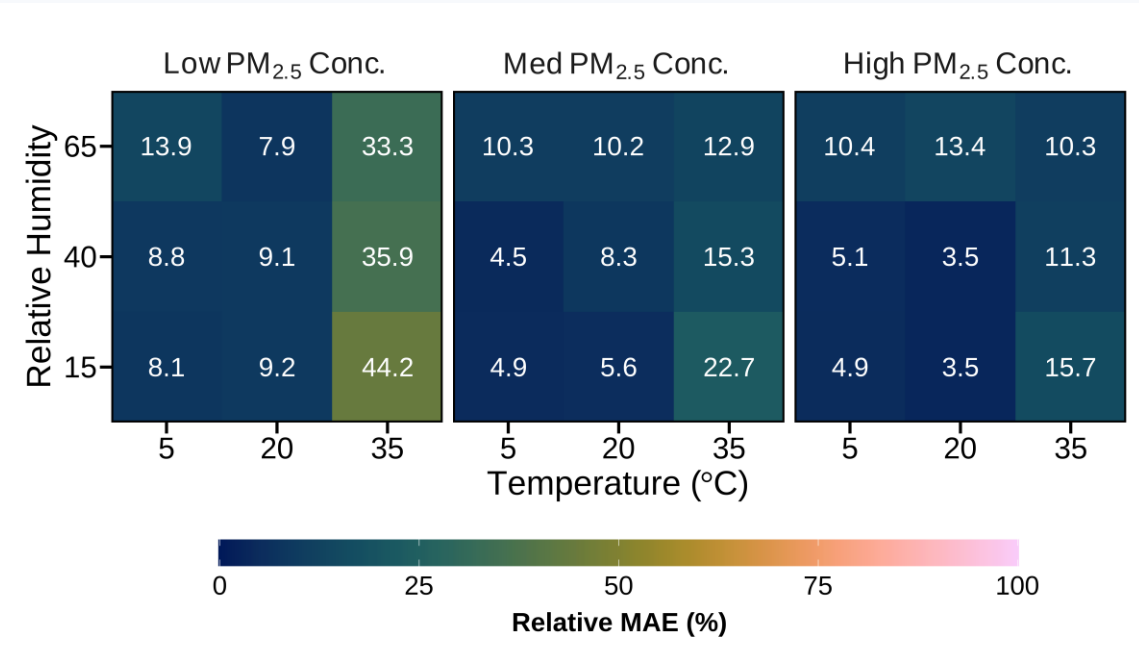




Section 5: $PM_{2.5}$

Section 5.2.4: Relative Mean Absolute Error

Relative MAE: effect of $PM_{2.5}$ concentration, temperature and RH



Interpretation:

- The Atmotube Pro sensors generally showed higher relative MAE values at 35°C for potassium chloride particles.

Section 6: Summary Metrics

		Initial VOC Concentration Ramp							
		0.06 ppm VOC	0.2 ppm VOC	0.4 ppm VOC	1.6 ppm VOC	2 ppm VOC	4 ppm VOC	6 ppm VOC	8 ppm VOC
Atmotube Pro	Average*	0.03	0.08	0.14	0.28	0.32	0.66	0.88	1.07
	SD*	0.00	0.00	0.00	0.00	0.00	0.03	0.05	0.03
	CV (RSD, %)	5.76	2.27	1.87	1.02	1.44	4.39	4.77	2.58
	Absolute IMV*	0.00	0.00	0.01	0.02	0.01	0.12	0.11	0.07
	Relative IMV (%)	5.35	5.17	5.94	6.09	2.58	17.89	12.73	6.16
Thermo 55i	Average*	0.06	0.21	0.41	1.66	2.09	4.13	5.86	8.04
	SD*	0.00	0.00	0.00	0.01	0.03	0.04	0.05	0.06
	CV (RSD, %)	2.48	0.78	1.19	0.75	1.36	1.01	0.90	0.74
Atmotube Pro vs Thermo 55i	Pearson R^2	0.95				0.91 to 0.99			
	Slope	0.14 to 0.16				0.12 to 0.13			
	Intercept*	0.04				0.04 to 0.16			
	MBE*	-0.03 to -0.02	-0.13	-0.28 to -0.27	-1.40 to -1.37	-1.78 to -1.76	-3.56 to -3.34	-5.05 to -4.84	-7.04 to -6.91
	$nMBE_{mean}$	-0.49 to -0.43	-0.63 to -0.59	-0.69 to -0.65	-0.84 to -0.82	-0.85 to -0.84	-0.86 to 0.81	-0.86 to -0.83	-0.88 to -0.86
	MAE*	0.02 to 0.03	0.13	0.27 to 0.28	1.37 to 1.40	1.76 to 1.78	3.34 to 3.56	4.84 to 5.05	6.91 to 7.04
	$nMAE_{mean}$	0.43 to 0.49	0.59 to 0.63	0.65 to 0.69	0.82 to 0.84	0.84 to 0.85	0.81 to 0.86	0.83 to 0.86	0.86 to 0.88
	RMSE*	0.02 to 0.03	0.13	0.27 to 0.28	1.37 to 1.40	1.76 to 1.78	3.34 to 3.56	4.84 to 5.05	6.91 to 7.04
	$nRMSE_{mean}$	0.43 to 0.49	0.59 to 0.63	0.65 to 0.69	0.82 to 0.84	0.84 to 0.85	0.81 to 0.86	0.83 to 0.86	0.86 to 0.88

*Units in ppm

Section 6: Summary Metrics

		Final VOC Concentration Ramp							
		0.06 ppm VOC	0.2 ppm VOC	0.4 ppm VOC	1.6 ppm VOC	2 ppm VOC	4 ppm VOC	6 ppm VOC	8 ppm VOC
Atmotube Pro	Average*	0.25	0.33	0.44	1.13	1.49	2.01	2.56	2.98
	SD*	0.00	0.00	0.01	0.01	0.03	0.05	0.05	0.03
	CV (RSD, %)	0.89	1.18	1.06	1.30	2.21	2.38	1.90	1.16
	Absolute IMV*	0.06	0.11	0.22	0.39	0.31	0.31	0.89	1.46
	Relative IMV (%)	25.66	33.31	49.54	34.84	20.61	15.36	34.86	49.02
Thermo 55i	Average*	0.06	0.20	040	1.63	1.94	3.92	5.98	8.01
	SD*	0.00	0.00	0.00	0.01	0.05	0.05	0.03	0.02
	CV (RSD, %)	3.38	1.09	0.75	0.81	2.56	1.17	0.46	0.24
Atmotube Pro vs Thermo 55i	Pearson R^2	0.99				0.78 to 0.98			
	Slope	0.39 to 0.80				0.16 to 0.49			
	Intercept*	0.17 to 0.29				0.66 to 1.10			
	MBE*	0.14 to 0.26	0.05 to 0.26	-0.10 to 0.29	-0.80 to -0.05	-0.68 to -0.11	-2.20 to -1.59	-4.01 to -2.39	-5.88 to -3.34
	$nMBE_{mean}$	2.36 to 4.35	0.27 to 1.26	-0.25 to 0.73	-0.49 to -0.03	-0.35 to -0.06	-0.56 to -0.40	-0.67 to -0.40	-0.73 to -0.42
	MAE*	0.14 to 0.26	0.05 to 0.26	0.07 to 0.29	0.05 to 0.80	0.11 to 0.68	1.59 to 2.20	2.39 to 4.01	3.34 to 5.88
	$nMAE_{mean}$	2.36 to 4.35	0.27 to 1.26	0.18 to 0.73	0.03 to 0.49	0.06 to 0.35	0.40 to 0.56	0.40 to 0.67	0.42 to 0.73
	RMSE*	0.14 to 0.26	0.05 to 0.26	0.07 to 0.29	0.06 to 0.80	0.12 to 0.69	1.59 to 2.20	2.39 to 4.01	3.34 to 5.88
	$nRMSE_{mean}$	2.37 to 4.35	0.27 to 1.26	0.18 to 0.73	0.04 to 0.49	0.06 to 0.35	0.41 to 0.56	0.40 to 0.67	0.42 to 0.73

*Units in ppm

Section 6: Summary Metrics

		$PM_{1.0}$				
		Very low	Low	Medium	High	Very High
Atmotube Pro	Average*	6.05	10.73	34.52	90.65	219.88
	SD*	0.97	1.10	1.50	2.04	2.27
	CV (RSD, %)	16.36	10.43	4.33	2.25	1.03
	Absolute IMV*	0.92	1.24	4.75	11.83	28.55
	Relative IMV (%)	15.15	11.55	13.77	13.05	12.99
GRIMM	Average*	7.18	12.01	37.82	92.12	193.47
	SD*	0.79	1.02	1.01	0.93	0.66
	CV (RSD, %)	11.03	8.51	2.67	1.01	0.34
Atmotube Pro vs GRIMM	Pearson R^2	0.99 to 1.00				
	Slope	1.02 to 1.29				
	Intercept*	-6.58 to -5.24				
	MBE*	-1.93 to -0.13	-2.16 to 0.15	-6.92 to 2.08	-10.27 to 11.99	4.24 to 58.64
	$nMBE_{mean}$	-0.27 to -0.02	-0.18 to 0.01	-0.18 to 0.05	-0.11 to 0.13	0.02 to 0.30
	MAE*	0.42 to 2.20	0.66 to 2.19	2.18 to 6.92	6.12 to 11.99	4.24 to 58.64
	$nMAE_{mean}$	0.06 to 0.31	0.05 to 0.18	0.06 to 0.18	0.07 to 0.13	0.02 to 0.30
	RMSE*	0.55 to 2.31	0.81 to 2.49	2.62 to 7.18	6.23 to 12.25	4.86 to 58.69
	$nRMSE_{mean}$	0.08 to 0.32	0.07 to 0.21	0.07 to 0.19	0.07 to 0.13	0.03 to 0.30

*Units in $\mu g/m^3$

Section 6: Summary Metrics

		PM$_{2.5}$				
		Very low	Low	Medium	High	Very High
Atmotube Pro	Average*	8.97	15.63	47.83	120.05	282.83
	SD*	1.25	1.62	2.26	3.27	4.43
	CV (RSD, %)	14.18	10.47	4.74	2.74	1.58
	Absolute IMV*	0.58	0.60	2.22	5.30	15.31
	Relative IMV (%)	6.46	3.87	4.65	4.42	5.41
FEM GRIMM	Average*	8.41	13.73	45.27	117.73	261.53
	SD*	1.04	1.40	1.50	1.73	1.65
	CV (RSD, %)	12.40	10.21	3.32	1.47	0.63
Atmotube Pro vs FEM GRIMM	Pearson R^2	1.00				
	Slope	1.00 to 1.11				
	Intercept*	-1.52 to -0.32				
	MBE*	-0.06 to 1.10	1.23 to 2.38	0.18 to 4.58	-3.03 to 7.57	5.42 to 35.97
	nMBE$_{mean}$	-0.01 to 0.13	0.09 to 0.17	0.00 to 0.10	-0.03 to 0.06	0.02 to 0.14
	MAE*	1.07 to 1.27	1.75 to 2.77	2.51 to 4.65	3.33 to 7.60	6.37 to 35.97
	nMAE$_{mean}$	0.13 to 0.15	0.13 to 0.20	0.06 to 0.10	0.03 to 0.06	0.02 to 0.14
	RMSE*	1.24 to 1.83	2.32 to 3.05	3.33 to 5.00	3.94 to 8.19	7.75 to 36.18
	nRMSE$_{mean}$	0.15 to 0.22	0.17 to 0.22	0.07 to 0.11	0.03 to 0.07	0.03 to 0.14

*Units in µg/m^3

Summary Metrics Guide

Average:	mean of individual sensor means at a given steady-state concentration; the grand mean
SD:	mean of individual sensor standard deviations (σ; measure of variation of the values about its mean) at a given steady-state concentration
CV (RSD):	mean of individual sensor coefficient of variations (relative standard deviation; the ratio of the standard deviation to the mean, expressed as a percentage) at a given steady-state concentration
Absolute IMV	intra-model variability expressed in absolute terms; standard deviation of individual sensor means at a given steady-state concentration
Relative IMV	intra-model variability expressed in relative terms; the ratio of the *Absolute IMV* to the *Average* at a given-steady-state concentration
SDL	estimated lower limit of detection of the sensors; calculated from the sensor vs. GC-FID reference regression line following ICH guidelines in *Validation of Analytical Procedures: Text and Methodology Q2(R1),* 2005
Pearson R^2:	the squared value of the Pearson correlation coefficient; the square of the covariance of the reference and sensor measurements divided by the product of their standard deviations (a value from 0 to 1)
Slope:	change in the sensor's value per unit increase in the reference monitor's value
Intercept:	the sensor's predicted value when the reference monitor observes zero
MBE:	mean bias error; mean of the differences between reference and sensor measurements at a given steady-state concentration
$nMBE_{mean}$:	mean bias error normalized with respect to the reference mean value at a given steady-state concentration
MAE:	mean absolute error; mean of the absolute differences between reference and sensor measurements at a given steady-state concentration
$nMAE_{mean}$:	mean absolute error normalized with respect to the reference mean value at a given steady-state concentration
RMSE:	root mean square error; the square root of the average squared differences between reference and sensor measurements at a given steady-state concentration
$nRMSE_{mean}$:	root mean square error normalized with respect to the reference mean value at a given steady-state concentration

Appendix: GC-FID VOC Results

Three **Atmotube Pro** sensors (units IDs: B21A, 3A25, 73CD) were evaluated in an AQ-SPEC environmental chamber under controlled temperatures, humidities, and volatile organic compound (VOC) concentrations. In addition to the Thermo 55i continuous VOC reference instrument, there was an Agilent 6890N GC-FID (coupled with an Entech 7100A preconcentrator) that served as a supplemental reference instrument. The supplemental reference instrument measured concentrations of each of the 4 species in the VOC blend test gas, was used as a check on the Thermo 55i reference instrument and to determine the sensor lower limit of detection, or SDL.

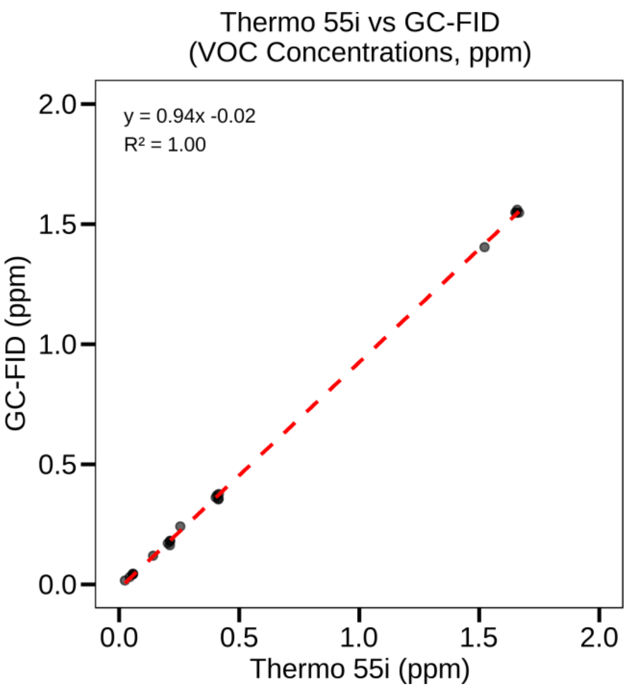
Atmotube Pro

Agilent 6890N GC-FID

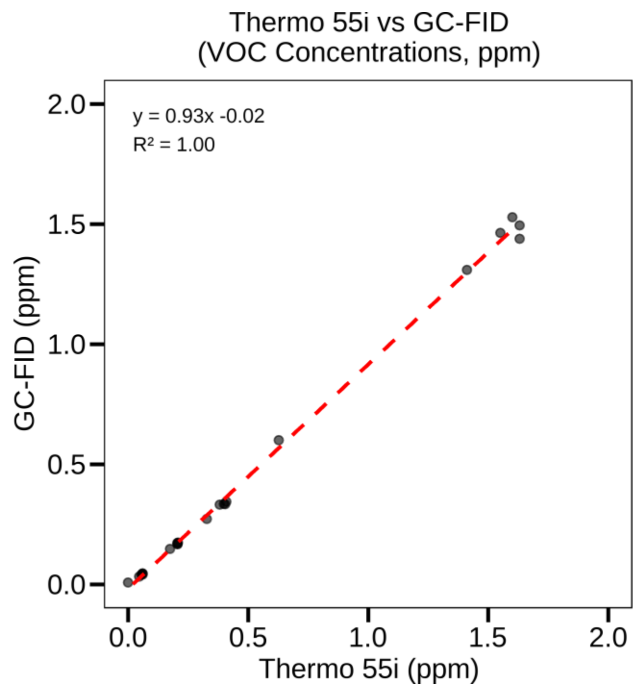
Parameter	Sensor: Atmotube Pro (raw sensor is Sensirion SGPC3)	Reference Instrument: Agilent 6890N GC-FID
Pollutant	Total VOC (hereinafter referred to as “VOC”)	Speciated VOC
Cost	$162 (at time of 2025 testing)	~$44,000 (plus ~$65,000 for the preconcentrator)
Weight	0.21 pounds	108 pounds
Dimensions (LxWxD)	3.4 x 2 x 0.9 inches	19.7 x 22.8 x 21.6 inches
Power	5 VDC	115 - 240 VAC
Battery	Yes (2000 mAh)	No
Data transmission	Bluetooth	Ethernet, serial, analog output
Internal memory	Yes (10 days)	No
Operating temperature range	-40 to 185 degrees F (raw sensor)	15°C - 35°C
Operating RH range	10 to 95% (noncondensing; raw sensor)	5% to 95%
Product website	https://atmotube.com/atmotube-pro	https://www.agilent.com/cs/library/specifications/Public/5989-3290EN.pdf
Operating principle	Metal Oxide	Flame Ionization Detection
Time resolution	1 minute	22 minutes (with preconcentrator and sequence specific to current method)
Concentration range	0 – 60 ppm	< 2 ppm per current method

Appendix: GC-FID VOC Results

Beginning of Evaluation



End of Evaluation



Interpretation:

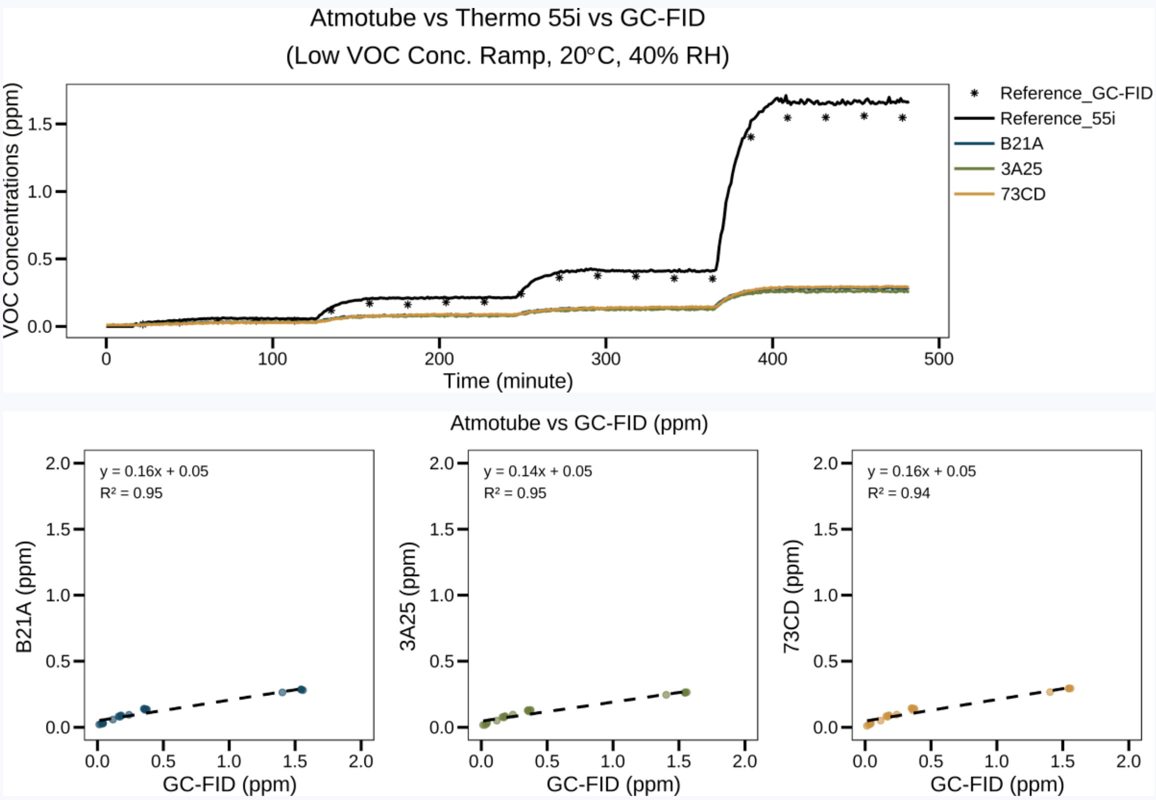
- Very strong correlations between the Thermo 55i and GC-FID (R^2 = 1.00).
- The two reference instruments reported similar VOC concentrations at both the beginning and the end of evaluation.

Appendix: GC-FID VOC Results

Linearity (R^2) – Initial Low Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.



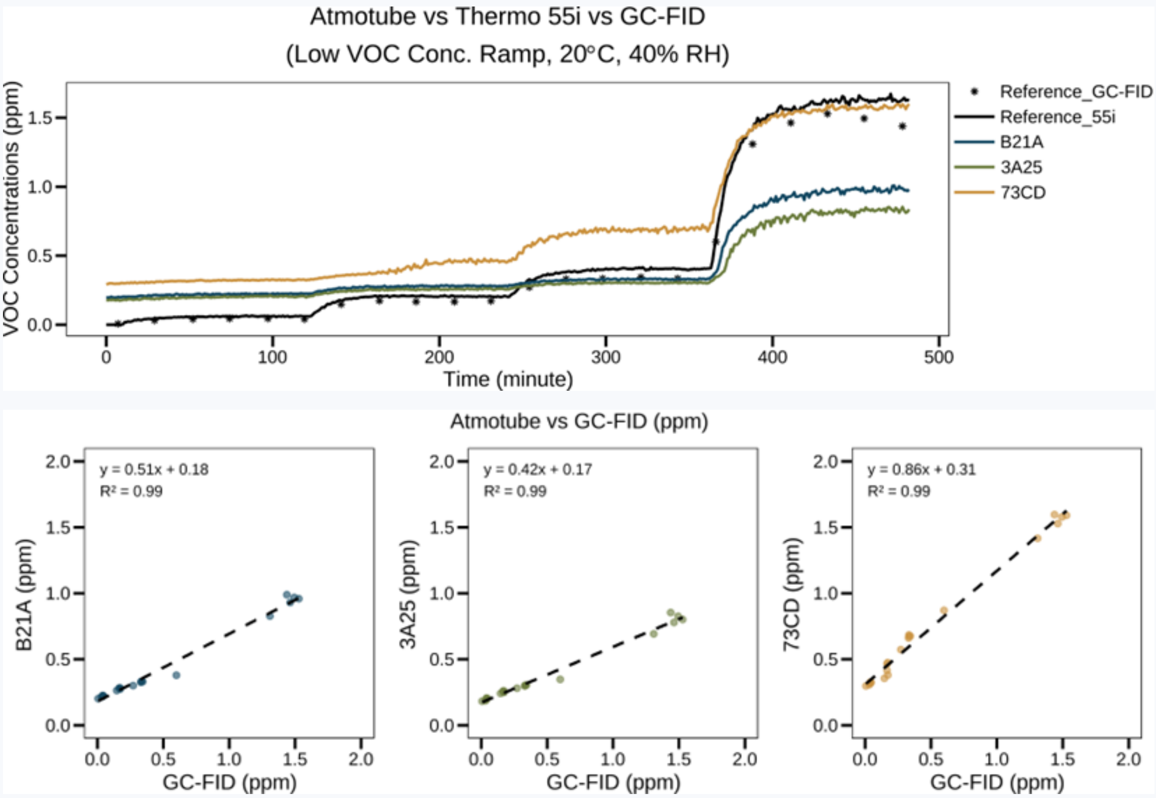
SDL, ppm	Unit B21A: 0.13-0.46 Unit 3A25: 0.14-0.47 Unit 7289: 0.14-0.49

Appendix: GC-FID VOC Results

Linearity (R^2) – Final Low Conc. Ramp

Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, readings flagged by the sensor, and invalid data points were eliminated from the data-set.

A summary of the mean R^2 between the sensor and reference instruments across all units tested.



SDL, ppm	Unit B21A: 0.06-0.22 Unit 3A25: 0.06-0.22 Unit 7289: 0.05-0.19