Field Evaluation Atmocube

South Coast AQMD

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Background

- From 06/14/2024 to 08/14/2024, three **Atmocube** multi-sensor units were deployed at the South Coast AQMD stationary ambient monitoring site in Rubidoux and were run side-by-side with Federal Equivalent Method (FEM) and Federal Reference Method (FRM) instruments measuring the same pollutants.

- Atmocube (*3 units tested*):
  - Gas Sensors: Electrochemical (ECSENSE ES1, non-FEM)
  - PM: Optical (Sensirion SPS30, non-FEM)
  - Each unit measures: CO (ppm), O_3 (ppm), $PM_{1.0}$ ($\mu g/m^3$), $PM_{2.5}$ ($\mu g/m^3$), PM_{10} ($\mu g/m^3$), T (°C), RH (%)
  - Unit cost: $800
  - Time resolution: 1-min
  - Units IDs: DF60, DA34, and BF98

- **South Coast AQMD Reference instruments:**
  - O_3 instrument (Teledyne T400, hereinafter FEM T400); cost: ~$7,000
    - Time resolution; 1-min
  - CO instrument (Horiba APMA 370, hereinafter FRM Horiba); cost: ~$10,000
    - Time resolution; 1-min
  - PM instrument (Teledyne API T640; FEM $PM_{2.5}$, hereinafter FEM T640); cost: $21,000
    - Time resolution: 1-min
    - Measures $PM_{1.0}$, $PM_{2.5}$, PM_{10} ($\mu g/m^3$)
  - PM instrument (MetOne BAM; FEM $PM_{2.5}$ & PM_{10}); cost: $20,000
    - Time resolution: 1-hr
    - Measures $PM_{2.5}$, PM_{10} ($\mu g/m^3$)
 - Met station (T, RH, P, WS, WD); cost: ~$5,000
    - Time resolution: 1-min

Carbon Monoxide (CO) in Atmocube

Data validation & recovery

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

- Data recovery for CO from Unit DF60, Unit DA34 and Unit BF98 was ~100%

- Data related to 4th of July activities were excluded from data analysis for all sensors and reference instruments

Atmocube; Intra-model variability

- Absolute intra-model variability was ~391.7 ppb for the CO measurements
(calculated as the standard deviation of the three sensor means)
- Relative intra-model variability was ~75.6% for the CO measurements
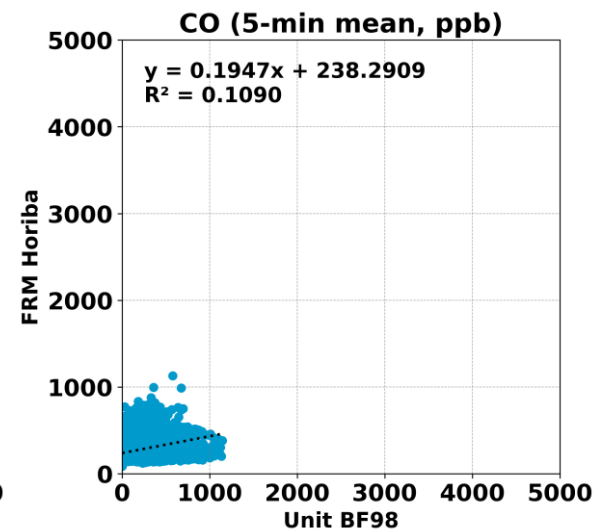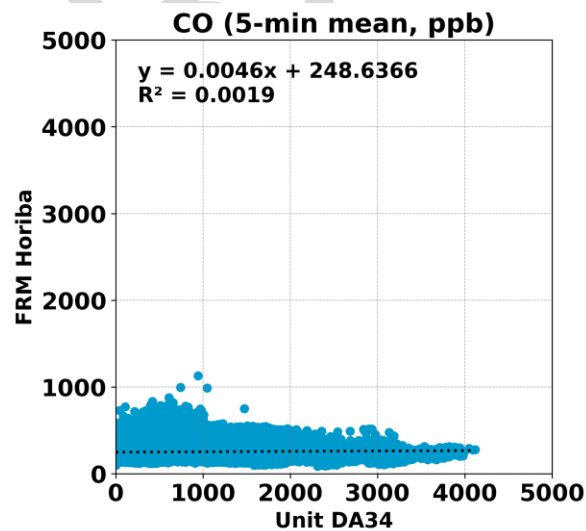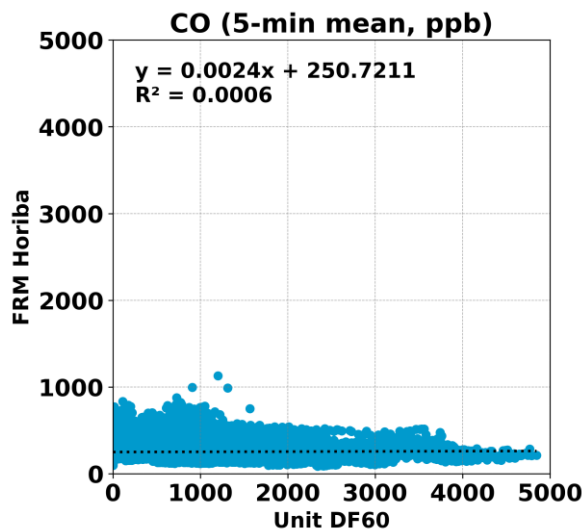(calculated as the absolute intra-model variability relative to the mean of the three sensor means)

Carbon Monoxide
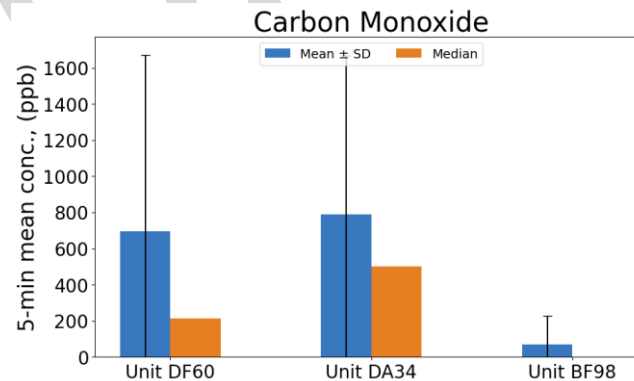
Atmocube vs FRM Horiba (CO; 5-min mean)

Atmocube vs FRM Horiba
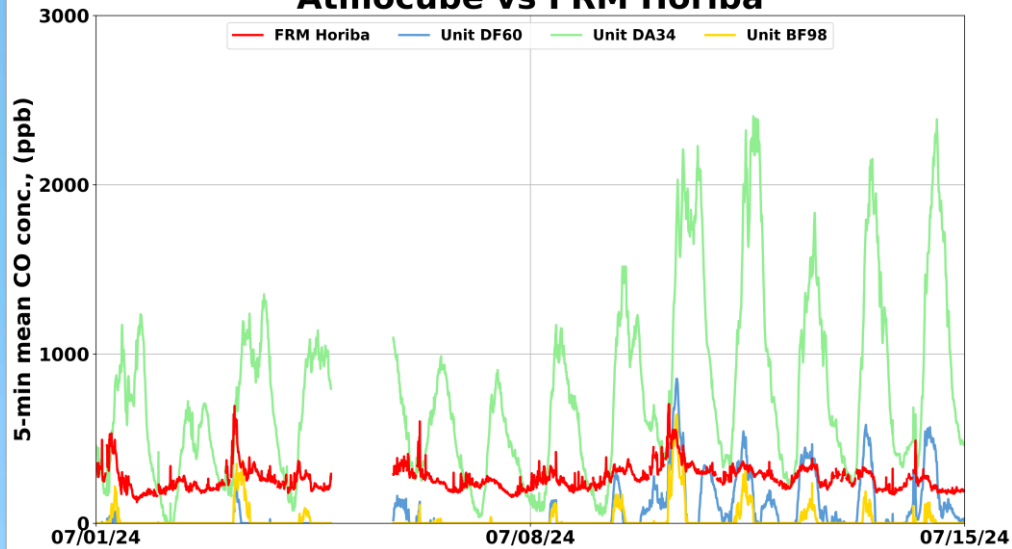
Legend: FRM Horiba — Unit DF60 — Unit DA34 — Unit BF98
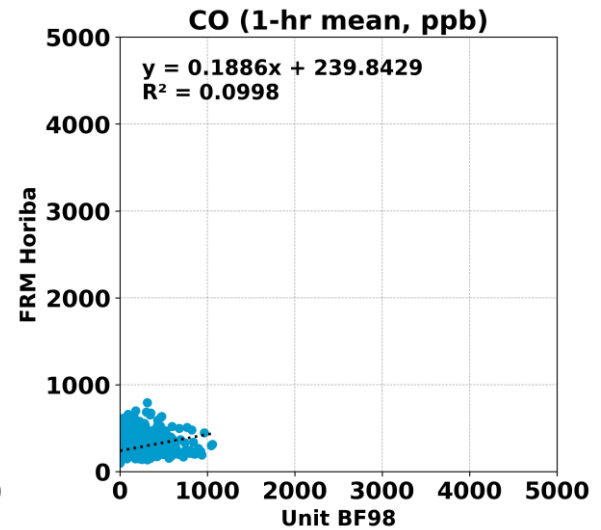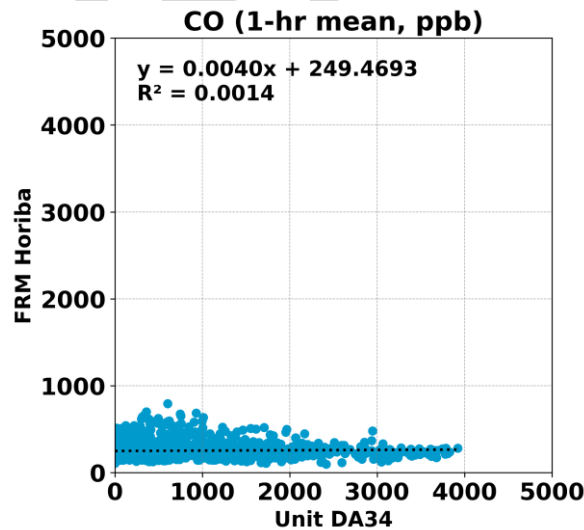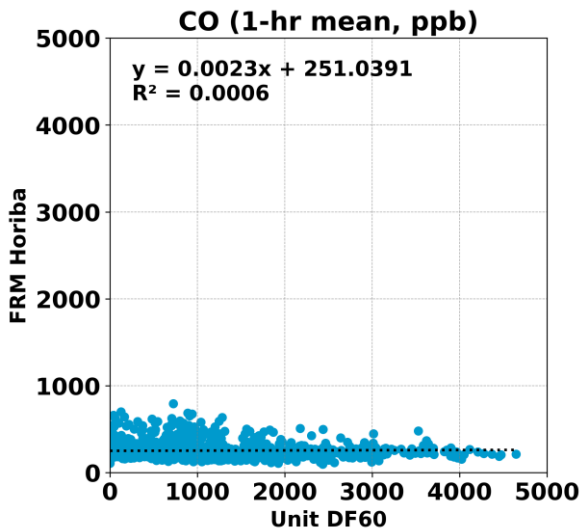
- The Atmocube sensors showed no to very weak correlation with the corresponding FRM Horiba CO data ($0.0 < R^2 < 0.11$)

- Overall, the Atmocube sensors overestimated the CO concentration as measured by the FRM Horiba CO instrument

- The Atmocube sensors did not seem to track the diurnal CO variations as recorded by the FRM Horiba instrument

CO (5-min mean, ppb)

$y = 0.0024x + 250.7211$
$R^2 = 0.0006$

CO (5-min mean, ppb)

$y = 0.0046x + 248.6366$
$R^2 = 0.0019$

CO (5-min mean, ppb)

$y = 0.1947x + 238.2909$
$R^2 = 0.1090$

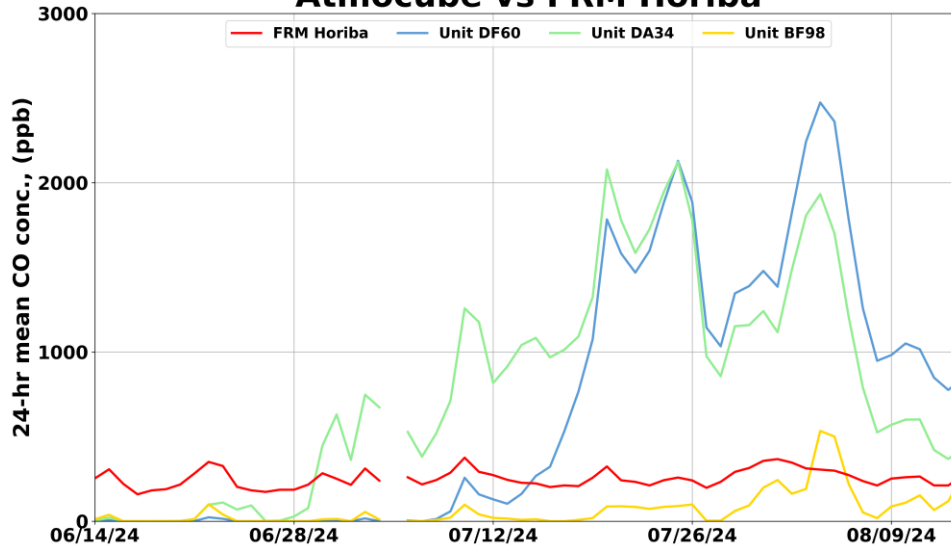# Atmocube vs FRM Horiba (CO; 1-hr mean)

Atmocube vs FRM Horiba
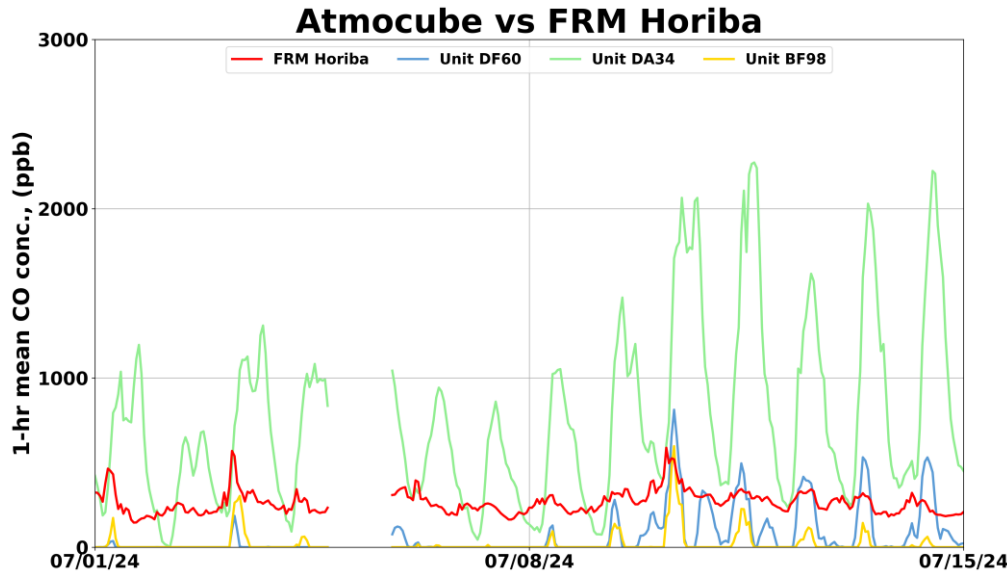
- The Atmocube sensors showed no correlation with the corresponding FRM Horiba CO data ($0.0 < R^2 < 0.1$)

- Overall, the Atmocube sensors overestimated the CO concentration as measured by the FRM Horiba CO instrument

- The Atmocube sensors did not seem to track the diurnal CO variations as recorded by the FRM Horiba instrument


CO (1-hr mean, ppb)
y = 0.0023x + 251.0391
R² = 0.0006

CO (1-hr mean, ppb)
y = 0.0040x + 249.4693
R² = 0.0014

CO (1-hr mean, ppb)
y = 0.1886x + 239.8429
R² = 0.0998

Atmocube vs FRM Horiba (CO; 24-hr mean)

- The Atmocube sensors showed very weak correlation with the corresponding FRM Horiba CO data ($0.11 < R^2 < 0.26$)

- Overall, the Atmocube sensors overestimated the CO concentration as measured by the FRM Horiba CO instrument

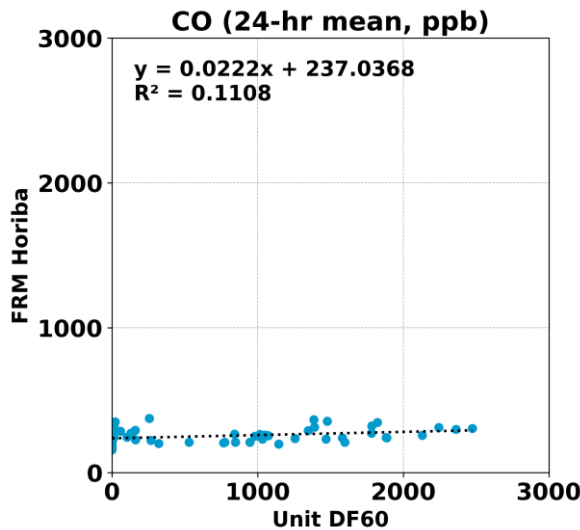- The Atmocube sensors did not seem to track the daily CO variations as recorded by the FRM Horiba instrument

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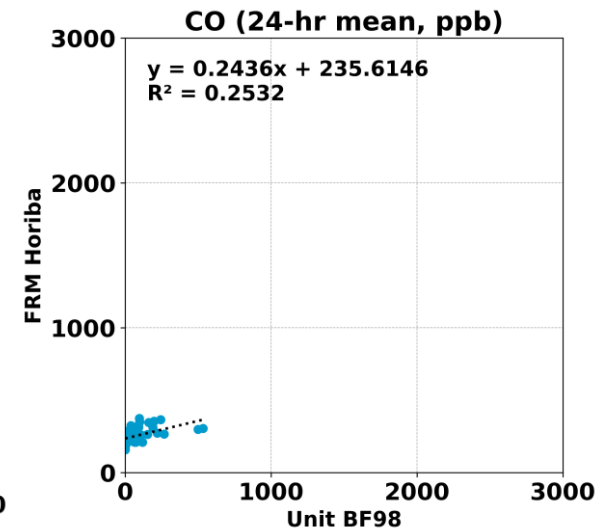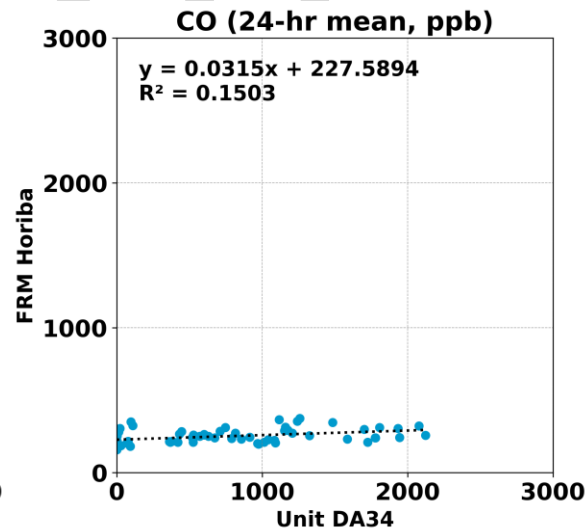
Summary: CO

	Average of 3 Sensors, CO		Atmocube vs FRM Horiba, CO						FRM Horiba, CO (ppb)		
	Average (ppb)	SD (ppb)	R^2	Slope	Intercept	MBE[1] (ppb)	MAE[2] (ppb)	RMSE[3] (ppb)	FRM Horiba Average	FRM Horiba SD	Range during the field evaluation
5-min	518.3	669.3	0.0 to 0.11	0.0 to 0.19	238.3 to 250.7	-179.7 to 572.2	218.2 to 699.2	239.1 to 1098.0	252.5	95.0	87.9 to 1128.0
1-hr	518.5	666.8	0.0 to 0.1	0.0 to 0.19	239.8 to 251.0	-184.9 to 532.7	220.0 to 662.0	239.5 to 1057.2	252.6	91.8	99.4 to 793.5
24-hr	517.9	505.0	0.11 to 0.25	0.02 to 0.24	227.6 to 237.0	-183.3 to 536.8	197.4 to 652.5	204.8 to 872.6	252.5	51.6	158.9 to 375.1

[1] Mean Bias Error (MBE): the difference between the sensors and the reference instruments. MBE indicates the tendency of the sensors to underestimate (negative MBE values) or overestimate (positive MBE values).
[2] Mean Absolute Error (MAE): the absolute difference between the sensors and the reference instruments. The larger MAE values, the higher measurement errors as compared to the reference instruments.
[3] Root Mean Square Error (RMSE): another metric to calculate measurement errors.

# Ozone (O_3)
in Atmocube

Data validation & recovery

- Basic QA/QC procedures were used to validate the collected data (i.e., obvious outliers, negative values, and invalid data-points were eliminated from the data-set)
- Data recovery for O_3 from Unit DF60, Unit DA34 and Unit BF98 was ~100%
- Data related to 4th of July activities were excluded from data analysis for all sensors and reference instruments

Atmocube; Intra-model variability

- Absolute intra-model variability was ~1.5 ppb for the ozone measurements (calculated as the standard deviation of the three sensor means)
- Relative intra-model variability was ~10.6% for the ozone measurements (calculated as the absolute intra-model variability relative to the mean of the three sensor means)
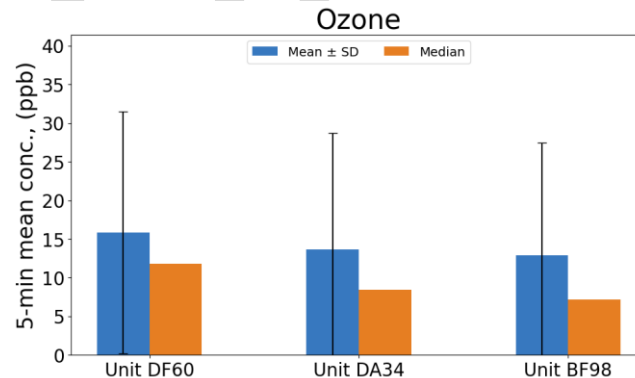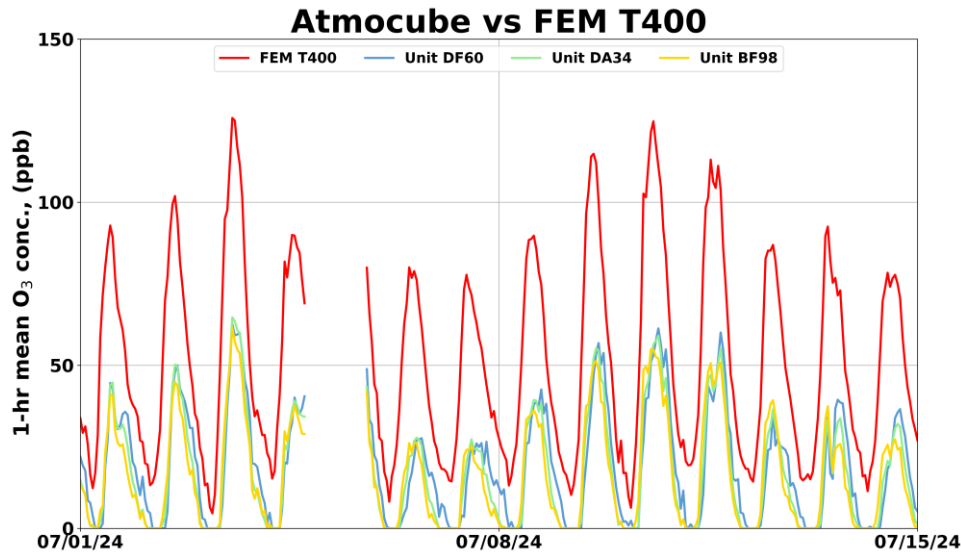
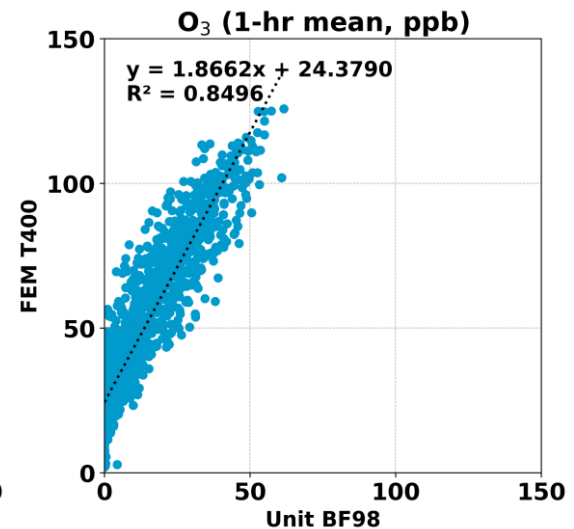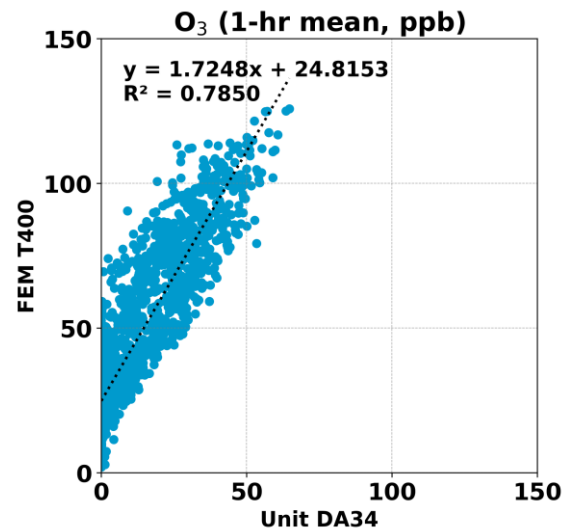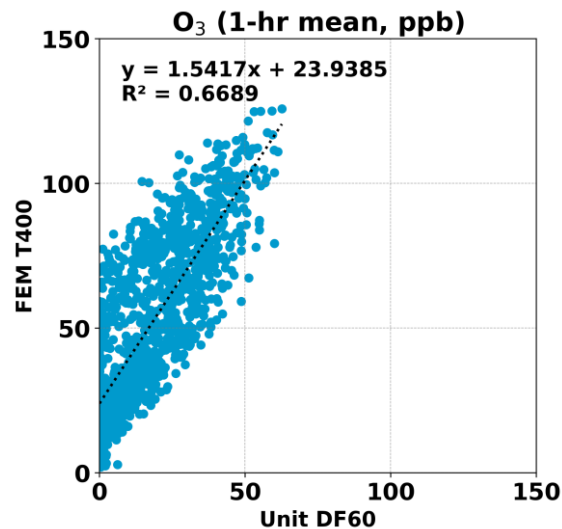# Atmocube vs FEM T400 (Ozone; 5-min mean)
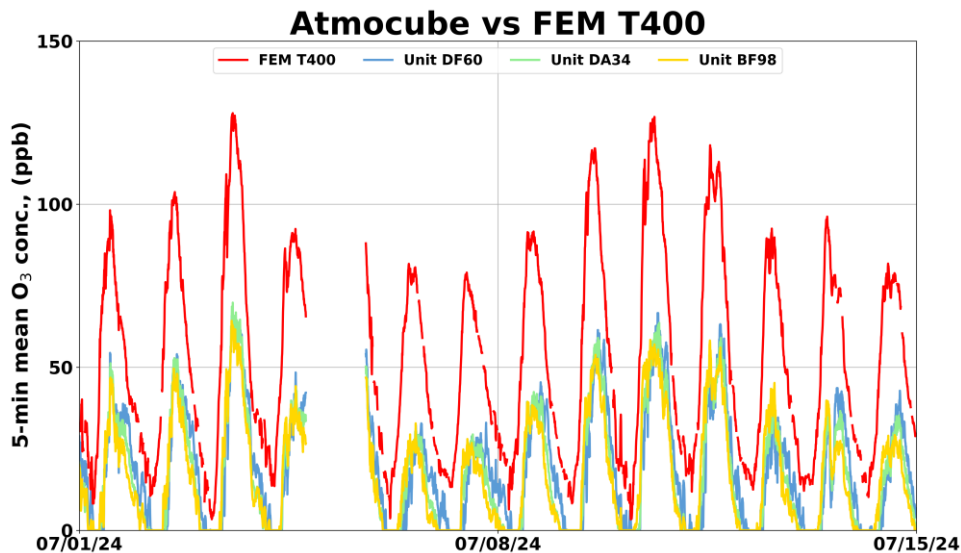
- The Atmocube sensors showed moderate to strong correlation with the corresponding FEM T400 ozone data ($0.64 < R^2 < 0.83$)

- Overall, the Atmocube sensors underestimated the ozone concentration as measured by the FEM T400 ozone instrument

- The Atmocube sensors seemed to track the diurnal ozone variations as recorded by the FEM T400 instrument
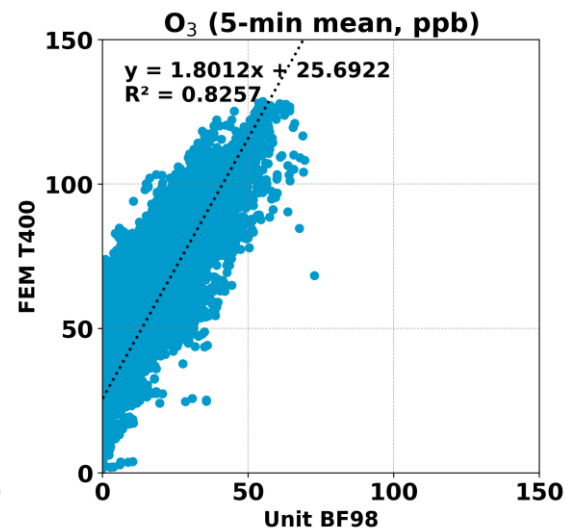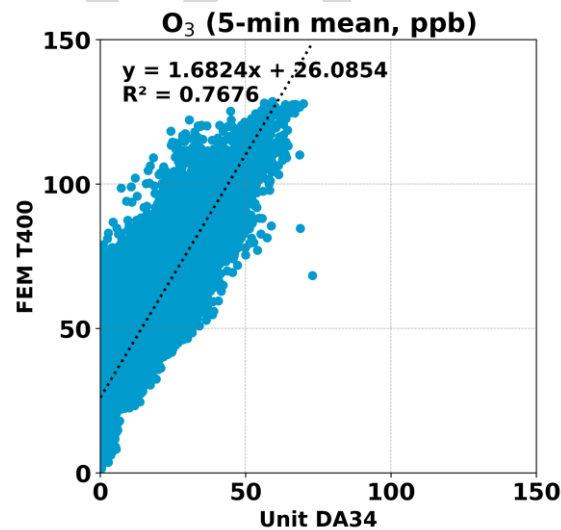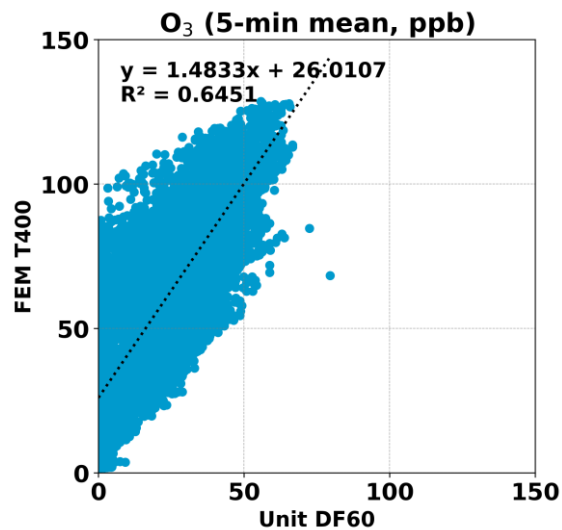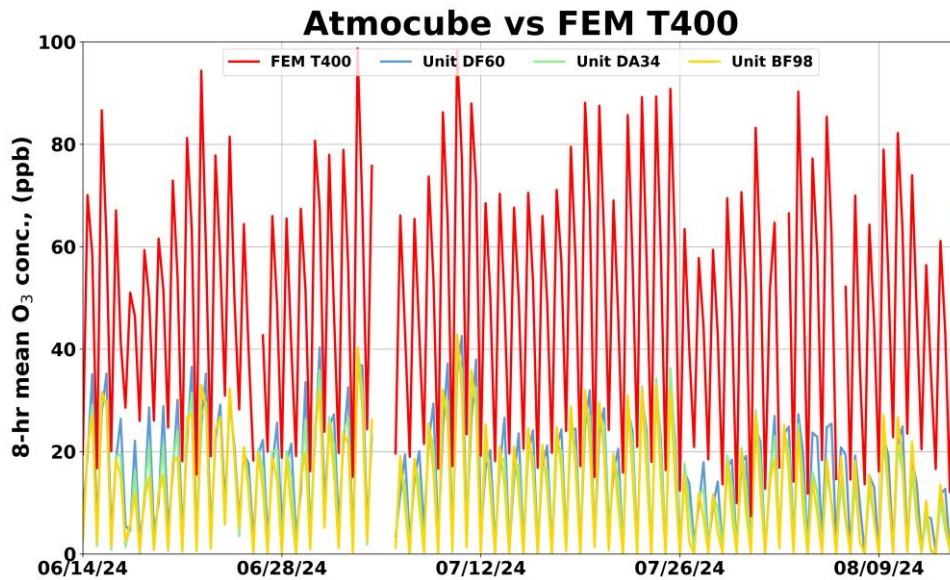
Atmocube vs FEM T400 (Ozone; 1-hr mean)

- The Atmocube sensors showed moderate to strong correlation with the corresponding FEM T400 ozone data ($0.66 < R^2 < 0.85$)

- Overall, the Atmocube sensors underestimated the ozone concentration as measured by the FEM T400 ozone instrument

- The Atmocube sensors seemed to track the diurnal ozone variations as recorded by the FEM T400 instrument
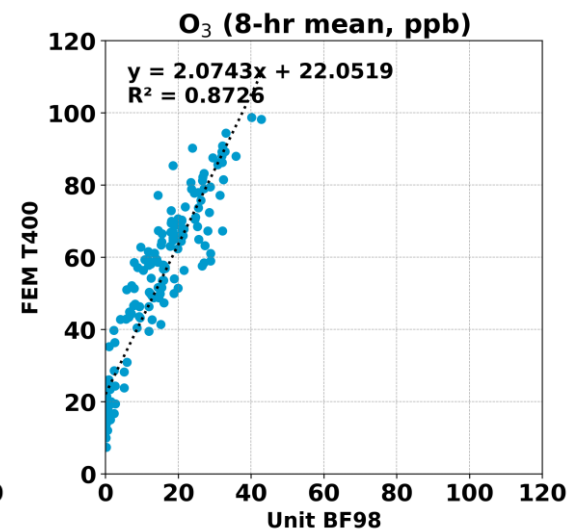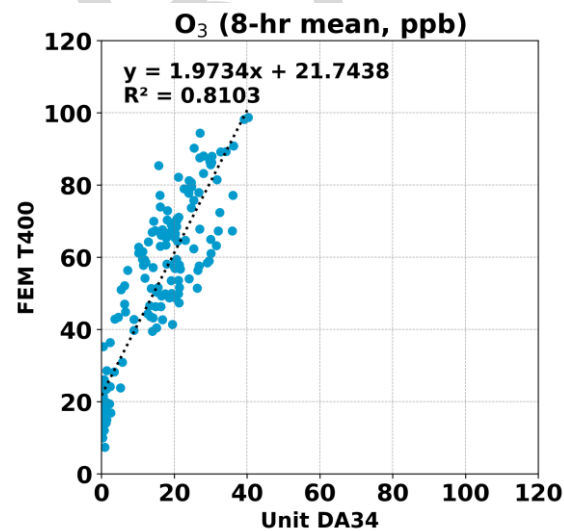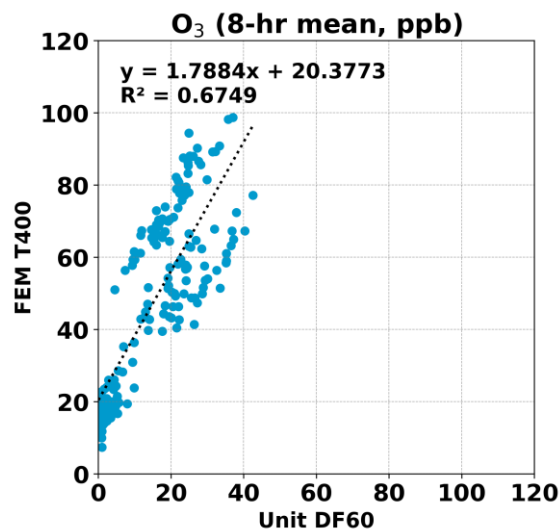
Atmocube vs FEM T400 (Ozone; 8-hr mean)

Atmocube vs FEM T400

Legend: FEM T400 · Unit DF60 · Unit DA34 · Unit BF98

y-axis: 8-hr mean O_3 conc., (ppb)
x-axis dates: 06/14/24, 06/28/24, 07/12/24, 07/26/24, 08/09/24

- The Atmocube sensors showed moderate to strong correlation with the corresponding FEM T400 ozone data ($0.67 < R^2 < 0.88$)

- Overall, the Atmocube sensors underestimated the ozone concentration as measured by the FEM T400 ozone instrument

- The Atmocube sensors seemed to track the daily ozone variations as recorded by the FEM T400 instrument

O_3 (8-hr mean, ppb)

y = 1.7884x + 20.3773
R^2 = 0.6749
(x-axis: Unit DF60, y-axis: FEM T400)

O_3 (8-hr mean, ppb)

y = 1.9734x + 21.7438
R^2 = 0.8103
(x-axis: Unit DA34, y-axis: FEM T400)

O_3 (8-hr mean, ppb)

y = 2.0743x + 22.0519
R^2 = 0.8726
(x-axis: Unit BF98, y-axis: FEM T400)

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Summary: Ozone

	Average of 3 Sensors, Ozone		Atmocube vs FEM T400, Ozone						FEM T400, Ozone (ppb)		
	Average (ppb)	SD (ppb)	R^2	Slope	Intercept	MBE[1] (ppb)	MAE[2] (ppb)	RMSE[3] (ppb)	FEM T400 Average	FEM T400 SD	Range during the field evaluation
5-min	14.1	15.1	0.65 to 0.83	1.48 to 1.80	25.7 to 26.1	-36.7 to -34.0	34.0 to 36.7	39.0 to 40.5	50.4	29.4	1.5 to 128.6
1-hr	14.1	14.8	0.67 to 0.85	1.54 to 1.87	23.9 to 24.8	-35.5 to -32.5	32.5 to 35.5	37.5 to 39.2	48.4	29.0	2.0 to 125.8
8-hr	14.0	11.2	0.67 to 0.87	1.79 to 2.07	20.4 to 22.1	-35.7 to -32.7	32.7 to 35.7	36.7 to 38.6	48.3	24.6	7.4 to 98.7

[1] Mean Bias Error (MBE): the difference between the sensors and the reference instruments. MBE indicates the tendency of the sensors to underestimate (negative MBE values) or overestimate (positive MBE values).

[2] Mean Absolute Error (MAE): the absolute difference between the sensors and the reference instruments. The larger MAE values, the higher measurement errors as compared to the reference instruments.

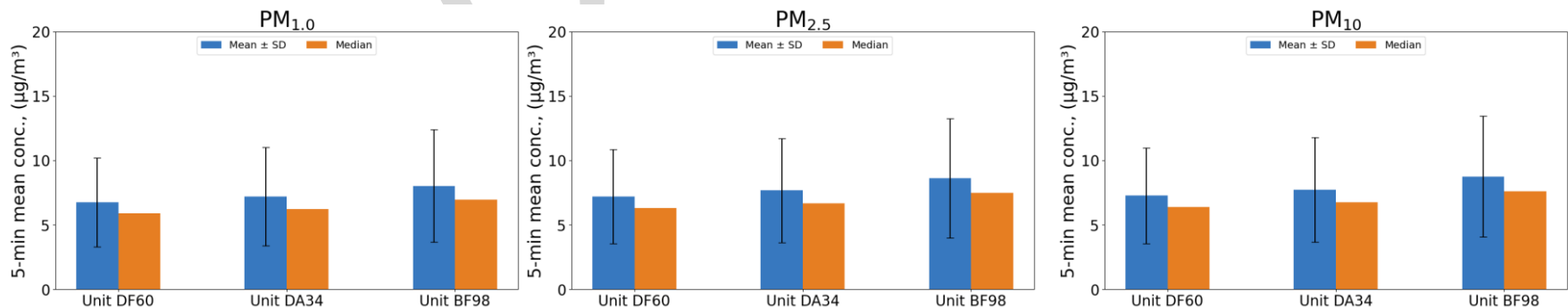[3] Root Mean Square Error (RMSE): another metric to calculate measurement errors.

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Particulate Matter (PM) in Atmocube

Data validation & recovery

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

- Data recovery from Unit DF60, Unit DA34 and Unit BF98 was ~97.5%, 100% and 100% for all PM measurements

- Data related to 4th of July activities were excluded from data analysis for all sensors and reference instruments
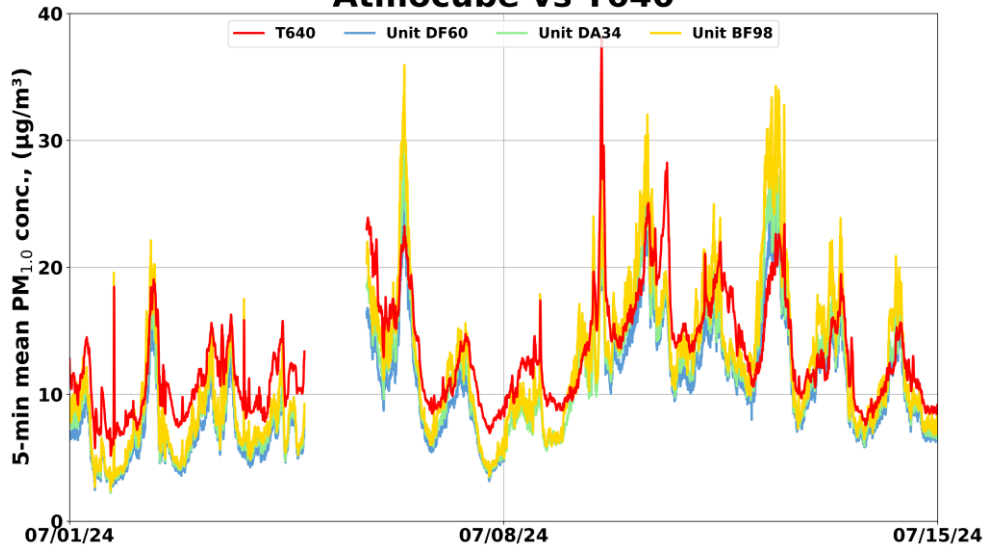
Atmocube; intra-model variability

- Absolute intra-model variability was ~0.6, ~0.7 and ~0.8 µg/m^3 for $PM_{1.0}$, $PM_{2.5}$ and PM_{10}, respectively (calculated as the standard deviation of the three sensor means)

- Relative intra-model variability was ~8.8%, ~9.2% and ~9.6% for $PM_{1.0}$, $PM_{2.5}$ and PM_{10}, respectively (calculated as the absolute intra-model variability relative to the mean of the three sensor means)
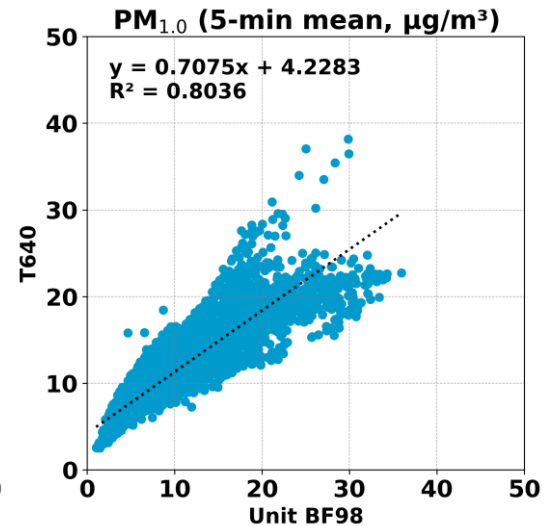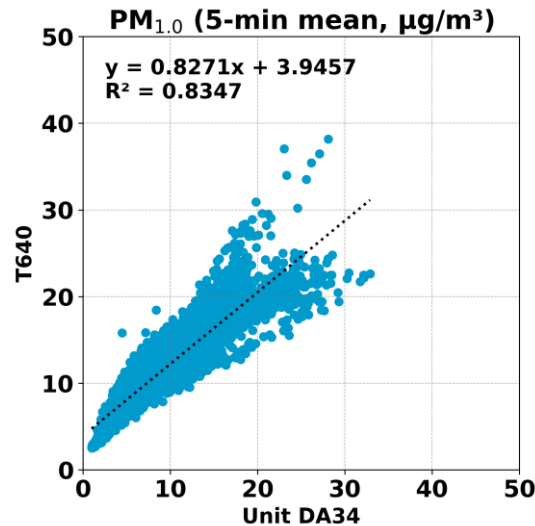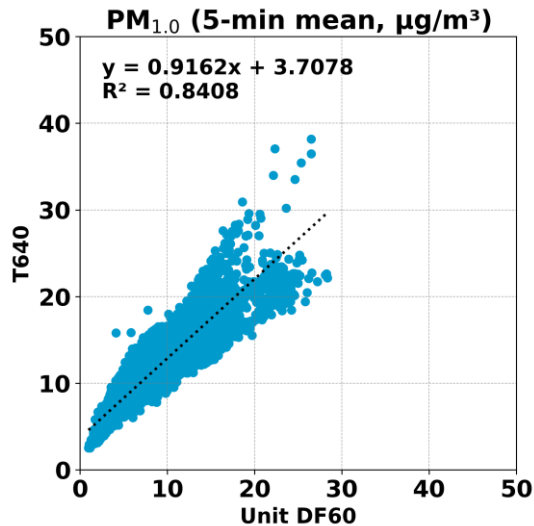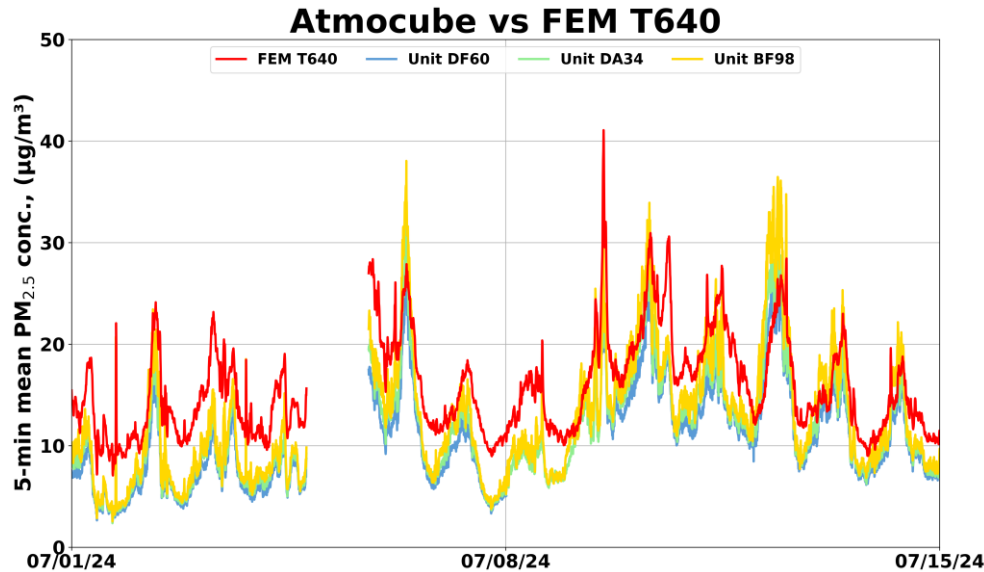

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Atmocube vs T640 (PM$_{1.0}$; 5-min mean)

- The Atmocube sensors showed strong correlations with the corresponding T640 data ($0.80 < R^2 < 0.85$)

- Overall, the Atmocube sensors underestimated the PM$_{1.0}$ mass concentrations as measured by T640

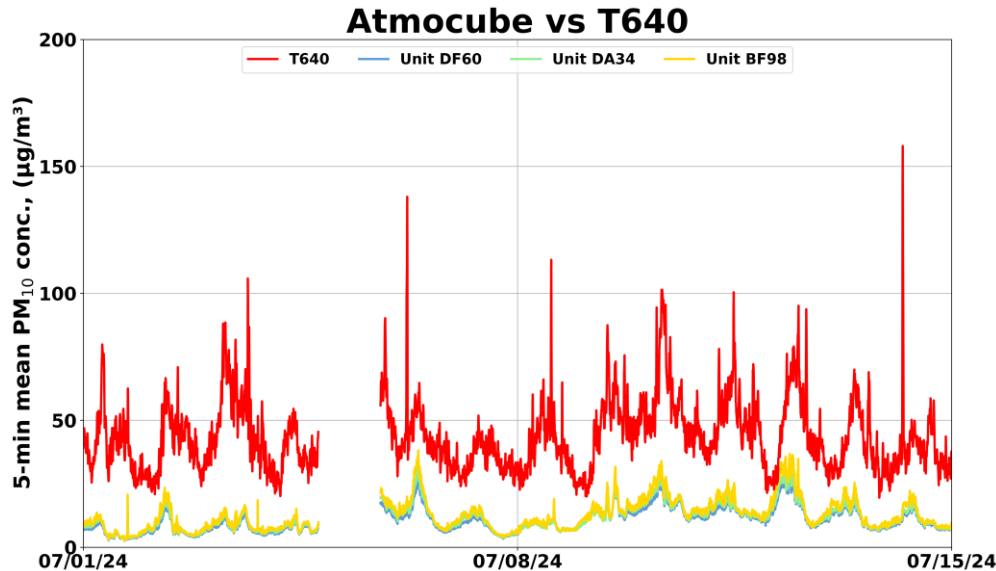- The Atmocube sensors seemed to track the PM$_{1.0}$ diurnal variations as recorded by T640
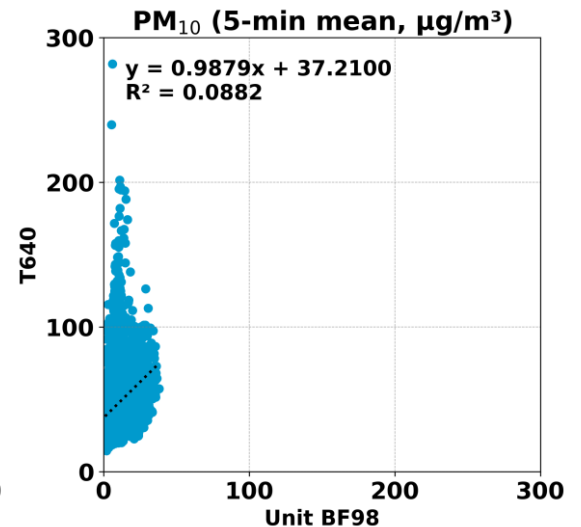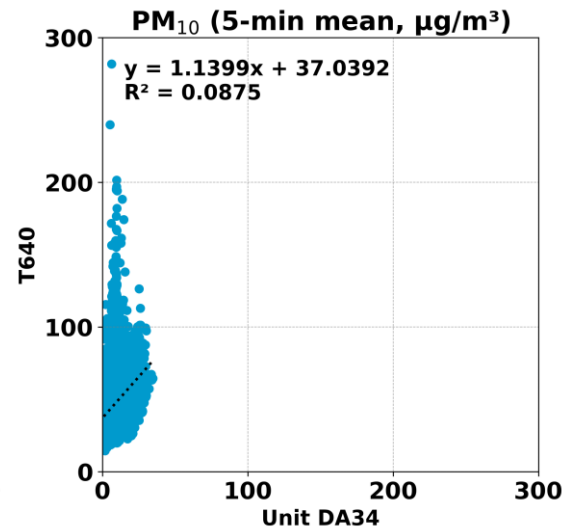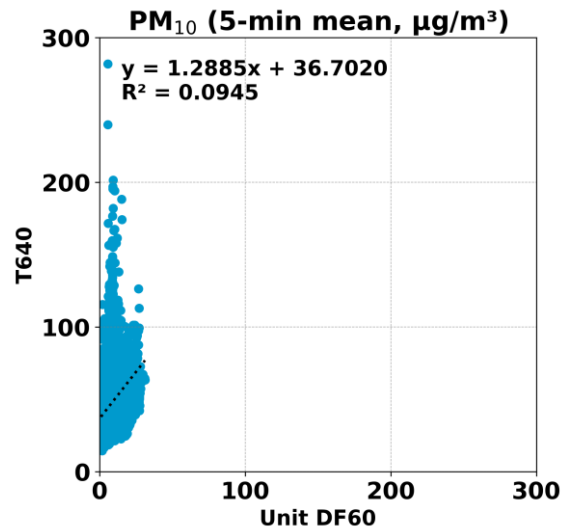
Atmocube vs FEM T640 (PM$_{2.5}$; 5-min mean)

Atmocube vs FEM T640

- The Atmocube sensors showed moderate correlations with the corresponding FEM T640 data ($0.64 < R^2 < 0.67$)

- Overall, the Atmocube sensors underestimated the PM$_{2.5}$ mass concentrations as measured by FEM T640

- The Atmocube sensors seemed to track the PM$_{2.5}$ diurnal variations as recorded by FEM T640

PM$_{2.5}$ (5-min mean, µg/m³)

$y = 0.9452x + 6.8558$
$R^2 = 0.6488$

PM$_{2.5}$ (5-min mean, µg/m³)

$y = 0.8678x + 6.9759$
$R^2 = 0.6622$

PM$_{2.5}$ (5-min mean, µg/m³)

$y = 0.7560x + 7.1283$
$R^2 = 0.6639$

Atmocube vs T640 (PM$_{10}$; 5-min mean)

Atmocube vs T640

- The Atmocube sensors showed no correlations with the corresponding T640 data ($0.08 < R^2 < 0.10$)

- Overall, the Atmocube sensors underestimated the PM$_{10}$ mass concentrations as measured by T640

- The Atmocube sensors did not seem to track the PM$_{10}$ diurnal variations as recorded by T640

Atmocube vs T640 (PM$_{1.0}$; 1-hr mean)
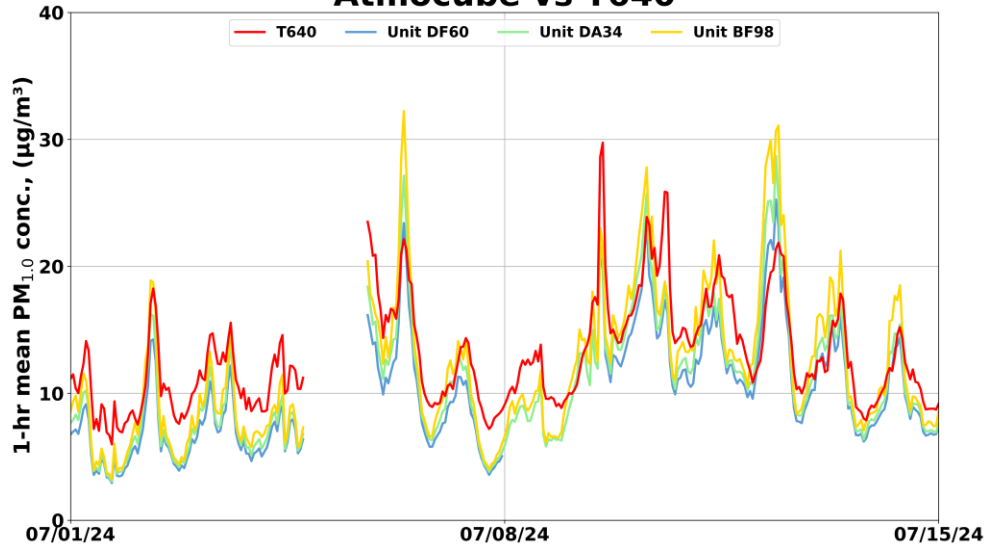
- The Atmocube sensors showed strong correlations with the corresponding T640 data ($0.82 < R^2 < 0.86$)

- Overall, the Atmocube sensors underestimated the PM$_{1.0}$ mass concentrations as measured by T640

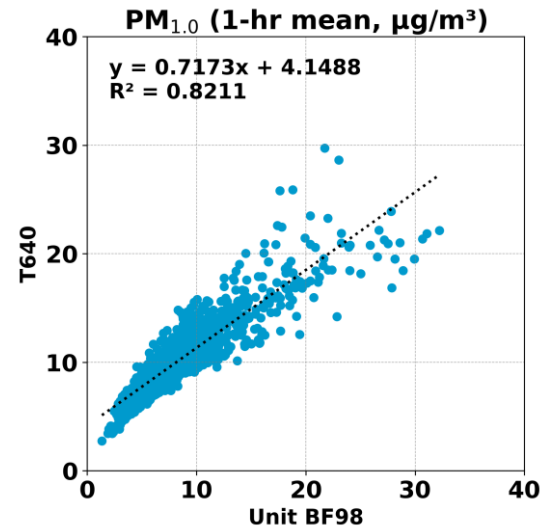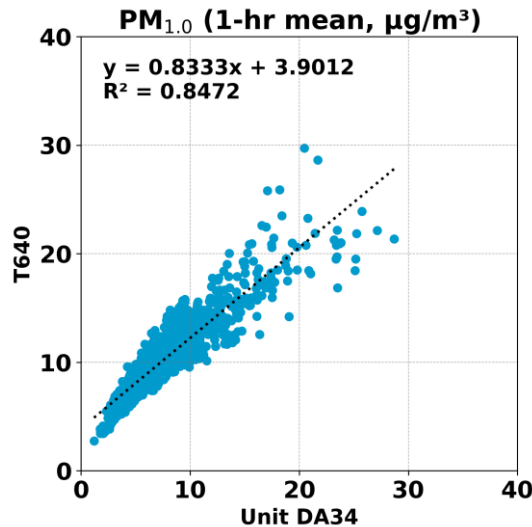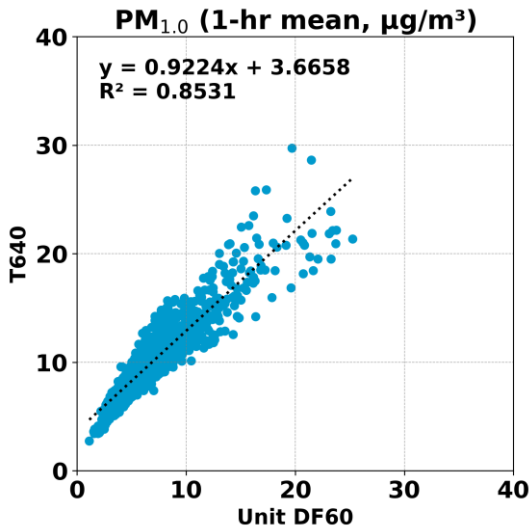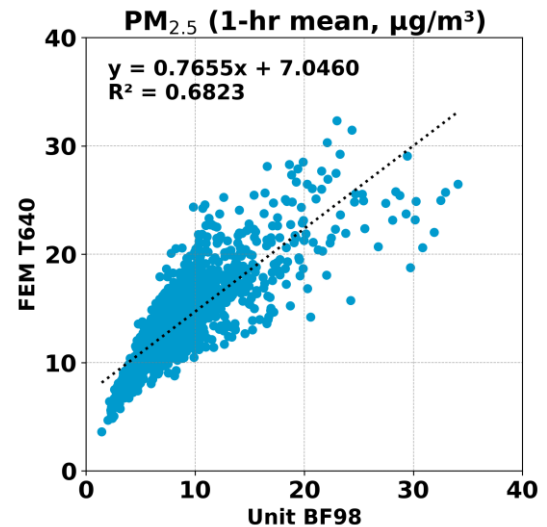- The Atmocube sensors seemed to track the PM$_{1.0}$ diurnal variations as recorded by T640
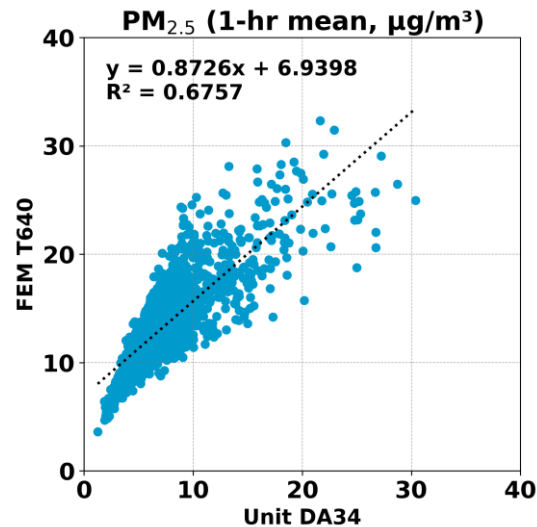
Atmocube vs FEM T640 (PM$_{2.5}$; 1-hr mean)

Atmocube vs FEM T640
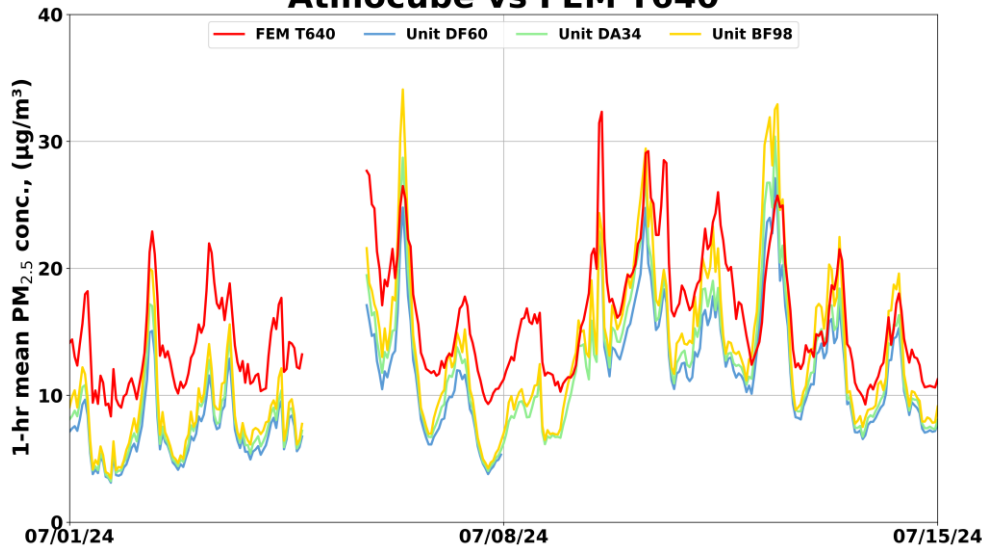
Legend: FEM T640, Unit DF60, Unit DA34, Unit BF98

- The Atmocube sensors showed moderate correlations with the corresponding FEM T640 data ($0.66 < R^2 < 0.69$)

- Overall, the Atmocube sensors underestimated the PM$_{2.5}$ mass concentrations as measured by FEM T640

- The Atmocube sensors seemed to track the PM$_{2.5}$ diurnal variations as recorded by FEM T640

PM$_{2.5}$ (1-hr mean, µg/m³)

$y = 0.9495x + 6.8253$
$R^2 = 0.6617$

Unit DF60

$y = 0.8726x + 6.9398$
$R^2 = 0.6757$

Unit DA34

$y = 0.7655x + 7.0460$
$R^2 = 0.6823$

Unit BF98

Atmocube vs T640 (PM_{10}; 1-hr mean)
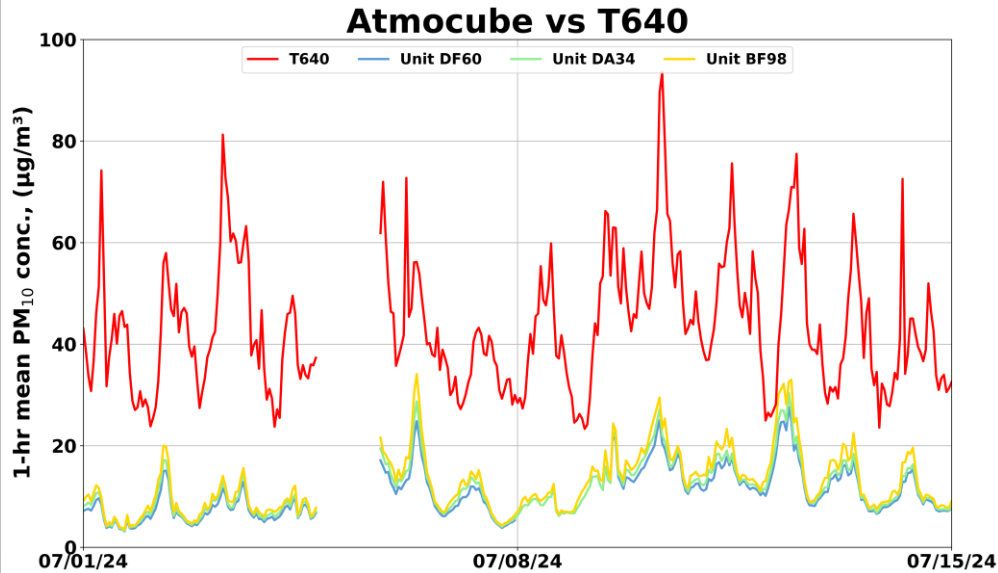
- The Atmocube sensors showed very weak correlations with the corresponding T640 data ($0.10 < R^2 < 0.12$)

- Overall, the Atmocube sensors underestimated the PM_{10} mass concentrations as measured by T640

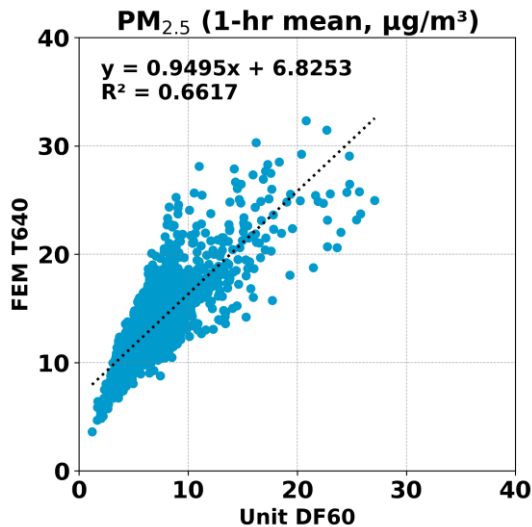- The Atmocube sensors did not seem to track the PM_{10} diurnal variations as recorded by T640
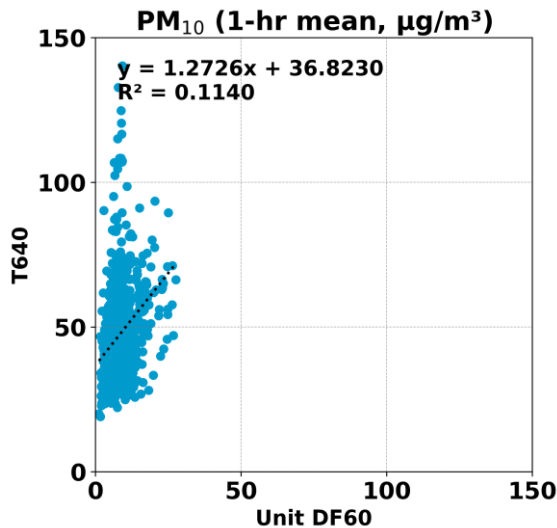
Atmocube vs T640 (PM$_{1.0}$; 24-hr mean)

- The Atmocube sensors showed strong to very strong correlations with the corresponding T640 data ($0.86 < R^2 < 0.91$)
- Overall, the Atmocube sensors underestimated the PM$_{1.0}$ mass concentrations as measured by T640
- The Atmocube sensors seemed to track the PM$_{1.0}$ daily variations as recorded by T640
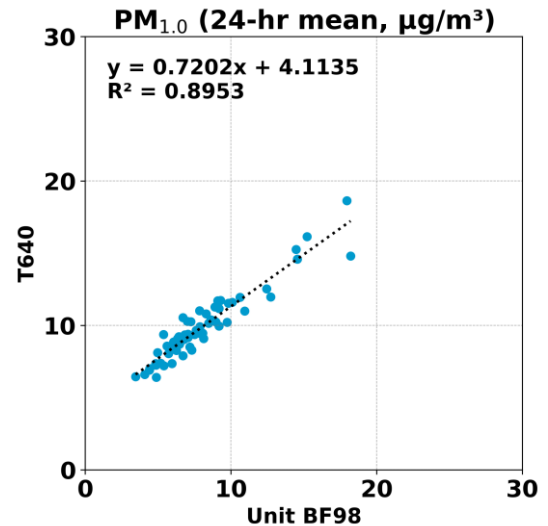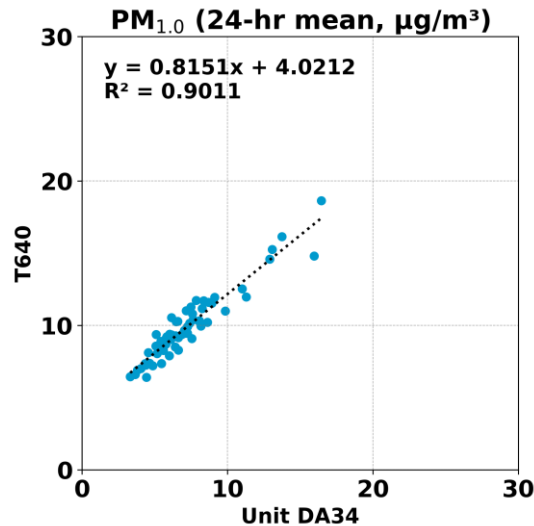
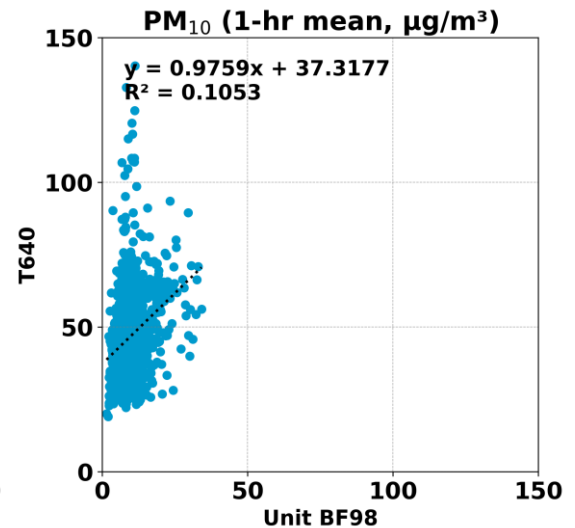# Atmocube vs FEM T640 (PM$_{2.5}$; 24-hr mean)
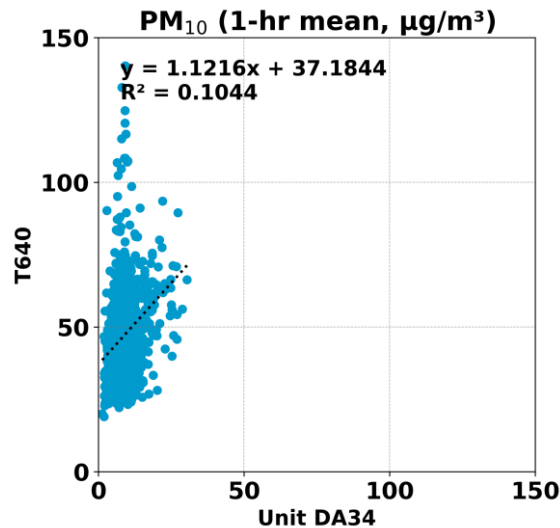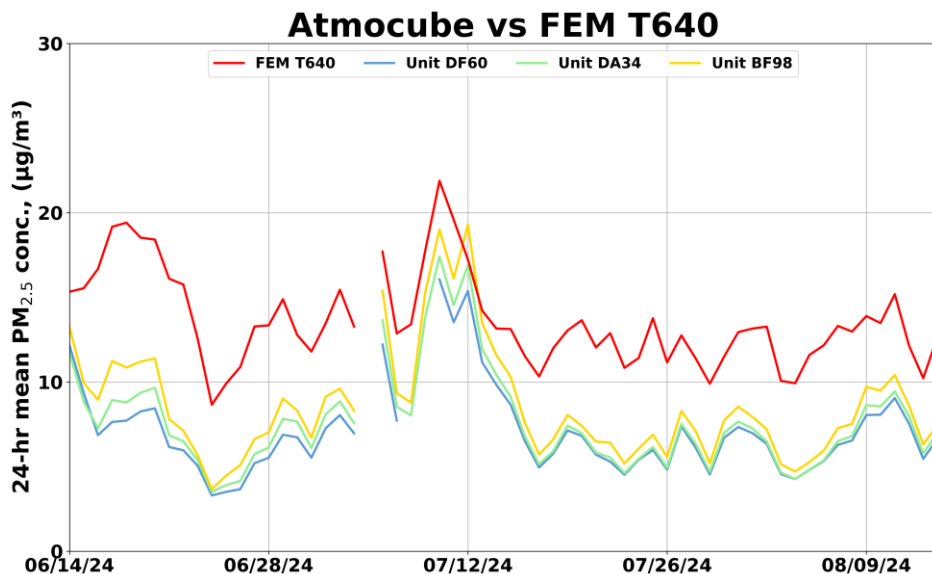

Atmocube vs FEM T640

- The Atmocube sensors showed moderate correlations with the corresponding FEM T640 data (0.56 < R^2 < 0.68)

- Overall, the Atmocube sensors underestimated the PM$_{2.5}$ mass concentrations as measured by FEM T640

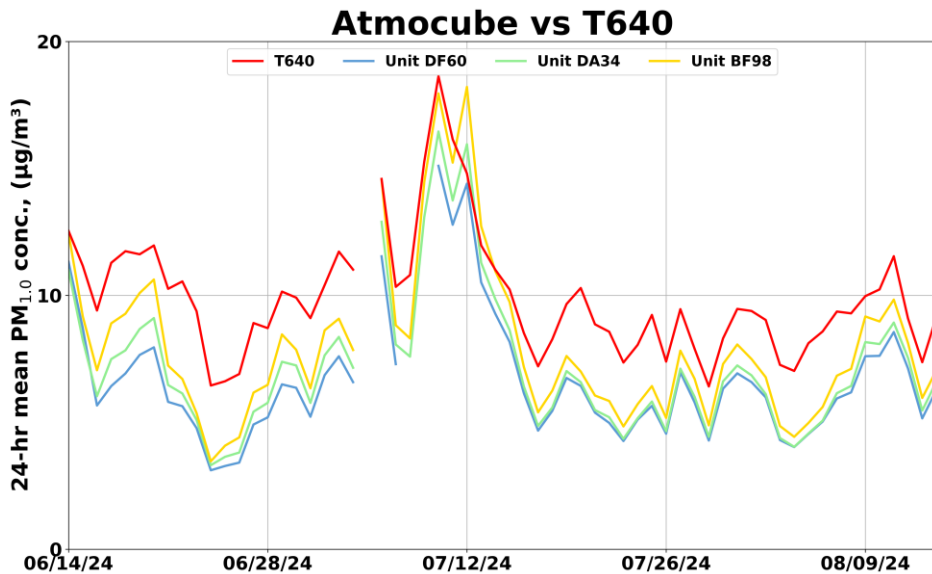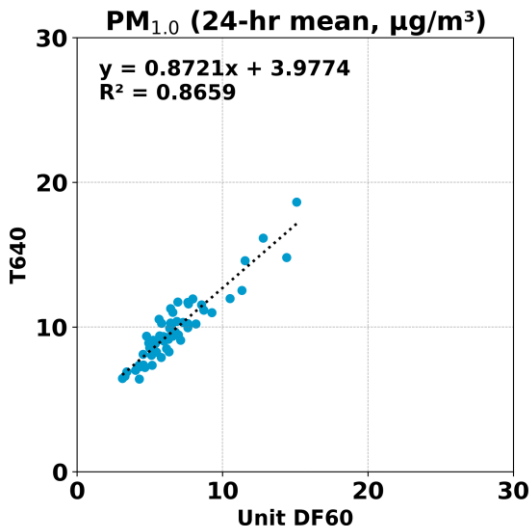- The Atmocube sensors seemed to track the PM$_{2.5}$ daily variations as recorded by FEM T640

PM$_{2.5}$ (24-hr mean, µg/m³)

$y = 0.7905x + 7.9403$
$R^2 = 0.5650$

PM$_{2.5}$ (24-hr mean, µg/m³)

$y = 0.7491x + 7.8728$
$R^2 = 0.6309$

PM$_{2.5}$ (24-hr mean, µg/m³)

$y = 0.6867x + 7.7090$
$R^2 = 0.6794$
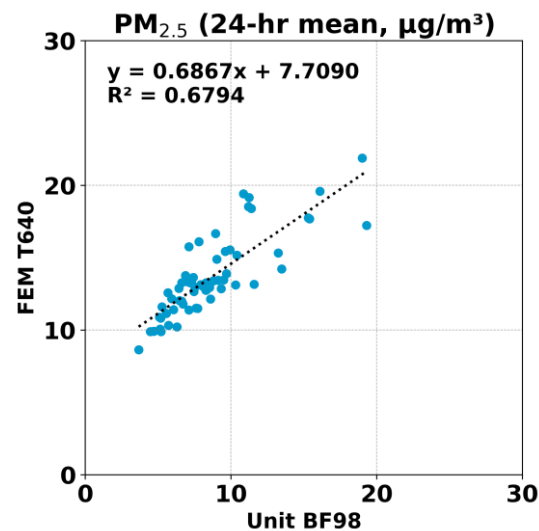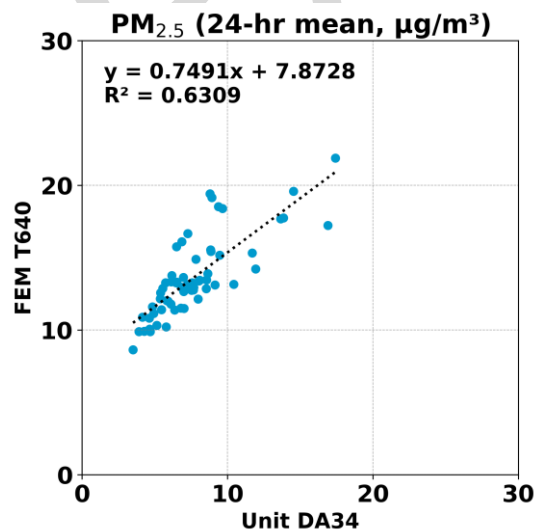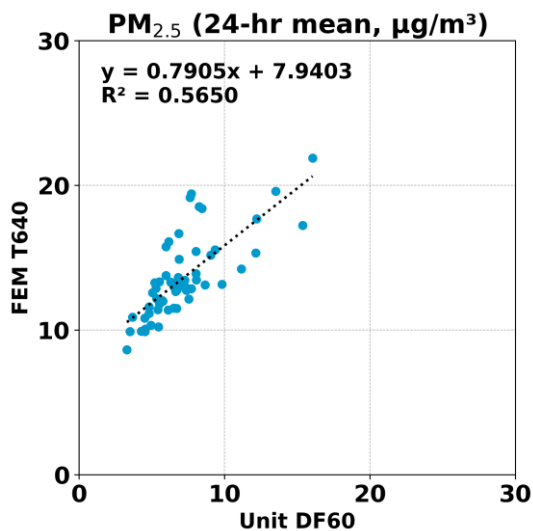
Atmocube vs T640 (PM$_{10}$; 24-hr mean)

Atmocube vs T640
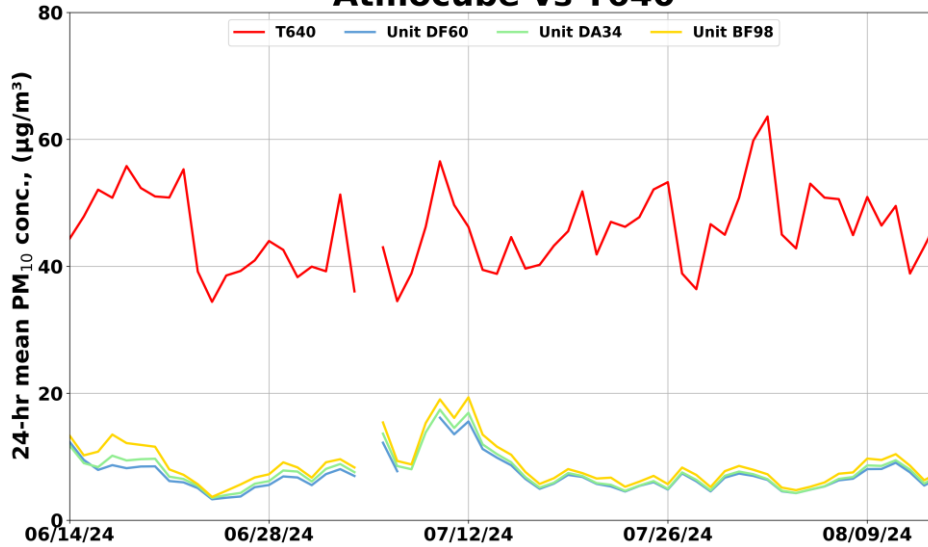
- The Atmocube sensors showed no correlations with the corresponding T640 data ($0.03 < R^2 < 0.05$)

- Overall, the Atmocube sensors underestimated the PM$_{10}$ mass concentrations as measured by T640

- The Atmocube sensors did not seem to track the PM$_{10}$ daily variations as recorded by T640

**PM$_{10}$ (24-hr mean, µg/m³)**

$y = 0.4651x + 42.5960$
$R^2 = 0.0374$

PM$_{10}$ (24-hr mean, µg/m³)

$y = 0.3788x + 42.8884$
$R^2 = 0.0310$

PM$_{10}$ (24-hr mean, µg/m³)

$y = 0.3828x + 42.4667$
$R^2 = 0.0415$

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Summary: PM

Average of 3 Sensors, PM$_{1.0}$		Atmocube vs T640, PM$_{1.0}$							T640 (PM$_{1.0}$, µg/m^3)		
Average (µg/m^3)	SD (µg/m^3)	R^2	Slope	Intercept	MBE[1] (µg/m^3)	MAE[2] (µg/m^3)	RMSE[3] (µg/m^3)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	7.4	3.9	0.80 to 0.84	0.71 to 0.92	3.7 to 4.2	-3.1 to -1.9	2.4 to 3.2	2.7 to 3.4	9.9	3.4	2.5 to 38.2
1-hr	7.4	3.8	0.82 to 0.85	0.72 to 0.92	3.7 to 4.1	-3.1 to -1.9	2.3 to 3.2	2.6 to 3.4	9.9	3.4	2.8 to 29.7
24-hr	7.3	2.8	0.87 to 0.90	0.72 to 0.87	4.0 to 4.1	-3.1 to -1.9	2.0 to 3.1	2.2 to 3.3	9.9	2.4	6.4 to 18.6
Average of 3 Sensors, PM$_{2.5}$		Atmocube vs FEM T640, PM$_{2.5}$							FEM T640 (PM$_{2.5}$, µg/m^3)		
Average (µg/m^3)	SD (µg/m^3)	R^2	Slope	Intercept	MBE[1] (µg/m^3)	MAE[2] (µg/m^3)	RMSE[3] (µg/m^3)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	7.9	4.1	0.65 to 0.66	0.76 to 0.95	6.9 to 7.1	-6.5 to -5.0	5.3 to 6.5	5.7 to 6.9	13.7	4.3	3.4 to 41.1
1-hr	7.9	4.0	0.66 to 0.68	0.77 to 0.95	6.8 to 7.0	-6.5 to -5.0	5.2 to 6.5	5.6 to 6.9	13.7	4.2	3.6 to 32.3
24-hr	7.8	3.0	0.57 to 0.68	0.69 to 0.79	7.7 to 7.9	-6.5 to -5.0	5.1 to 6.5	5.3 to 6.7	13.6	2.8	8.6 to 21.9
Average of 3 Sensors, PM$_{10}$		Atmocube vs T640, PM$_{10}$							T640 (PM$_{10}$, µg/m^3)		
Average (µg/m^3)	SD (µg/m^3)	R^2	Slope	Intercept	MBE[1] (µg/m^3)	MAE[2] (µg/m^3)	RMSE[3] (µg/m^3)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	7.9	4.1	0.09	0.99 to 1.29	36.7 to 37.2	-38.8 to -37.1	37.1 to 38.8	40.0 to 41.5	45.9	15.5	14.6 to 281.8
1-hr	7.9	4.1	0.10 to 0.11	0.98 to 1.27	36.8 to 37.3	-38.8 to -37.1	37.1 to 38.8	39.3 to 40.9	45.9	13.8	19.1 to 140.3
24-hr	7.9	3.0	0.03 to 0.04	0.38 to 0.47	42.5 to 42.9	-38.8 to -37.1	37.1 to 38.8	37.6 to 39.3	45.8	6.4	34.4 to 63.6

[1] Mean Bias Error (MBE): the difference between the sensors and the reference instruments. MBE indicates the tendency of the sensors to underestimate (negative MBE values) or overestimate (positive MBE values).

[2] Mean Absolute Error (MAE): the absolute difference between the sensors and the reference instruments. The larger MAE values, the higher measurement errors as compared to the reference instruments.

[3] Root Mean Square Error (RMSE): another metric to calculate measurement errors.

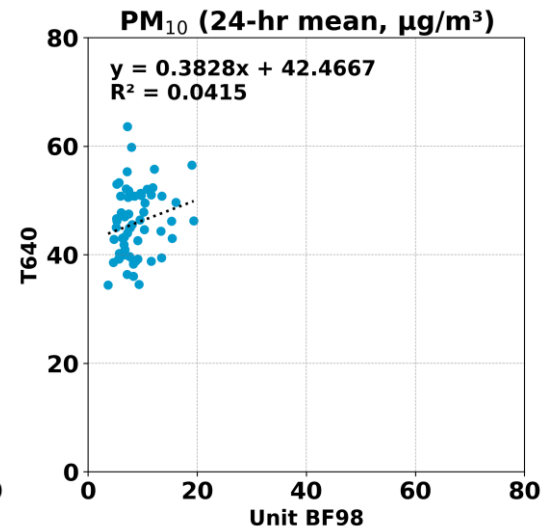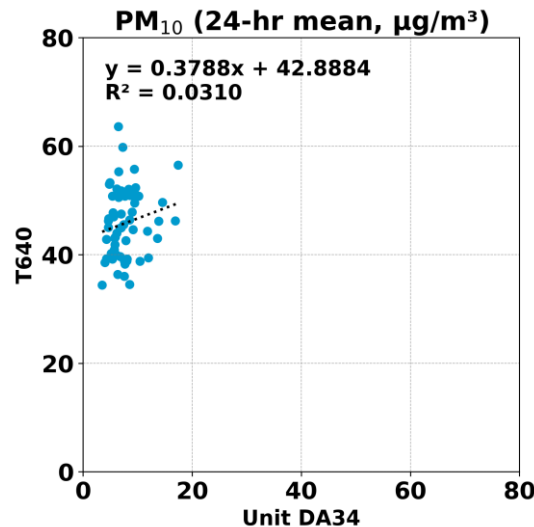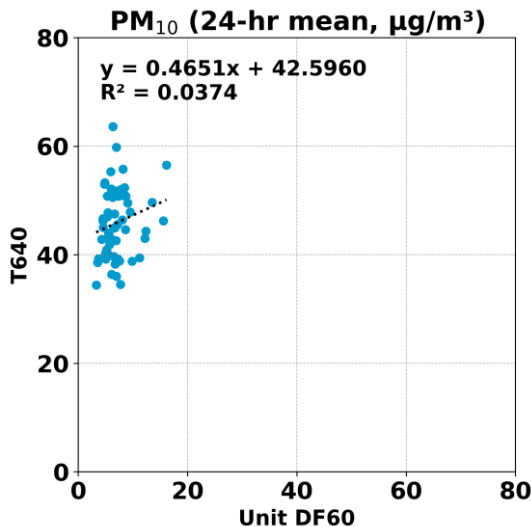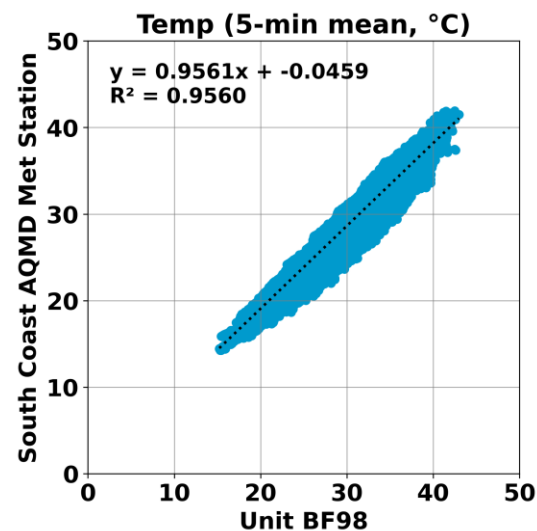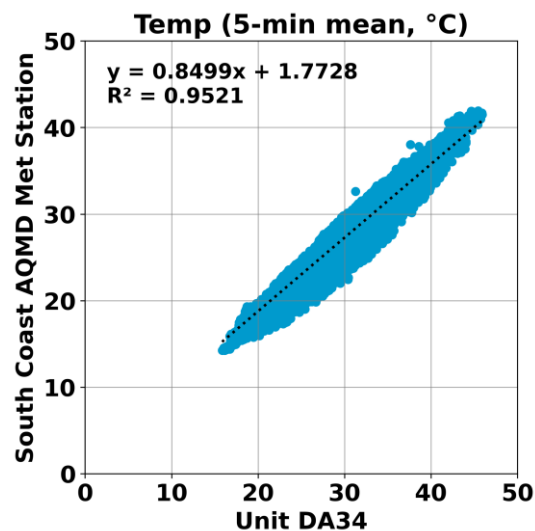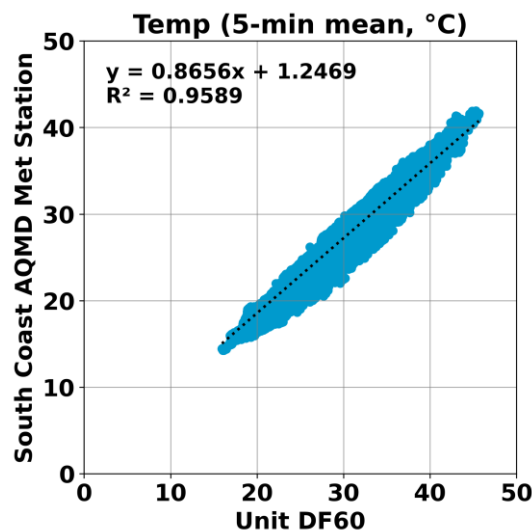# Atmocube vs South Coast AQMD Met Station (Temp; 5-min mean)

Atmocube vs. South Coast AQMD Met Station
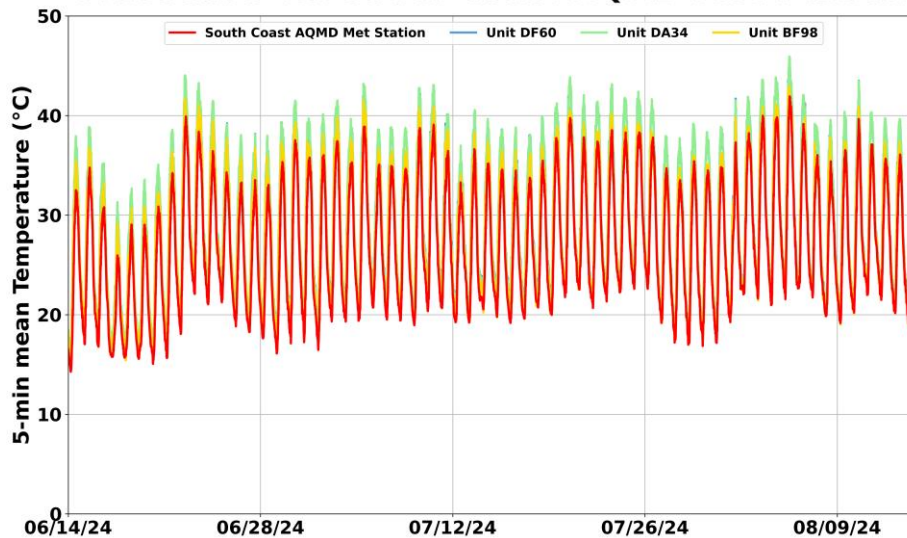
- The Atmocube sensors showed very strong correlations with the corresponding South Coast AQMD Met Station data ($0.95 < R^2 < 0.96$)

- Overall, the Atmocube sensors overestimated the temperature measurement as recorded by South Coast AQMD Met Station

- The Atmocube sensors seemed to track the diurnal temperature variations as recorded by South Coast AQMD Met Station

Temp (5-min mean, °C)

$y = 0.8656x + 1.2469$
$R^2 = 0.9589$

Temp (5-min mean, °C)

$y = 0.8499x + 1.7728$
$R^2 = 0.9521$

Temp (5-min mean, °C)

$y = 0.9561x + -0.0459$
$R^2 = 0.9560$

Atmocube vs South Coast AQMD Met Station (RH; 5-min mean)

Atmocube vs. South Coast AQMD Met Station
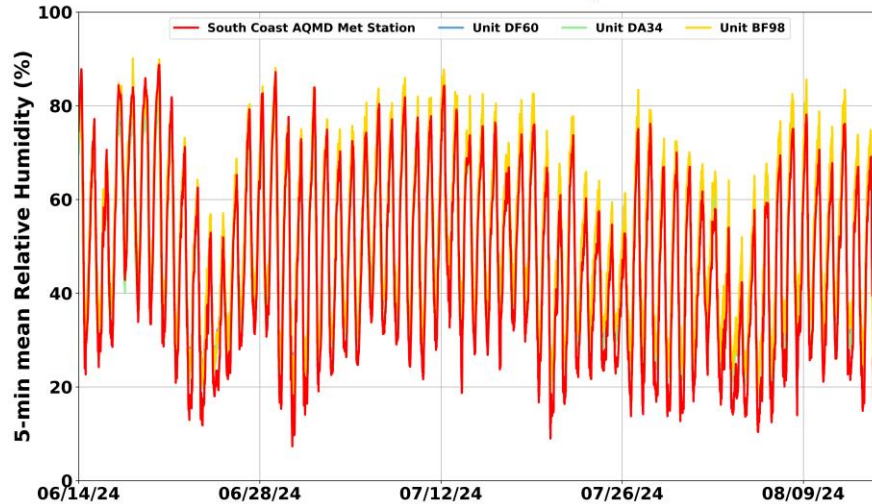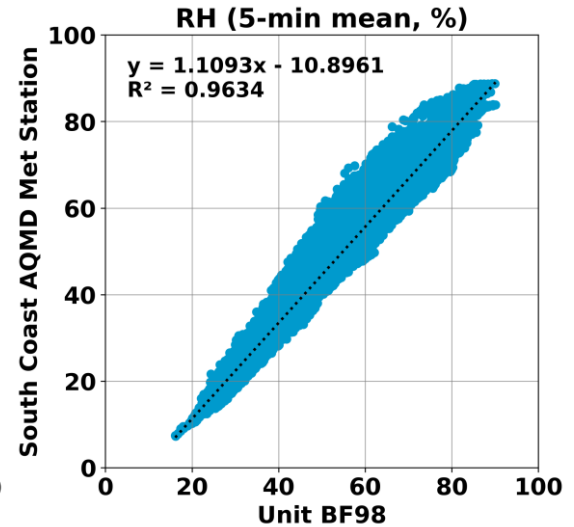
- Atmocube sensors showed very strong correlations with the corresponding South Coast AQMD Met Station data ($0.95 < R^2 < 0.97$)

- Overall, the Atmocube sensors overestimated the RH measurement as recorded by South Coast AQMD Met Station

- The Atmocube sensors seemed to track the diurnal RH variations as recorded by South Coast AQMD Met Station

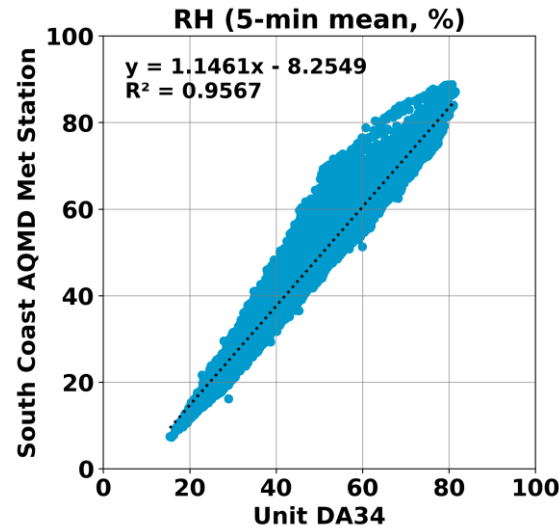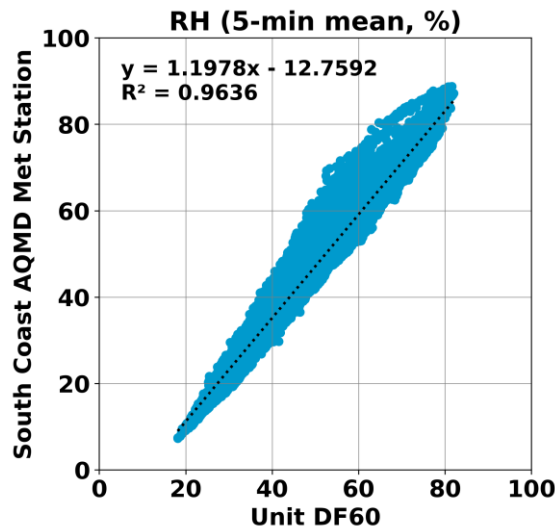RH (5-min mean, %)

y = 1.1978x − 12.7592
R^2 = 0.9636

RH (5-min mean, %)

y = 1.1461x − 8.2549
R^2 = 0.9567

RH (5-min mean, %)

y = 1.1093x − 10.8961
R^2 = 0.9634

Discussion

- The three **Atmocube** sensors' data recovery for CO, O_3, and all PM fractions was ~100%, ~100%, and ~99.2% , respectively.

- The absolute intra-model variability for CO and O_3 was ~391.7 ppb and ~1.5 ppb respectively. Absolute intra-model variability was ~0.6, ~0.7 and ~0.8 $\mu g/m^3$ for $PM_{1.0}$, $PM_{2.5}$ and PM_{10}, respectively

- During the <u>entire</u> field deployment testing period:
  - CO sensors showed no to very weak correlation with the FRM Horiba instrument ($0.0 < R^2 < 0.11$, 5-min mean) and generally overestimated the corresponding FRM Horiba data
  - Ozone sensors showed moderate to strong correlation with the FEM T400 instrument ($0.64 < R^2 < 0.83$, 5-min mean) and generally underestimated the corresponding FEM T400 data
  - The Atmocube sensors showed strong correlations with the corresponding T640 $PM_{1.0}$ data ($0.82 < R^2 < 0.86$, 1-hr mean), moderate correlations with the corresponding FEM T640 $PM_{2.5}$ data ($0.66 < R^2 < 0.69$, 1-hr mean) and very weak correlations with the corresponding T640 reference PM_{10} data ($0.10 < R^2 < 0.12$; 1-hr mean). The sensors underestimated $PM_{1.0}$, $PM_{2.5}$ and PM_{10} mass concentrations as measured by the reference instruments
  - Temperature and relative humidity sensors showed very strong correlations with the South Coast AQMD Met Station T and RH data, respectively ($R^2 \sim 0.95$ for T and $R^2 \sim 0.96$ for RH) and overestimated both the T and RH data as recorded by the South Coast AQMD Met Station

- No sensor calibration was performed by South Coast AQMD staff for this evaluation.

- Laboratory chamber testing is necessary to fully evaluate the performance of these sensors under controlled T and RH conditions, and known target and interferent pollutants concentrations.

- <u>These results are still preliminary</u>