Field Evaluation MetOne ES-405 Particulate Profiler

South Coast AQMD

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Background

- From 12/24/2020 to 2/24/2021, three **MetOne ES-405 Particulate Profiler (hereinafter MetOne ES-405)** sensors were deployed at the South Coast AQMD stationary ambient monitoring site in Rubidoux and were run side-by-side with Federal Equivalent Method (FEM) instruments measuring the same pollutants

- MetOne ES-405 (*3 units tested*):
  - Particle sensor: optical; non-FEM (right angle laser scattering)
  - Each unit reports: $PM_{1.0}$, $PM_{2.5}$ and PM_{10} ($\mu g/m^3$)
  - Also measures: $PM_{4.0}$ ($\mu g/m^3$)
  - Unit cost: $5,200
  - Time resolution: 1-min
  - Units IDs: 1744, 1745, 1746
  - Units are equipped with a heated inlet which will be activated when the user-set setpoint is exceeded (usually at 40% RH)

- GRIMM (*reference instrument*):
  - Optical particle counter (FEM $PM_{2.5}$)
  - Measures $PM_{1.0}$, $PM_{2.5}$, and PM_{10} ($\mu g/m^3$)
  - Cost: ~$25,000 and up
  - Time resolution: 1-min

- MetOne BAM (*reference instrument*):
  - Beta-attenuation monitor (FEM $PM_{2.5}$ & PM_{10})
  - Measures $PM_{2.5}$ & PM_{10} ($\mu g/m^3$)
  - Unit cost: ~$20,000
  - Time resolution: 1-hr

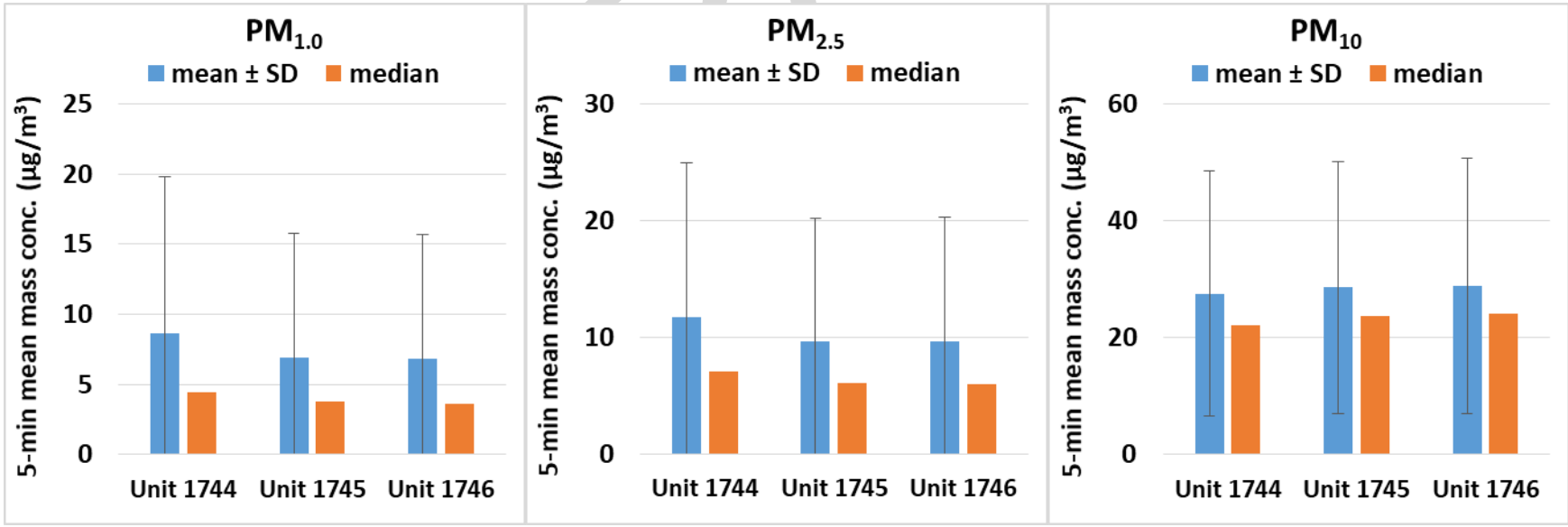
- Teledyne API T640 (*reference instrument*):
  - Optical particle counter (FEM $PM_{2.5}$)
  - Measures $PM_{1.0}$, $PM_{2.5}$ and PM_{10} ($\mu g/m^3$)
  - Unit cost: ~$21,000
  - Time resolution: 1-min

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 all units was 100% for all PM measurements

MetOne ES-405; intra-model variability

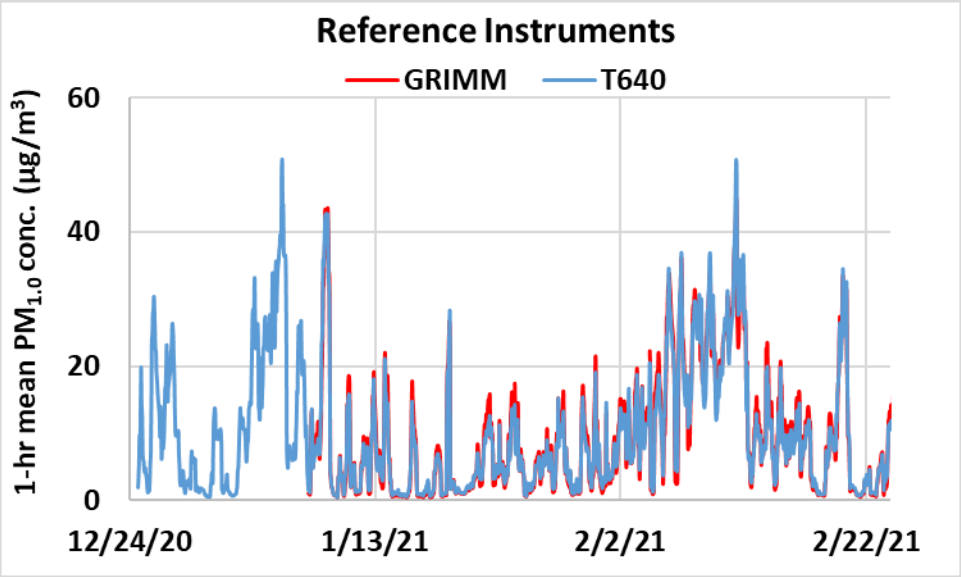
- Absolute intra-model variability was ~ 0.83, 0.97 and 0.59 µg/m^3 for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10,}$ respectively (calculated as the standard deviation of the three sensor means)
- Relative intra-model variability was ~ 11.1%, 9.4% and 2.1% for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10,}$ respectively (calculated as the absolute intra-model variability relative to the mean of the three sensor means)

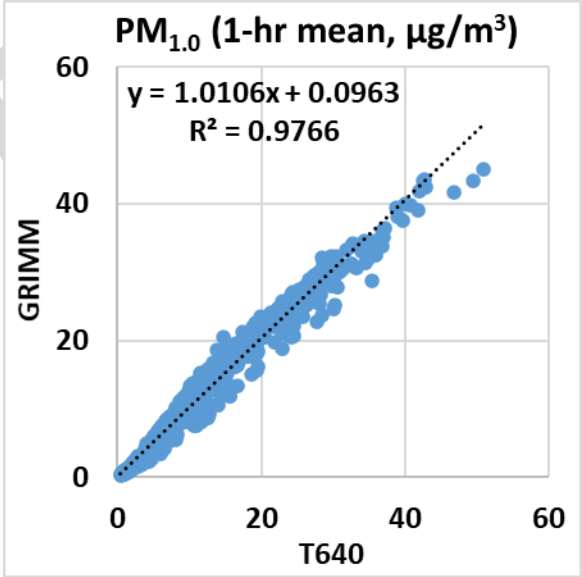


Reference Instruments: $PM_{1.0}$ GRIMM and T640

- Data recovery for $PM_{1.0}$ from GRIMM and T640 was ~ 78%* and ~ 100%, respectively.
- Very strong correlations between the reference instruments for $PM_{1.0}$ measurements (R^2 ~ 0.98) were observed.

**Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.*

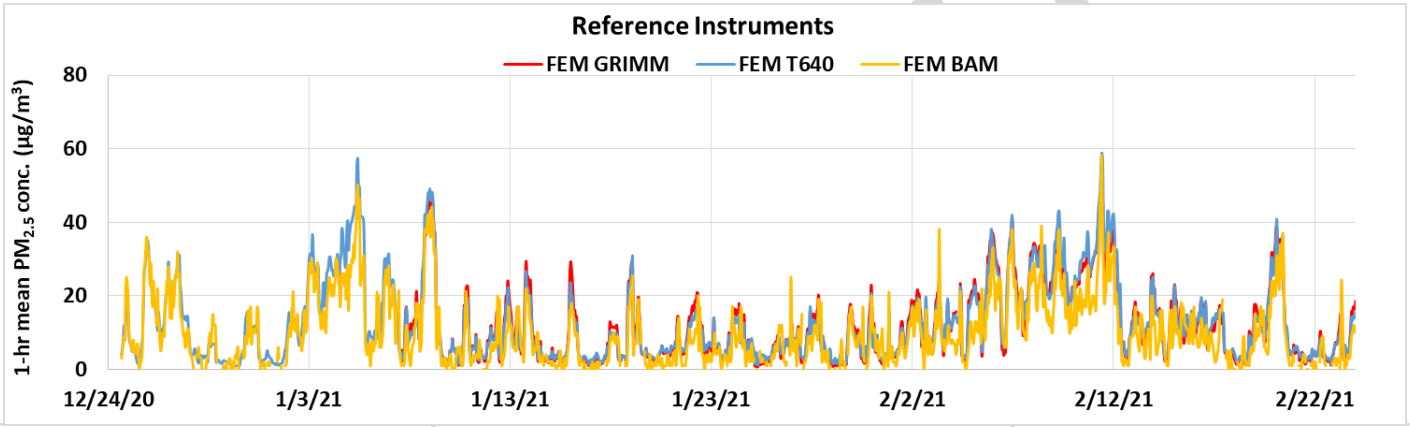


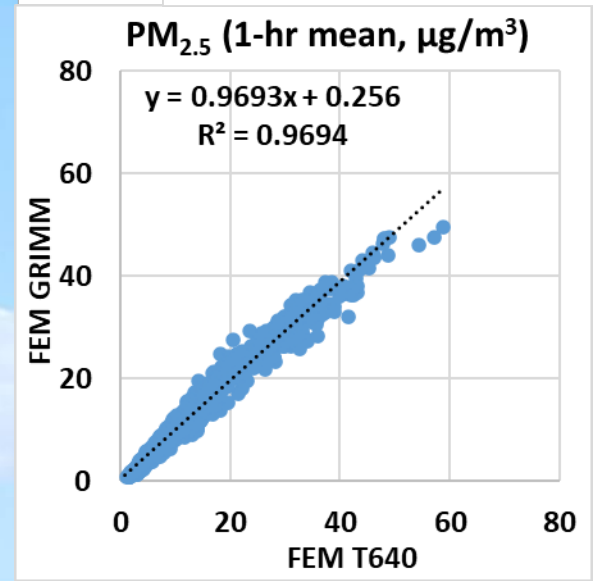


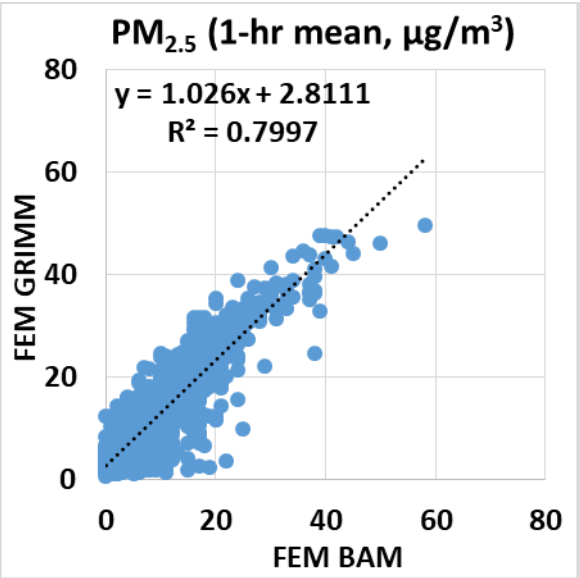
Reference Instruments: $PM_{2.5}$ FEM GRIMM, FEM BAM and FEM T640

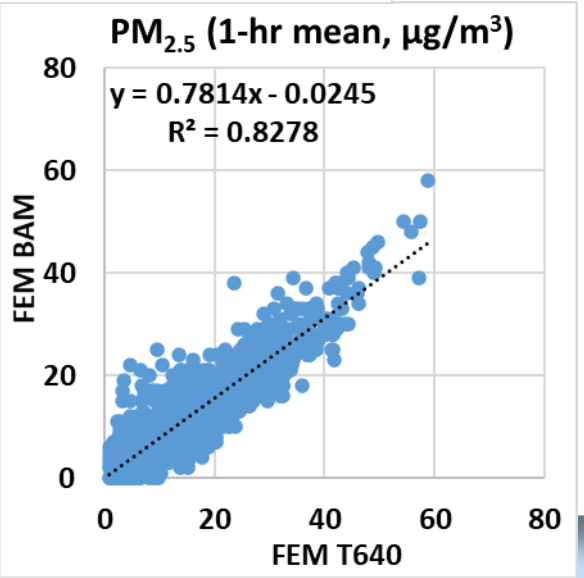
- Data recovery for $PM_{2.5}$ from FEM GRIMM, FEM BAM and FEM T640 was ~ 78%*, ~ 92% and ~ 100%, respectively.
- Strong to very strong correlations between the reference instruments for $PM_{2.5}$ measurements ($0.79 < R^2 < 0.97$) were observed.

Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





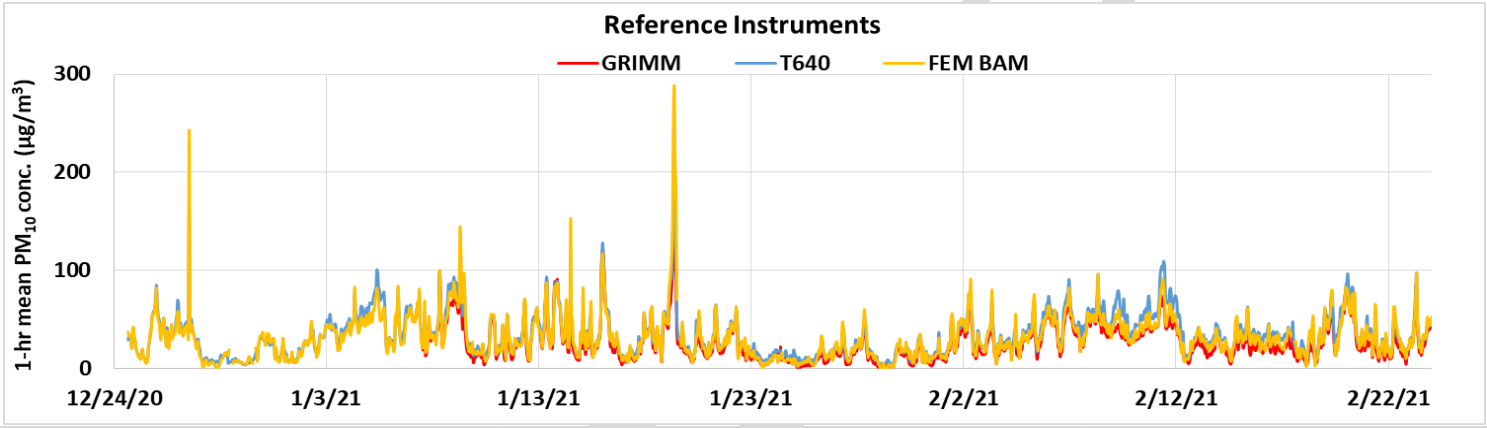


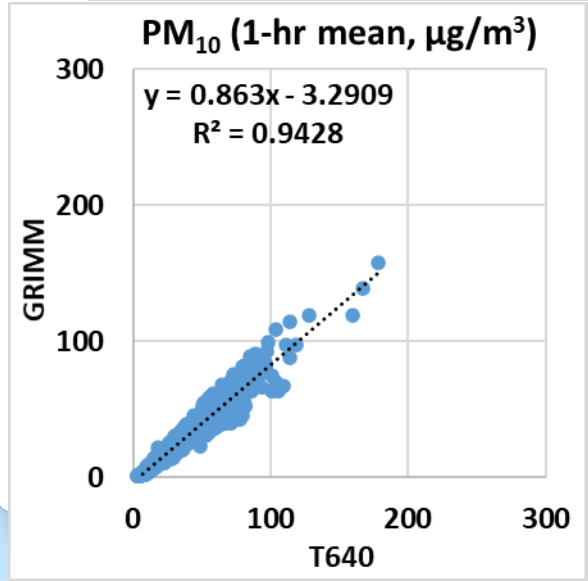


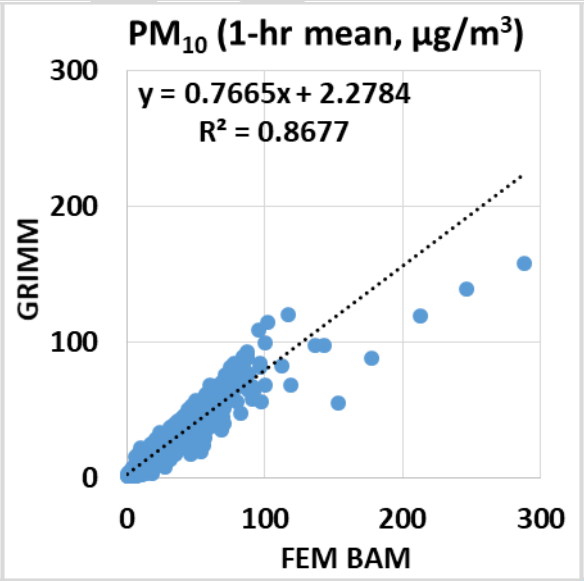
Reference Instruments: PM_{10} GRIMM, FEM BAM and T640

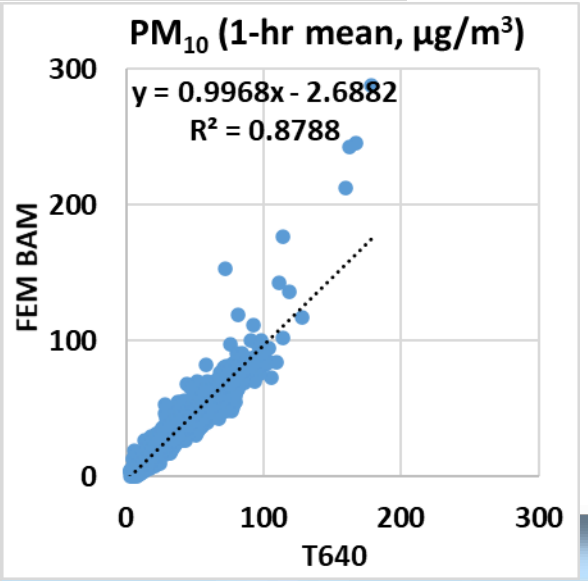
- Data recovery for PM_{10} from GRIMM, FEM BAM and T640 was ~ 78%*, ~ 99% and ~ 100%, respectively.
- Strong to very strong correlations between the reference instruments for PM_{10} measurements ($0.86 < R^2 < 0.95$) were observed.

Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.

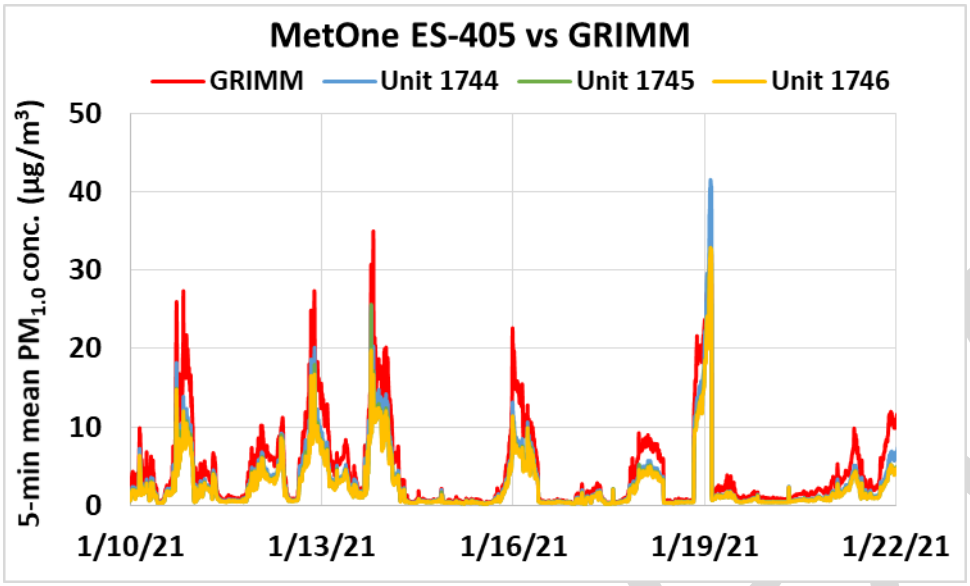






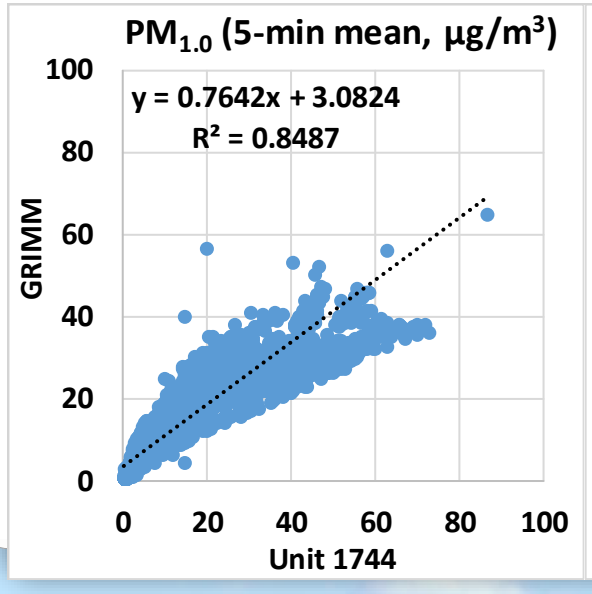


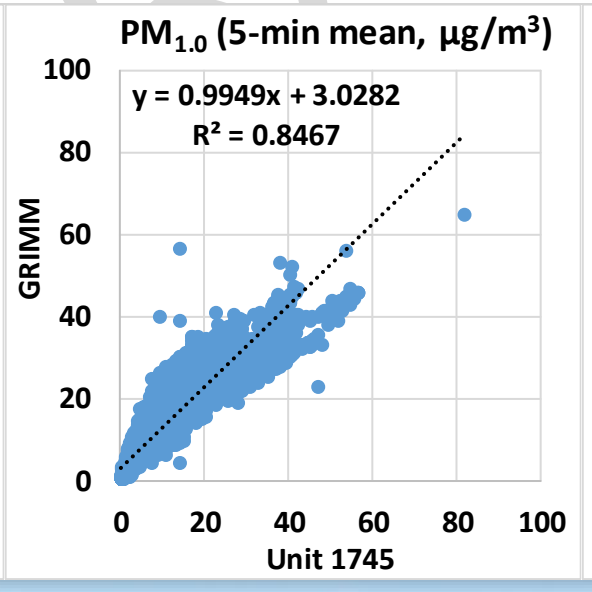
MetOne ES-405 vs GRIMM ($PM_{1.0}$; 5-min mean)

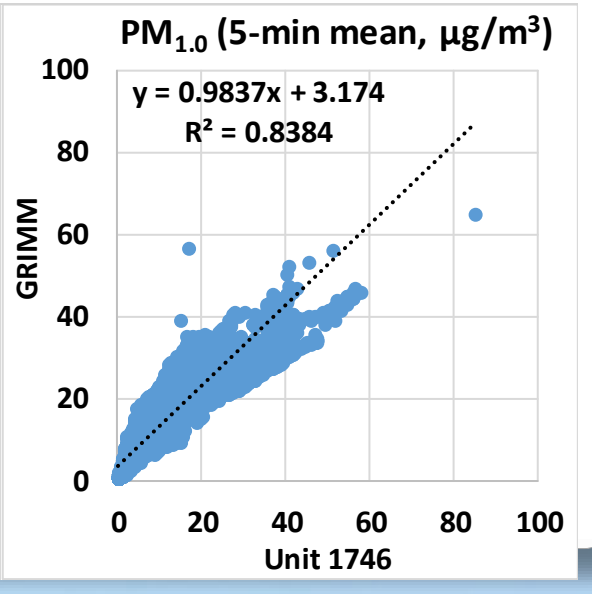


- The MetOne ES-405 sensors showed strong correlations with the corresponding GRIMM data ($0.83 < R^2 < 0.85$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM

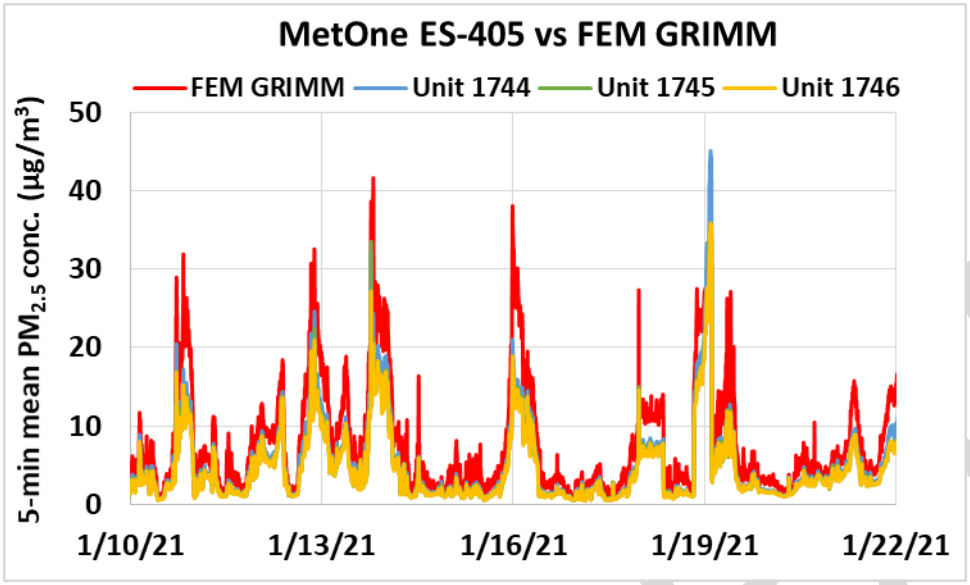
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





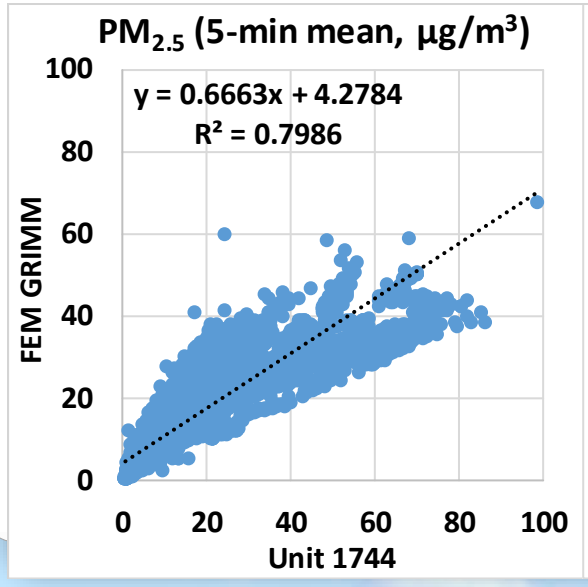


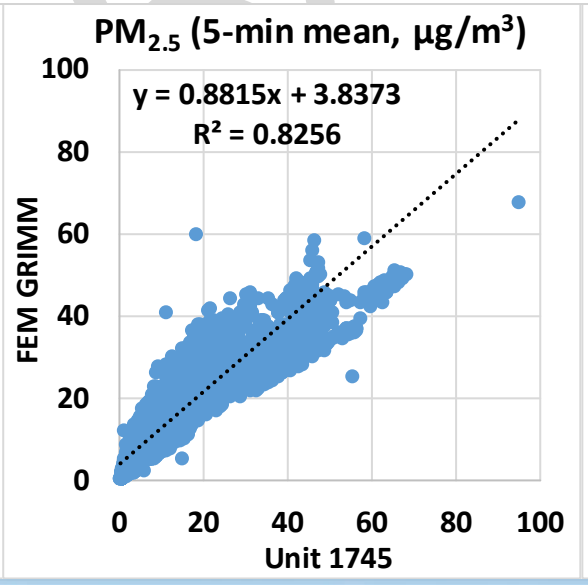
MetOne ES-405 vs FEM GRIMM ($PM_{2.5}$; 5-min mean)

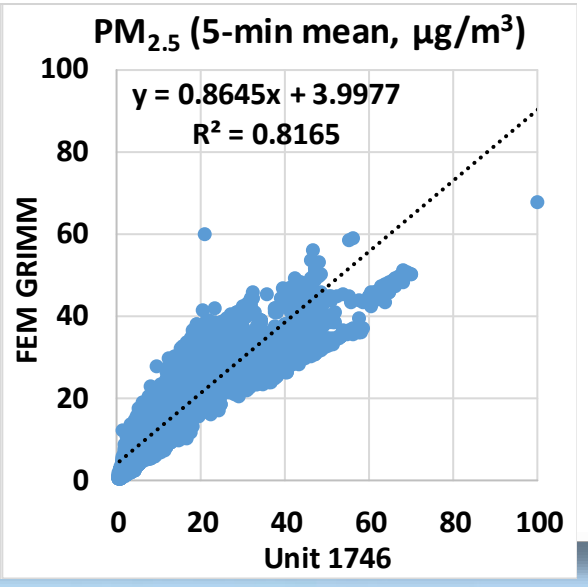


- The MetOne ES-405 sensors showed strong correlations with the corresponding FEM GRIMM data ($0.79 < R^2 < 0.83$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM

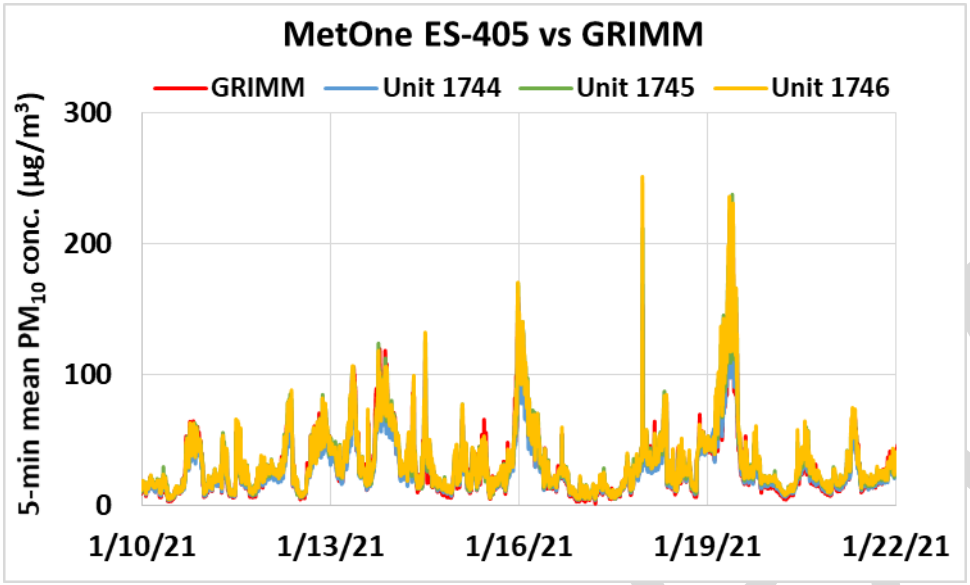
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





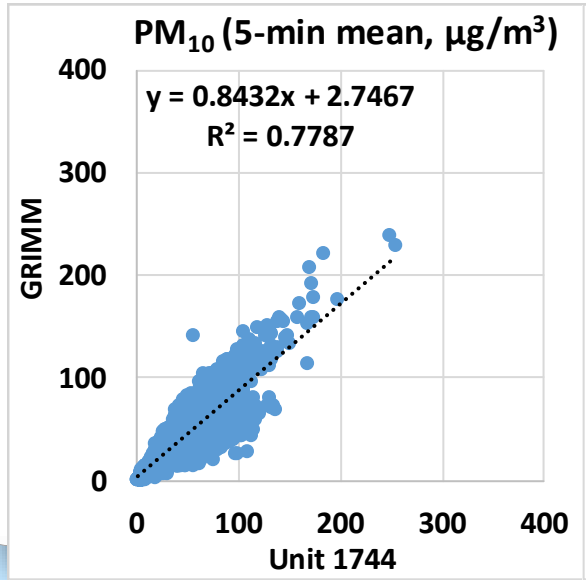


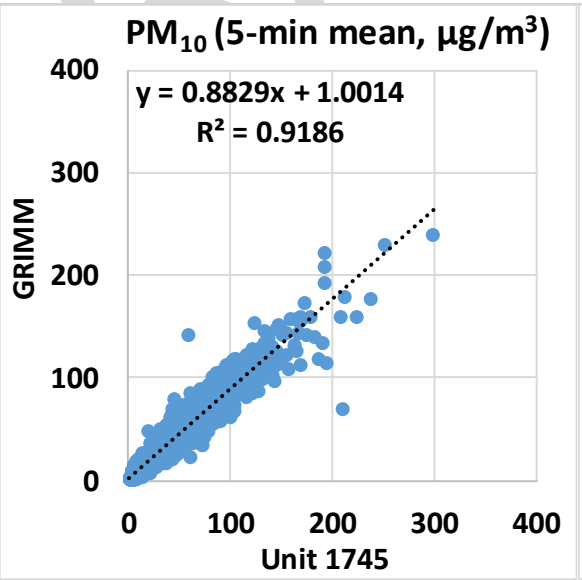
MetOne ES-405 vs GRIMM (PM_{10}; 5-min mean)

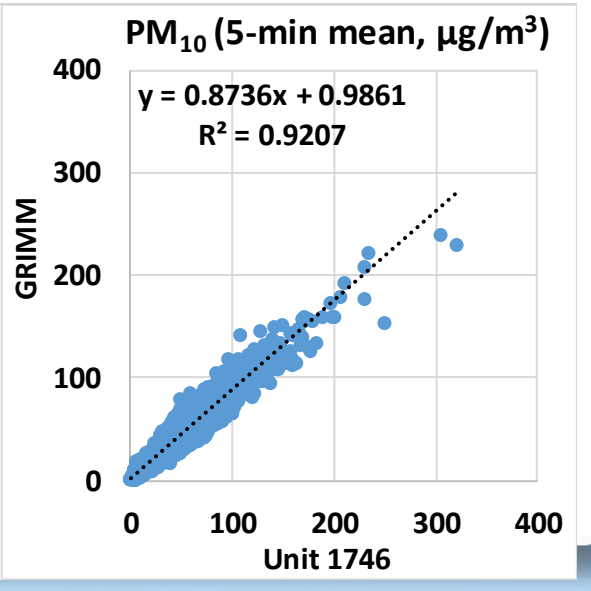


- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM data ($0.77 < R^2 < 0.93$)
- Overall, the MetOne ES-405 sensors overestimated the PM_{10} mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM

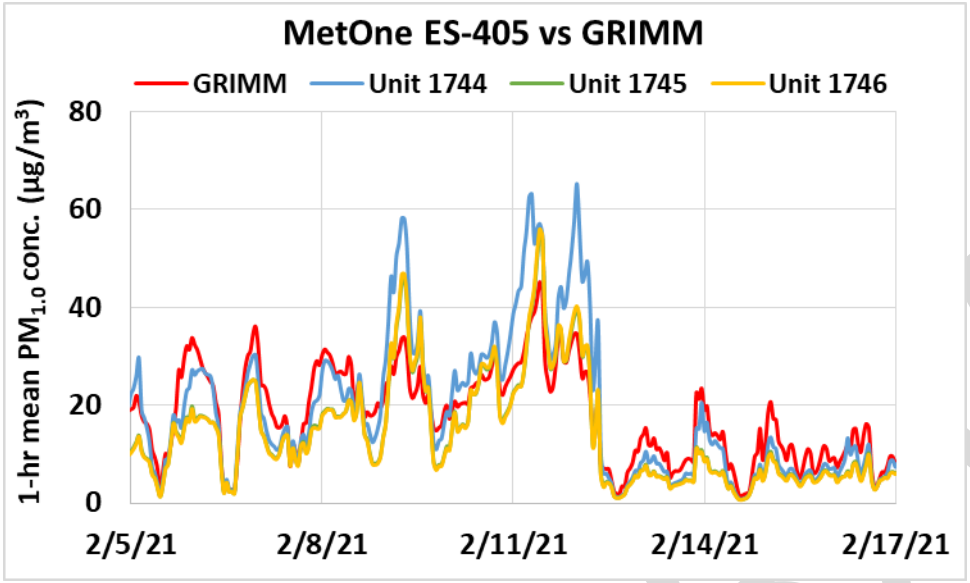
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





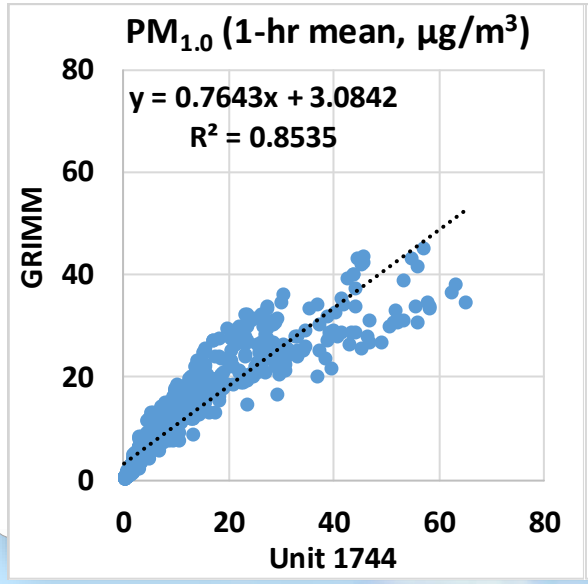


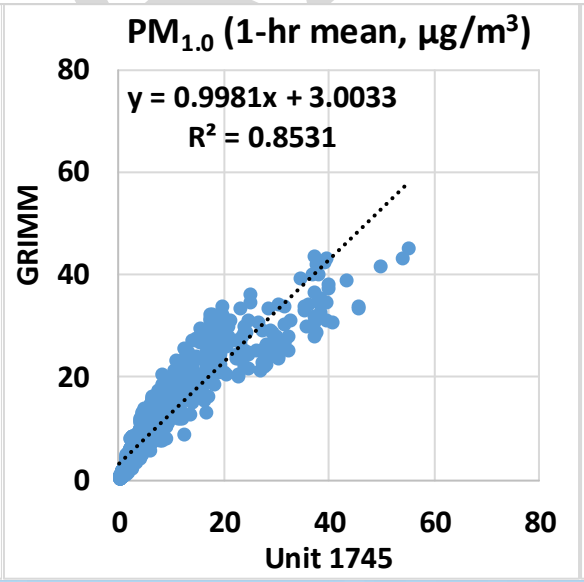
MetOne ES-405 vs GRIMM ($PM_{1.0}$; 1-hr mean)

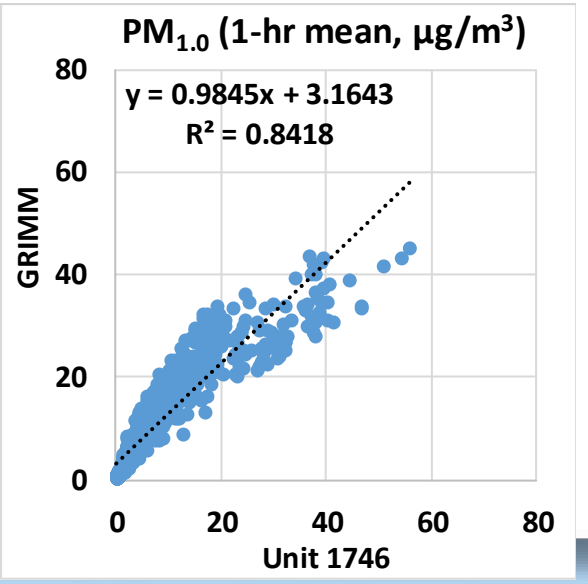


- The MetOne ES-405 sensors showed strong correlations with the corresponding GRIMM data ($0.84 < R^2 < 0.86$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM

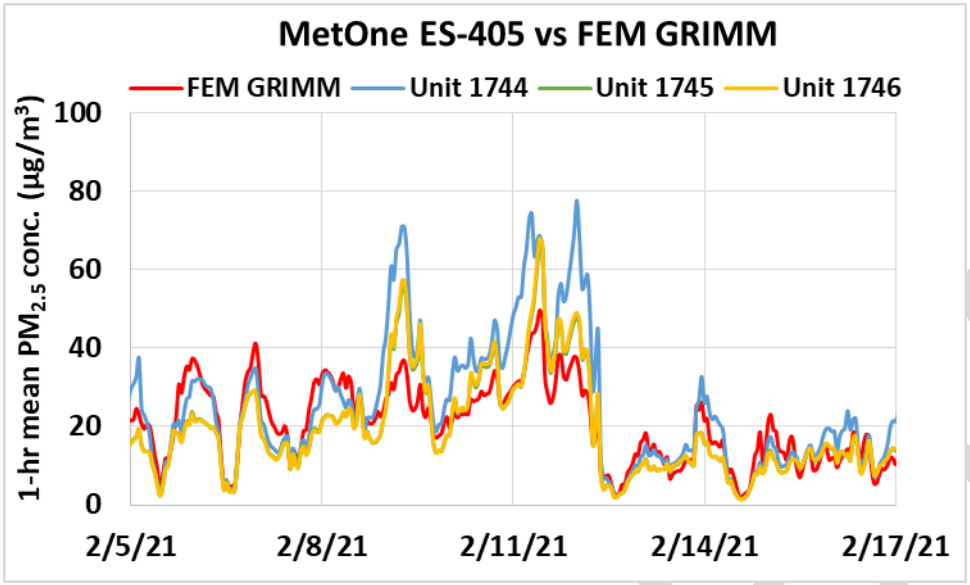
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





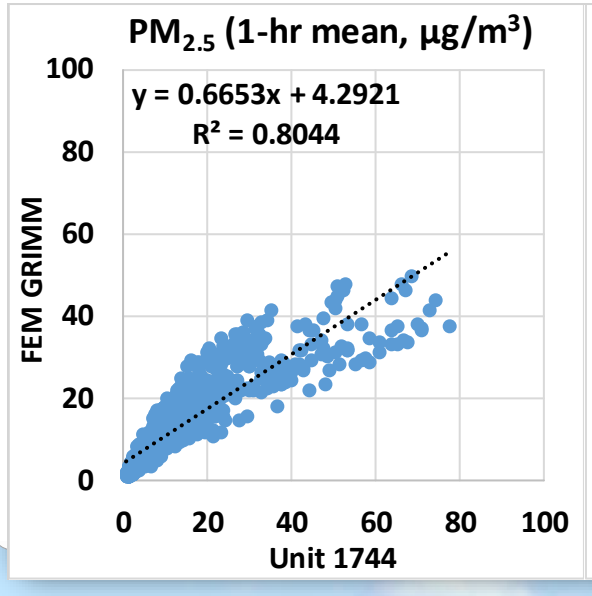


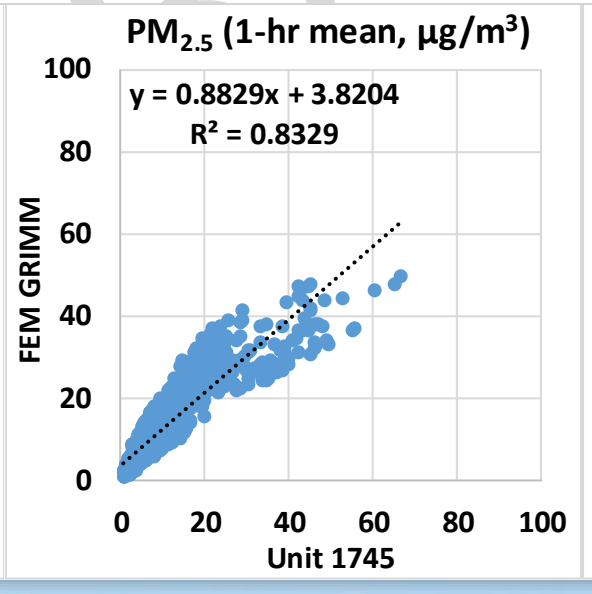
MetOne ES-405 vs FEM GRIMM ($PM_{2.5}$; 1-hr mean)

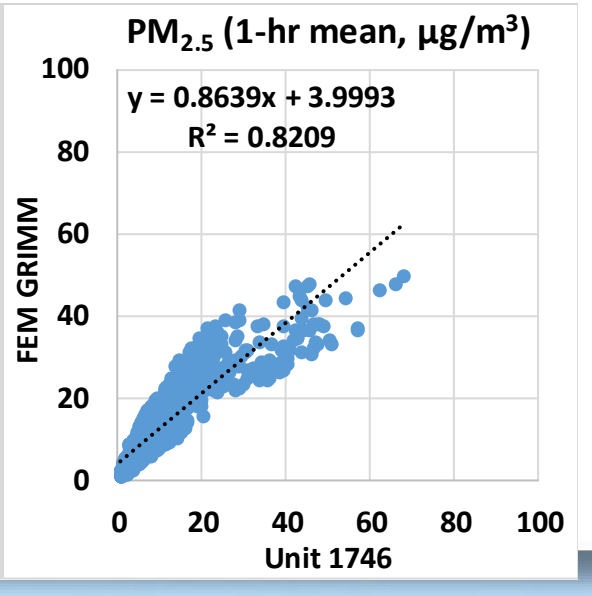


- The MetOne ES-405 sensors showed strong correlations with the corresponding FEM GRIMM data ($0.80 < R^2 < 0.84$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM

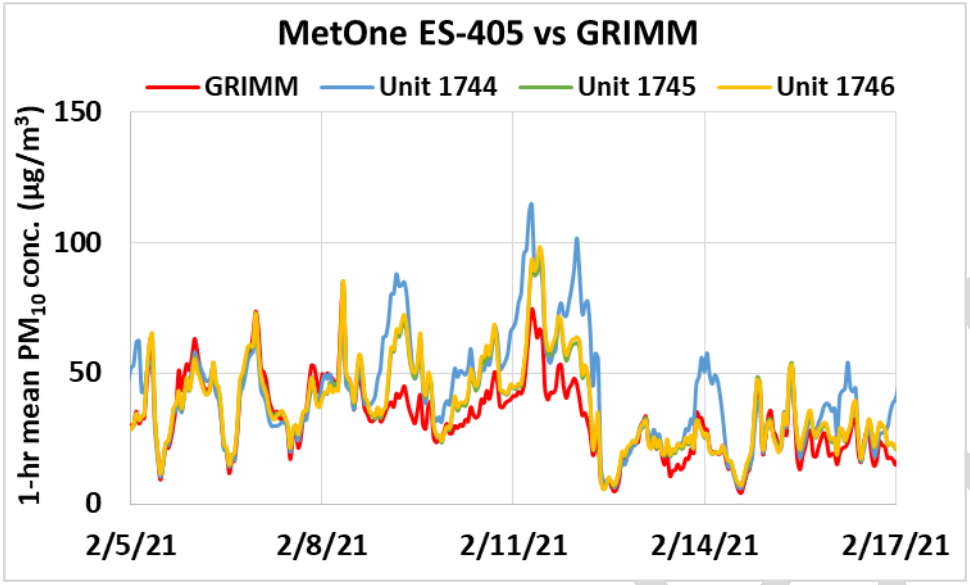
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





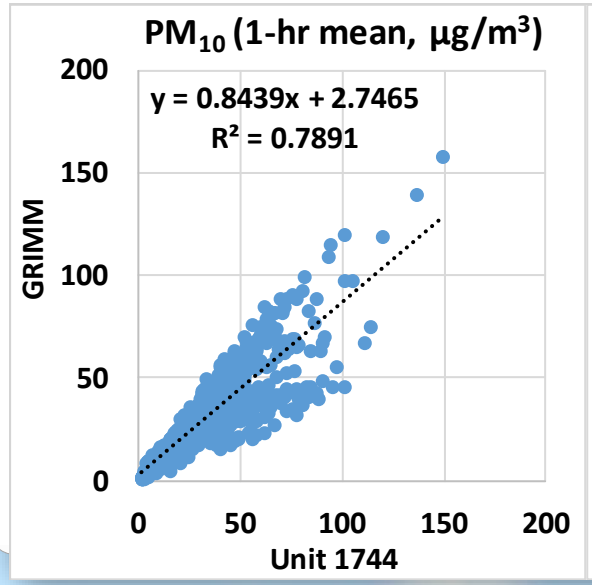


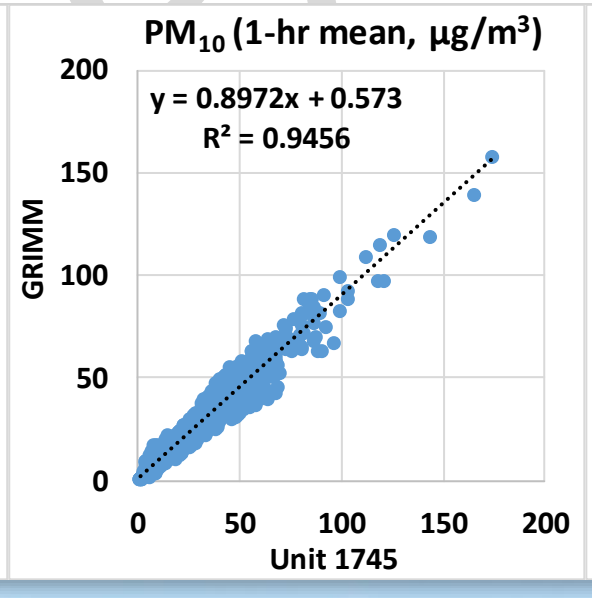
MetOne ES-405 vs GRIMM (PM_{10}; 1-hr mean)

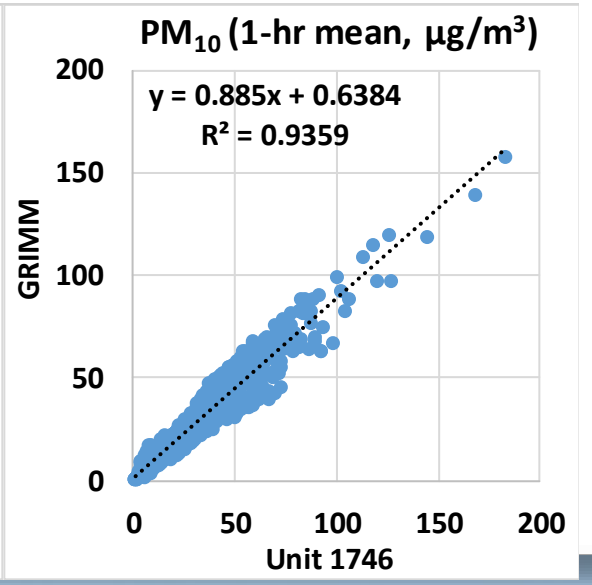


- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM data ($0.78 < R^2 < 0.95$)
- Overall, the MetOne ES-405 sensors overestimated the PM_{10} mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM

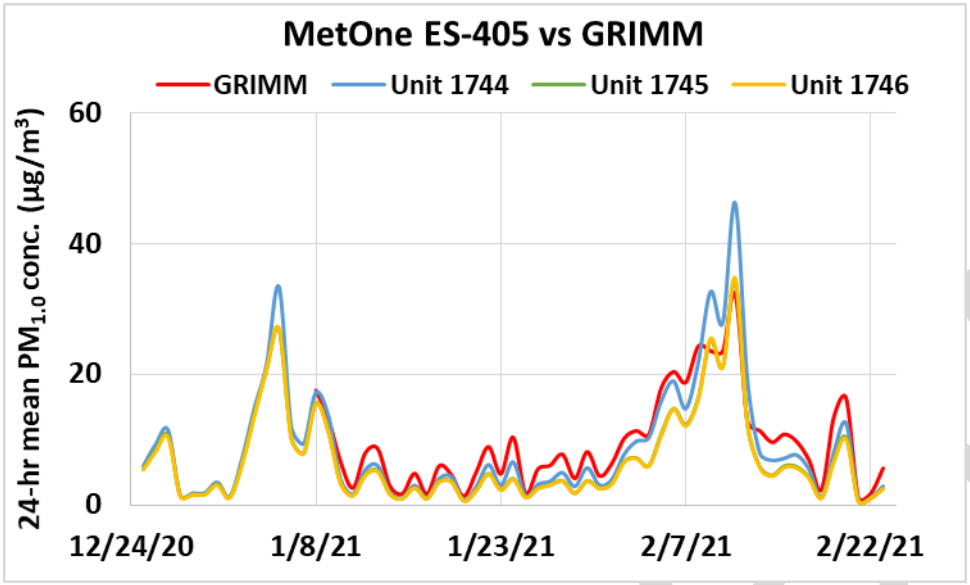
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





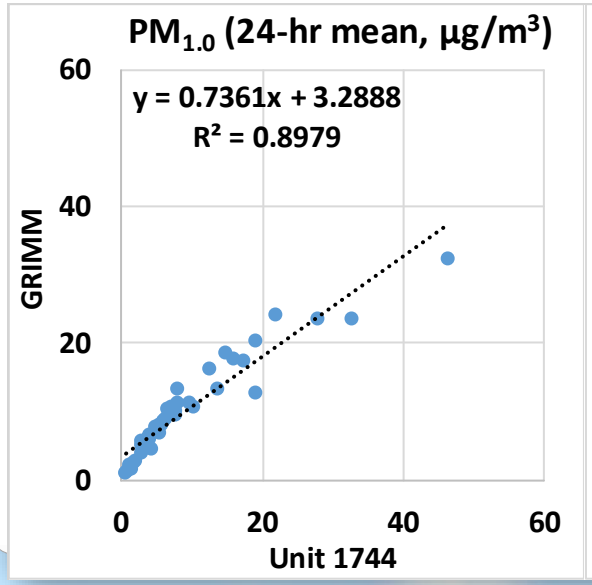


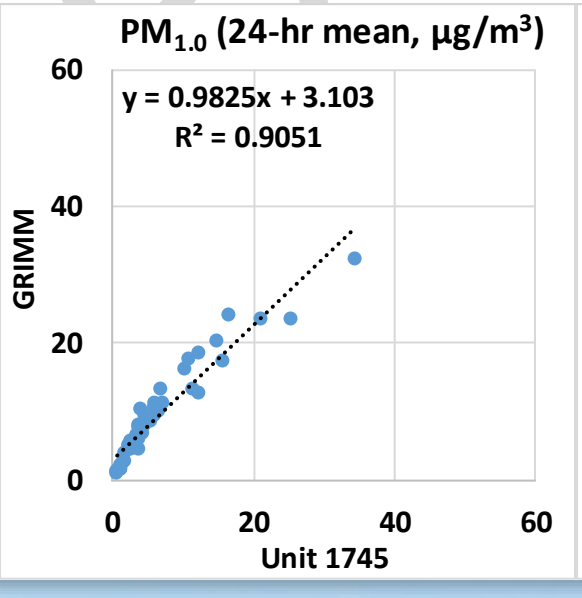
MetOne ES-405 vs GRIMM ($PM_{1.0}$; 24-hr mean)

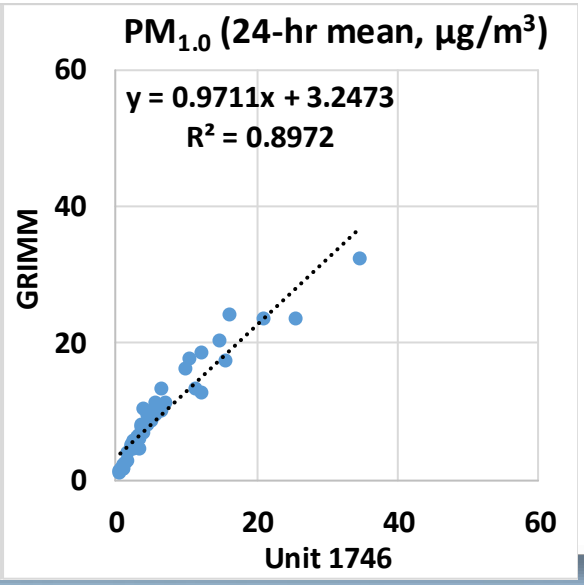


- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM data ($0.89 < R^2 < 0.91$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM

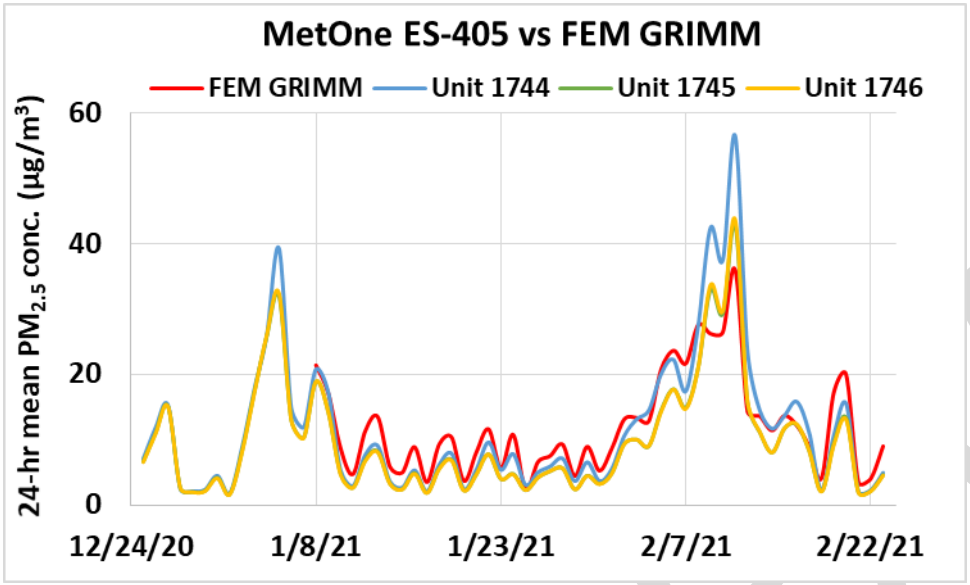
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





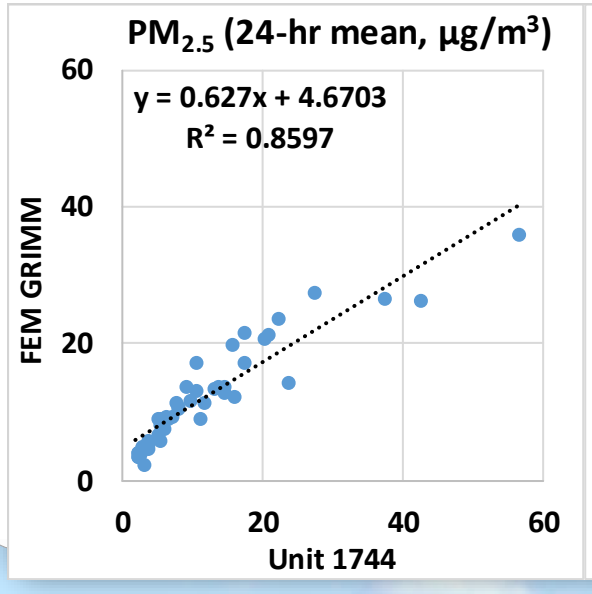


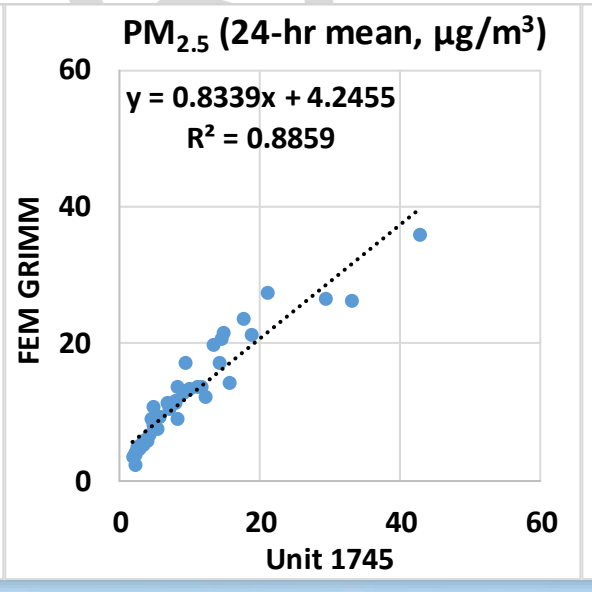
MetOne ES-405 vs FEM GRIMM ($PM_{2.5}$; 24-hr mean)

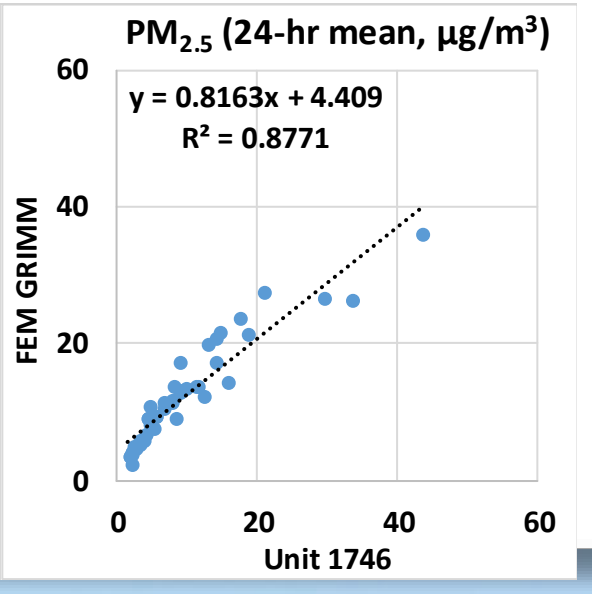


- The MetOne ES-405 sensors showed strong correlations with the corresponding FEM GRIMM data ($0.85 < R^2 < 0.89$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM

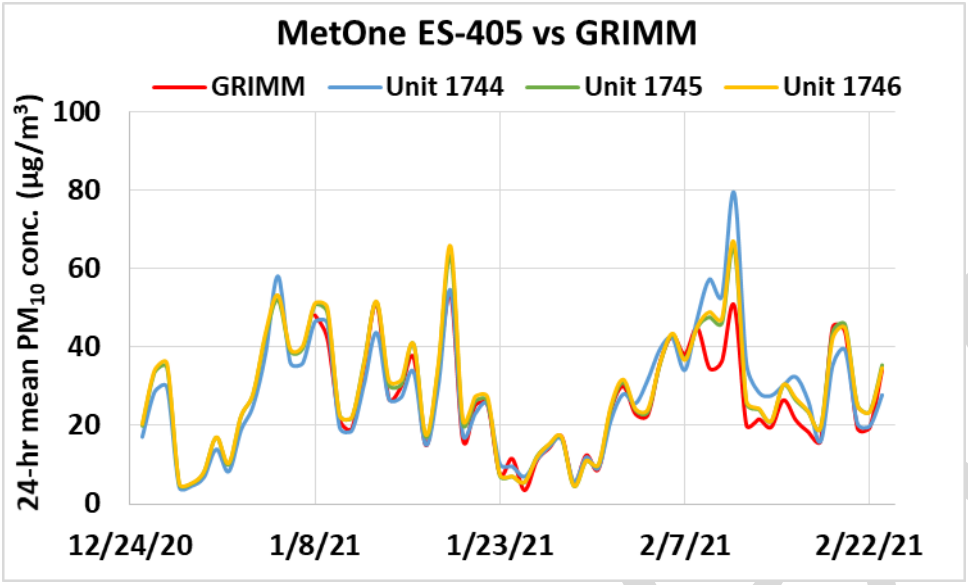
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.





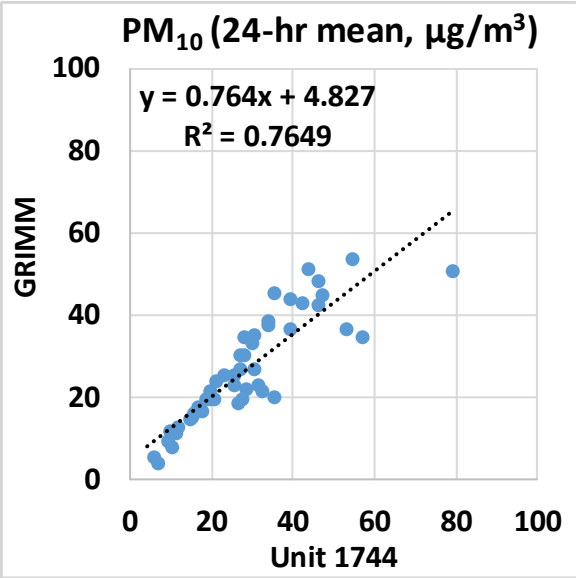


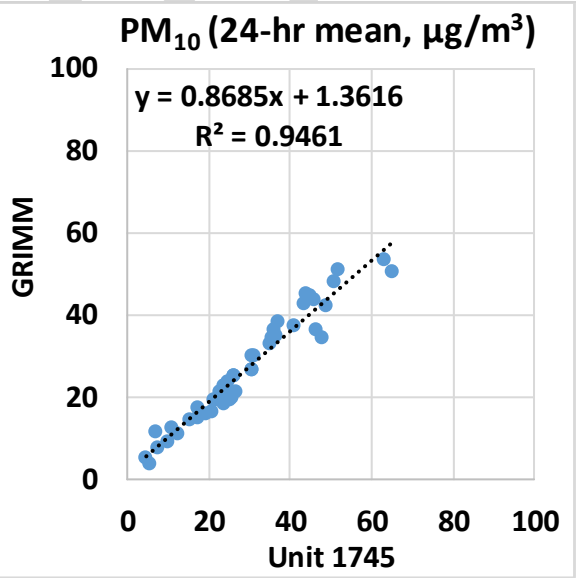
MetOne ES-405 vs GRIMM (PM_{10}; 24-hr mean)

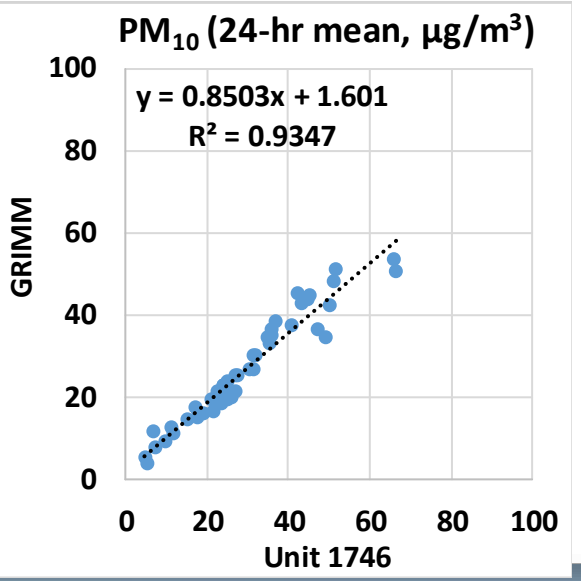


- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM data ($0.76 < R^2 < 0.95$)
- Overall, the MetOne ES-405 sensors overestimated the PM_{10} mass concentrations as measured by GRIMM
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM

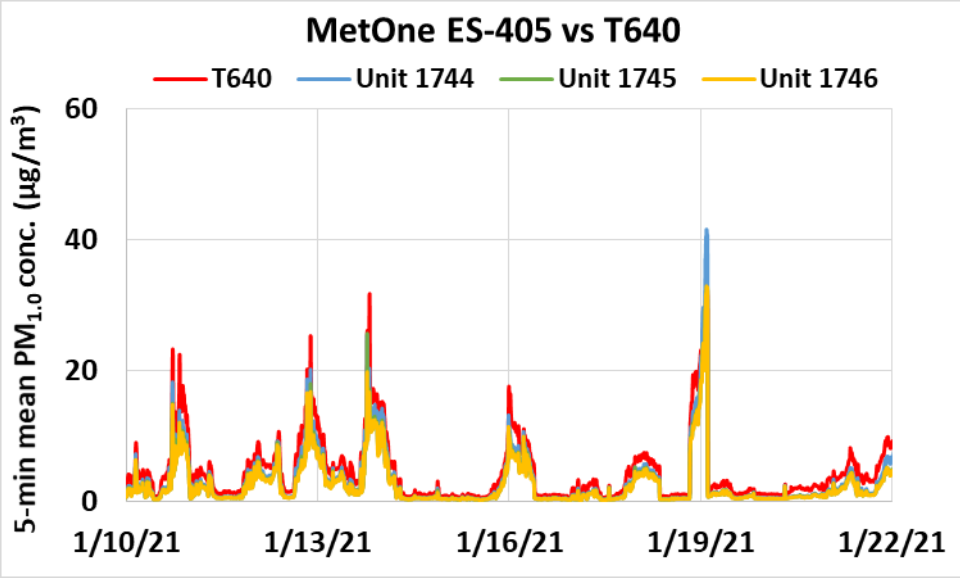
Note: GRIMM was under maintenance between 12/24/2020 and 1/7/2021.



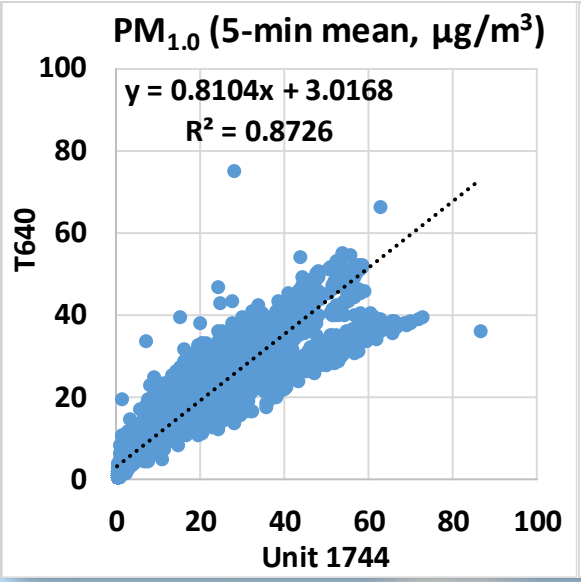


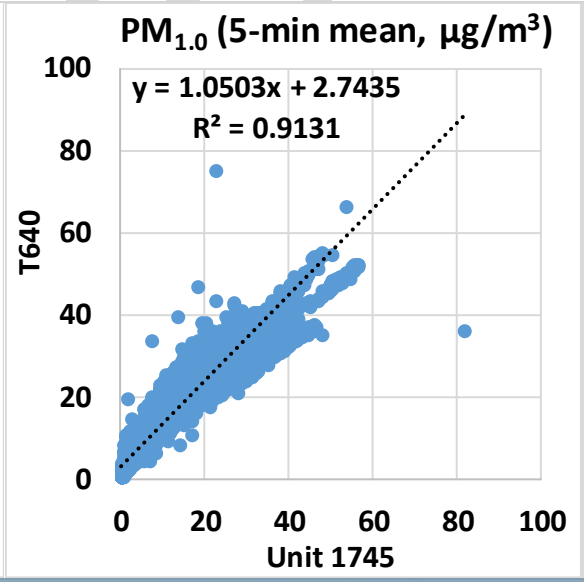


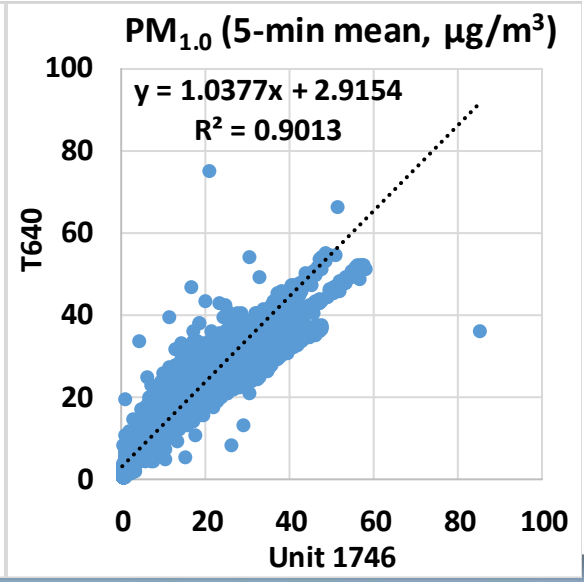
MetOne ES-405 vs T640 ($PM_{1.0}$; 5-min mean)



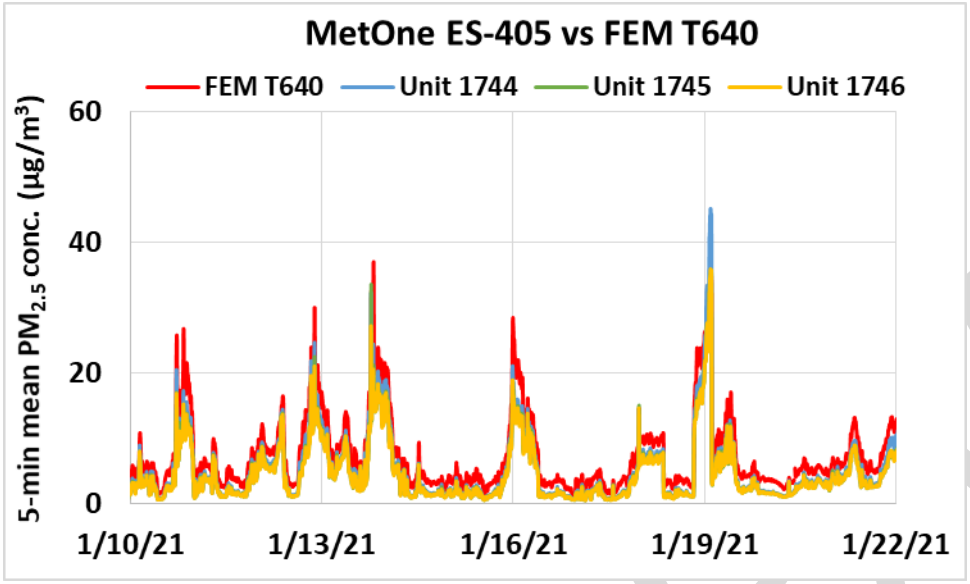
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding T640 data ($0.87 < R^2 < 0.92$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



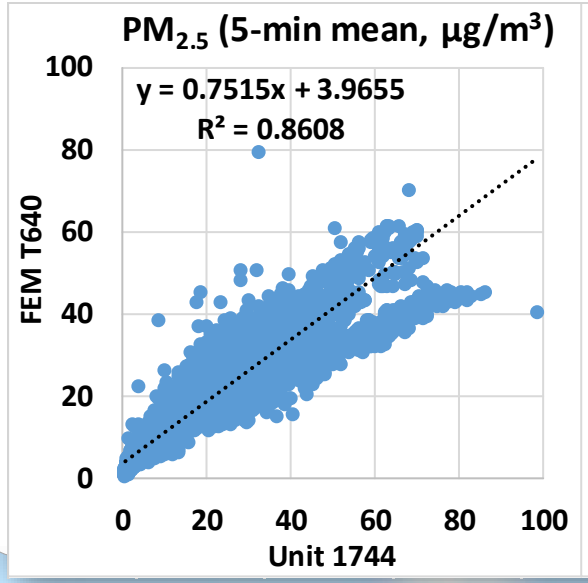


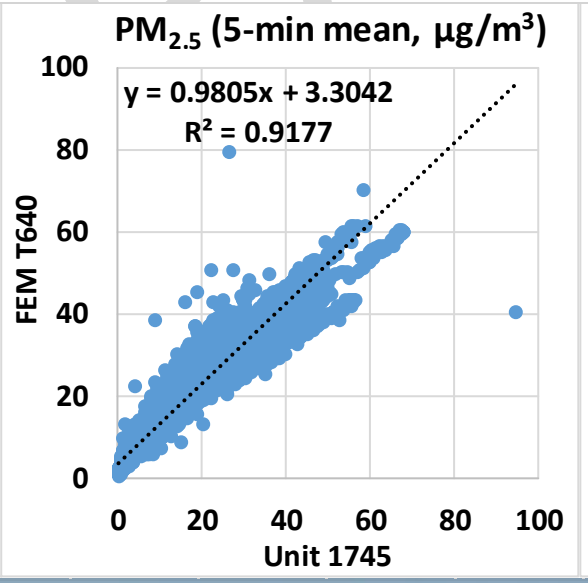


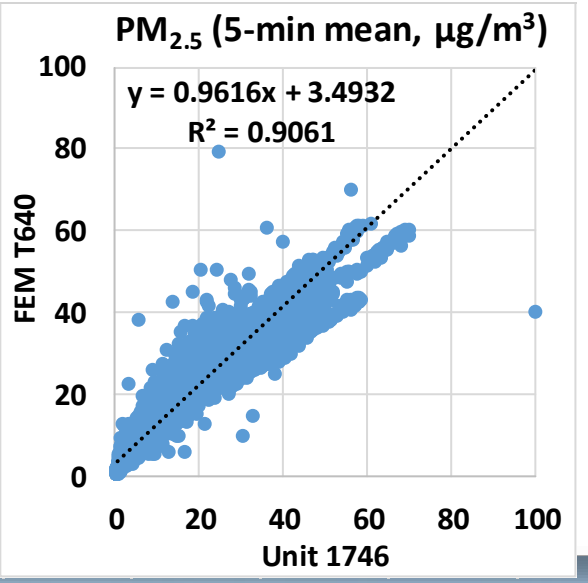
MetOne ES-405 vs FEM T640 ($PM_{2.5}$; 5-min mean)



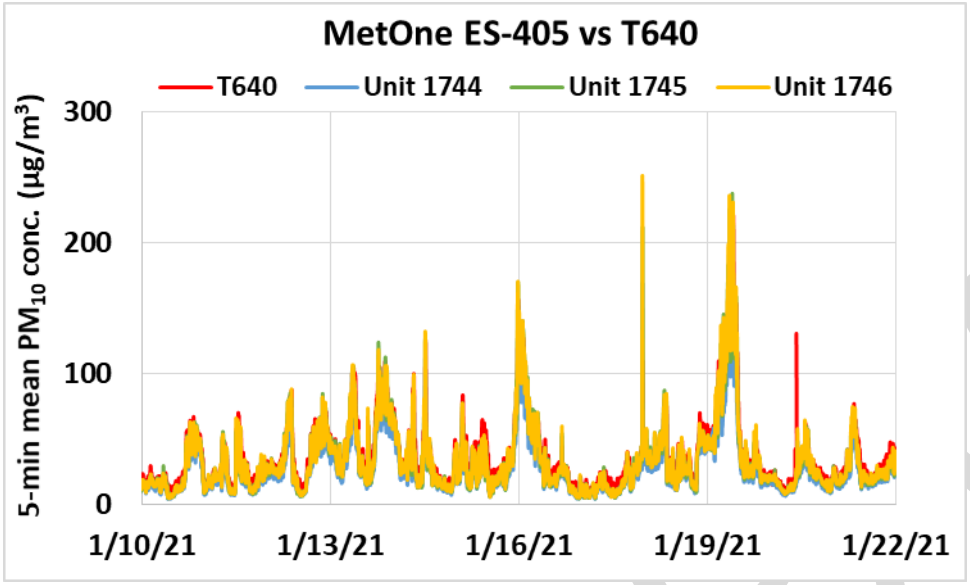
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding FEM T640 data ($0.86 < R^2 < 0.92$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



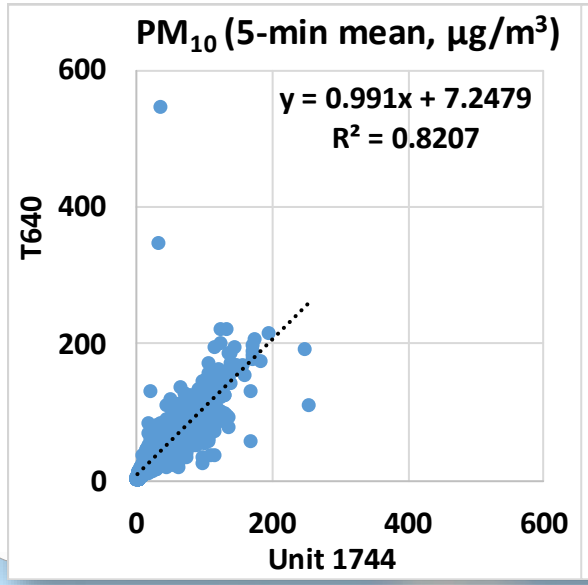


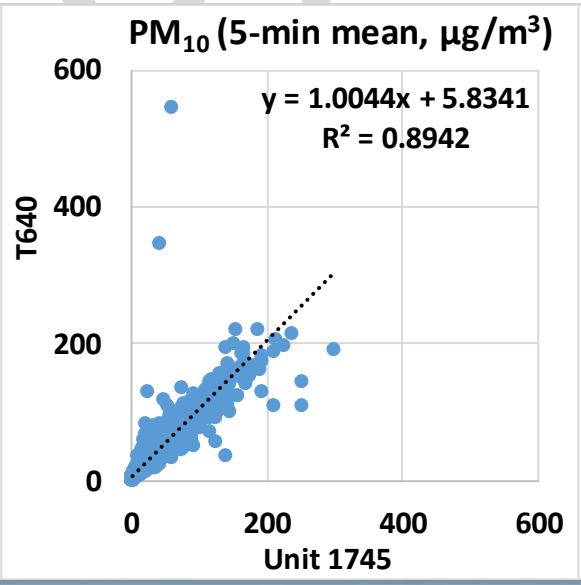


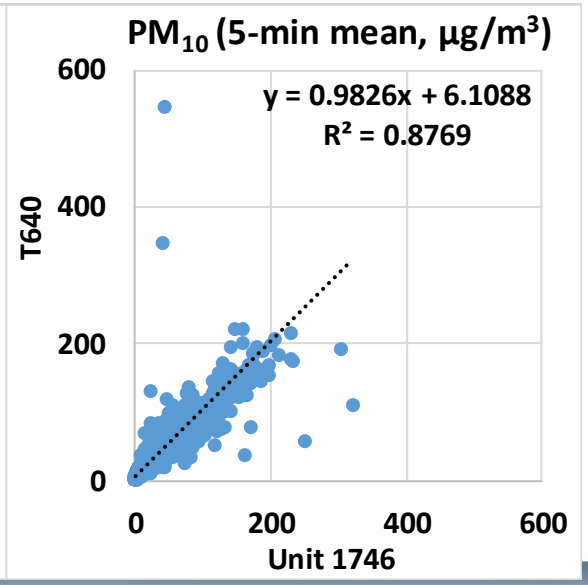
MetOne ES-405 vs T640 (PM_{10}; 5-min mean)



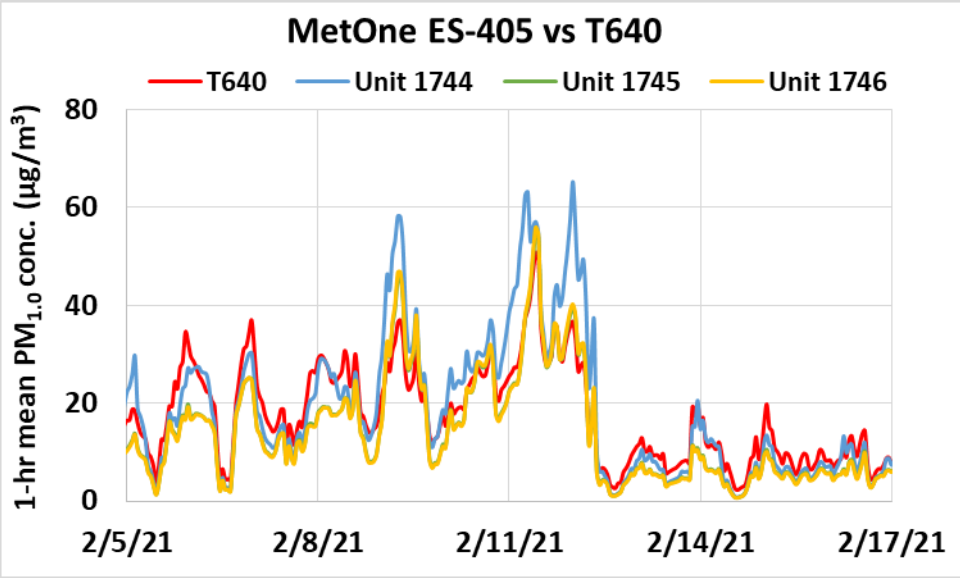
- MetOne ES-405 sensors showed strong correlations with the corresponding T640 data ($0.82 < R^2 < 0.90$)
- Overall, the MetOne ES-405 sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by T640



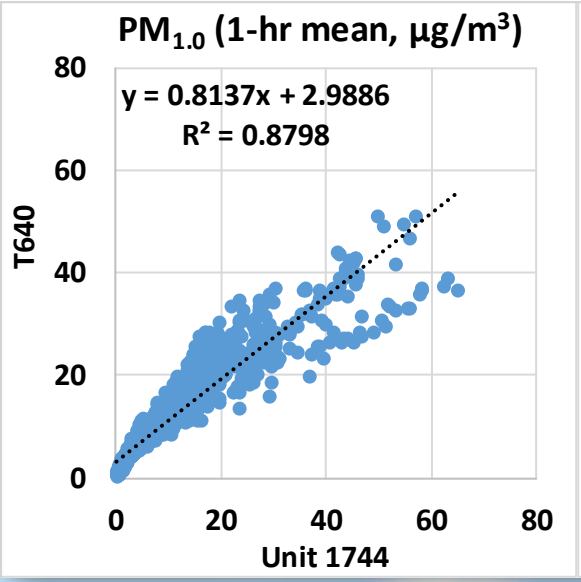


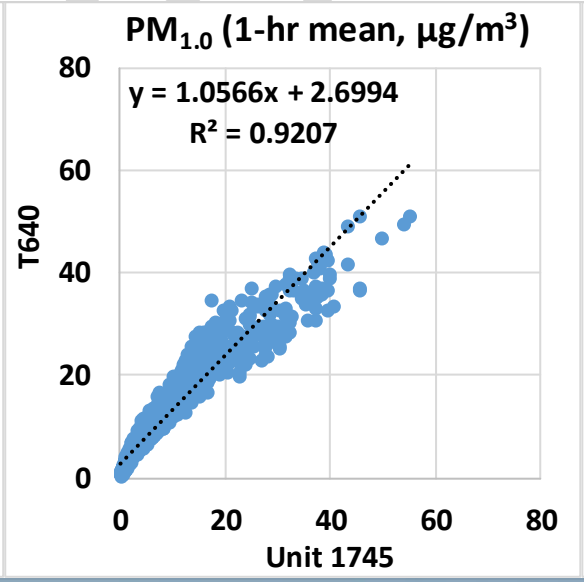


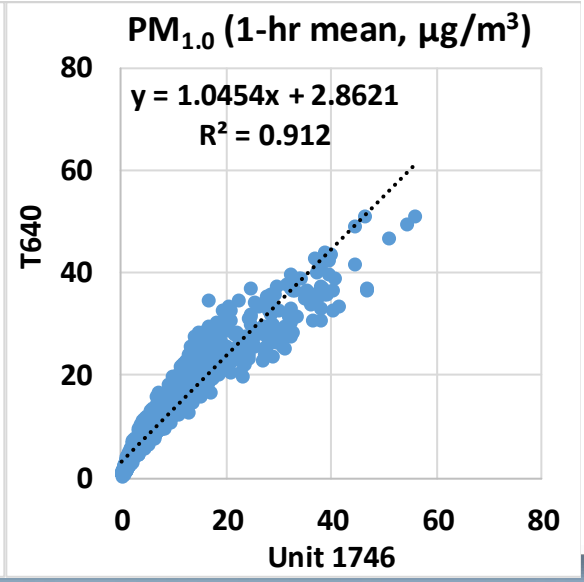
MetOne ES-405 vs T640 ($PM_{1.0}$; 1-hr mean)



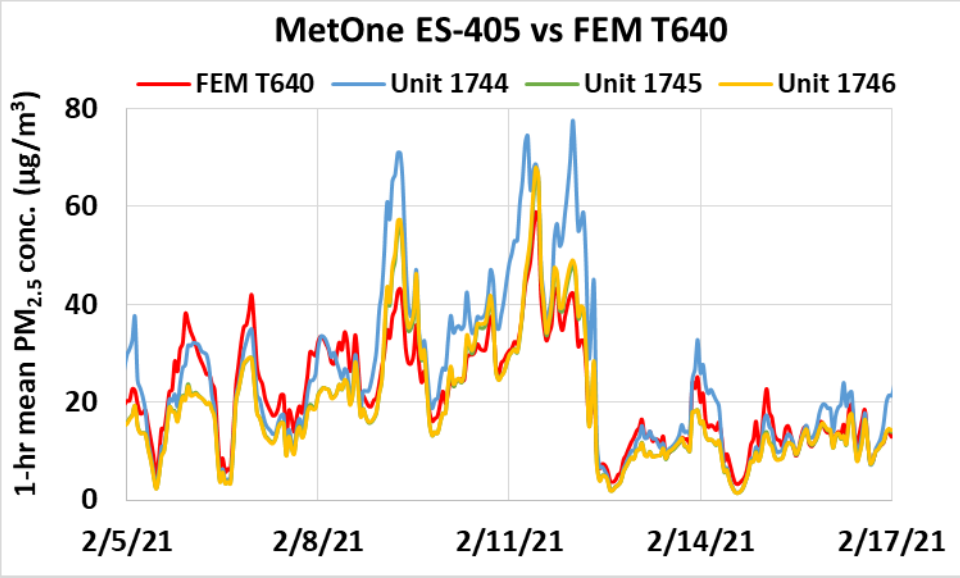
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding T640 data ($0.87 < R^2 < 0.93$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



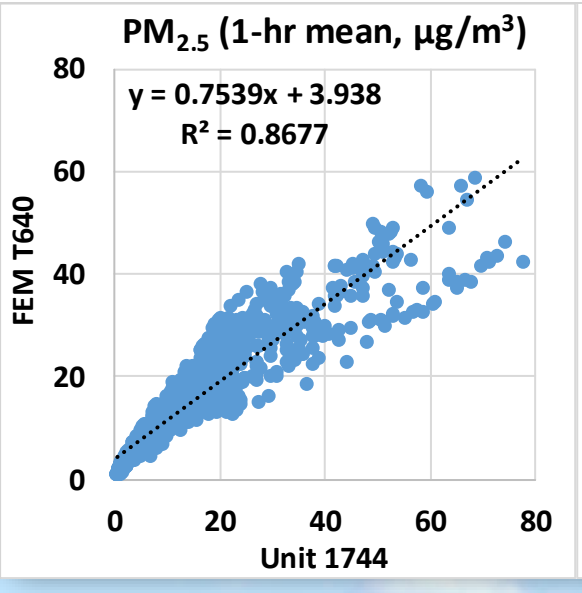


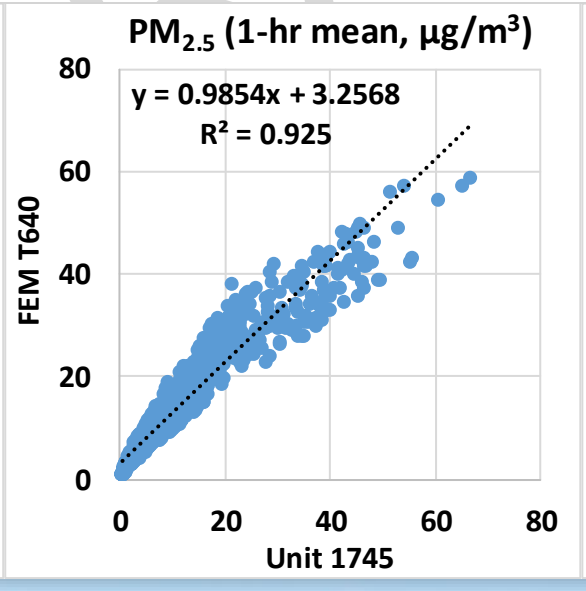


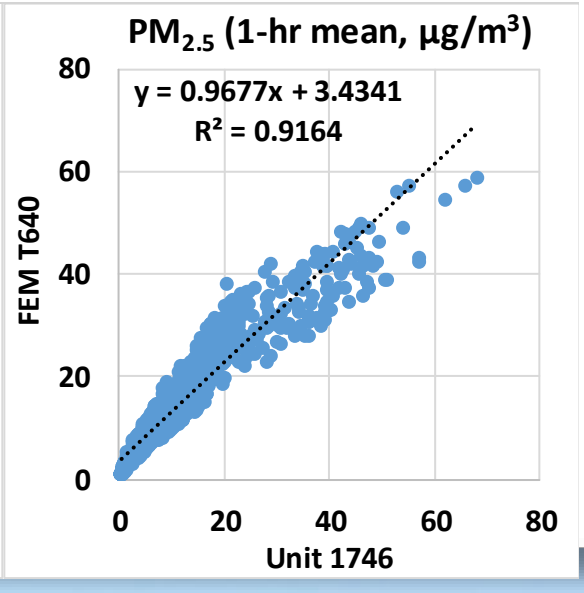
MetOne ES-405 vs FEM T640 ($PM_{2.5}$; 1-hr mean)



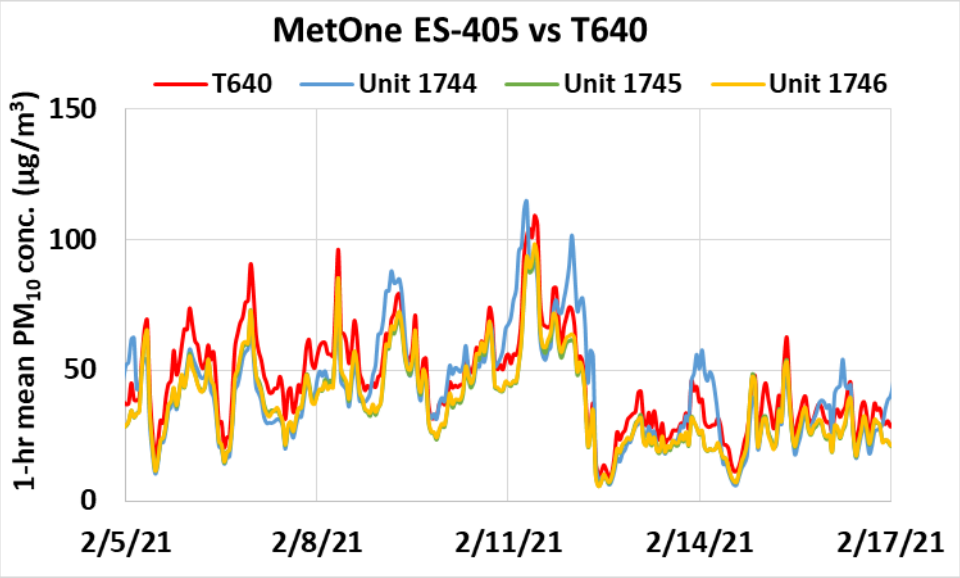
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding FEM T640 data ($0.86 < R^2 < 0.93$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



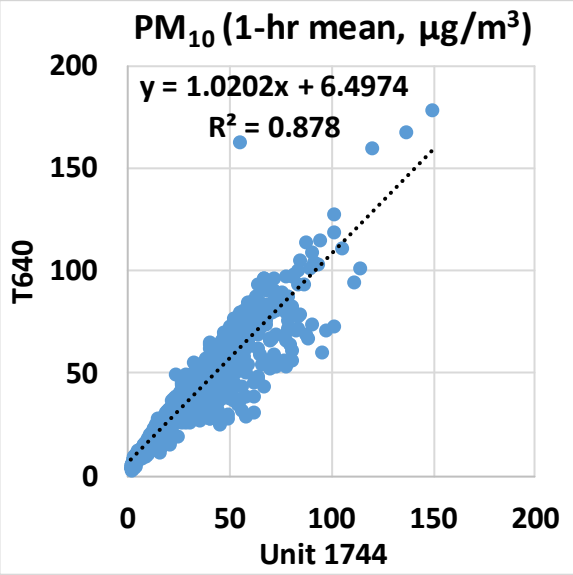


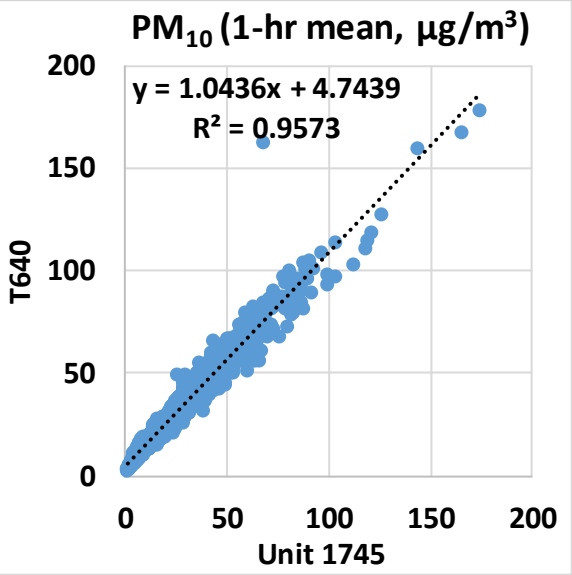


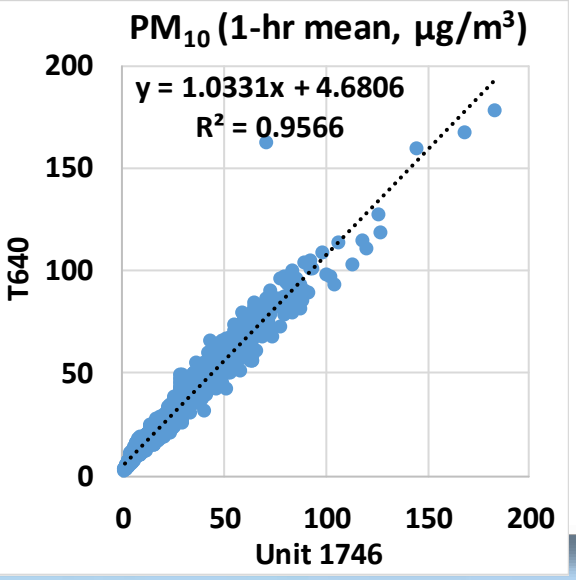
MetOne ES-405 vs T640 (PM_{10}; 1-hr mean)



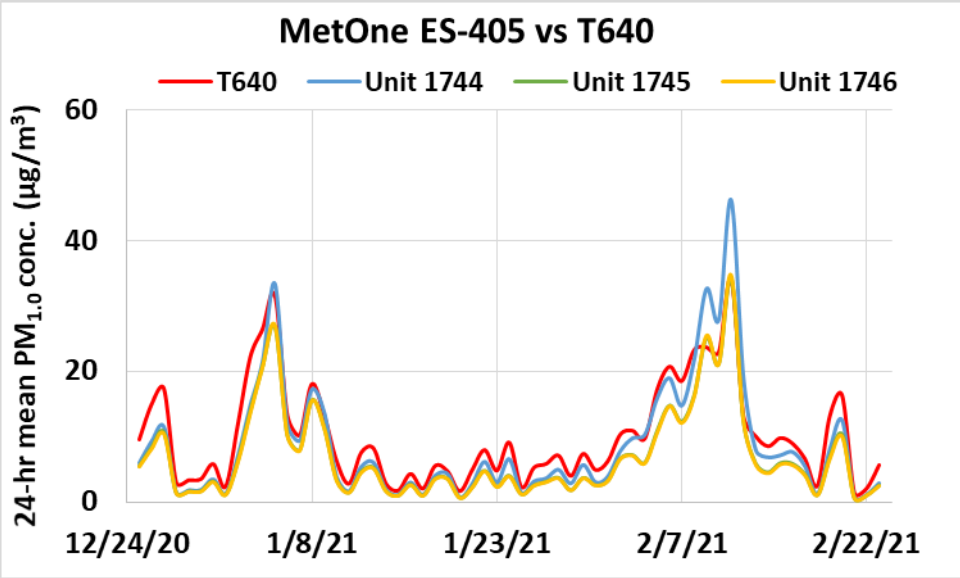
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding T640 data ($0.87 < R^2 < 0.96$)
- Overall, the MetOne ES-405 sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by T640



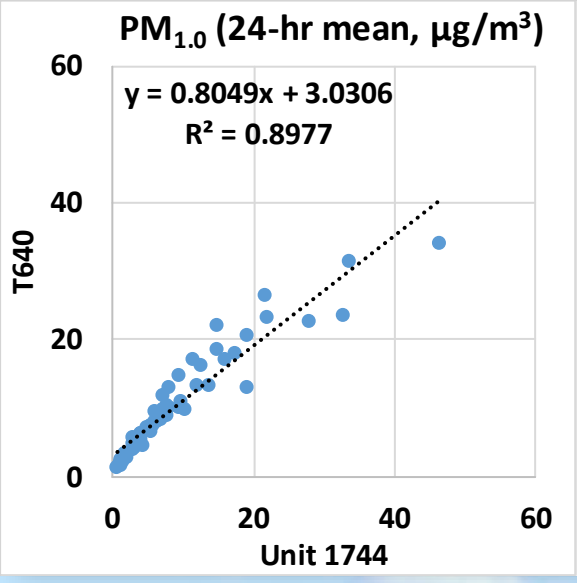


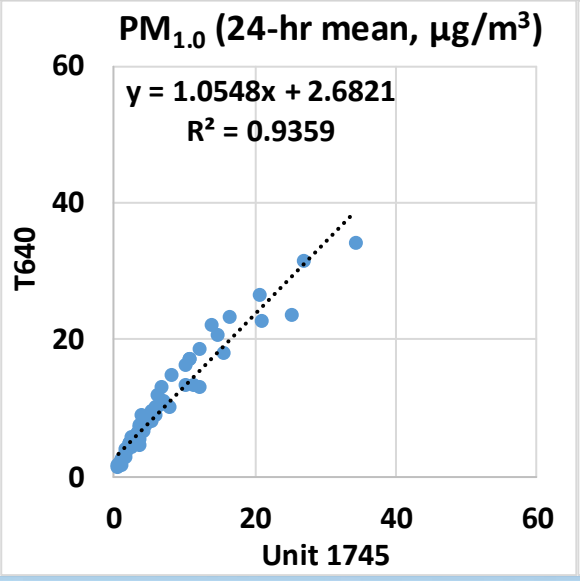


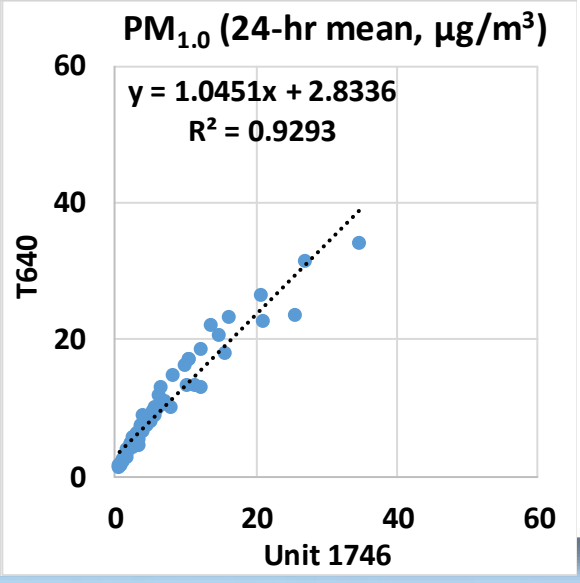
MetOne ES-405 vs T640 ($PM_{1.0}$; 24-hr mean)



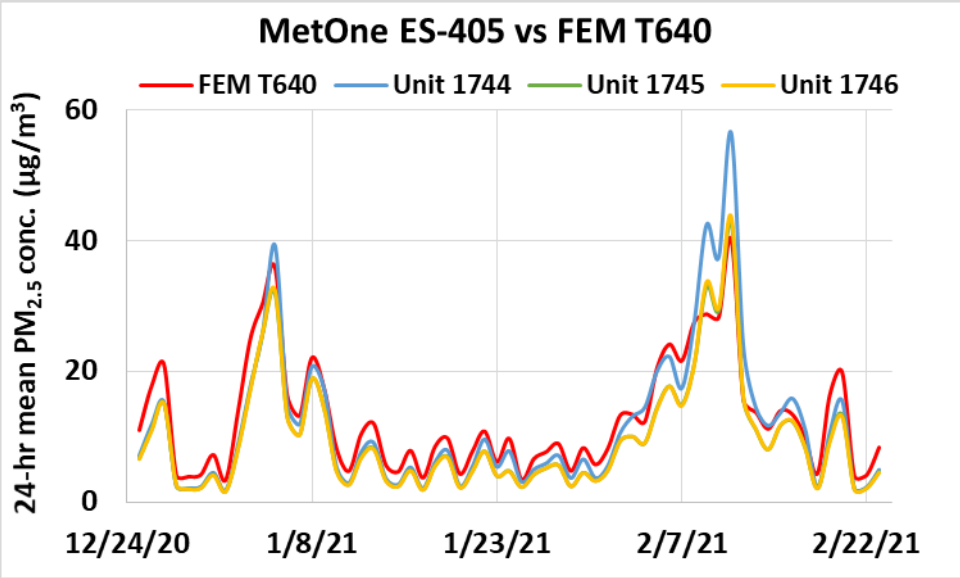
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding T640 data ($0.89 < R^2 < 0.94$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



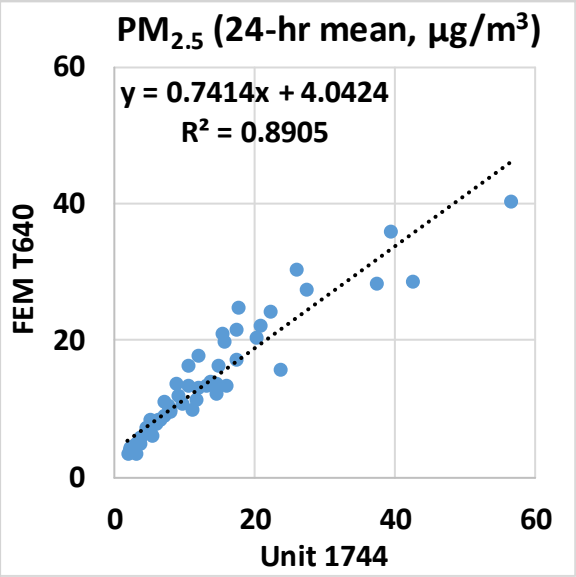


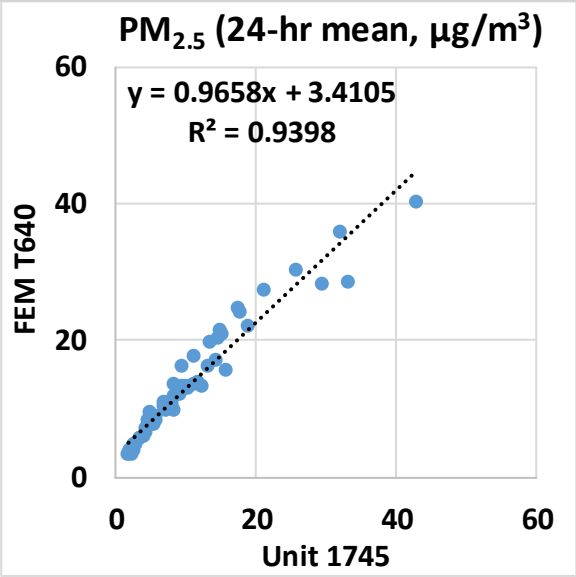


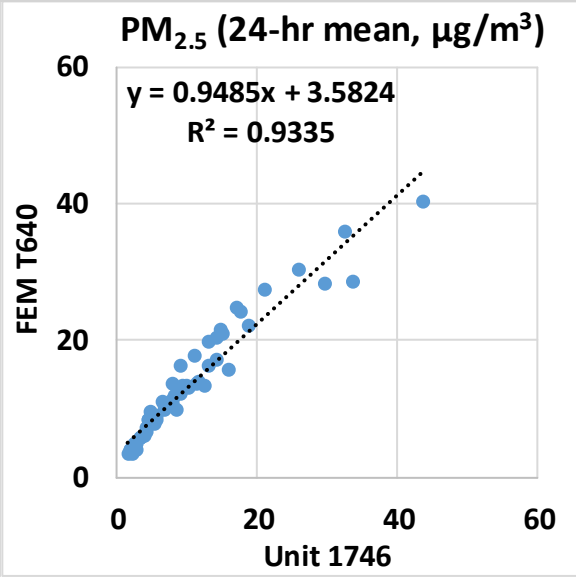
MetOne ES-405 vs FEM T640 ($PM_{2.5}$; 24-hr mean)



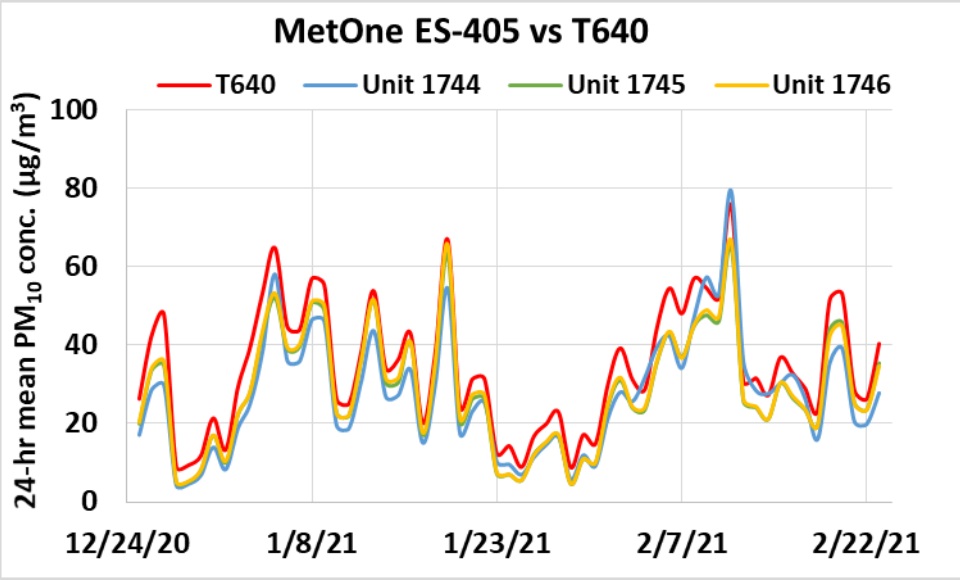
- The MetOne ES-405 sensors showed strong to very strong correlations with the corresponding FEM T640 data ($0.89 < R^2 < 0.94$)
- Overall, the MetOne ES-405 sensors underestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



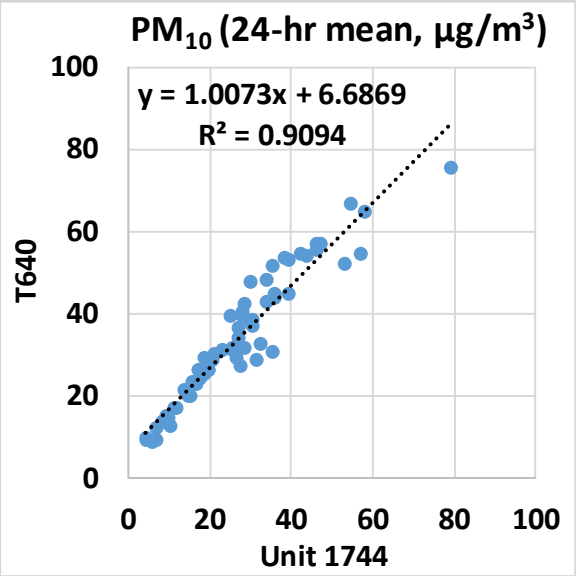


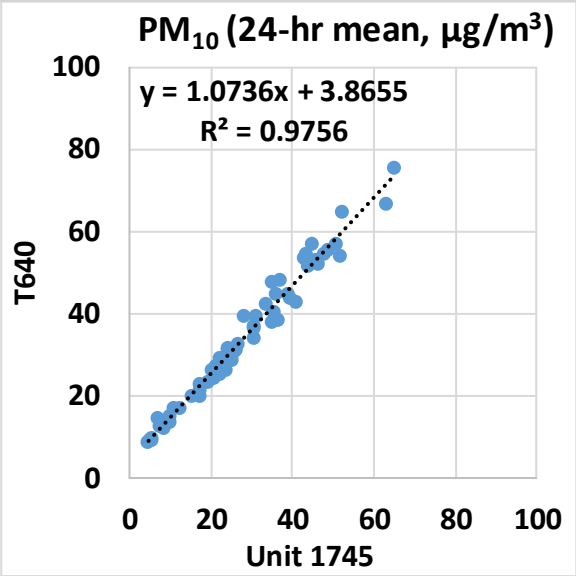


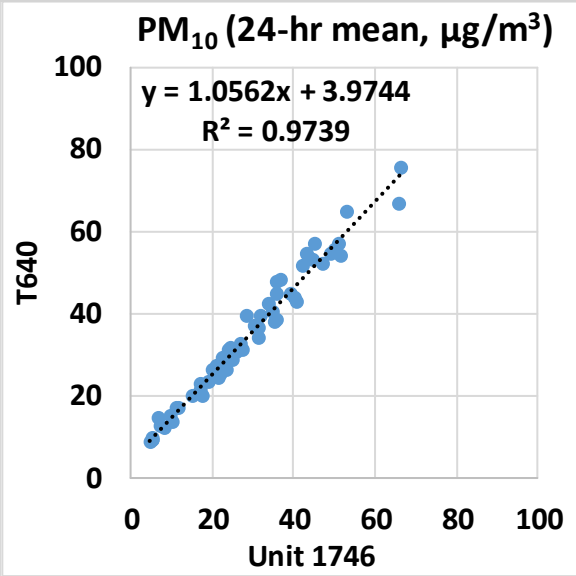
MetOne ES-405 vs T640 (PM_{10}; 24-hr mean)



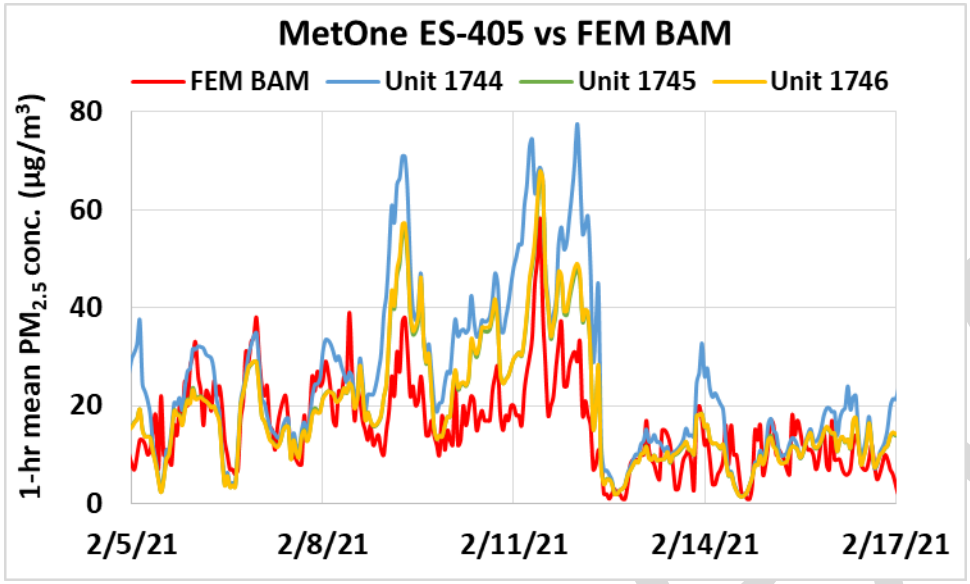
- The MetOne ES-405 sensors showed very strong correlations with the corresponding T640 data ($0.90 < R^2 < 0.98$)
- Overall, the MetOne ES-405 sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by T640



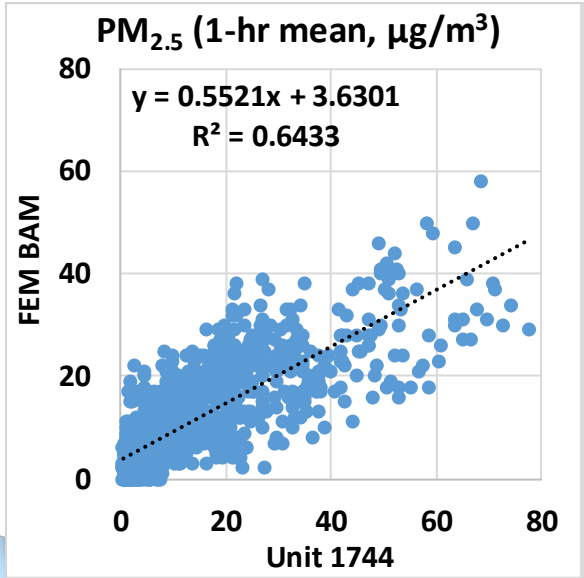


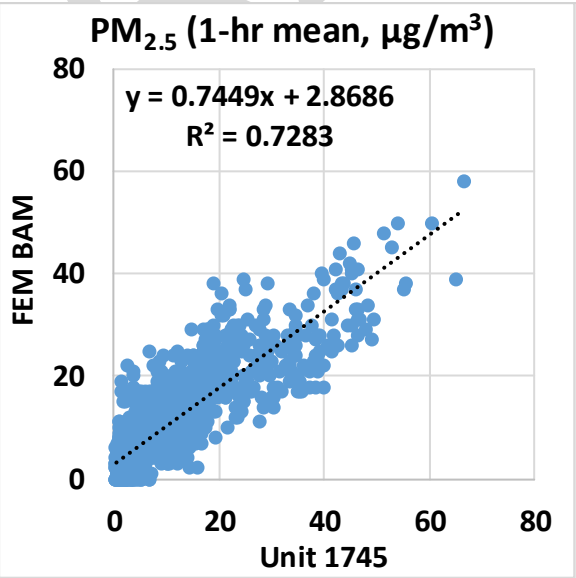


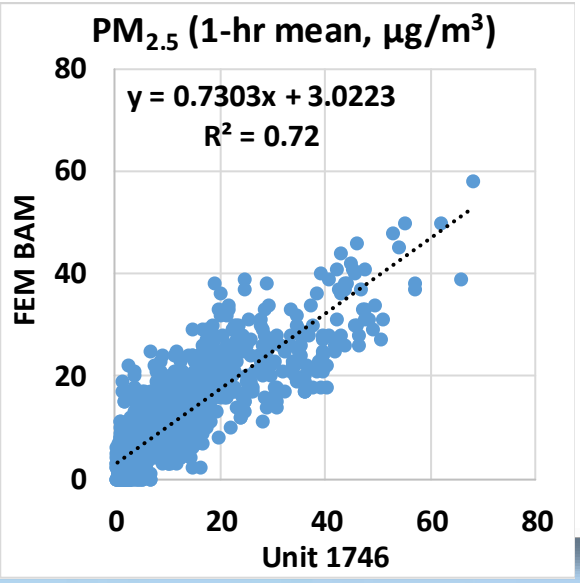
MetOne ES-405 vs FEM BAM ($PM_{2.5}$; 1-hr mean)



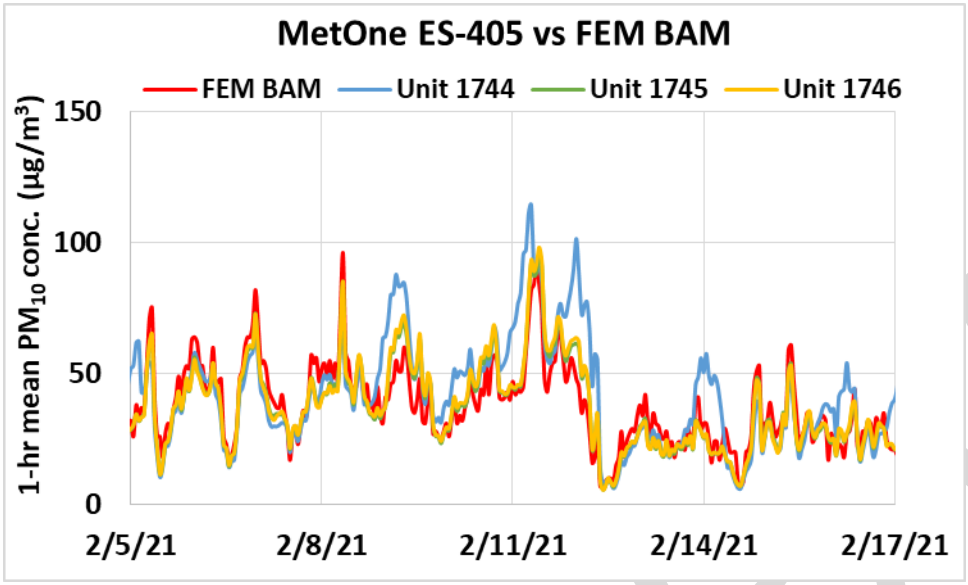
- The MetOne ES-405 sensors showed moderate to strong correlations with the corresponding FEM BAM data ($0.64 < R^2 < 0.73$)
- Overall, the MetOne ES-405 sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM BAM
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM BAM



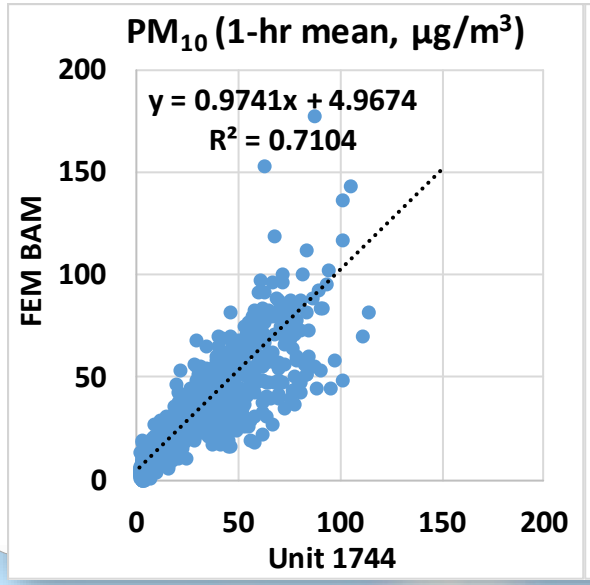


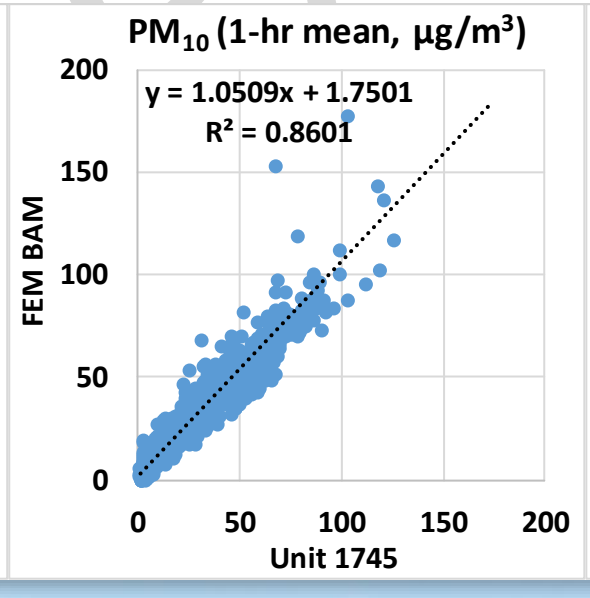


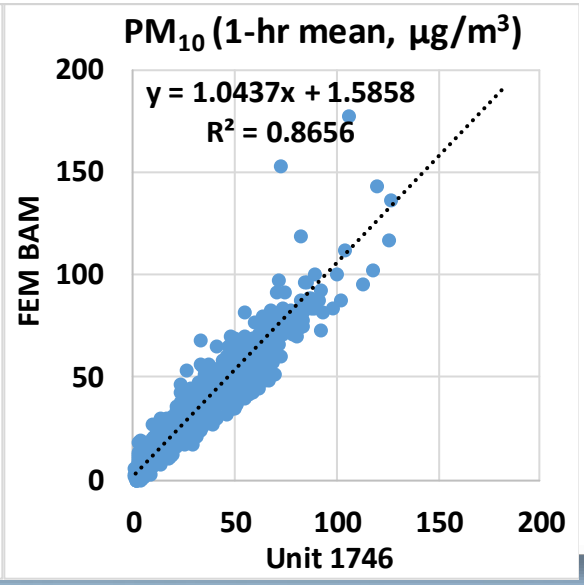
MetOne ES-405 vs FEM BAM (PM_{10}; 1-hr mean)



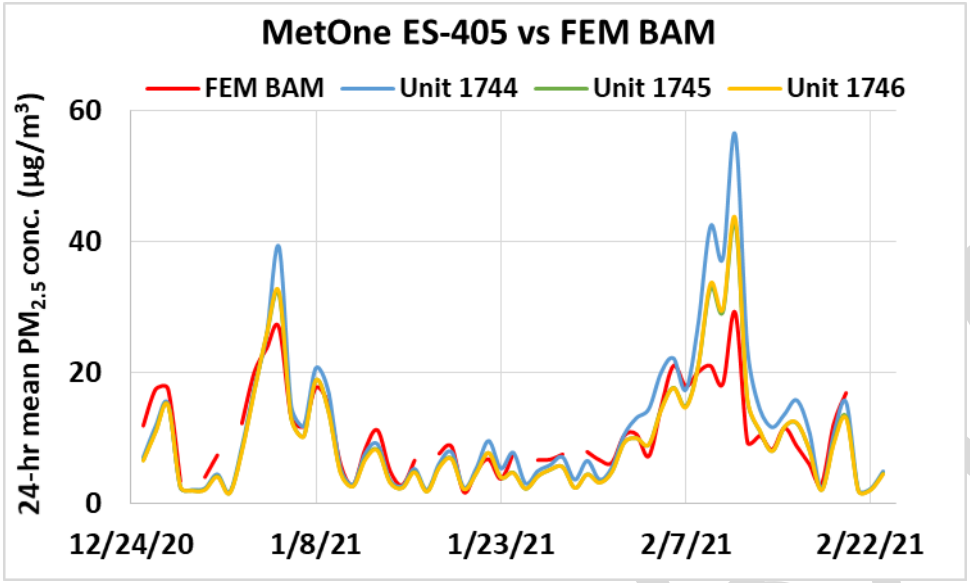
- The MetOne ES-405 sensors showed strong correlations with the corresponding FEM BAM data ($0.71 < R^2 < 0.87$)
- Overall, the MetOne ES-405 sensors underestimated the PM_{10} mass concentrations measured by FEM BAM
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by FEM BAM



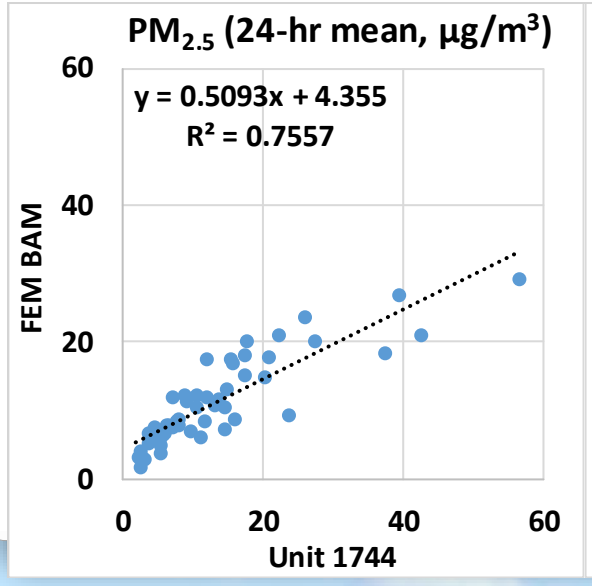


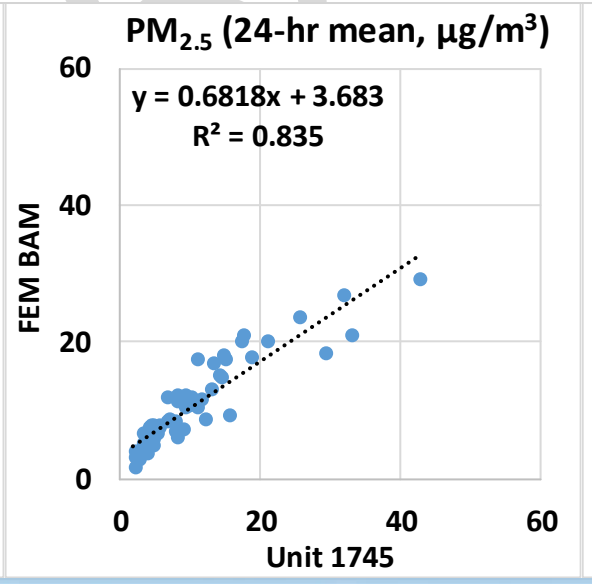


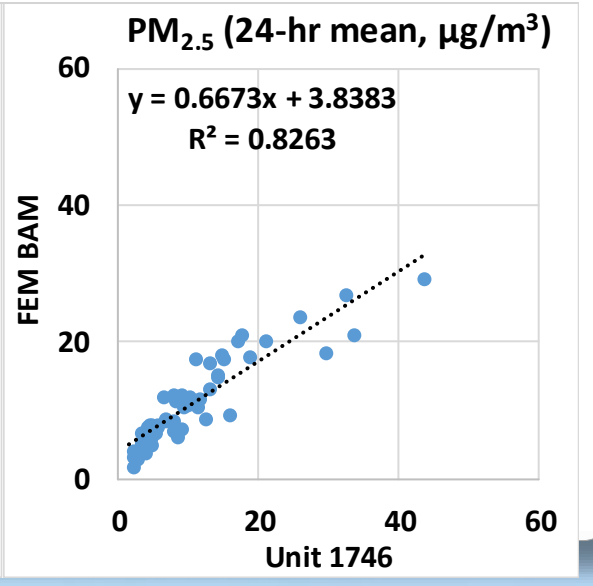
MetOne ES-405 vs FEM BAM ($PM_{2.5}$; 24-hr mean)



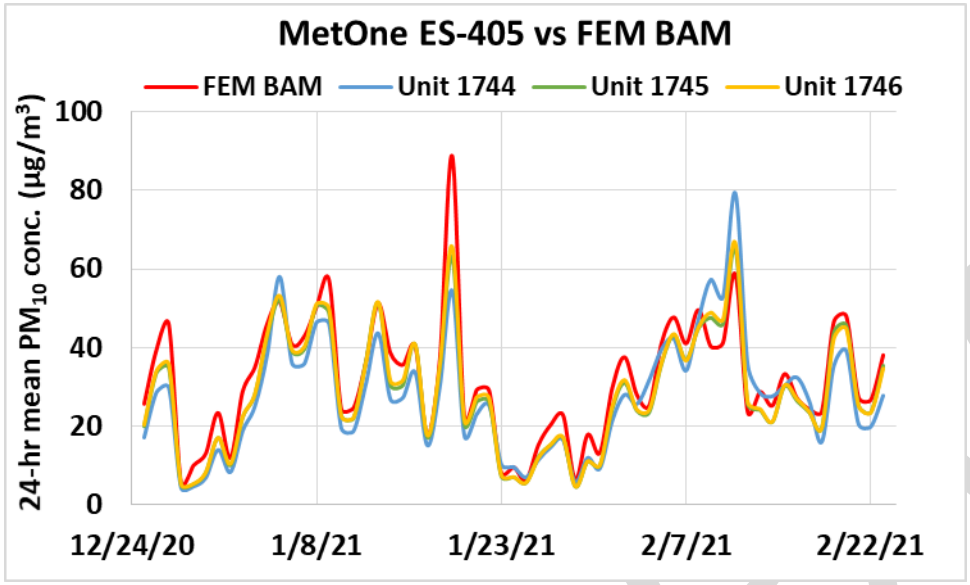
- The MetOne ES-405 sensors showed strong correlations with the corresponding FEM BAM data ($0.75 < R^2 < 0.84$)
- Overall, the MetOne ES-405 sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM BAM
- The MetOne ES-405 sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM BAM



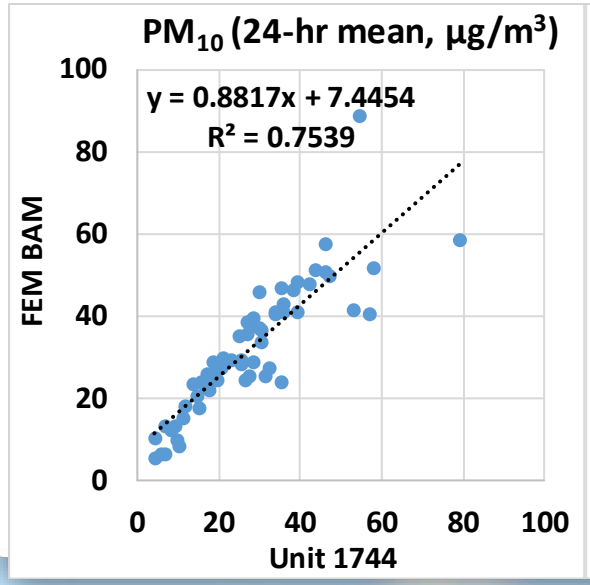


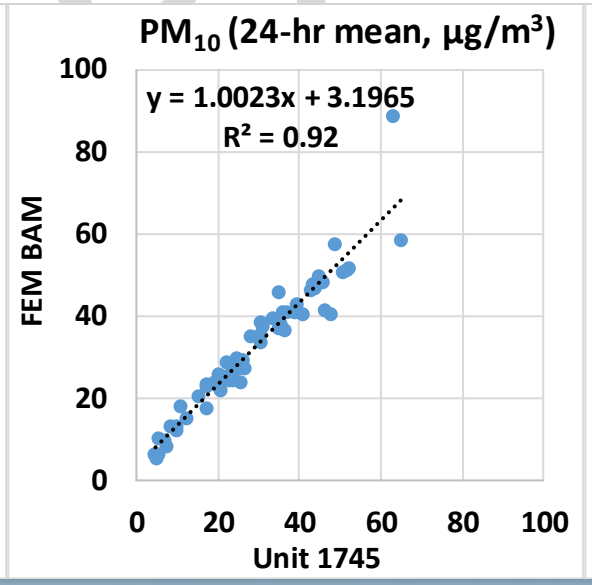


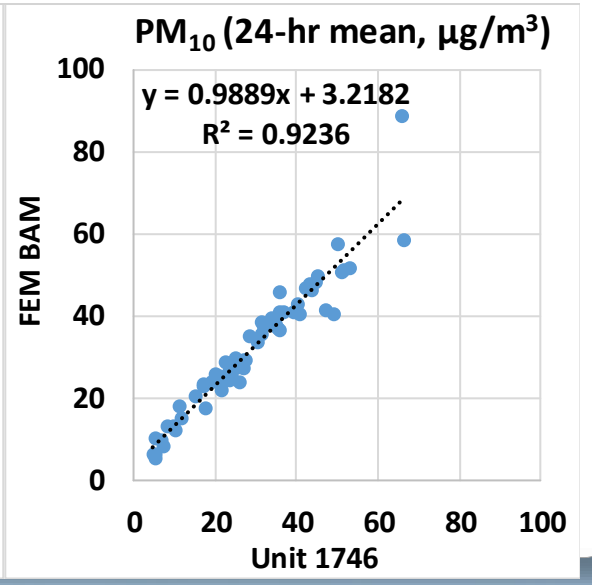
MetOne ES-405 vs FEM BAM (PM_{10}; 24-hr mean)



- MetOne ES-405 sensors showed strong to very strong correlations with the corresponding FEM BAM data ($0.75 < R^2 < 0.93$)
- Overall, the MetOne ES-405 sensors underestimated the PM_{10} mass concentrations measured by FEM BAM
- The MetOne ES-405 sensors seemed to track the PM_{10} diurnal variations as recorded by FEM BAM







Summary

	Average of 3 Sensors, $PM_{1.0}$		MetOne ES-405 vs GRIMM & T640, $PM_{1.0}$						GRIMM & T640 ($PM_{1.0}$, $\mu g/m^3$)		
	Average ($\mu g/m^3$)	SD ($\mu g/m^3$)	R^2	Slope	Intercept	MBE[1] ($\mu g/m^3$)	MAE[2] ($\mu g/m^3$)	RMSE[3] ($\mu g/m^3$)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	7.5	9.6	0.84 to 0.91	0.76 to 1.05	2.7 to 3.2	-3.2 to -1.1	2.8 to 3.6	6.4 to 9.2	9.5 to 10.0	9.3 to 9.7	0.2 to 74.9
1-hr	7.5	9.5	0.84 to 0.92	0.76 to 1.06	2.7 to 3.2	-3.2 to -1.1	2.8 to 3.5	4.1 to 4.8	9.5 to 10.0	9.2 to 9.6	0.3 to 50.9
24-hr	7.5	7.7	0.90 to 0.94	0.74 to 1.05	2.7 to 3.3	-3.1 to -1.1	2.5 to 3.2	3.3 to 3.8	9.5 to 10.0	7.0 to 7.6	1.0 to 34.0
	Average of 3 Sensors, $PM_{2.5}$		MetOne ES-405 vs FEM GRIMM, FEM BAM & FEM T640, $PM_{2.5}$						FEM GRIMM, FEM BAM & FEM T640 ($PM_{2.5}$, $\mu g/m^3$)		
	Average ($\mu g/m^3$)	SD ($\mu g/m^3$)	R^2	Slope	Intercept	MBE[1] ($\mu g/m^3$)	MAE[2] ($\mu g/m^3$)	RMSE[3] ($\mu g/m^3$)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	10.3	11.5	0.80 to 0.92	0.67 to 0.98	3.3 to 4.3	-3.1 to -0.4	3.5 to 4.0	6.6 to 12.1	12.0 to 12.8	10.1 to 10.8	0.3 to 79.2
1-hr	10.3	11.3	0.64 to 0.93	0.55 to 0.99	2.9 to 4.3	-3.1 to 2.0	3.4 to 5.1	4.3 to 8.4	10.5 to 12.7	9.2 to 10.6	0 to 58.8
24-hr	10.4	9.4	0.76 to 0.94	0.51 to 0.97	3.4 to 4.7	-3.1 to 2.0	2.6 to 3.7	3.7 to 6.6	11.0 to 12.8	6.4 to 8.5	1.8 to 40.2
	Average of 3 Sensors, PM_{10}		MetOne ES-405 vs GRIMM, FEM BAM & T640, PM_{10}						GRIMM, FEM BAM and T640 (PM_{10}, $\mu g/m^3$)		
	Average ($\mu g/m^3$)	SD ($\mu g/m^3$)	R^2	Slope	Intercept	MBE[1] ($\mu g/m^3$)	MAE[2] ($\mu g/m^3$)	RMSE[3] ($\mu g/m^3$)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	28.3	21.5	0.78 to 0.92	0.84 to 1.00	1.0 to 7.2	-7.0 to 2.8	4.5 to 8.9	12.6 to 19.5	27.1 to 34.5	20.5 to 23.1	0.34 to 547.2
1-hr	28.3	20.6	0.71 to 0.96	0.84 to 1.05	0.6 to 6.5	-7.0 to 2.8	3.8 to 8.6	5.6 to 12.3	27.1 to 34.5	19.6 to 23.4	0 to 288
24-hr	28.2	14.9	0.75 to 0.98	0.76 to 1.07	1.4 to 7.4	-6.8 to 2.8	2.9 to 7.3	4.4 to 8.9	26.8 to 34.4	13.0 to 15.9	3.5 to 88.8

[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.

Discussion

- The three **MetOne ES-405** sensors' data recovery from all units was 100% for all PM measurements
- The absolute intra-model variability was ~ 0.83, ~ 0.97 and ~ 0.59 µg/m^3 for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10,}$ respectively
- Very strong correlations between GRIMM and T640 for $PM_{1.0}$ (R^2 ~ 0.98, 1-hr mean); strong to very strong correlations between FEM GRIMM, FEM BAM and FEM T640 for $PM_{2.5}$ ($0.79 < R^2 < 0.97$, 1-hr mean) and strong to very strong correlations between GRIMM, FEM BAM and T640 for PM_{10} ($0.86 < R^2 < 0.95$, 1-hr mean) mass concentration measurements
- $PM_{1.0}$ mass concentrations measured by MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM and T640 data ($0.84 < R^2 < 0.93$, 1-hr mean). The sensors underestimated $PM_{1.0}$ mass concentrations as measured by GRIMM and T640
- $PM_{2.5}$ mass concentrations measured by MetOne ES-405 sensors showed moderate to very strong correlations with the corresponding FEM GRIMM, FEM BAM and FEM T640 data ($0.64 < R^2 < 0.93$, 1-hr mean). The sensors underestimated $PM_{2.5}$ mass concentrations as measured by FEM GRIMM and FEM T640 and overestimated $PM_{2.5}$ mass concentrations as measured by FEM BAM
- PM_{10} mass concentrations measured by MetOne ES-405 sensors showed strong to very strong correlations with the corresponding GRIMM, FEM BAM and T640 data ($0.71 < R^2 < 0.96$; 1-hr mean). The sensors underestimated PM_{10} mass concentrations as measured by T640 and FEM BAM and overestimated PM_{10} mass concentrations as measured by GRIMM
- No sensor calibration was performed by South Coast AQMD Staff prior to the beginning of this test
- Laboratory chamber testing is necessary to fully evaluate the performance of these sensors under known aerosol concentrations and controlled temperature and relative humidity conditions
- All results are still preliminary