Field Evaluation
QuantAQ - MODULAIR-PM

South Coast AQMD

AQ-SPEC
Air Quality Sensor Performance Evaluation Center

Background

- From 09/10/2021 to 11/05/2021, three **QuantAQ - MODULAIR-PM (hereinafter MODULAIR-PM)** 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

- MODULAIR-PM (*3 units tested*):
  - Two Particle sensors: non-FEM (nephelometer Plantower PMS5003 + optical particle counter Alphasense OPC-N3)
  - Each unit reports: $PM_{1.0}$, $PM_{2.5}$ and PM_{10} ($\mu g/m^3$), Temperature (°C), RH (%)
  - Unit cost: $1295 + $300/yr for QuantAQ Cloud
  - Time resolution: 1-min
  - Units IDs: 0055, 0059, 0069

- 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

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

- Met Station (T, RH, P, WS, WD):
  - Cost: ~$5,000
  - Time resolution: 1-min

PM Data Handling

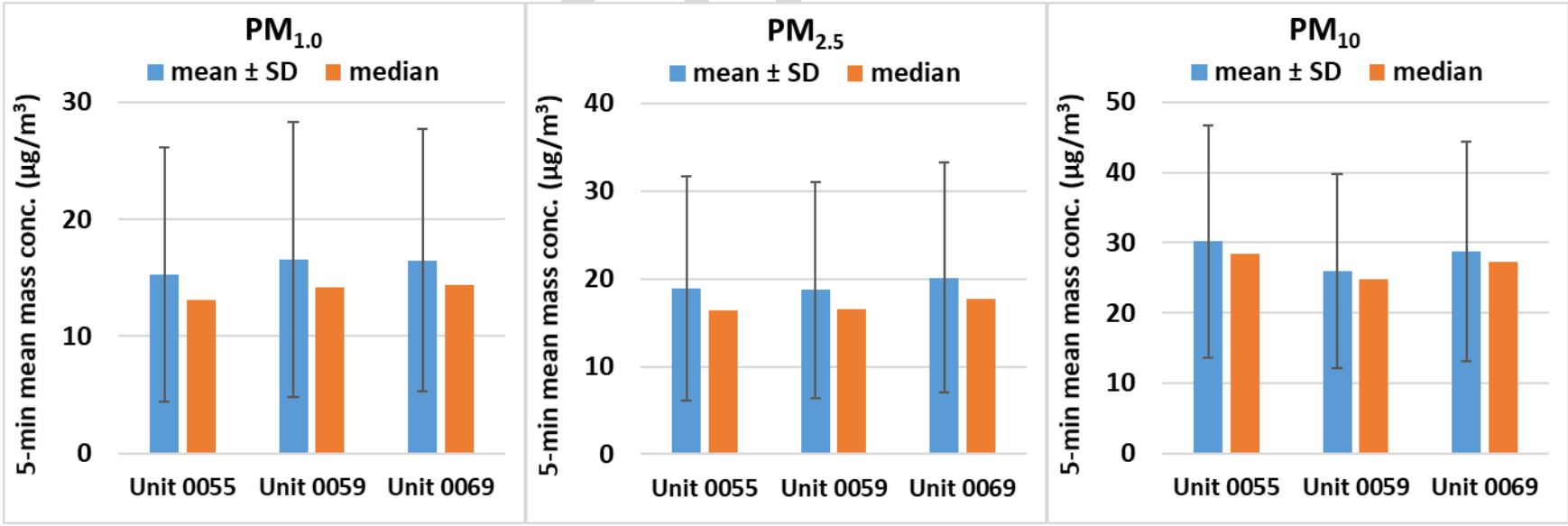
- The QuantAQ – MODULAIR-PM sensor uses a combination of two optical particle sensors (OPS): a nephelometer (Plantower PMS5003) and an optical particle counter (Alphasense OPC-N3) to characterize $PM_{1.0}$, $PM_{2.5}$, and PM_{10}. QuantAQ also provides users with full access to all raw data from each sensor component, including the 24-bin size distribution from the OPC-N3 (0.35 to 40 µm). The spectra from the nephelometer and OPC are then combined to form the basis of the reported in-situ $PM_{1.0}$, $PM_{2.5}$, and PM_{10} mass concentrations.
- In addition to the raw sensor inputs, size-specific hygroscopicity and density assumptions are built into the PM models. On-board measurements of RH are used to inform and correct-for hygroscopic growth in accord with model assumptions.

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

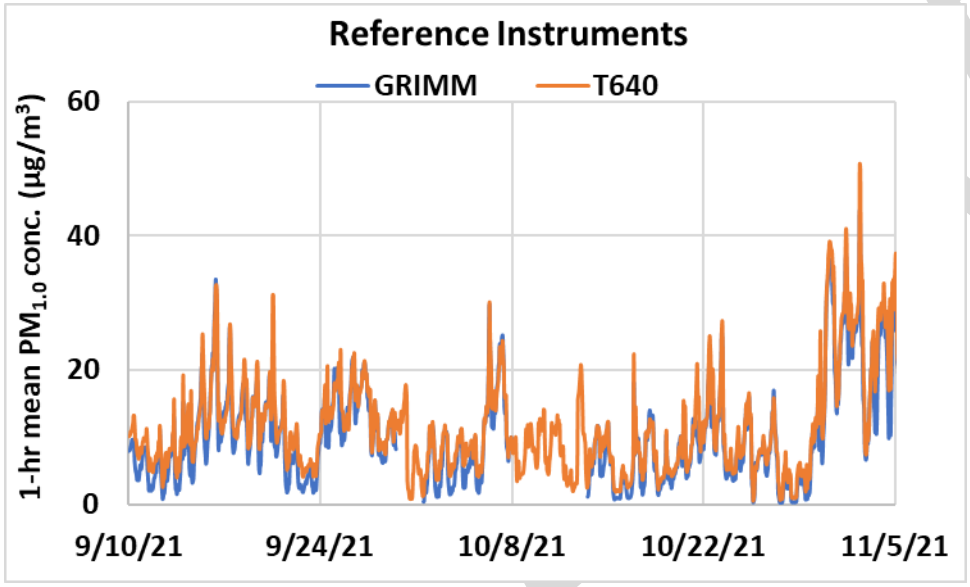
MODULAIR-PM; intra-model variability

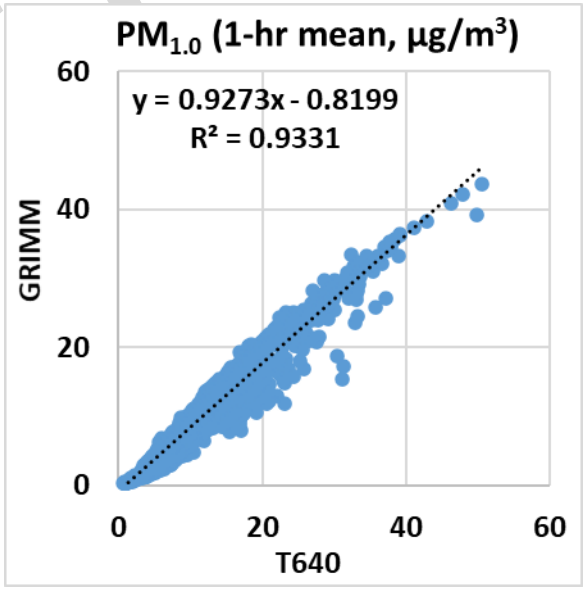
- Absolute intra-model variability was ~ 0.59, 0.62 and 1.77 µg/m^3 for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10,}$ respectively (calculated as the standard deviation of the three sensor means)
- Relative intra-model variability was ~ 3.7%, 3.2% and 6.3% for $PM_{1.0}$, $PM_{2.5}$ and $PM_{10,}$ respectively (calculated as the absolute intra-model variability relative to the mean of the three sensor means)



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

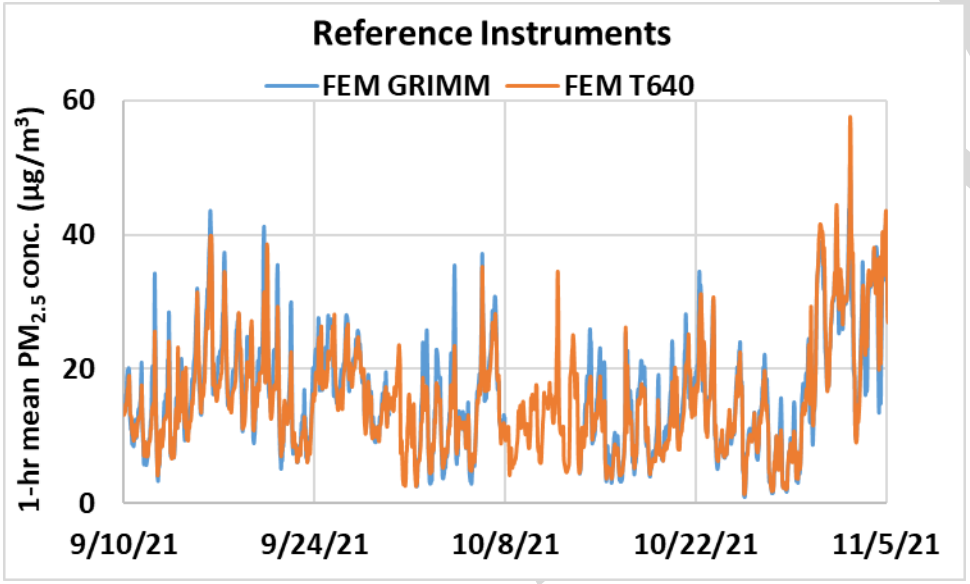
- Data recovery for $PM_{1.0}$ from GRIMM and T640 was ~ 88% and 99%, respectively.
- Very strong correlations between the reference instruments for $PM_{1.0}$ measurements (R^2 ~ 0.93) were observed.

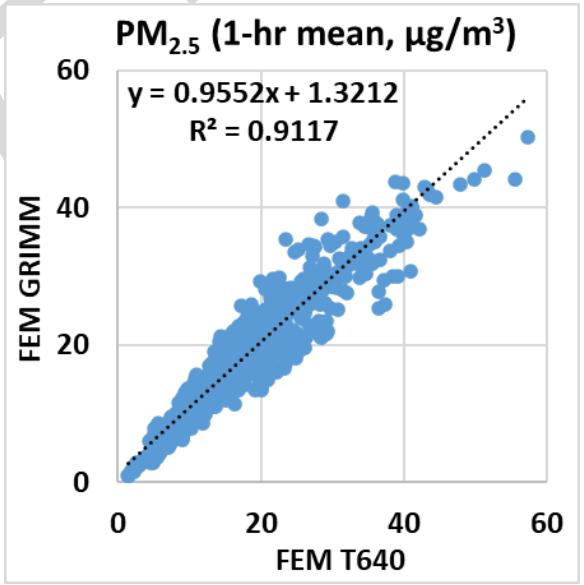




Reference Instruments: $PM_{2.5}$ FEM GRIMM and FEM T640

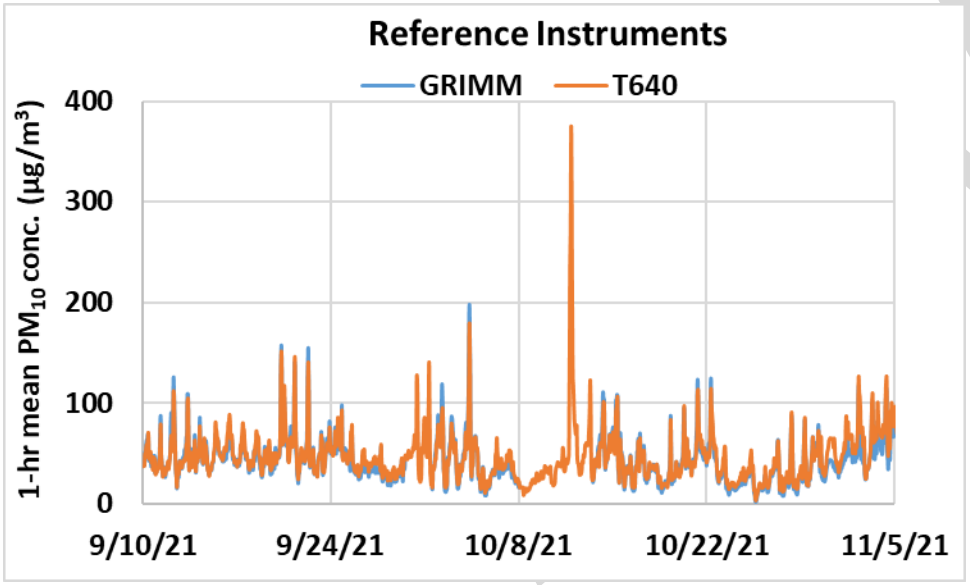
- Data recovery for $PM_{2.5}$ from FEM GRIMM and FEM T640 was ~ 88% and 99%, respectively.
- Very strong correlations between the reference instruments for $PM_{2.5}$ measurements (R^2 ~ 0.91) were observed.

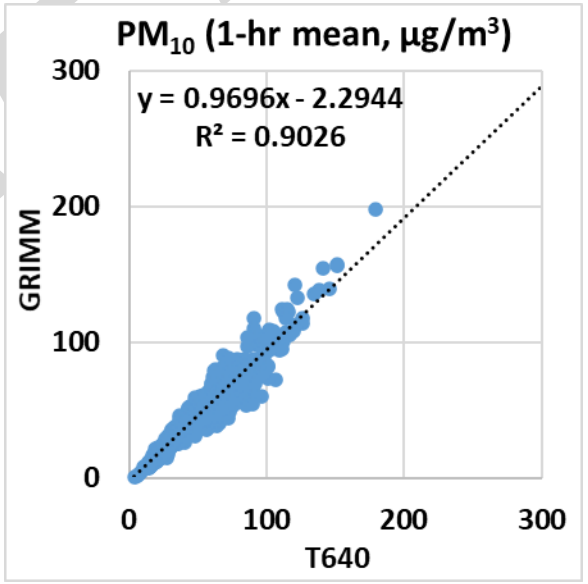




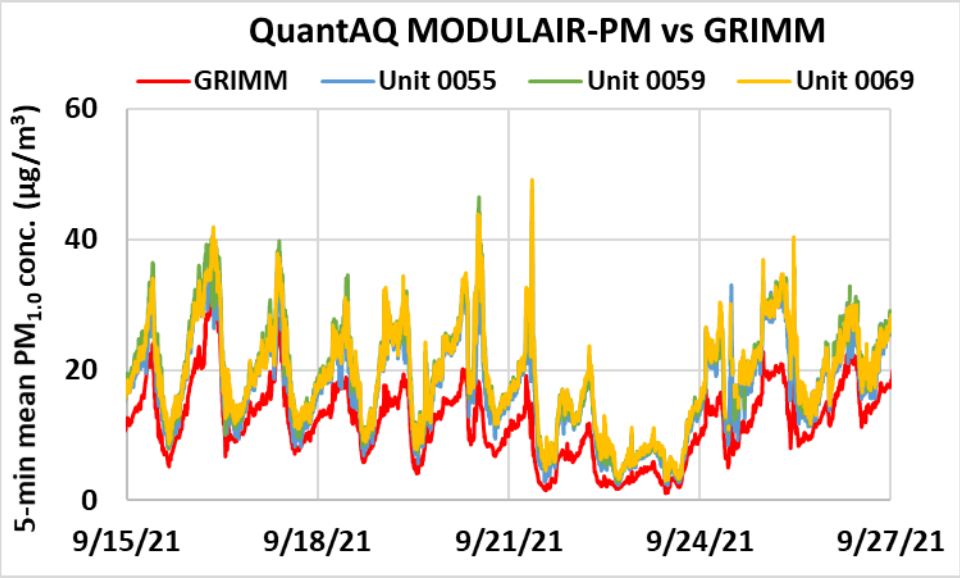
Reference Instruments: PM_{10} GRIMM and T640

- Data recovery for PM_{10} from GRIMM and T640 was ~ 88% and 99%, respectively.
- Very strong correlations between the reference instruments for PM_{10} measurements (R^2 ~ 0.90) were observed.

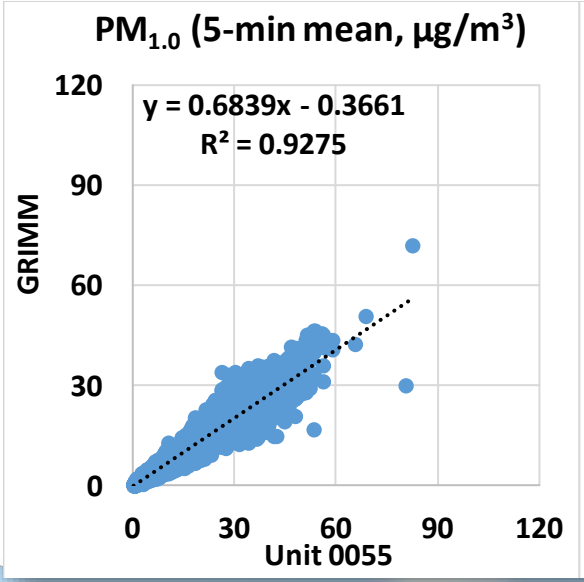


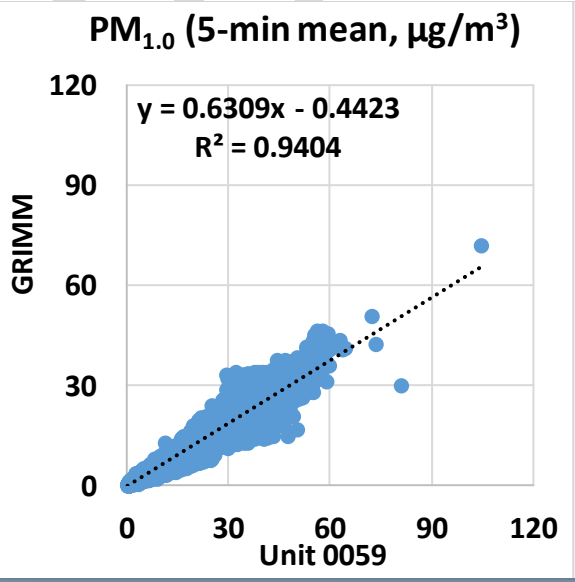


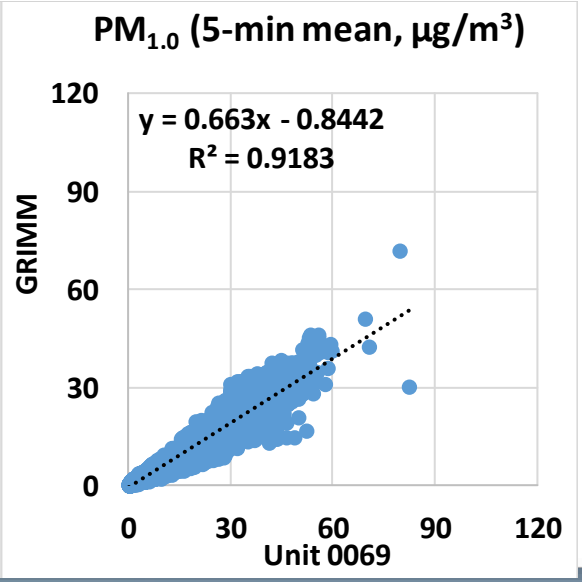
MODULAIR-PM vs GRIMM ($PM_{1.0}$; 5-min mean)



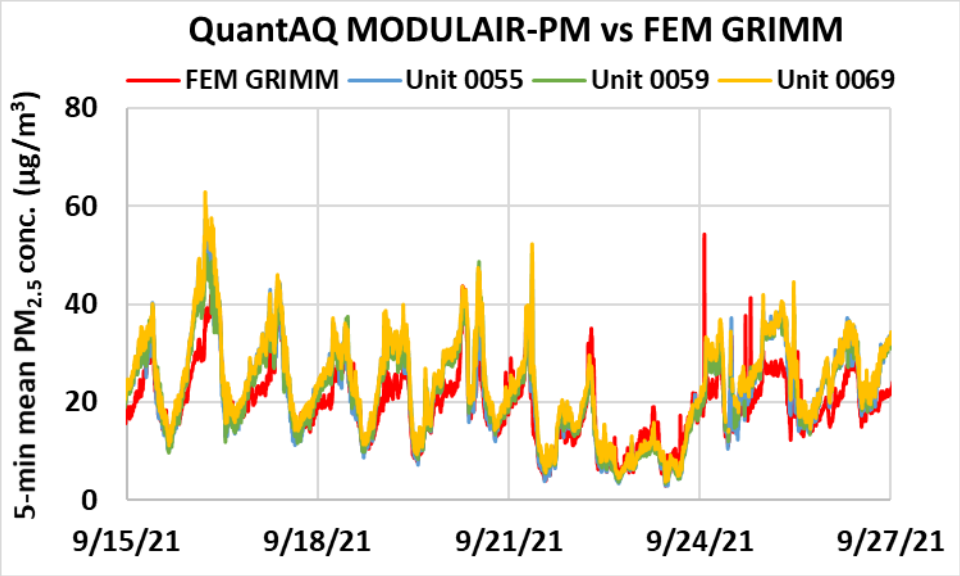
- The MODULAIR-PM sensors showed very strong correlations with the corresponding GRIMM data ($0.91 < R^2 < 0.95$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM



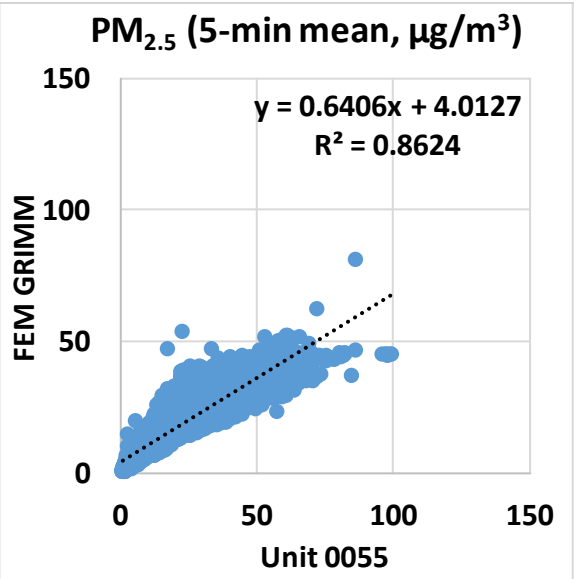


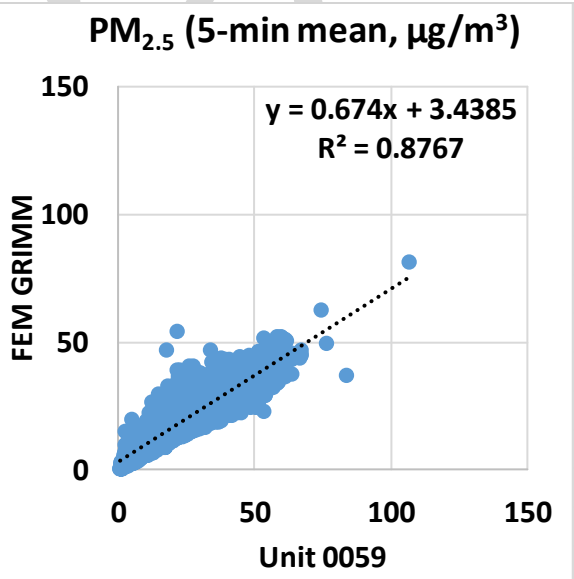


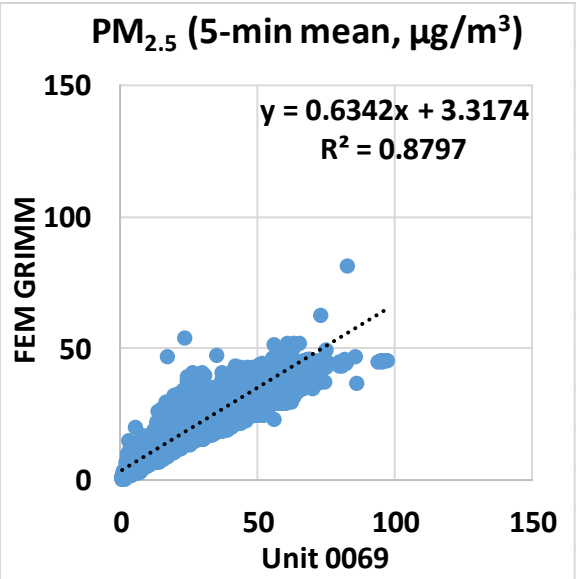
MODULAIR-PM vs FEM GRIMM ($PM_{2.5}$; 5-min mean)



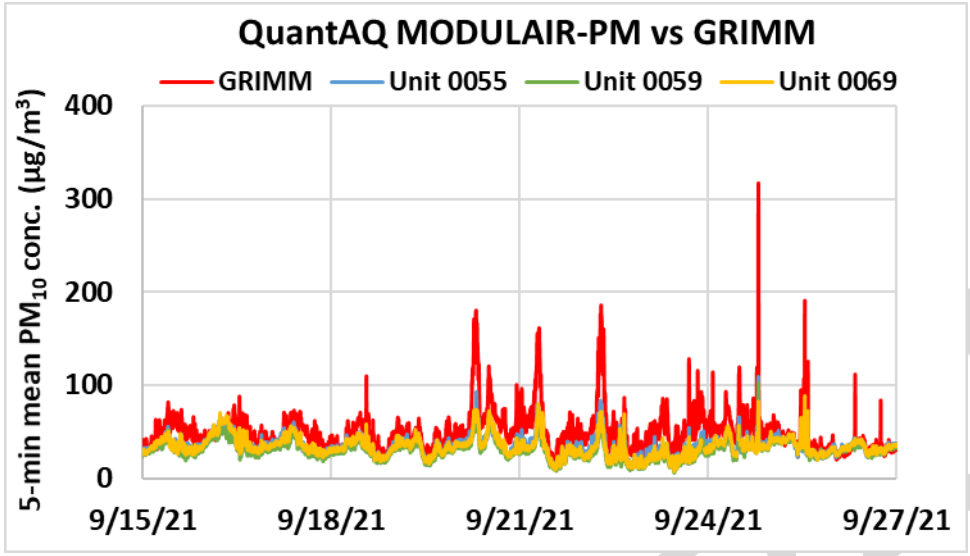
- The MODULAIR-PM sensors showed strong correlations with the corresponding FEM GRIMM data ($0.86 < R^2 < 0.88$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM



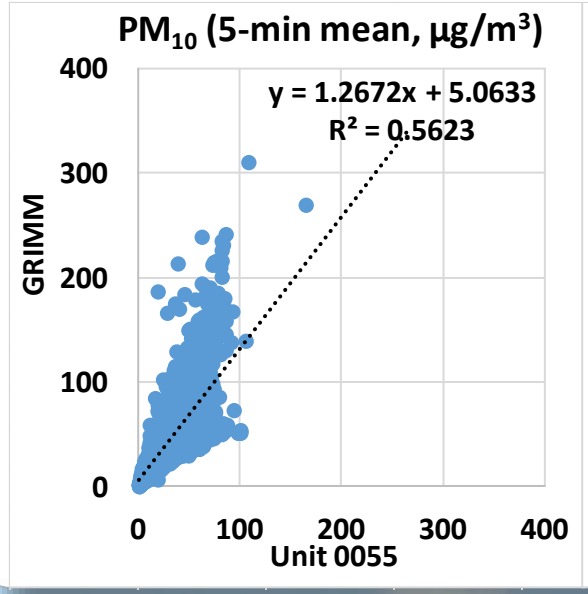


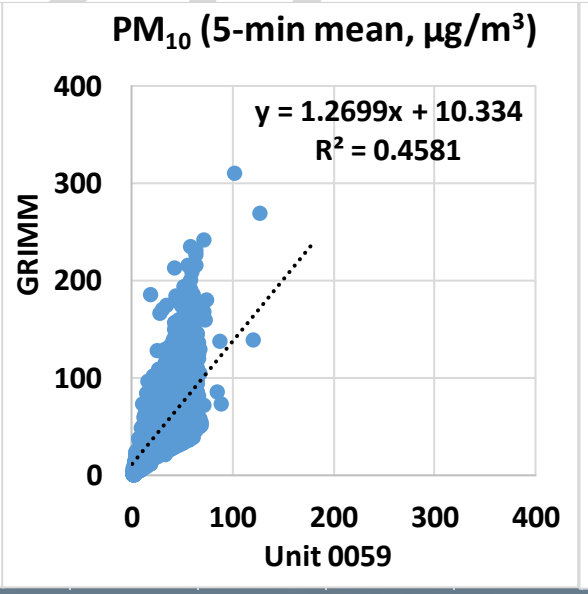


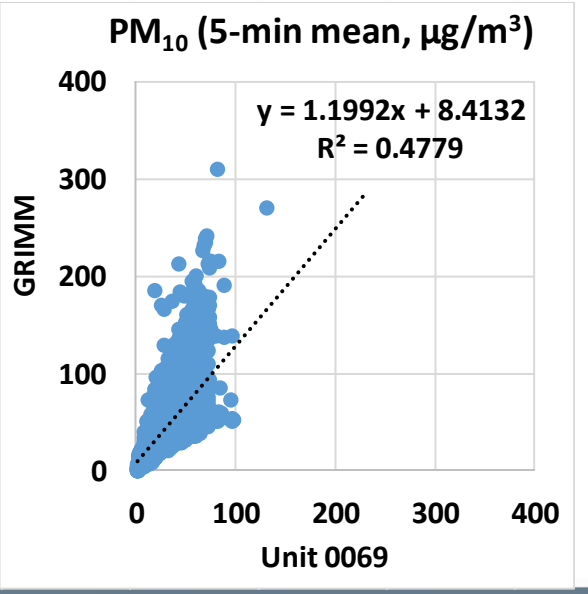
MODULAIR-PM vs GRIMM (PM_{10}; 5-min mean)



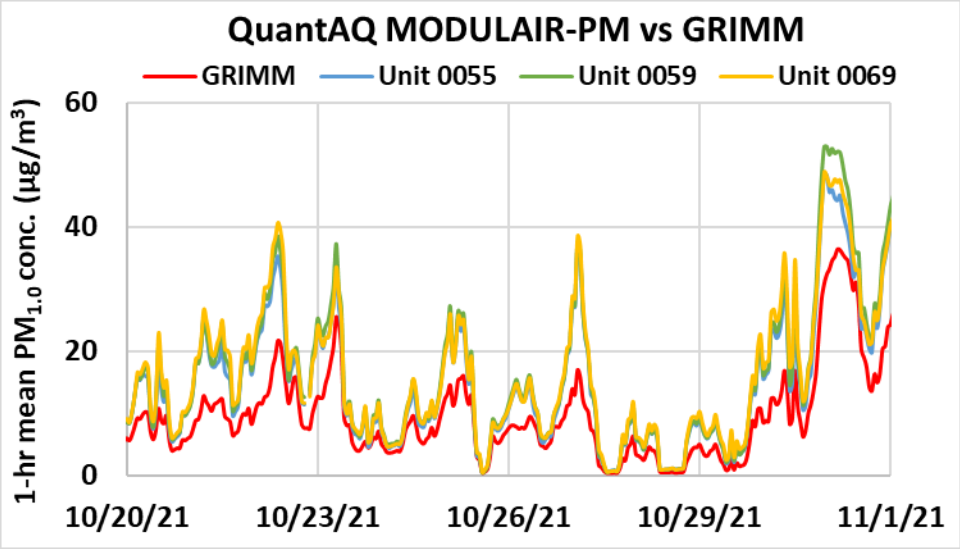
- The MODULAIR-PM sensors showed weak to moderate correlations with the corresponding GRIMM data ($0.45 < R^2 < 0.57$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM



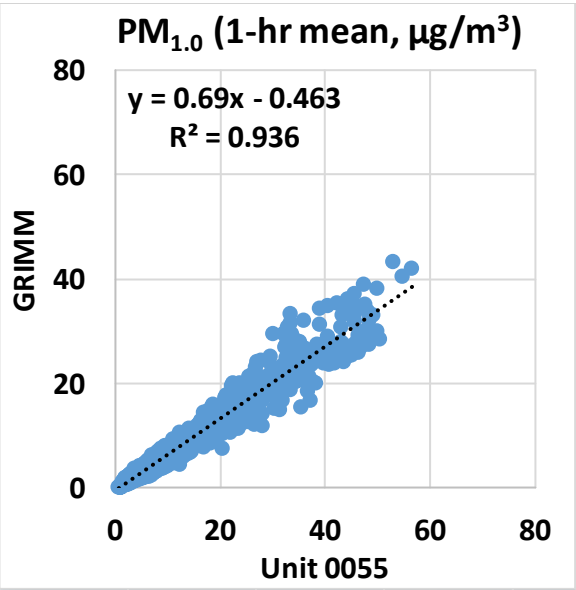


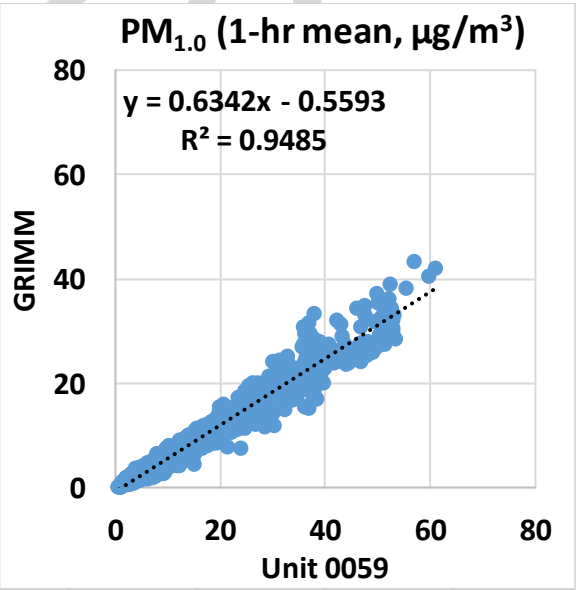


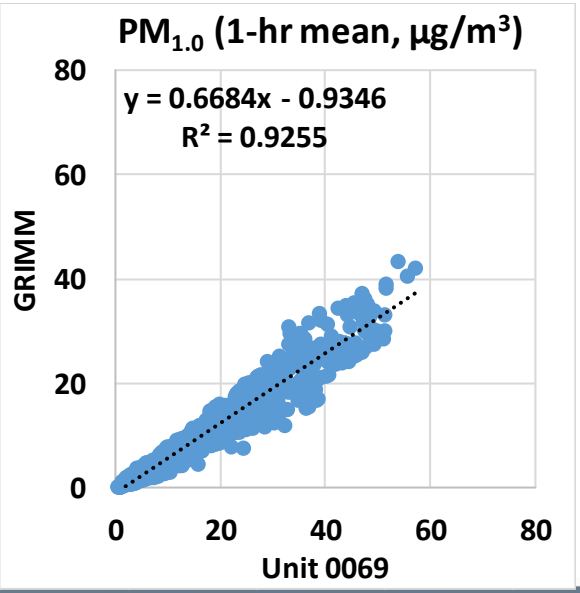
MODULAIR-PM vs GRIMM ($PM_{1.0}$; 1-hr mean)



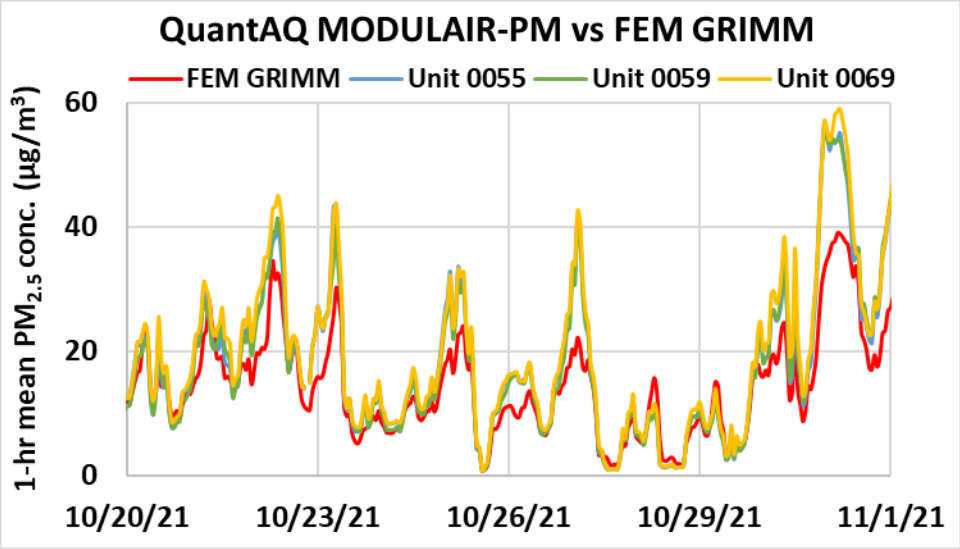
- The MODULAIR-PM sensors showed very strong correlations with the corresponding GRIMM data ($0.92 < R^2 < 0.95$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM



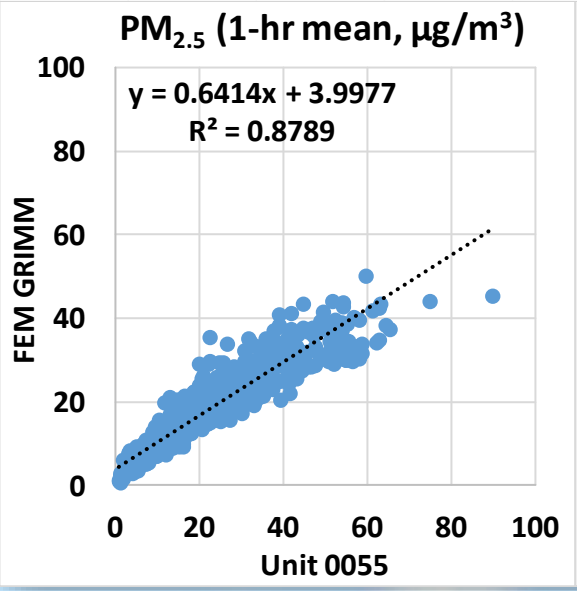


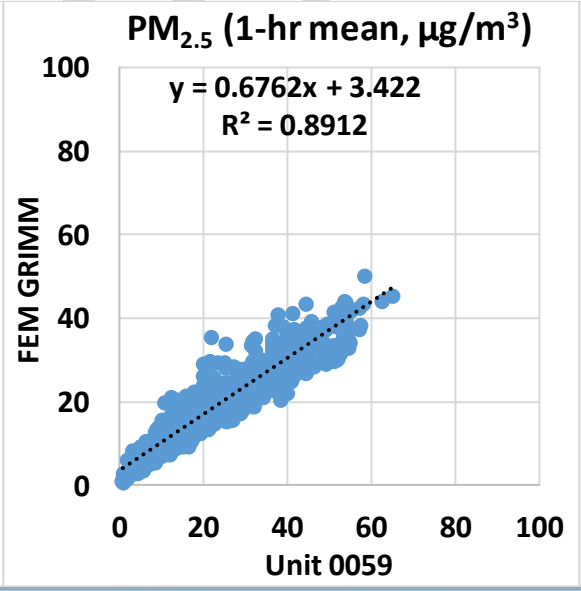


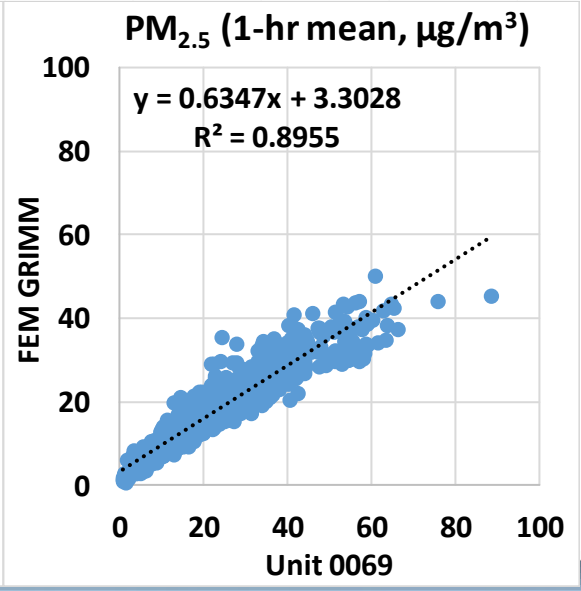
MODULAIR-PM vs FEM GRIMM ($PM_{2.5}$; 1-hr mean)



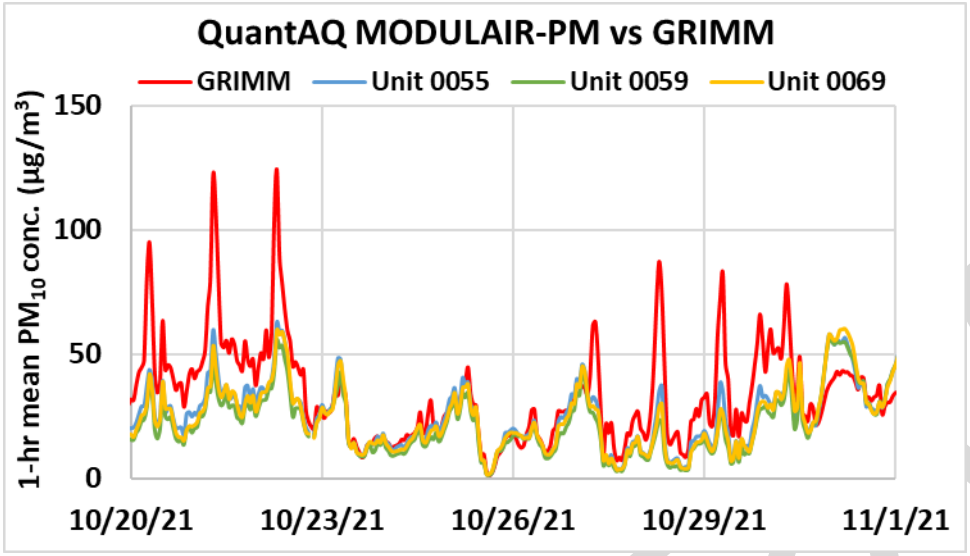
- The MODULAIR-PM sensors showed strong correlations with the corresponding FEM GRIMM data ($0.87 < R^2 < 0.90$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM



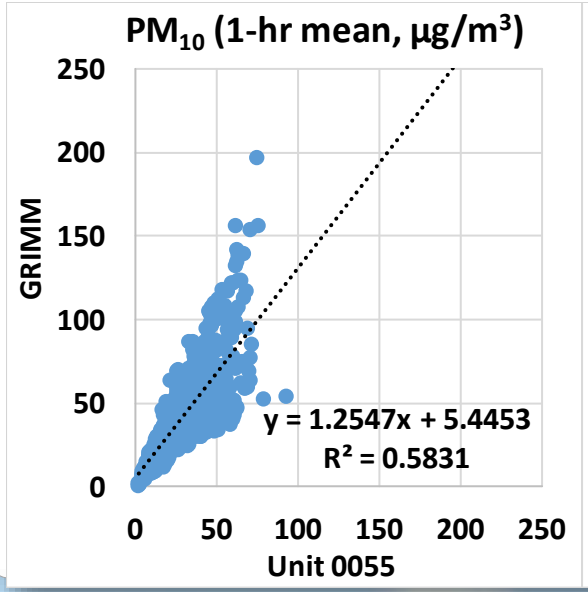


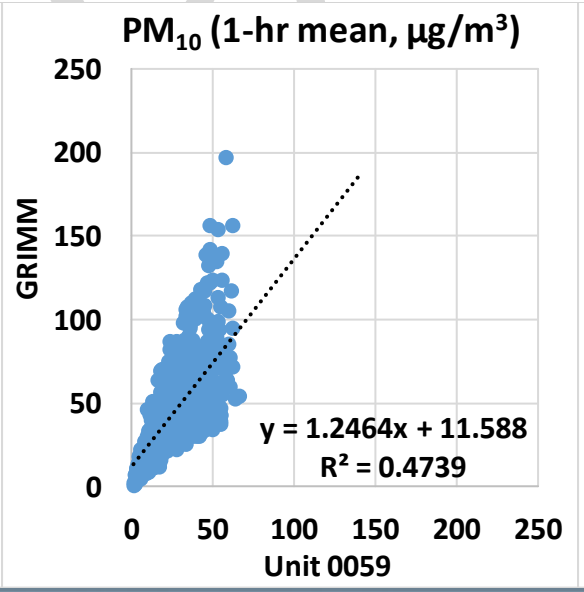


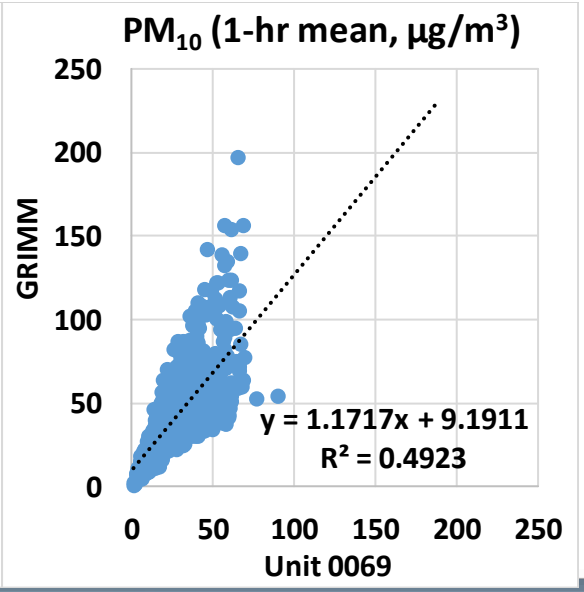
MODULAIR-PM vs GRIMM (PM_{10}; 1-hr mean)



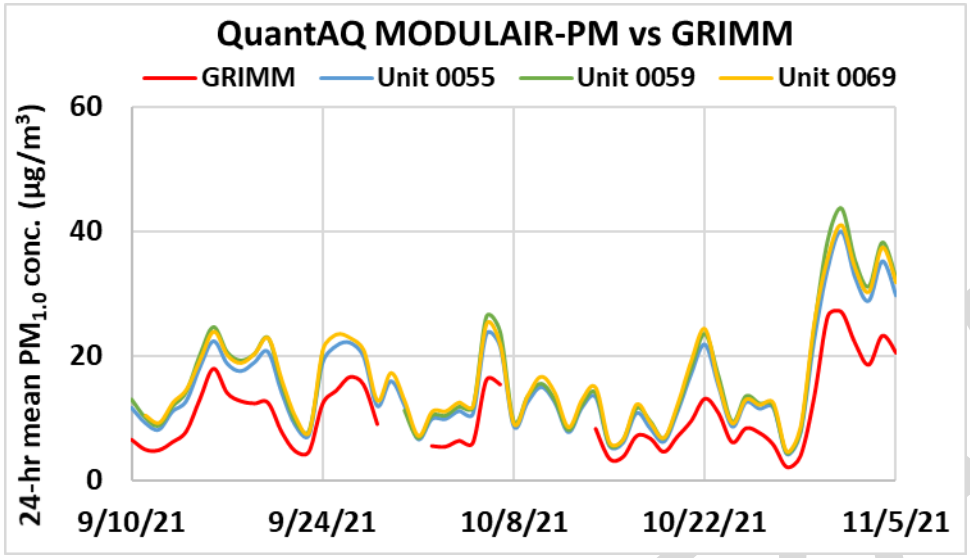
- The MODULAIR-PM sensors showed weak to moderate correlations with the corresponding GRIMM data ($0.47 < R^2 < 0.59$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM



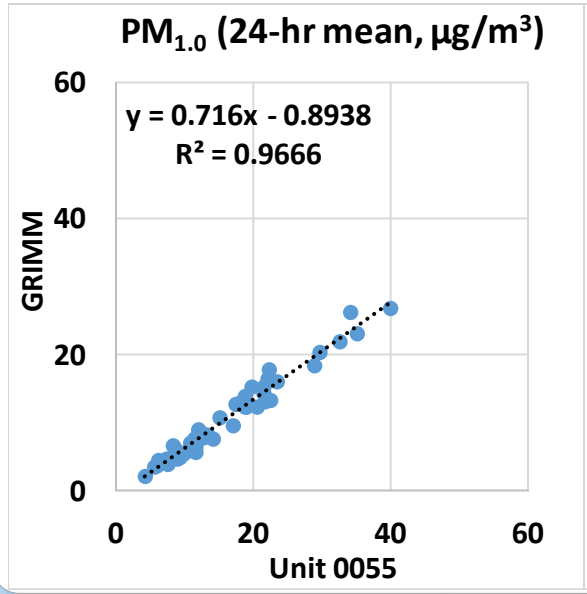


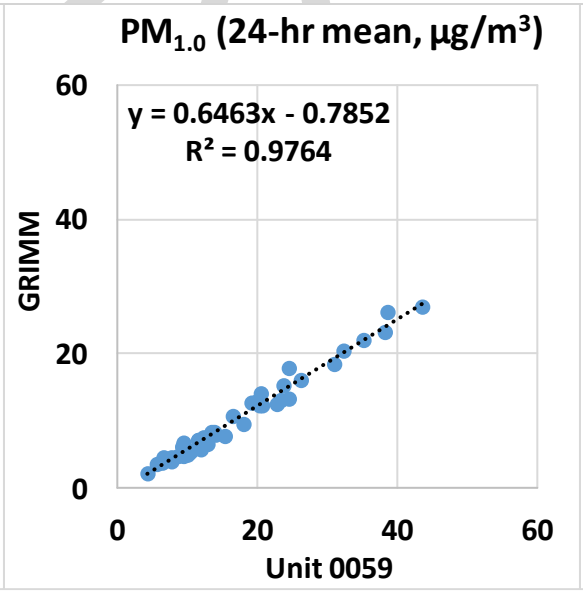


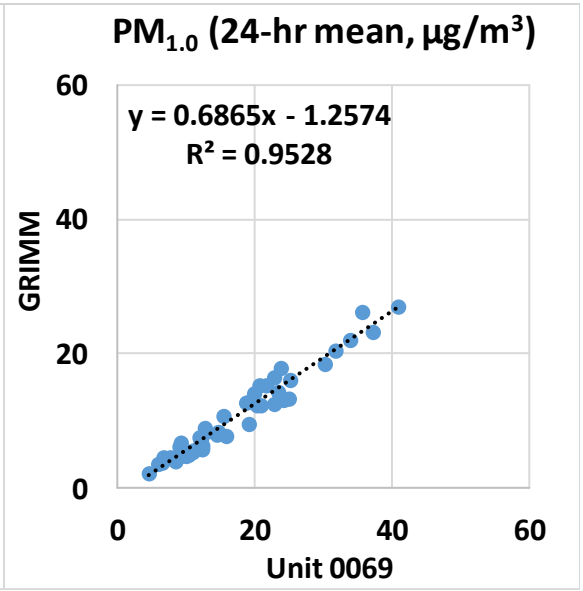
MODULAIR-PM vs GRIMM ($PM_{1.0}$; 24-hr mean)



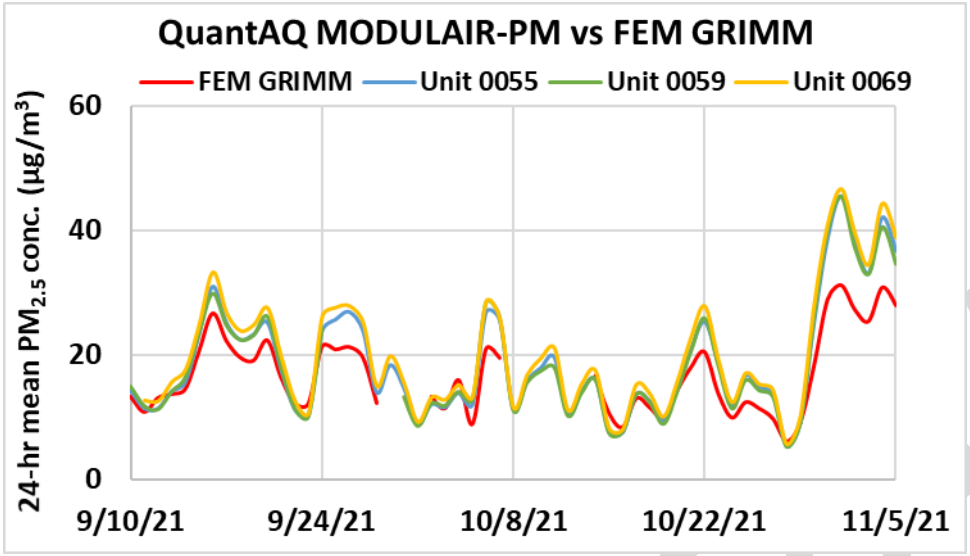
- The MODULAIR-PM sensors showed very strong correlations with the corresponding GRIMM data ($0.95 < R^2 < 0.98$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by GRIMM



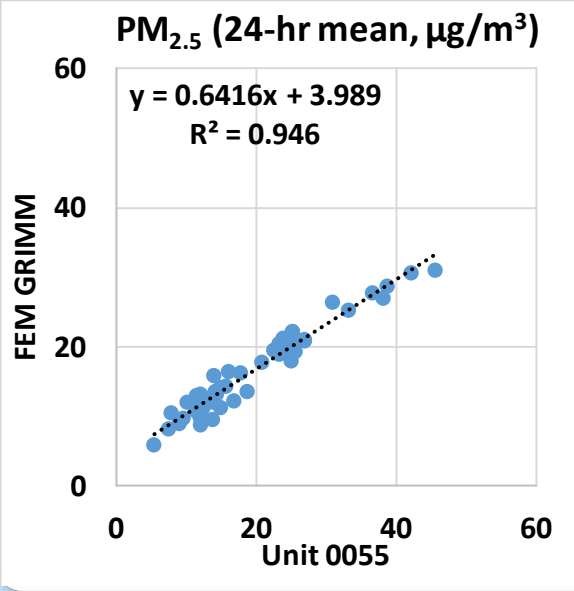


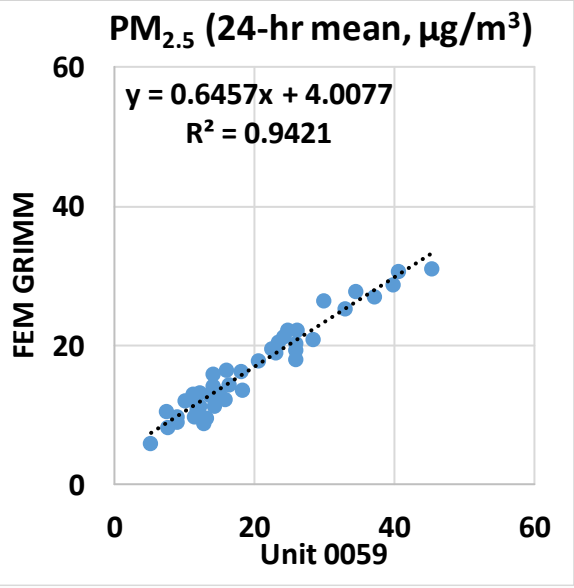


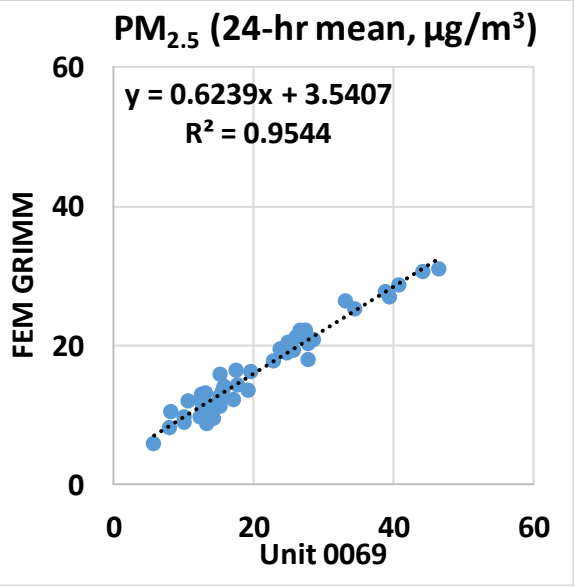
MODULAIR-PM vs FEM GRIMM ($PM_{2.5}$; 24-hr mean)



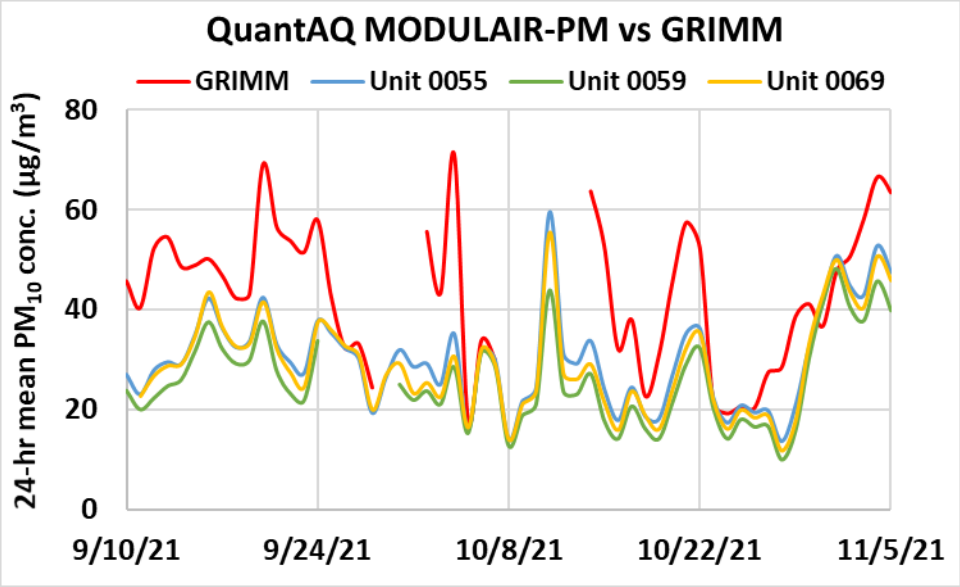
- The MODULAIR-PM sensors showed very strong correlations with the corresponding FEM GRIMM data ($0.94 < R^2 < 0.96$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM GRIMM
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM GRIMM



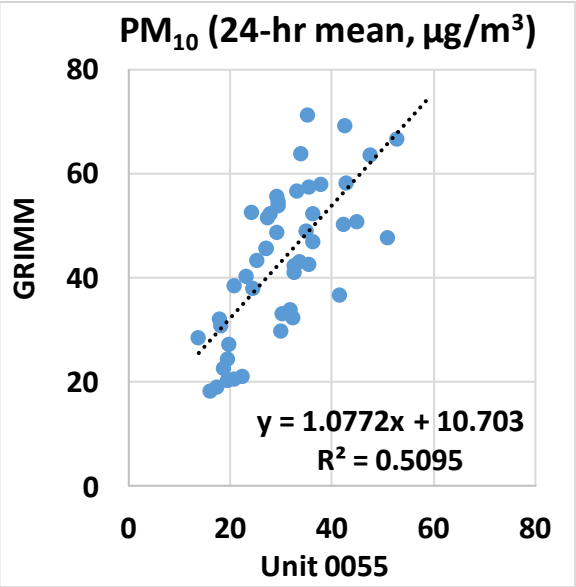


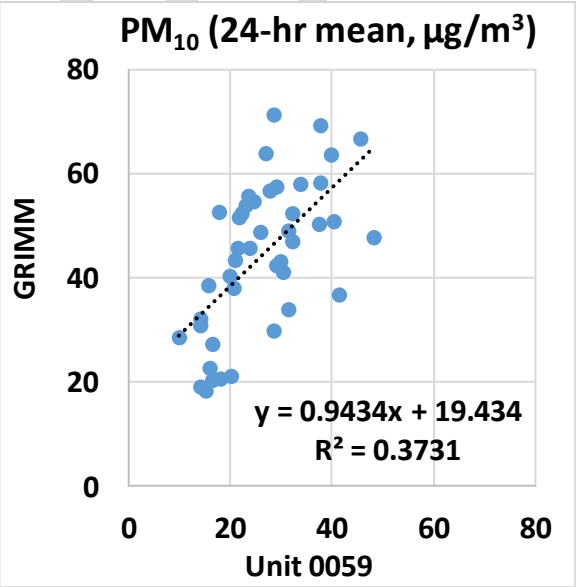


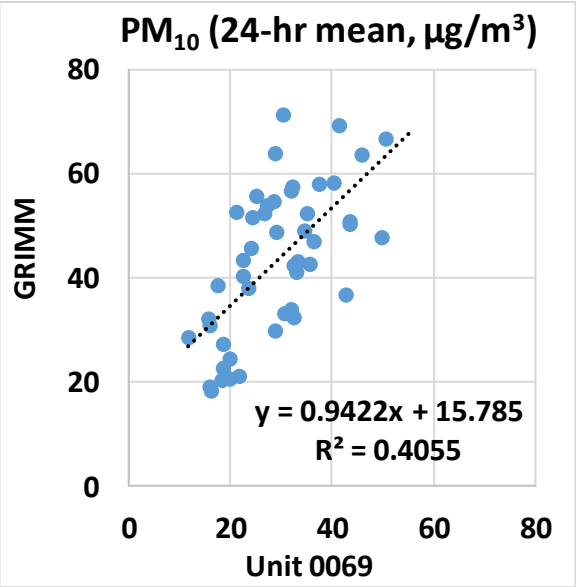
MODULAIR-PM vs GRIMM (PM_{10}; 24-hr mean)



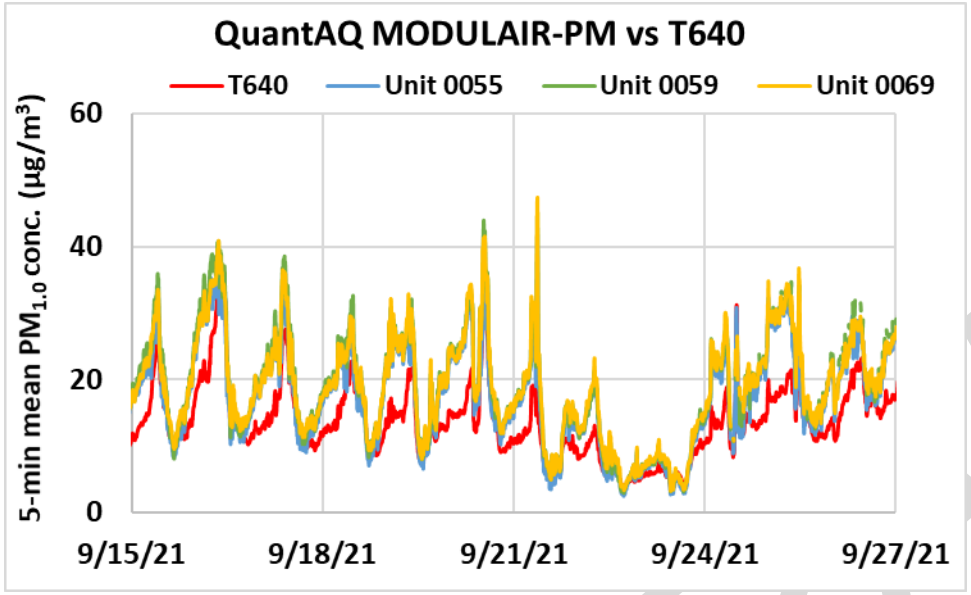
- The MODULAIR-PM sensors showed weak to moderate correlations with the corresponding GRIMM data ($0.37 < R^2 < 0.51$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by GRIMM
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by GRIMM



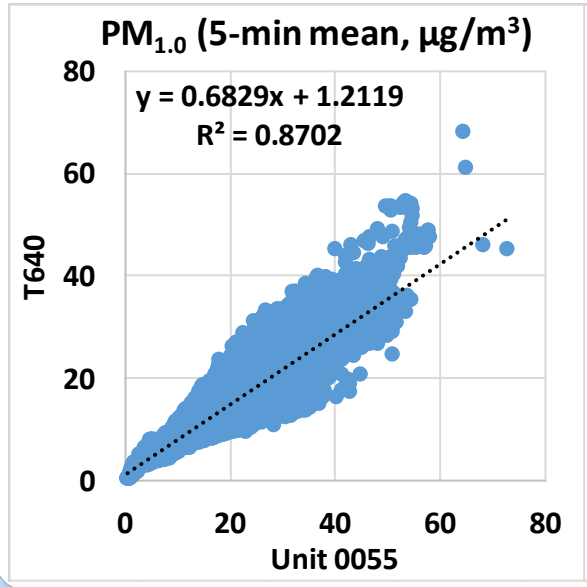


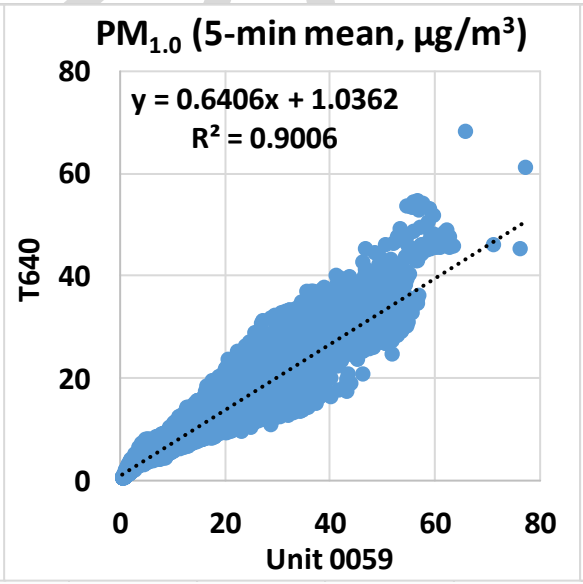


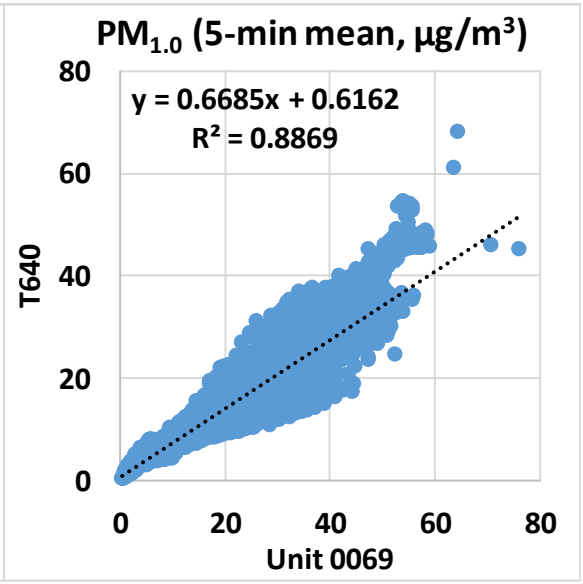
MODULAIR-PM vs T640 ($PM_{1.0}$; 5-min mean)



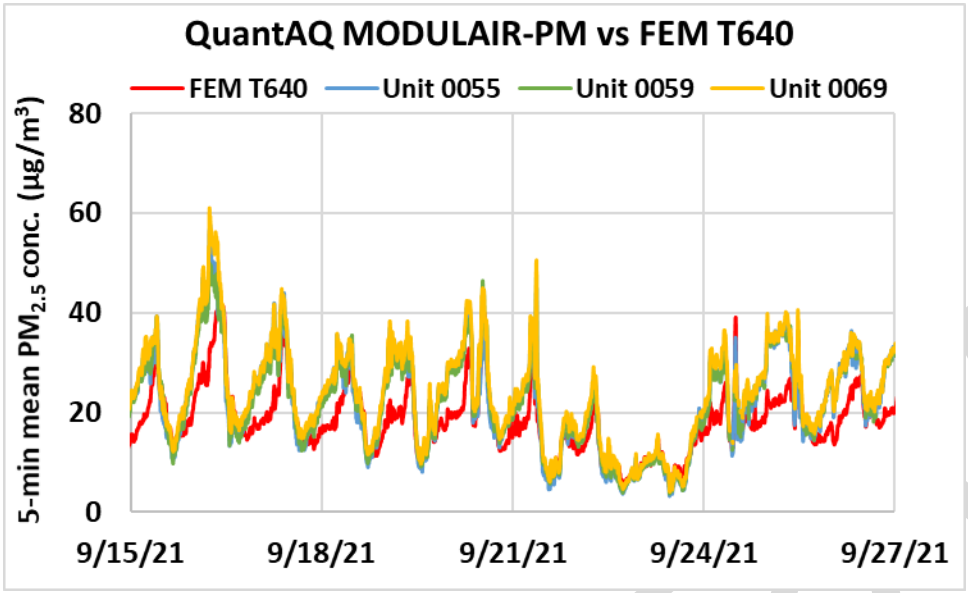
- The MODULAIR-PM sensors showed strong to very strong correlations with the corresponding T640 data ($0.87 < R^2 < 0.91$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



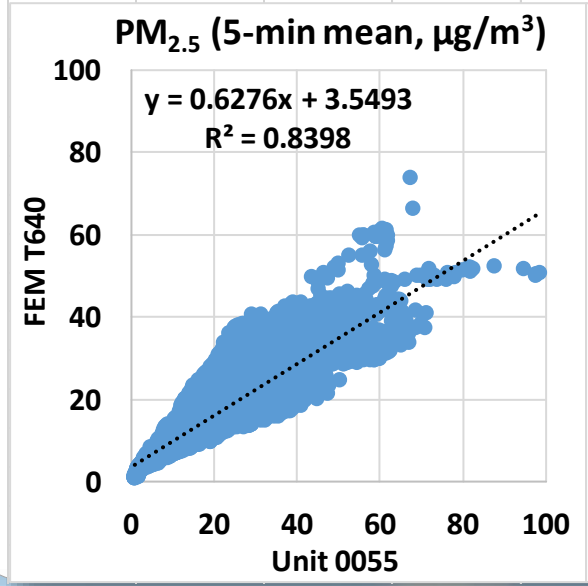


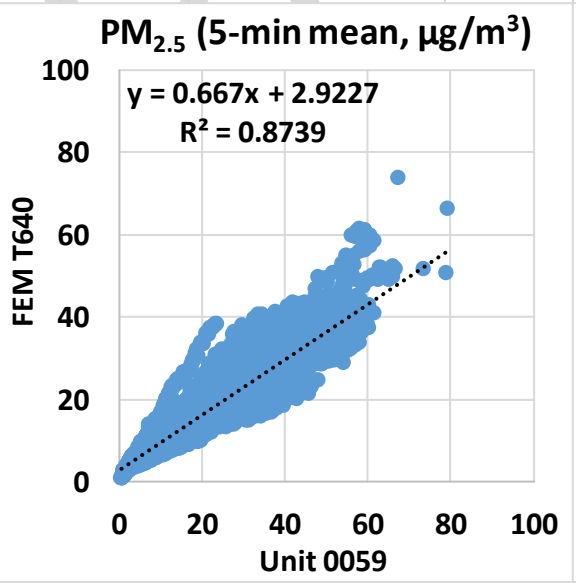


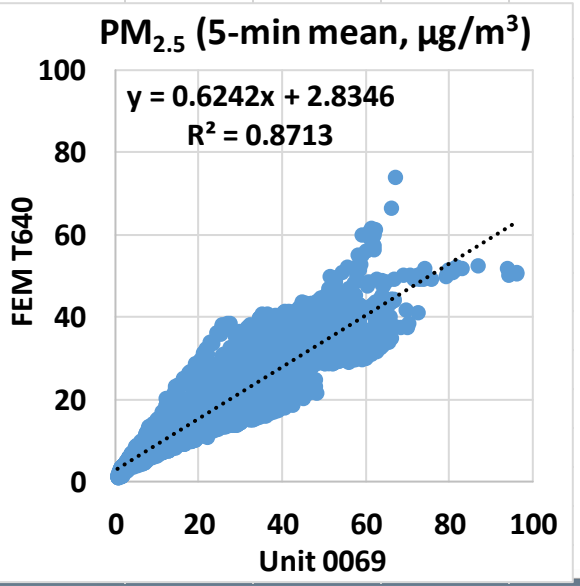
MODULAIR-PM vs FEM T640 ($PM_{2.5}$; 5-min mean)



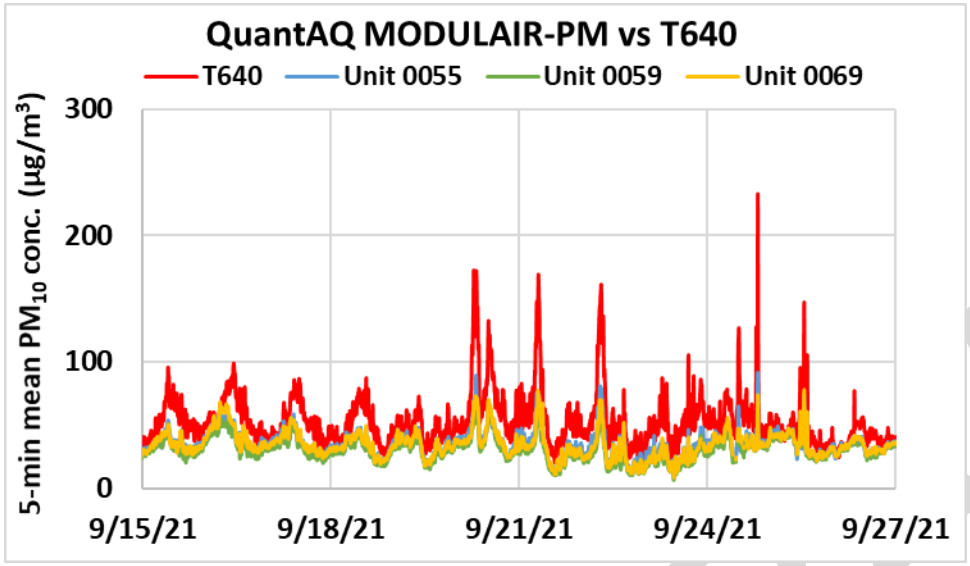
- The MODULAIR-PM sensors showed strong correlations with the corresponding FEM T640 data ($0.83 < R^2 < 0.88$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



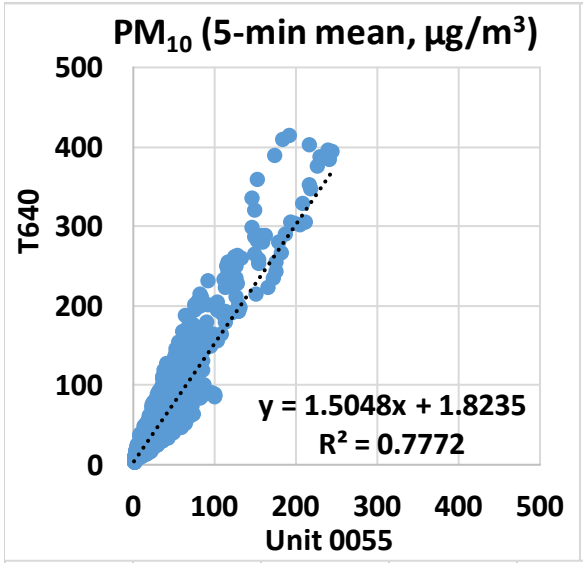


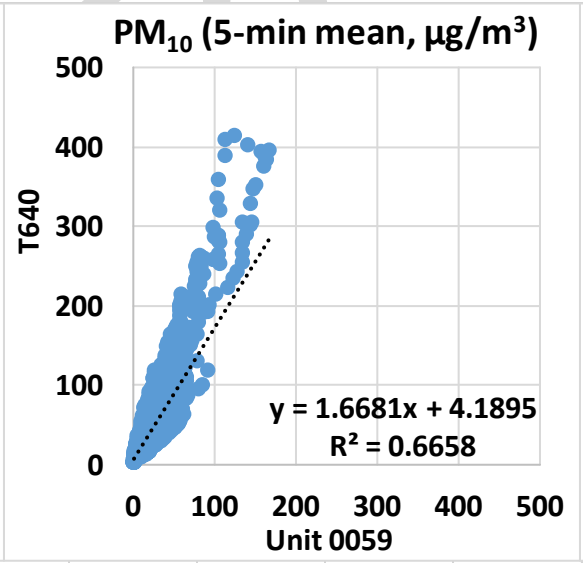


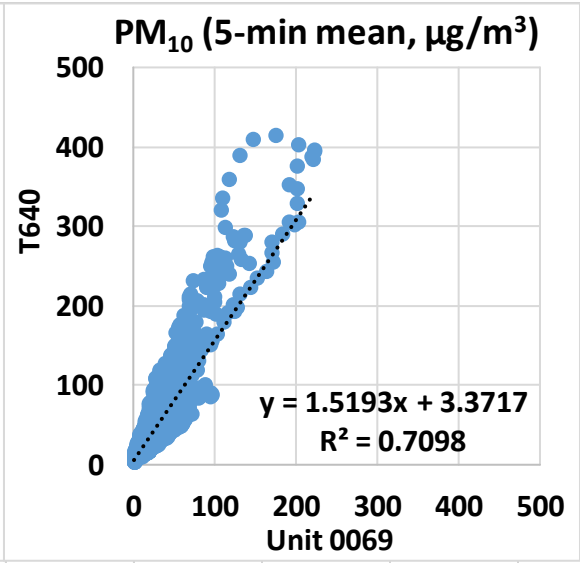
MODULAIR-PM vs T640 (PM_{10}; 5-min mean)



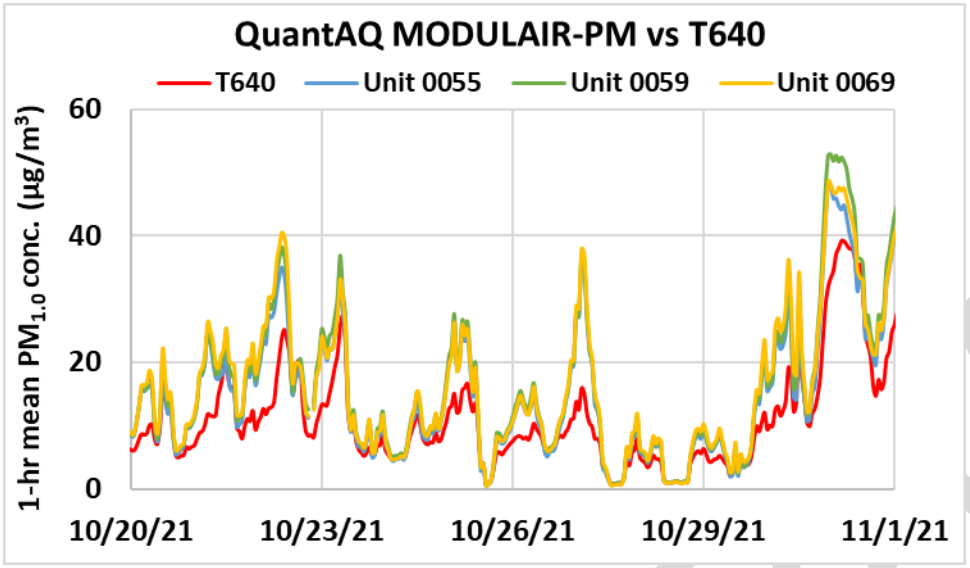
- MODULAIR-PM sensors showed moderate to strong correlations with the corresponding T640 data ($0.66 < R^2 < 0.78$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by T640



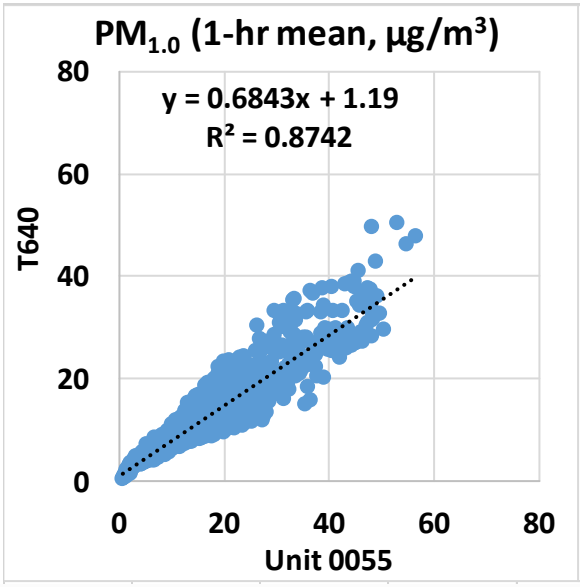


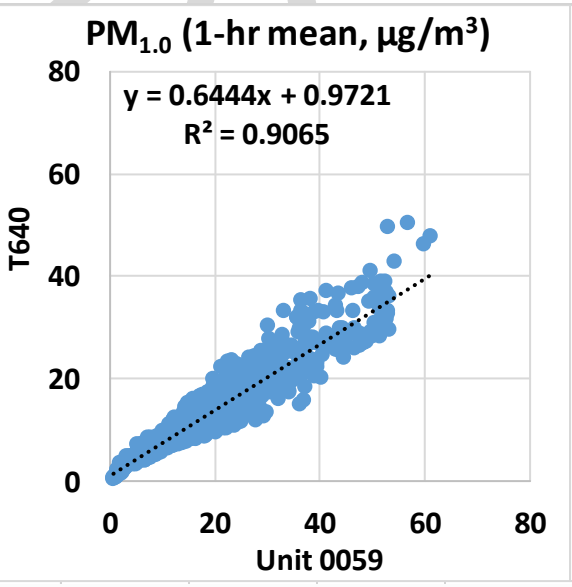


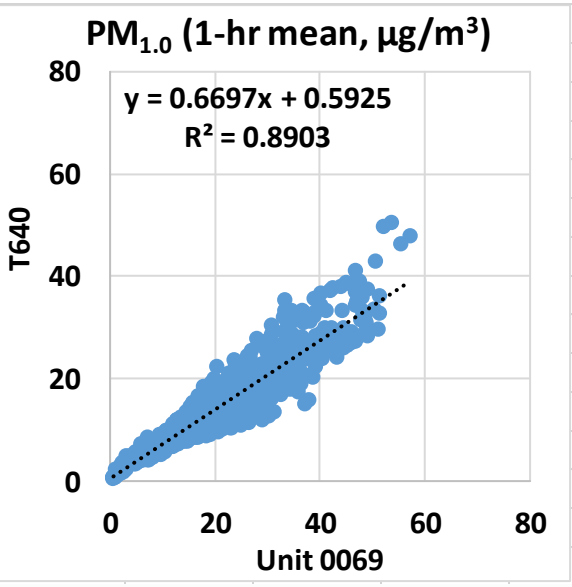
MODULAIR-PM vs T640 ($PM_{1.0}$; 1-hr mean)



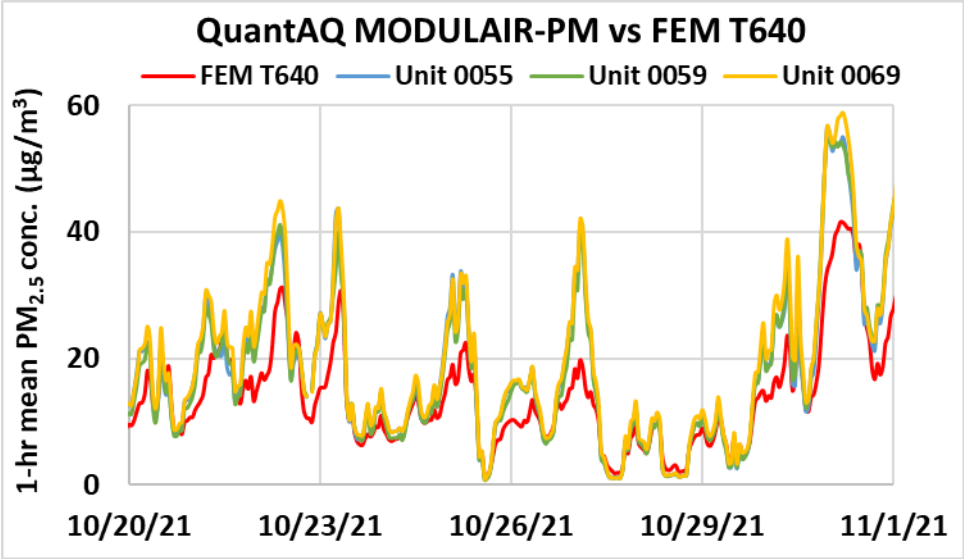
- The MODULAIR-PM sensors showed strong to very strong correlations with the corresponding T640 data ($0.87 < R^2 < 0.91$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



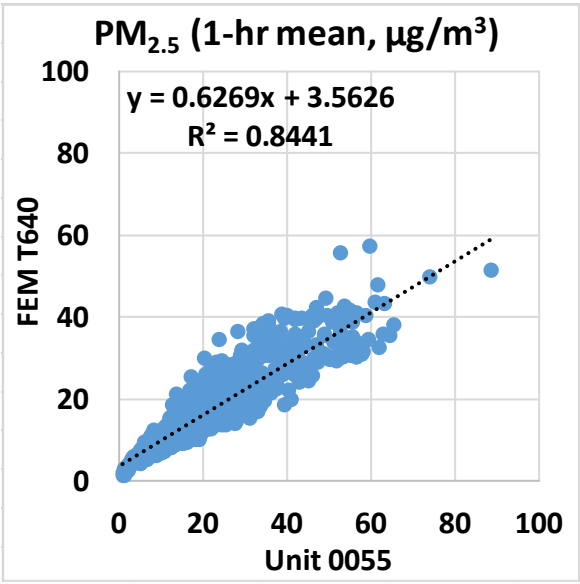


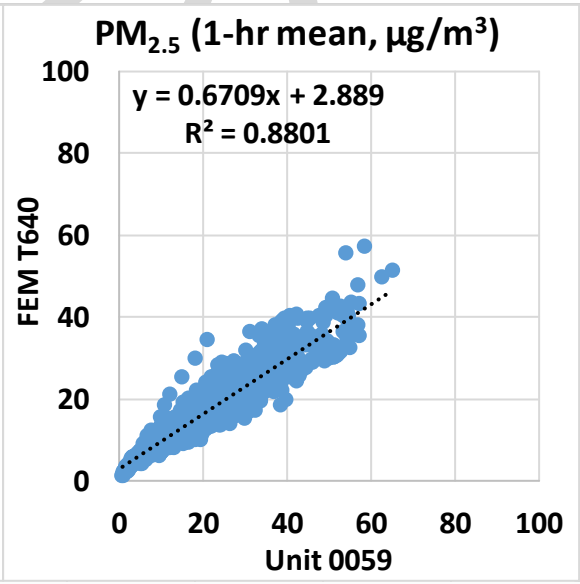


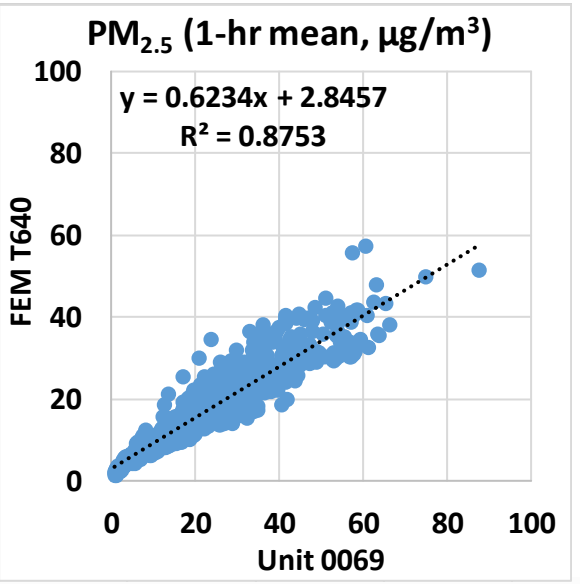
MODULAIR-PM vs FEM T640 ($PM_{2.5}$; 1-hr mean)



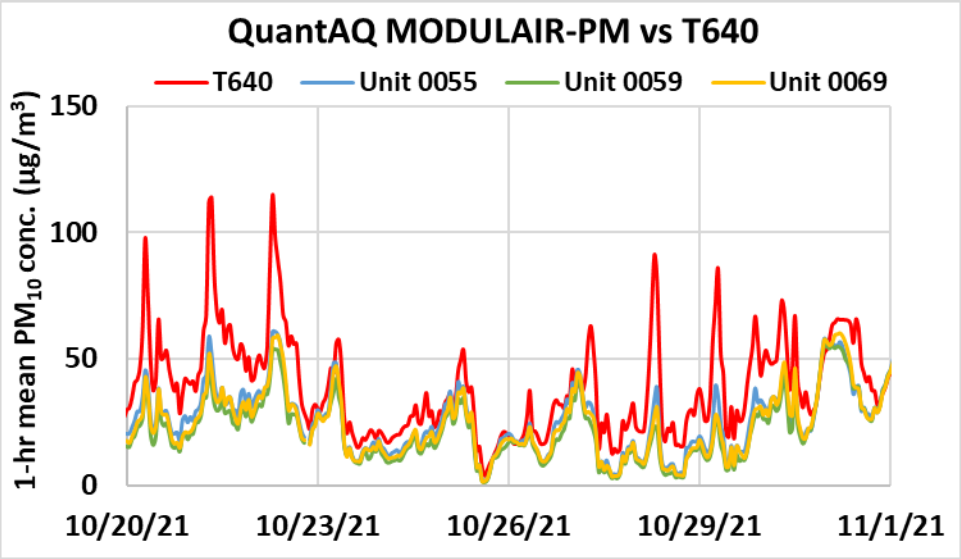
- The MODULAIR-PM sensors showed strong correlations with the corresponding FEM T640 data ($0.84 < R^2 < 0.89$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



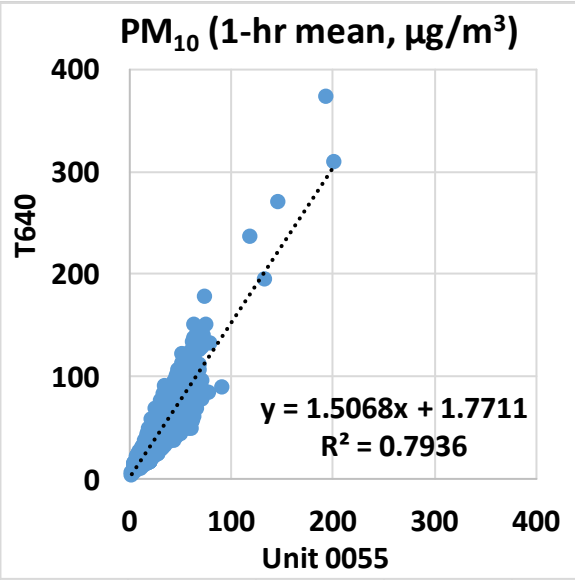


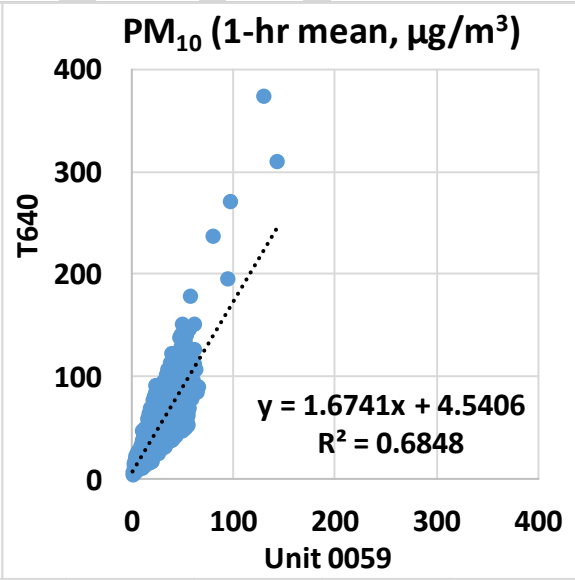


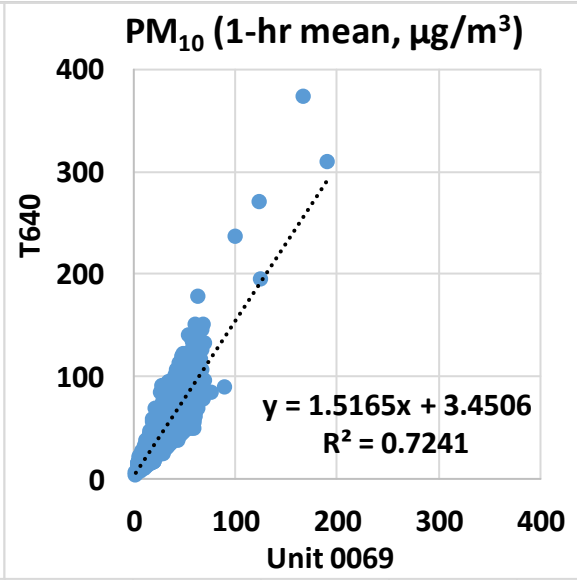
MODULAIR-PM vs T640 (PM_{10}; 1-hr mean)



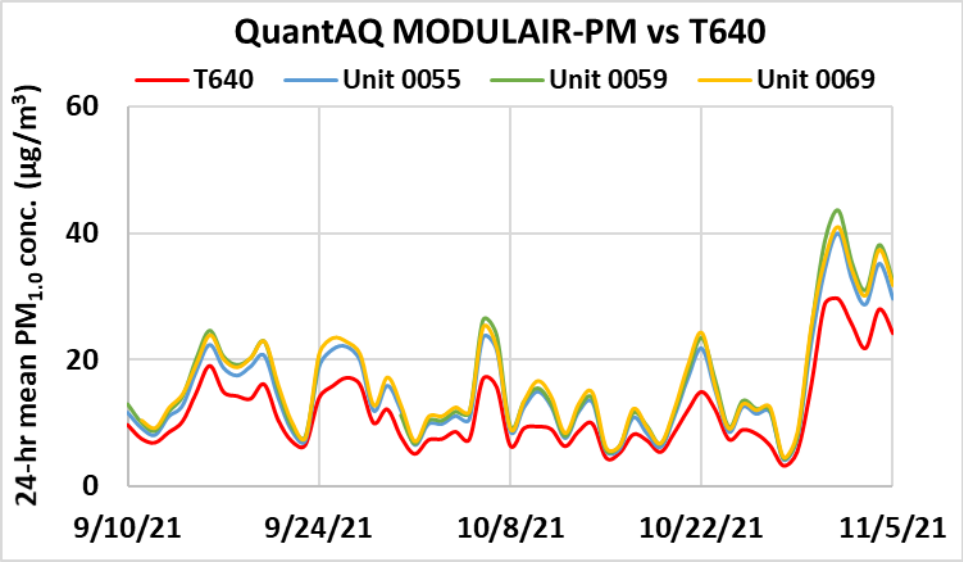
- The MODULAIR-PM sensors showed moderate to strong correlations with the corresponding T640 data ($0.68 < R^2 < 0.80$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by T640



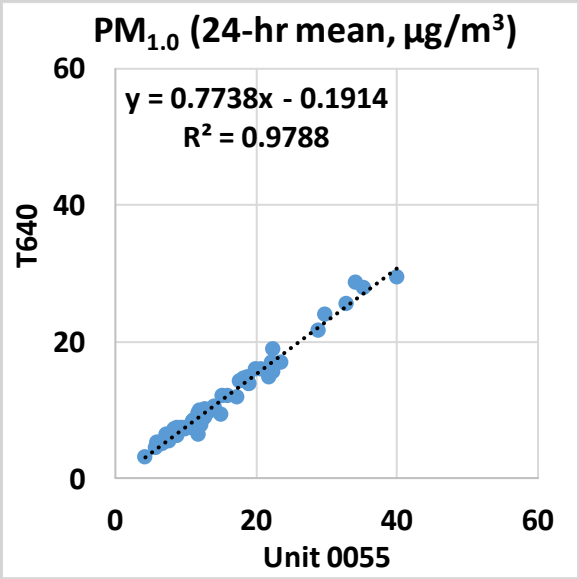


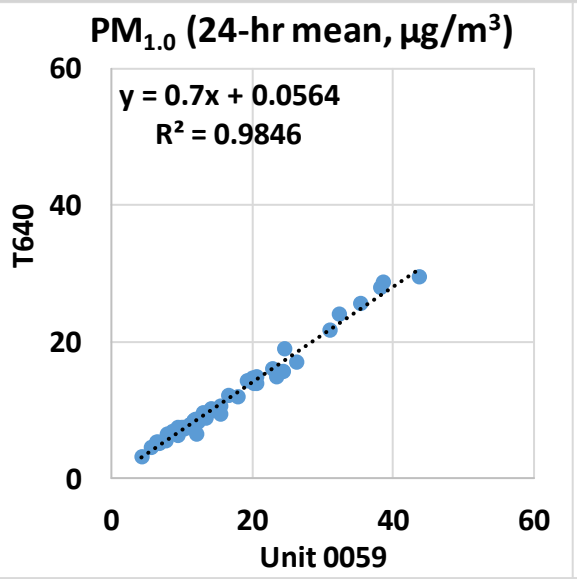


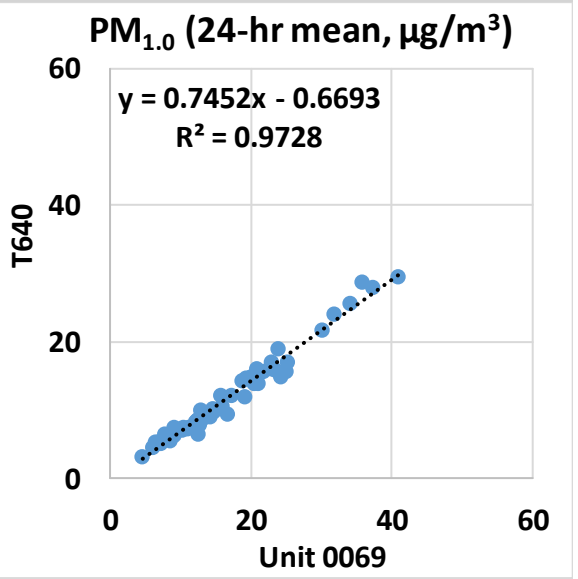
MODULAIR-PM vs T640 ($PM_{1.0}$; 24-hr mean)



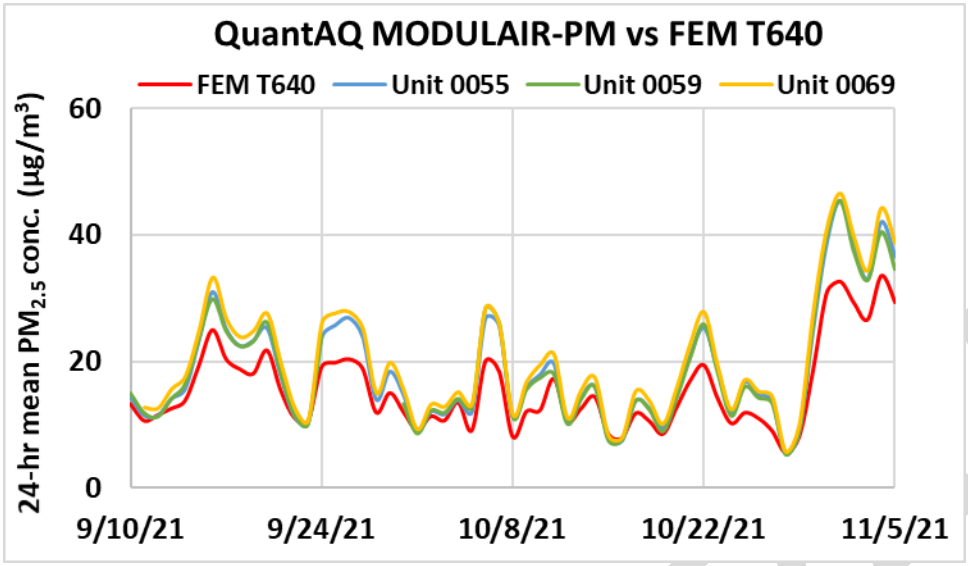
- The MODULAIR-PM sensors showed very strong correlations with the corresponding T640 data ($0.97 < R^2 < 0.99$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{1.0}$ mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the $PM_{1.0}$ diurnal variations as recorded by T640



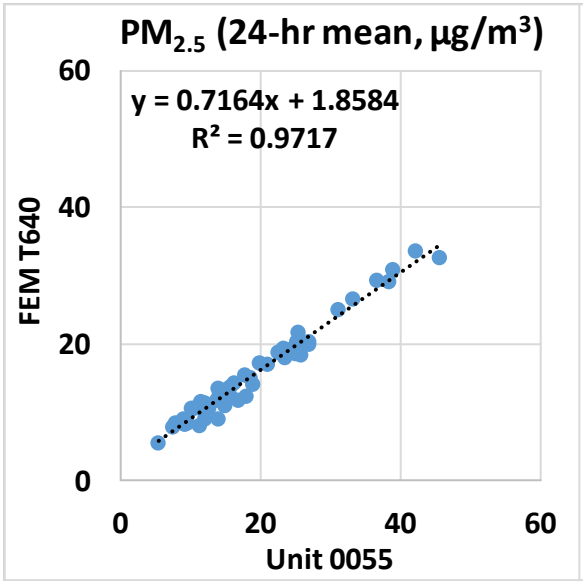


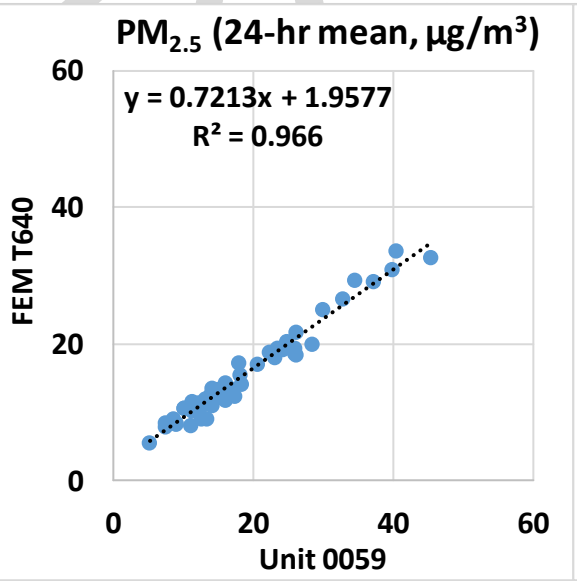


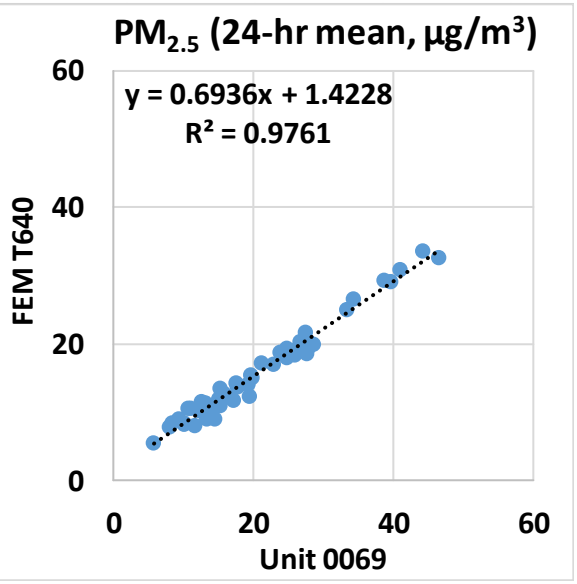
MODULAIR-PM vs FEM T640 ($PM_{2.5}$; 24-hr mean)



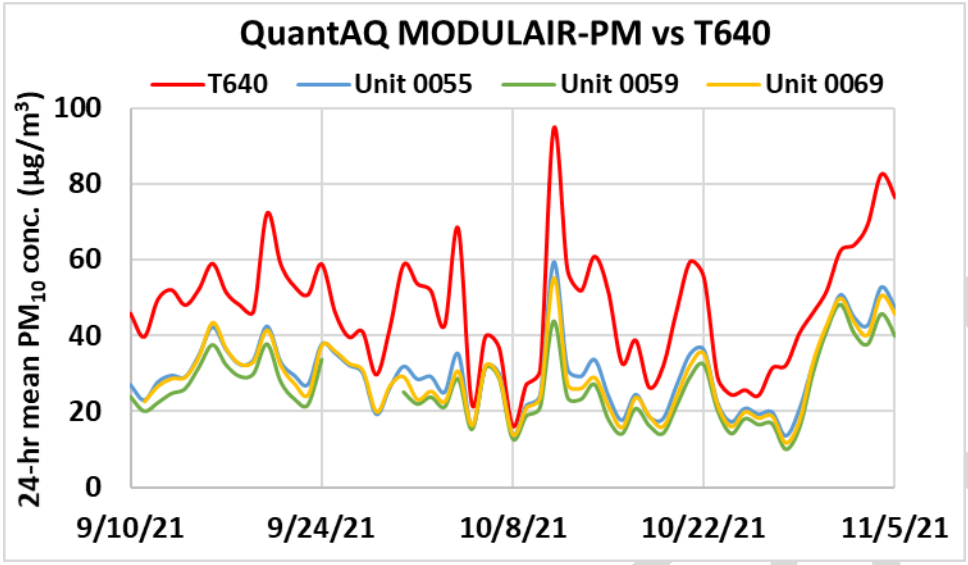
- The MODULAIR-PM sensors showed very strong correlations with the corresponding FEM T640 data ($0.96 < R^2 < 0.98$)
- Overall, the MODULAIR-PM sensors overestimated the $PM_{2.5}$ mass concentrations as measured by FEM T640
- The MODULAIR-PM sensors seemed to track the $PM_{2.5}$ diurnal variations as recorded by FEM T640



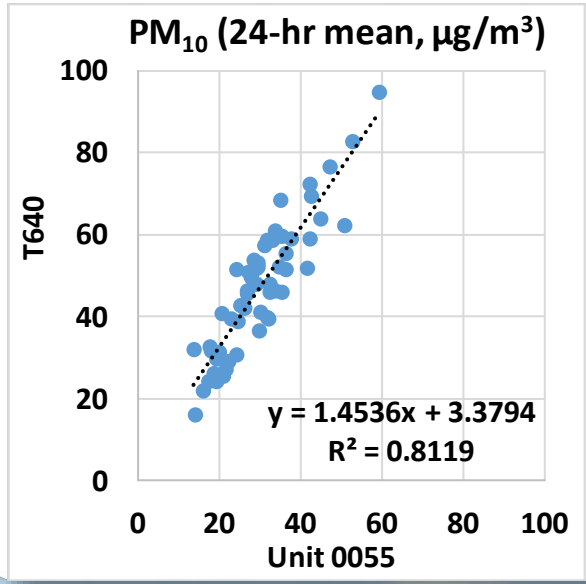


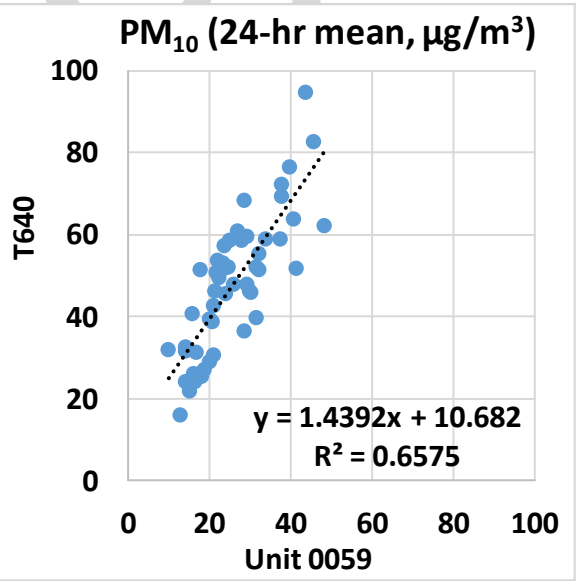


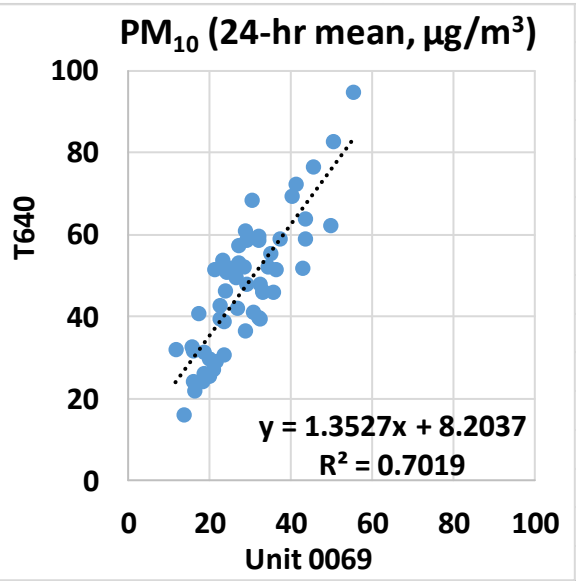
MODULAIR-PM vs T640 (PM_{10}; 24-hr mean)



- The MODULAIR-PM sensors showed moderate to strong correlations with the corresponding T640 data ($0.65 < R^2 < 0.82$)
- Overall, the MODULAIR-PM sensors underestimated the PM_{10} mass concentrations as measured by T640
- The MODULAIR-PM sensors seemed to track the PM_{10} diurnal variations as recorded by T640







Summary

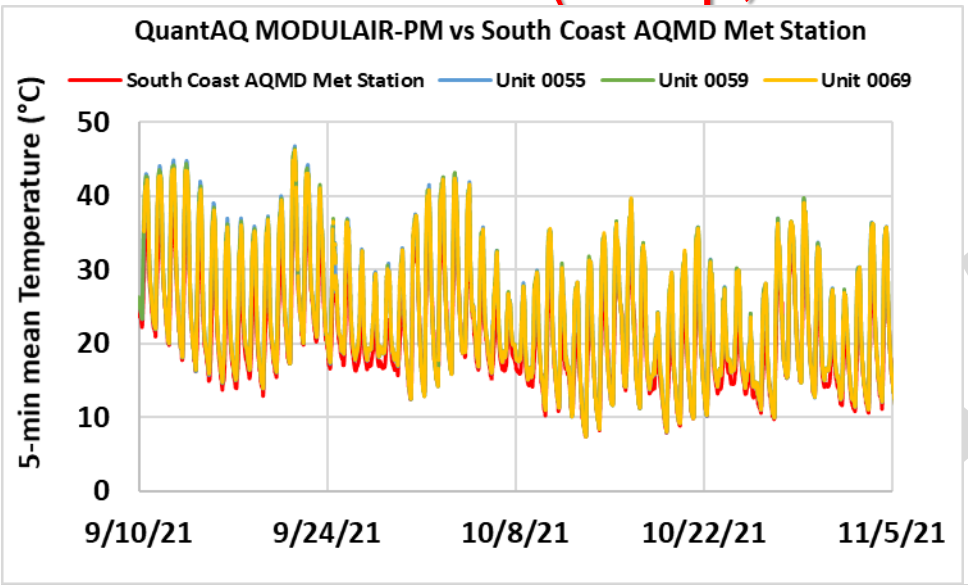
	Average of 3 Sensors, $PM_{1.0}$		MODULAIR-PM vs GRIMM & T640, $PM_{1.0}$						GRIMM & T640 ($PM_{1.0}$, $\mu g/m^3$)		
	Average ($\mu g/m^3$)	SD ($\mu g/m^3$)	R^2	Slope	Intercept	MBE[1] ($\mu g/m^3$)	MAE[2] ($\mu g/m^3$)	RMSE[3] ($\mu g/m^3$)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	16.2	11.2	0.87 to 0.94	0.63 to 0.68	-0.8 to 1.2	3.7 to 6.8	4.1 to 6.8	5.7 to 8.3	10.6 to 11.8	7.7 to 7.8	0.2 to 72.2
1-hr	16.1	11.1	0.87 to 0.95	0.63 to 0.69	-0.9 to 1.2	3.7 to 6.8	4.0 to 6.8	5.7 to 8.3	10.6 to 11.8	7.6 to 7.7	0.3 to 50.7
24-hr	16.2	8.5	0.95 to 0.98	0.65 to 0.77	-1.3 to 0.1	3.7 to 6.9	3.7 to 6.9	4.2 to 7.6	10.7 to 11.8	6.1 to 6.3	2.2 to 29.6
	Average of 3 Sensors, $PM_{2.5}$		MODULAIR-PM vs FEM GRIMM & FEM T640, $PM_{2.5}$						FEM GRIMM & 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	19.4	12.6	0.84 to 0.88	0.62 to 0.67	2.8 to 4.0	2.9 to 4.8	4.0 to 5.2	5.9 to 7.5	15.5 to 16.6	8.6 to 8.9	0.6 to 81.5
1-hr	19.3	12.5	0.84 to 0.90	0.62 to 0.68	2.8 to 4.0	2.8 to 4.8	3.9 to 5.2	5.8 to 7.4	15.5 to 16.6	8.5 to 8.8	0.9 to 57.4
24-hr	19.3	9.3	0.94 to 0.98	0.62 to 0.72	1.4 to 4.0	2.9 to 4.8	3.2 to 4.9	4.3 to 6.0	15.5 to 16.7	6.3 to 6.6	5.4 to 33.6
	Average of 3 Sensors, PM_{10}		MODULAIR-PM vs GRIMM & T640, PM_{10}						GRIMM & 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	15.3	0.46 to 0.78	1.20 to 1.67	1.8 to 10.3	-21.5 to -13.1	14.7 to 21.6	21.0 to 28.5	43.2 to 47.3	24.1 to 27.7	0.8 to 414.7
1-hr	28.3	14.8	0.47 to 0.79	1.17 to 1.67	1.8 to 11.6	-21.9 to -13.1	14.6 to 22.0	19.8 to 28.4	43.2 to 47.3	22.4 to 26.7	1.2 to 374.1
24-hr	28.4	9.5	0.37 to 0.81	0.94 to 1.45	3.4 to 19.4	-22.1 to -13.0	13.5 to 22.1	16.3 to 24.3	43.3 to 47.3	14.0 to 15.7	16.0 to 94.6

[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).

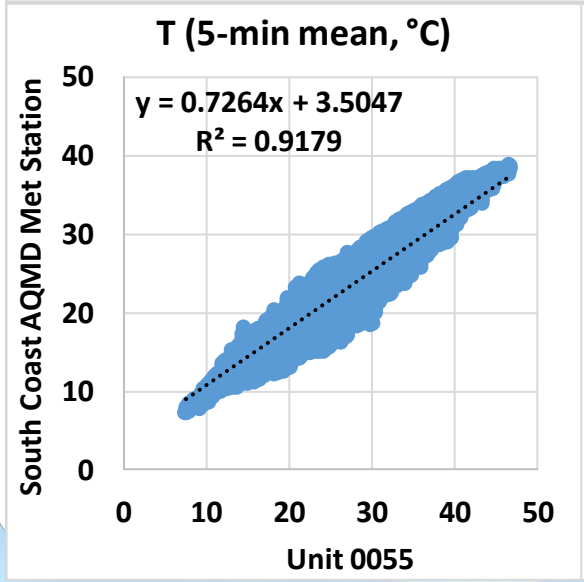
[2] Mean Absolute Error (MAE): the absolute difference between the sensors and the reference instruments. The larger MAE values, the higher measurement errors as compared to the reference instruments.

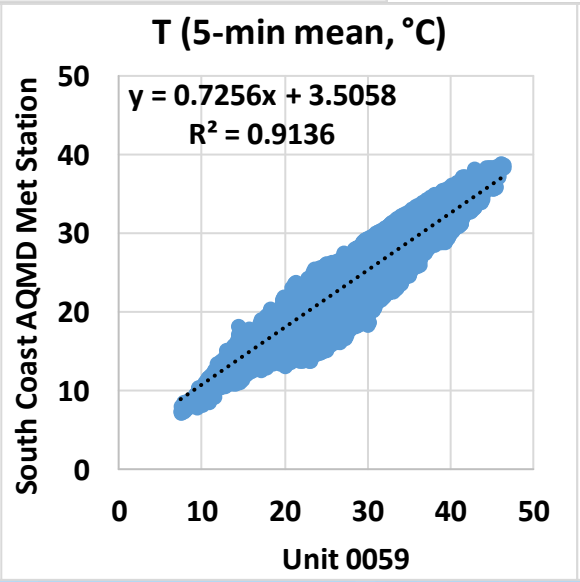
[3] Root Mean Square Error (RMSE): another metric to calculate measurement errors.

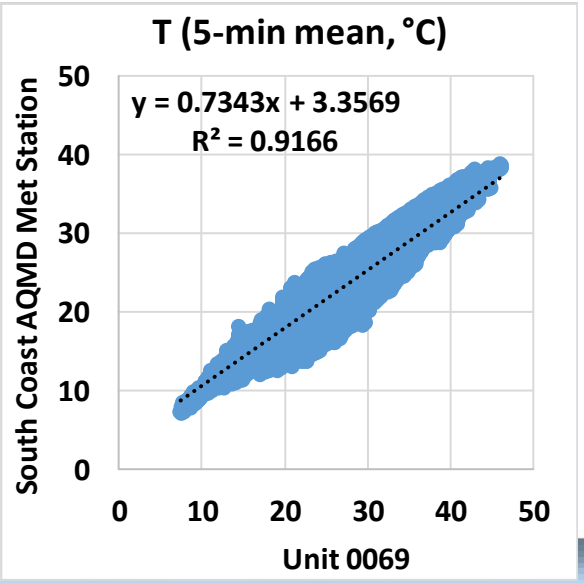
MODULAIR-PM vs South Coast AQMD Met Station (Temp; 5-min mean)



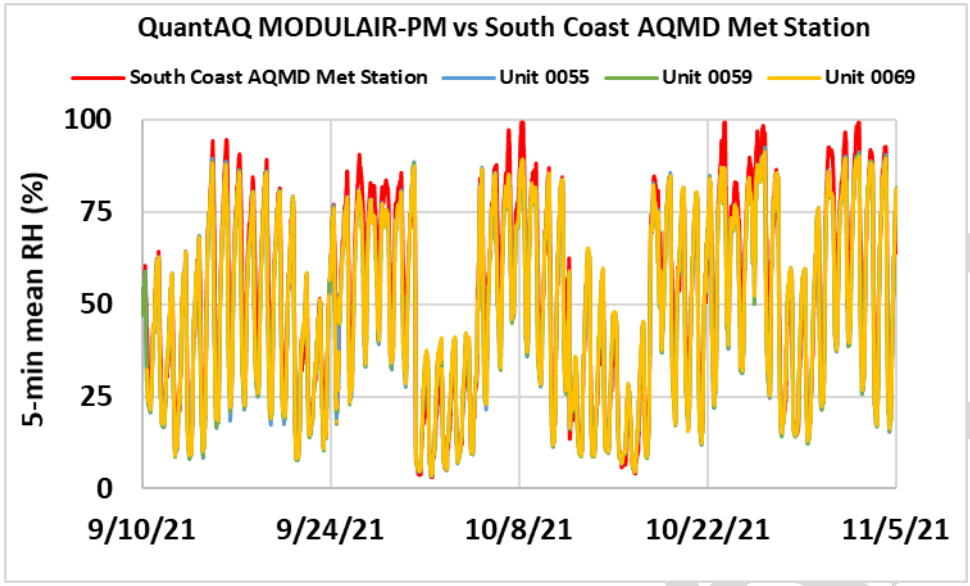
- The MODULAIR-PM sensors showed very strong correlations with the corresponding South Coast AQMD Met Station data (R^2 ~ 0.92)
- Overall, the MODULAIR-PM sensors overestimated the temperature measurement as recorded by South Coast AQMD Met Station
- The MODULAIR-PM sensors seemed to track the diurnal temperature variations as recorded by South Coast AQMD Met Station



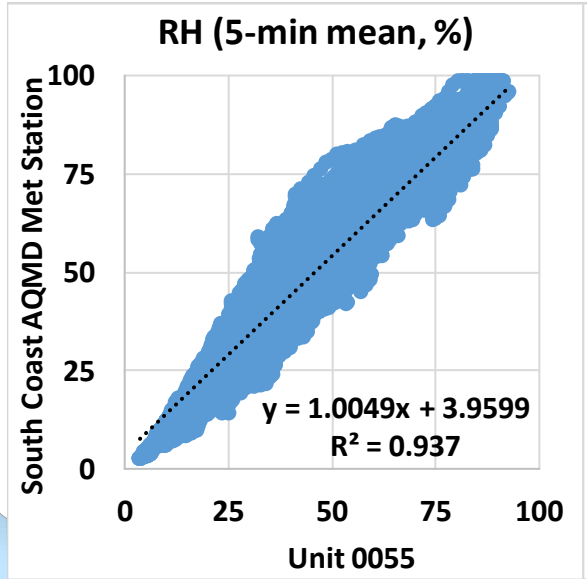


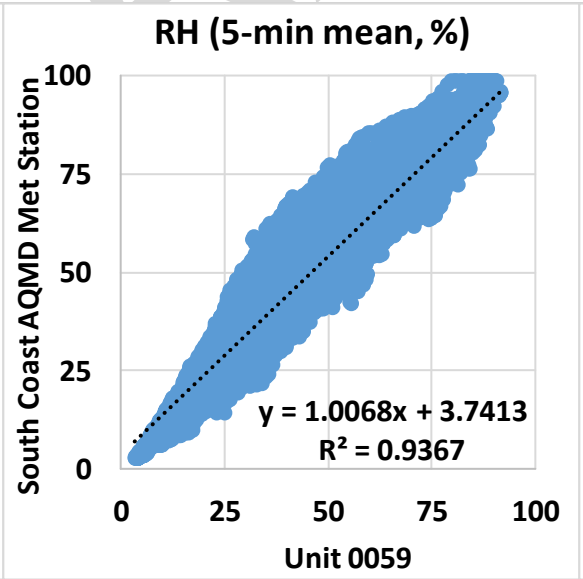


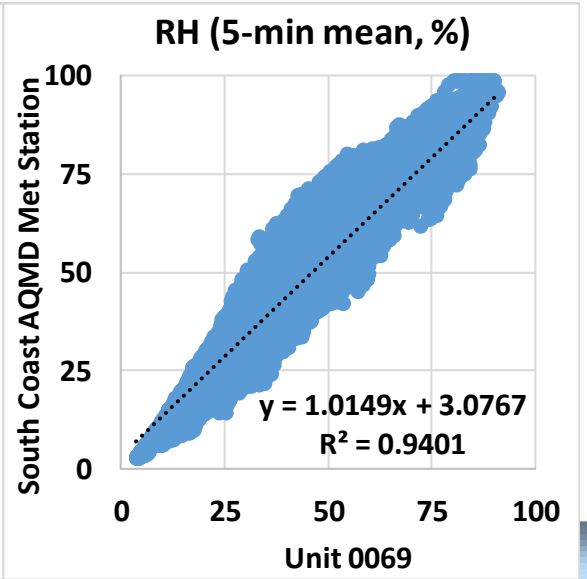
MODULAIR-PM vs South Coast AQMD Met Station (RH; 5-min mean)



- The MODULAIR-PM sensors showed very strong correlations with the corresponding South Coast AQMD Met Station data (R^2 ~ 0.94)
- Overall, the MODULAIR-PM sensors underestimated the RH measurement as recorded by South Coast AQMD Met Station
- The MODULAIR-PM sensors seemed to track the diurnal RH variations as recorded by South Coast AQMD Met Station







Discussion

- The three **MODULAIR-PM** sensors' data recovery from all units was ~ 100% for all PM measurements
- The absolute intra-model variability was ~ 0.59, 0.62 and 1.77 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 ~ 0.93, 1-hr mean); very strong correlations between FEM GRIMM and FEM T640 for $PM_{2.5}$ (R^2 ~ 0.91, 1-hr mean) and very strong correlations between GRIMM and T640 for PM_{10} (R^2 ~ 0.90, 1-hr mean) mass concentration measurements
- $PM_{1.0}$ mass concentrations measured by the MODULAIR-PM sensors showed strong to very strong correlations with the corresponding GRIMM and T640 data ($0.87 < R^2 < 0.95$, 1-hr mean). The sensors overestimated $PM_{1.0}$ mass concentrations as measured by GRIMM and T640
- $PM_{2.5}$ mass concentrations measured by the MODULAIR-PM sensors showed strong correlations with the corresponding FEM GRIMM and FEM T640 data ($0.84 < R^2 < 0.90$, 1-hr mean). The sensors overestimated $PM_{2.5}$ mass concentrations as measured by FEM GRIMM and FEM T640
- PM_{10} mass concentrations measured by the MODULAIR-PM sensors showed weak to strong correlations with the corresponding GRIMM and T640 data ($0.47 < R^2 < 0.80$; 1-hr mean). The sensors underestimated PM_{10} mass concentrations as measured by GRIMM and T640
- 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