

Field Evaluation Sensirion Nubo Air



Background

- From 02/13/2021 to 04/14/2021, three **Sensirion Nubo Monitor One (NMO-LTE)** sensors (hereinafter **Sensirion Nubo Air**) 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
- Sensirion Nubo Air (3 units tested):
 - Particle sensor: **optical; non-FEM (dual Sensirion SPS30)**
 - Each unit reports: PM_{1.0} and PM_{2.5} (µg/m³), temperature (°C), RH (%), pressure (hPa) and dew point (°C)
 - **Unit cost: \$1700 per unit (includes 12 months subscription)**
 - Time resolution: 5-min (1-min data can be accessed via API)
 - Units IDs: 1523, 1833, 3127
 - Key differences between the two generations of Sensirion Nubo sensors (1st generation: Sensirion Nubo; 2nd generation: Sensirion Nubo Air):
 - Cartridge system: for easy maintenance, future upgrade with more parameters and modular parameter selection
 - Battery and data buffer to increase data availability
 - Solar option
 - Improved weatherproofing
 - Further improved design for T and RH measurements
 - Pressure parameter added
- GRIMM (reference instrument):
 - Optical particle counter (**FEM PM_{2.5}**)
 - Measures PM_{1.0}, PM_{2.5} and PM₁₀ (µg/m³)
 - **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 PM₁₀ (µg/m³)
 - **Unit cost: ~\$21,000**
 - Time resolution: 1-min
- Met station (T, RH, P, WS, WD), **cost: ~\$5,000**
 - Time resolution: 1-min

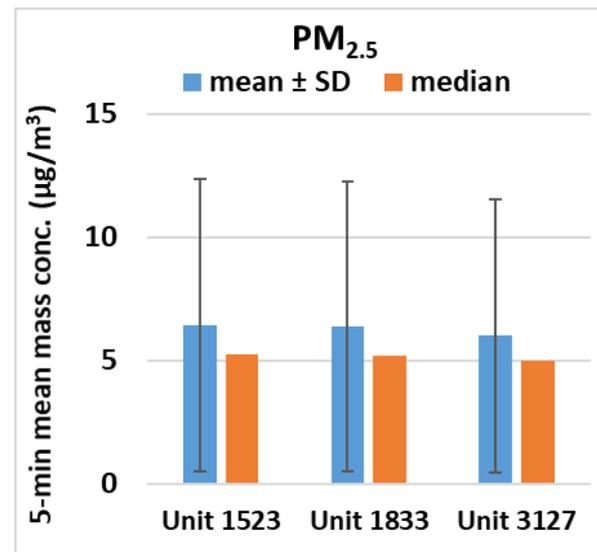
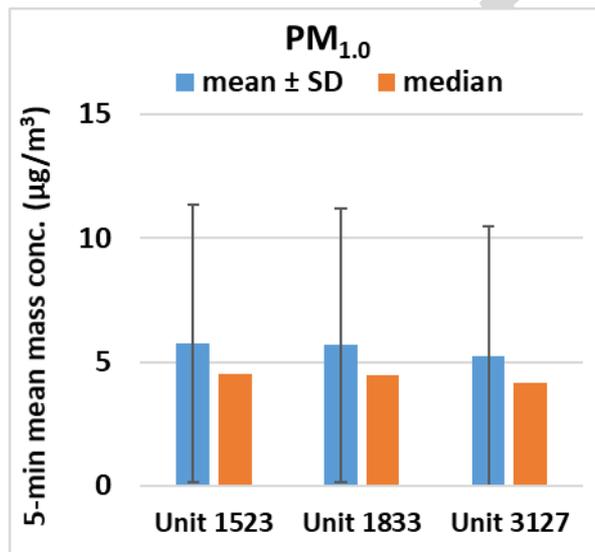


Data validation & recovery

- 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 units 1523, 1833 and 3127 was ~100%, 97% and 99% respectively, for PM_{1.0} and PM_{2.5} measurements

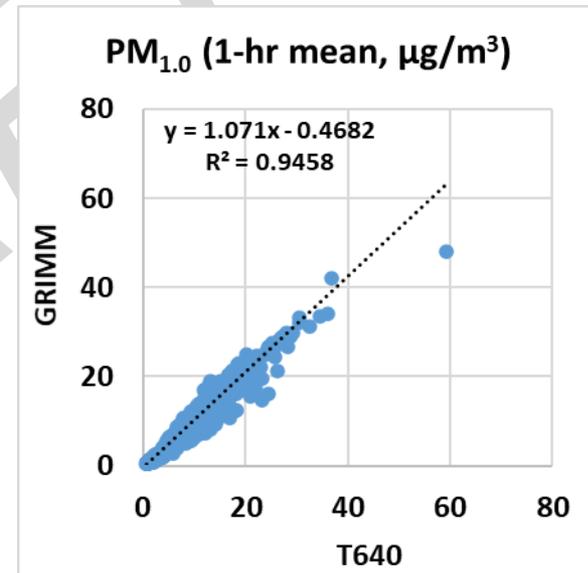
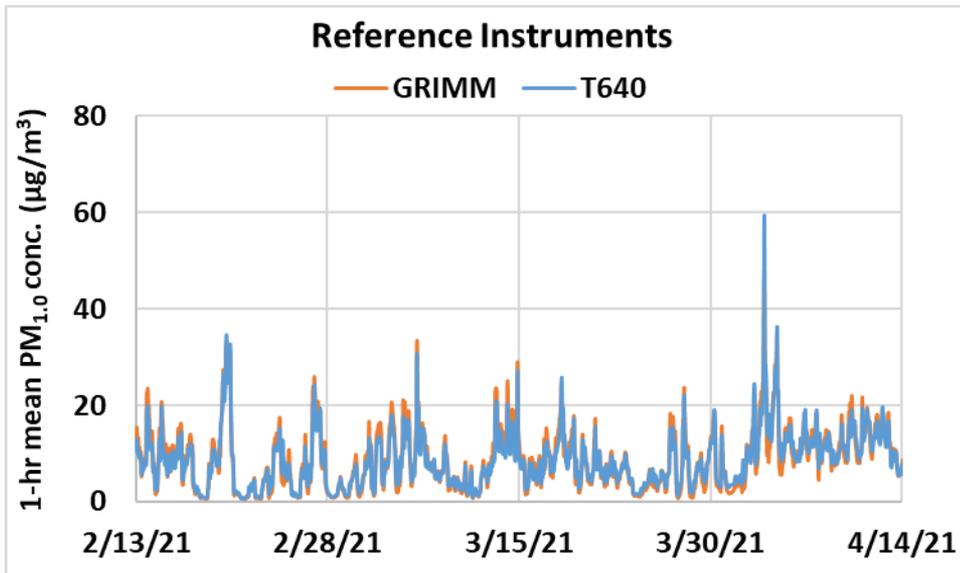
Sensirion Nubo Air; intra-model variability

- Absolute intra-model variability was ~ 0.23, and 0.20 $\mu\text{g}/\text{m}^3$ for PM_{1.0} and PM_{2.5}, respectively (calculated as the standard deviation of the three sensor means)
- Relative intra-model variability was ~ 4.2 % and 3.2 % for PM_{1.0} and PM_{2.5}, respectively (calculated as the absolute intra-model variability relative to the mean of the three sensor means)



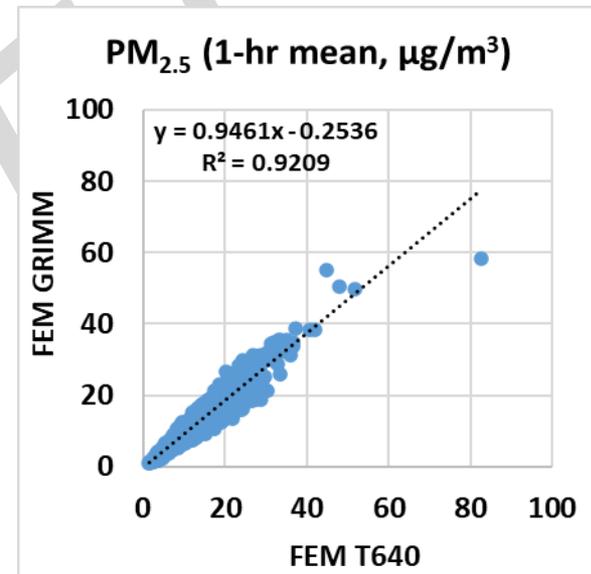
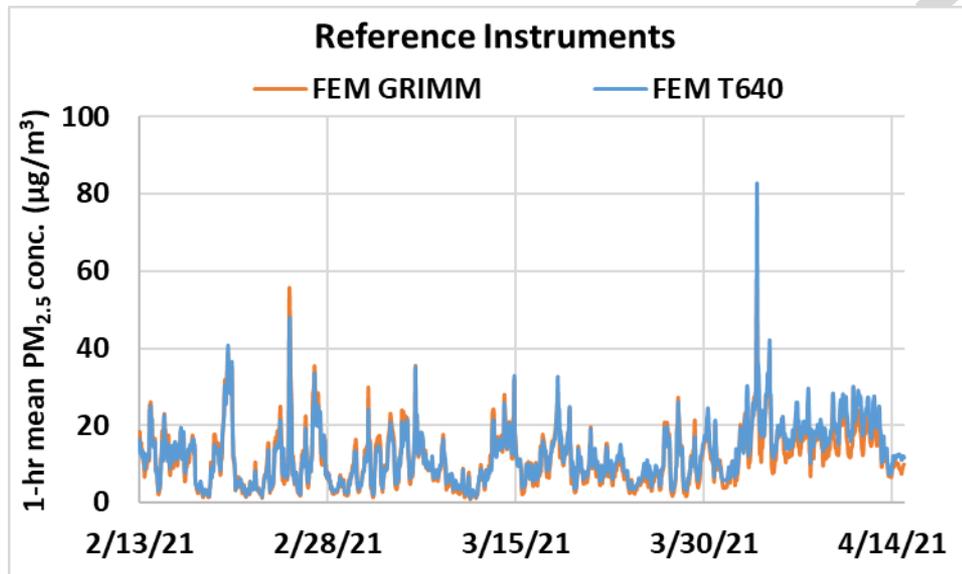
Reference Instruments: PM_{1.0} GRIMM & T640

- Data recovery from GRIMM and T640 was ~ 100% for PM_{1.0} measurements
- Very strong correlations between GRIMM and T640 for PM_{1.0} measurements ($R^2 \sim 0.95$) were observed

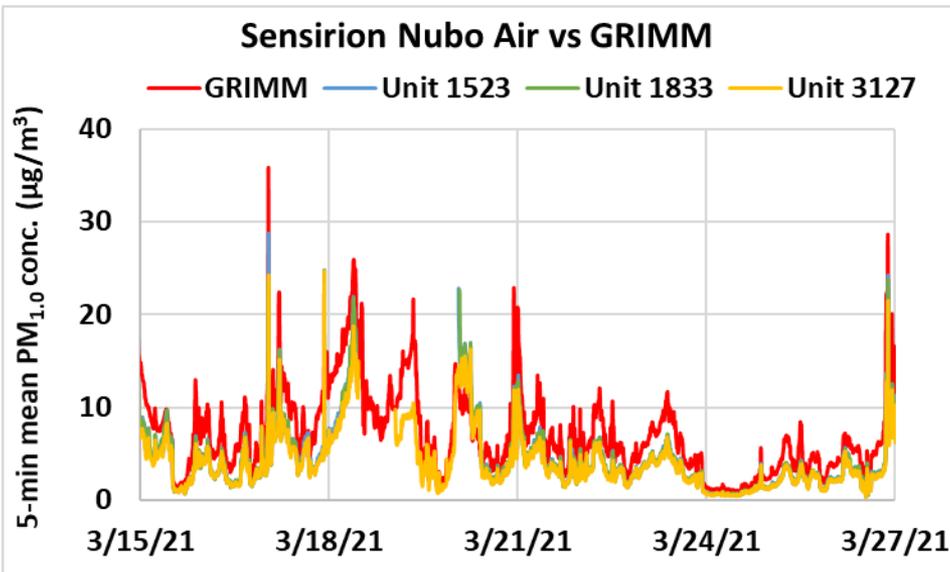


Reference Instruments: PM_{2.5} FEM GRIMM & FEM T640

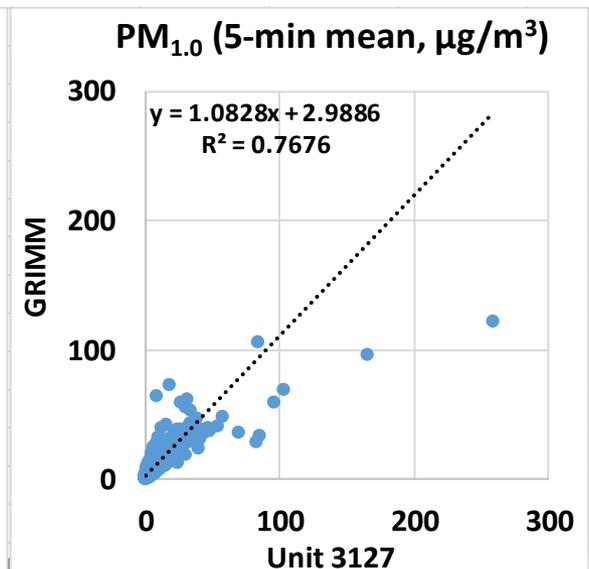
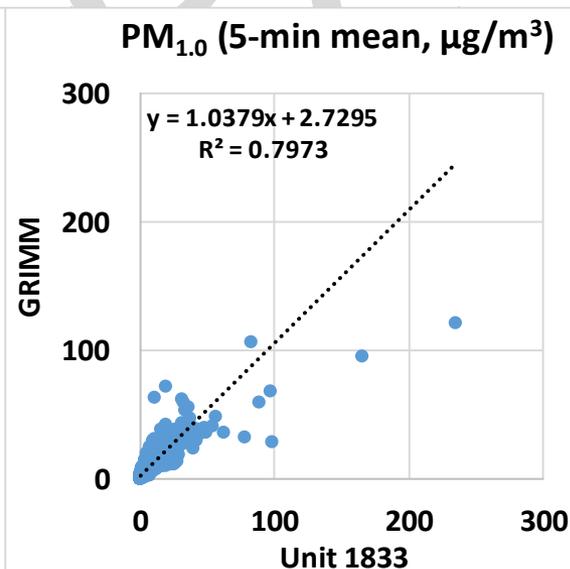
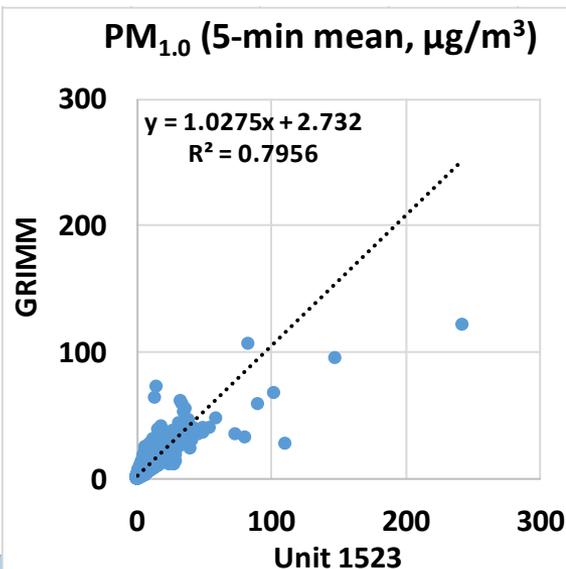
- Data recovery from FEM GRIMM and FEM T640 was ~ 100% for PM_{2.5} measurements
- Very strong correlations between FEM GRIMM and FEM T640 for PM_{2.5} measurements ($R^2 \sim 0.92$) were observed



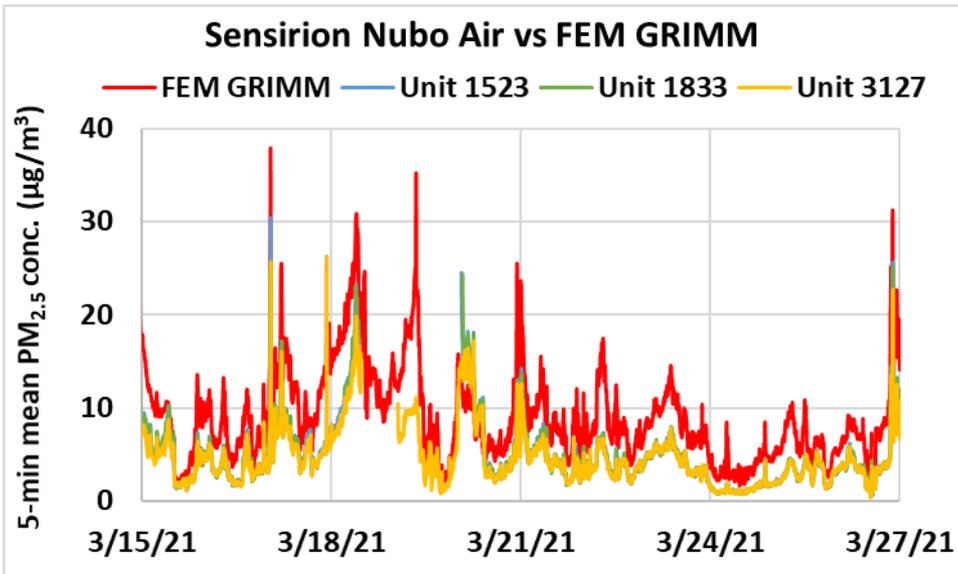
Sensirion Nubo Air vs GRIMM (PM_{1.0}; 5-min mean)



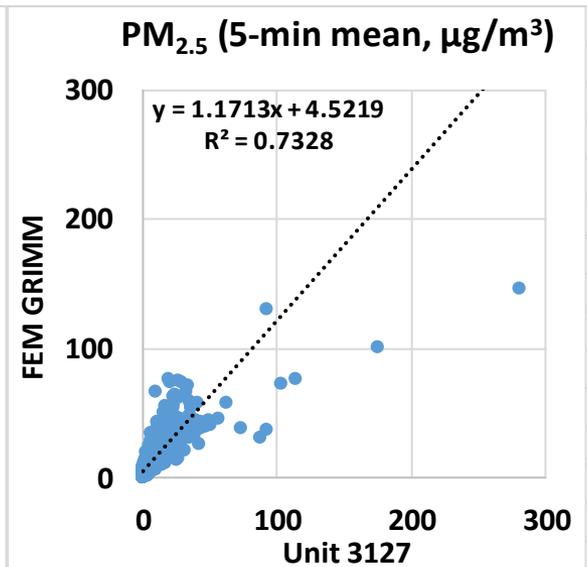
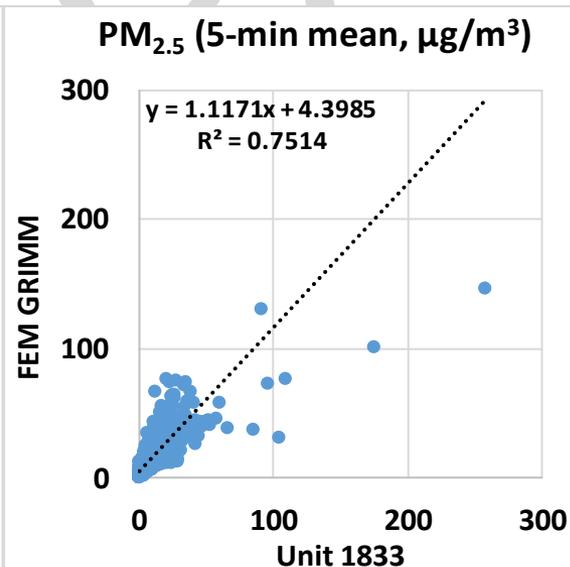
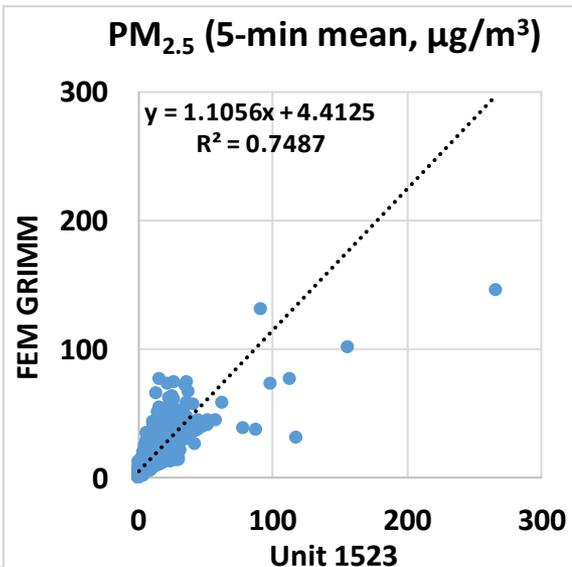
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding GRIMM data ($0.76 < R^2 < 0.80$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by GRIMM



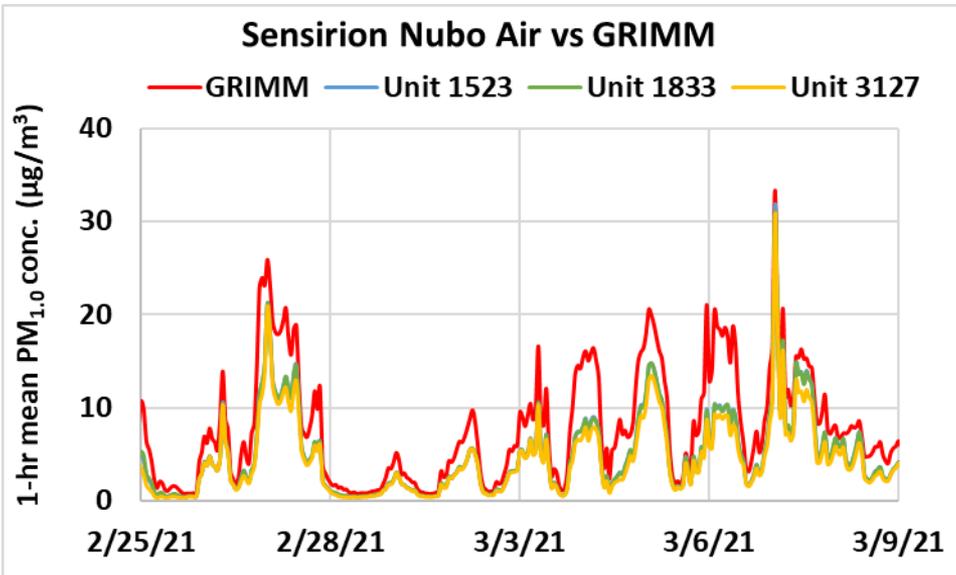
Sensirion Nubo Air vs FEM GRIMM (PM_{2.5}; 5-min mean)



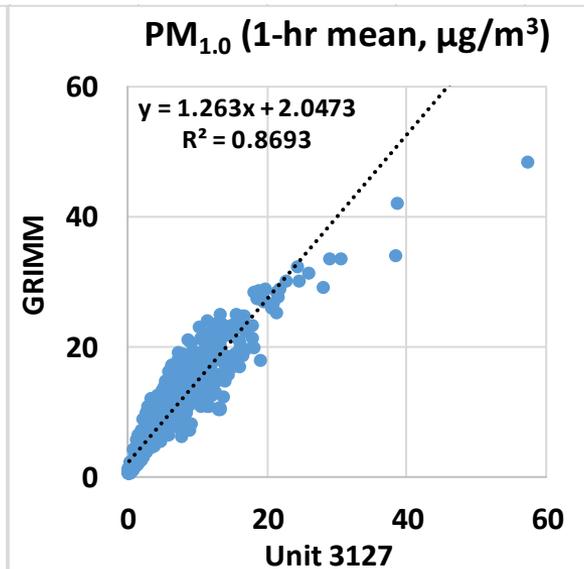
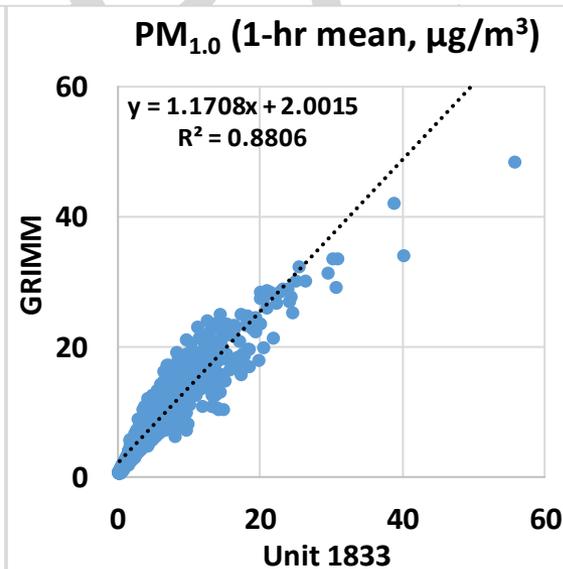
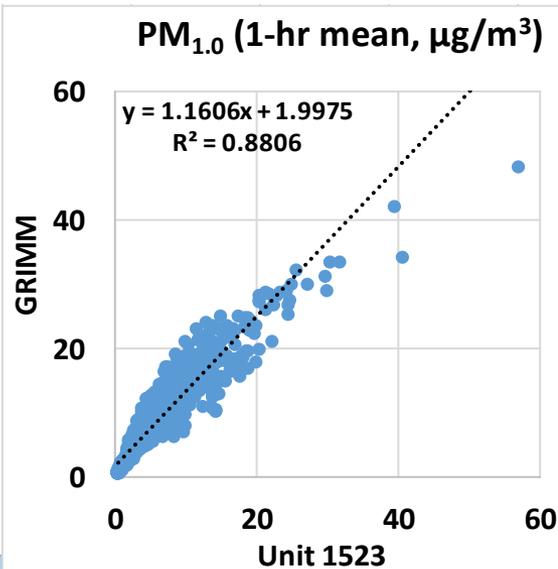
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM GRIMM data ($0.73 < R^2 < 0.76$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM GRIMM



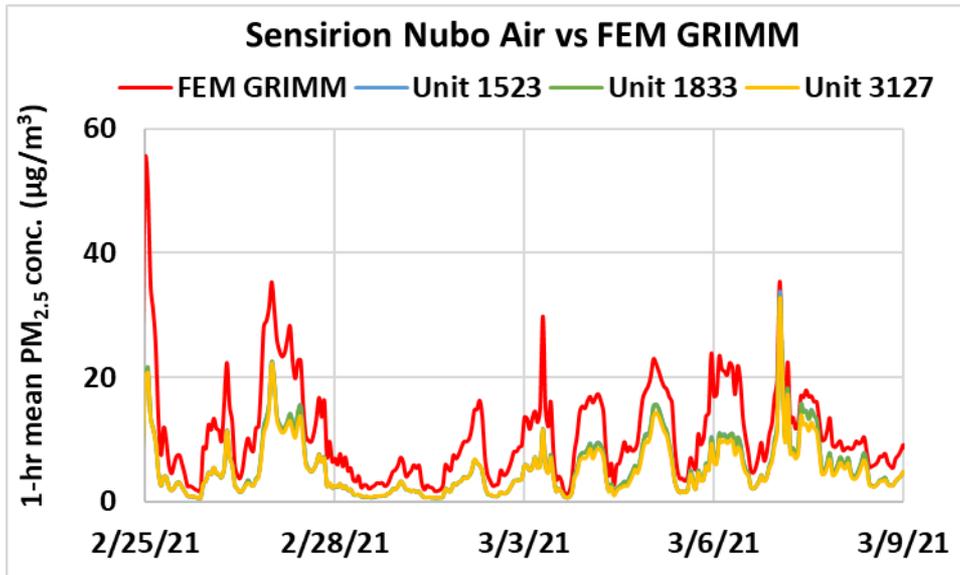
Sensirion Nubo Air vs GRIMM (PM_{1.0}; 1-hr mean)



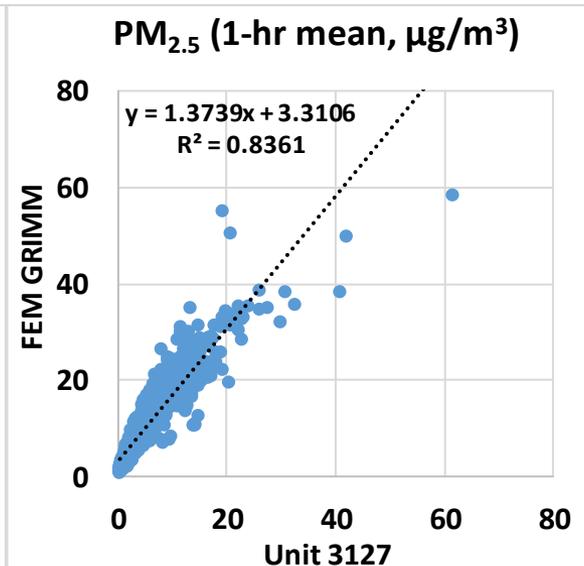
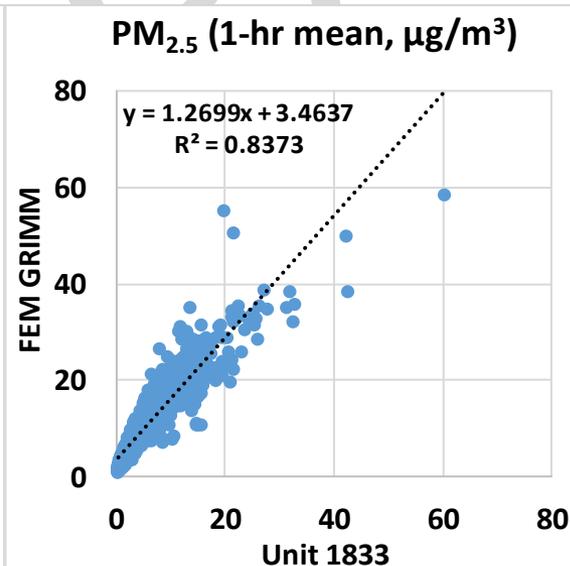
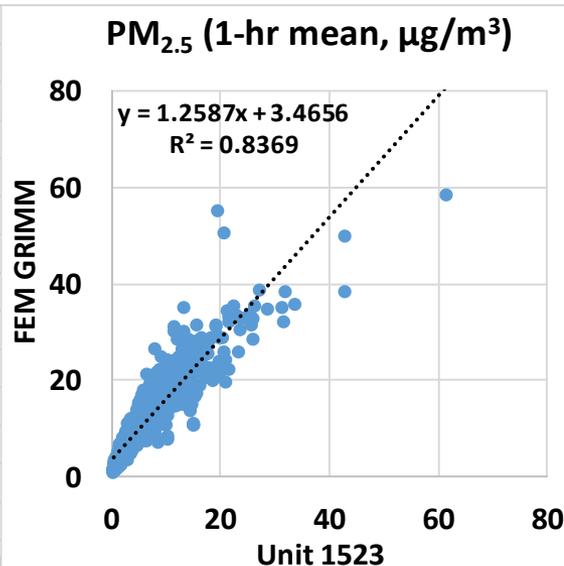
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding GRIMM data ($0.86 < R^2 < 0.89$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by GRIMM



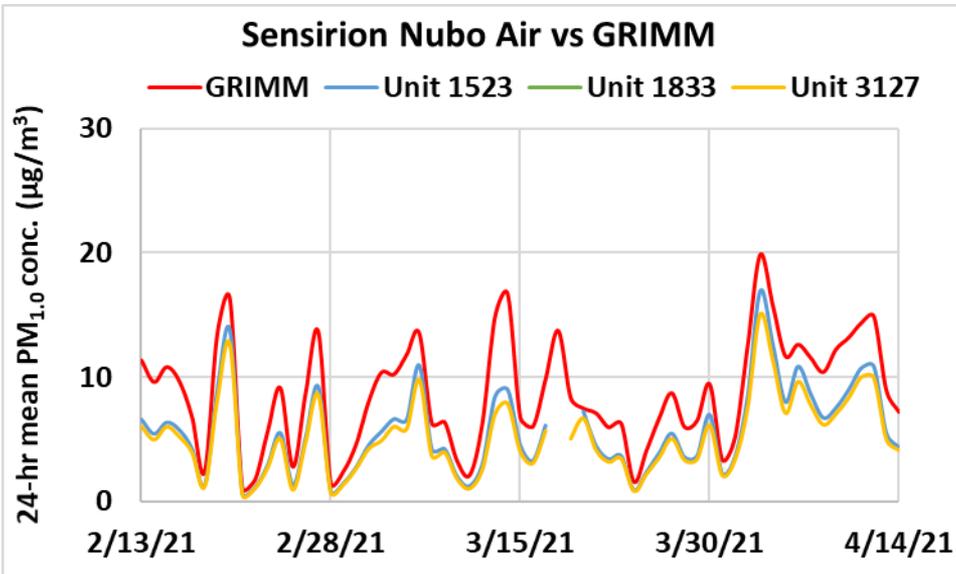
Sensirion Nubo Air vs FEM GRIMM (PM_{2.5}; 1-hr mean)



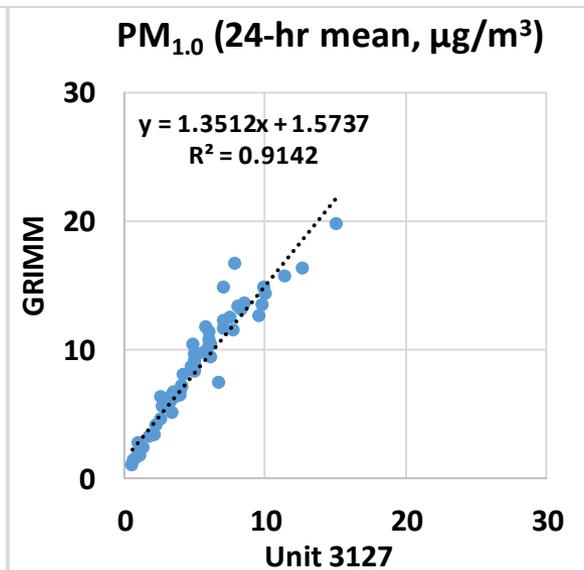
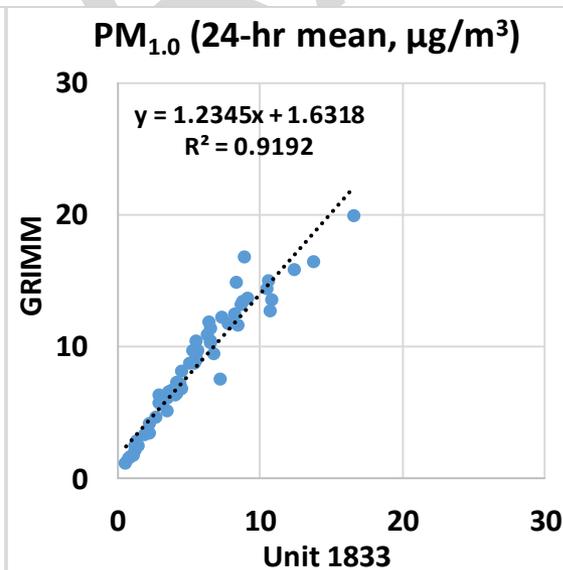
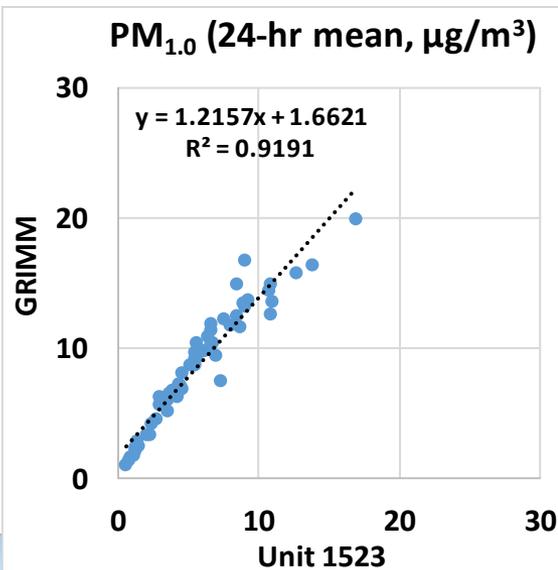
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM GRIMM data ($0.83 < R^2 < 0.84$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM GRIMM



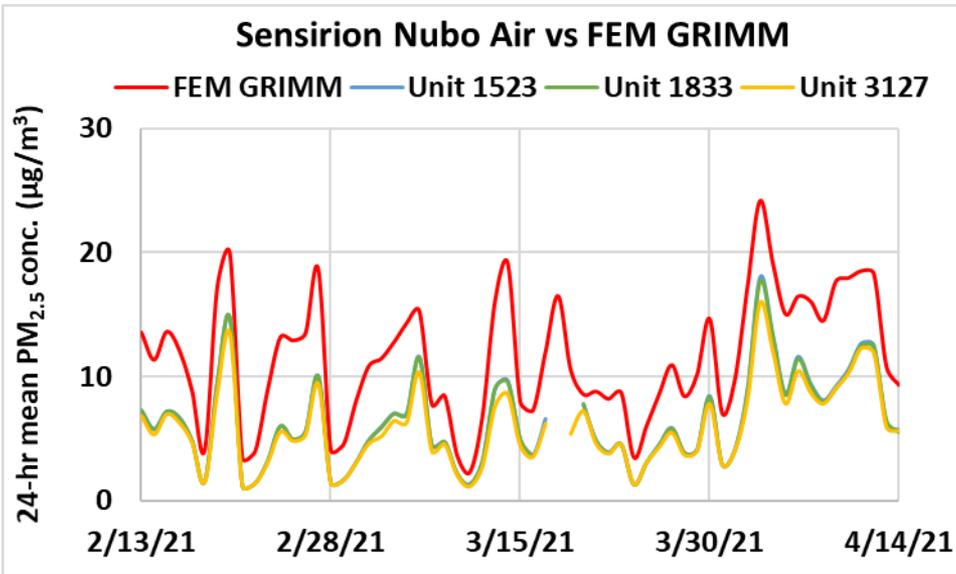
Sensirion Nubo Air vs GRIMM (PM_{1.0}; 24-hr mean)



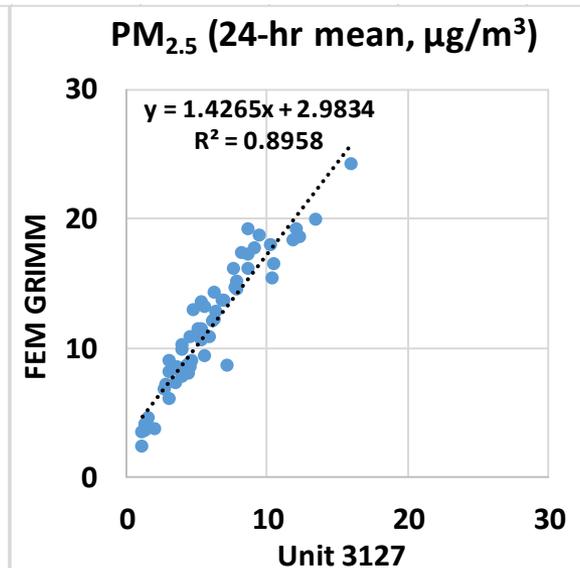
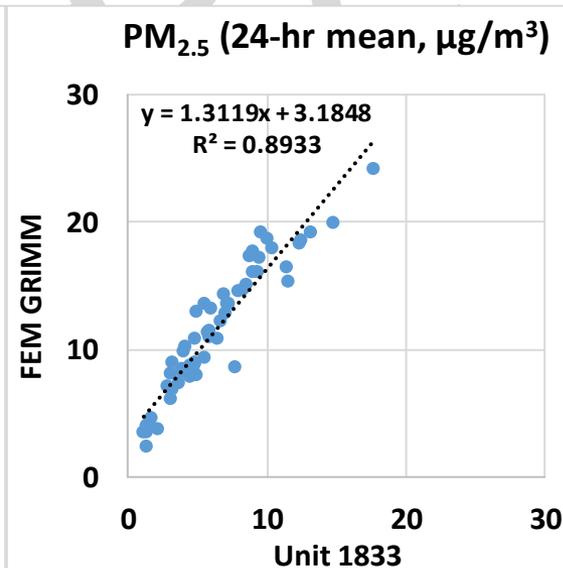
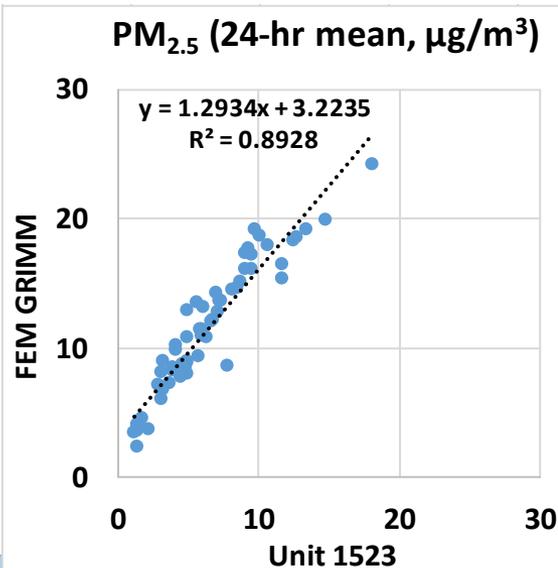
- The Sensirion Nubo Air sensors showed very strong correlations with the corresponding GRIMM data ($0.91 < R^2 < 0.92$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by GRIMM



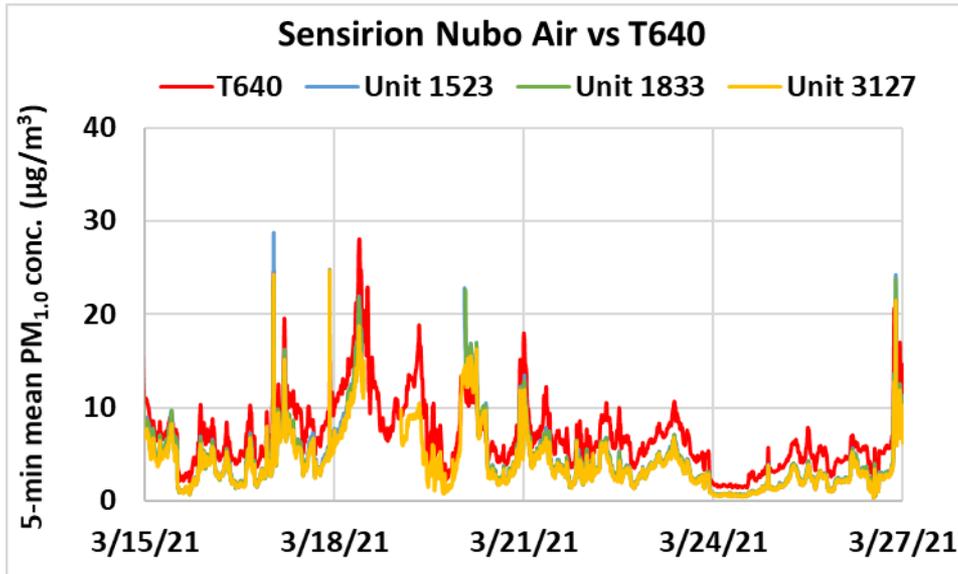
Sensirion Nubo Air vs FEM GRIMM (PM_{2.5}; 24-hr mean)



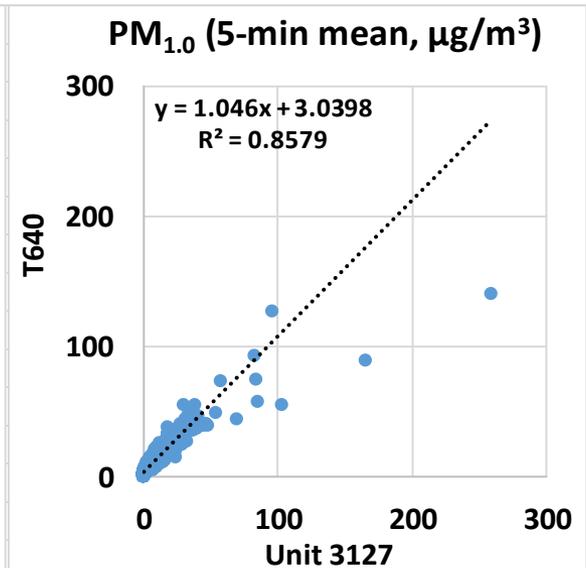
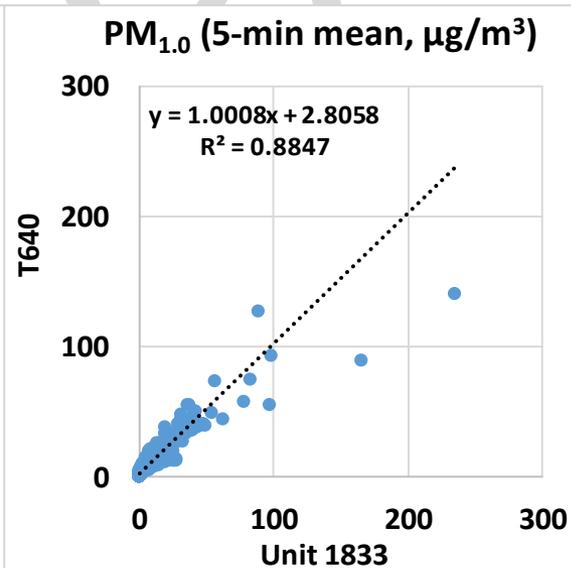
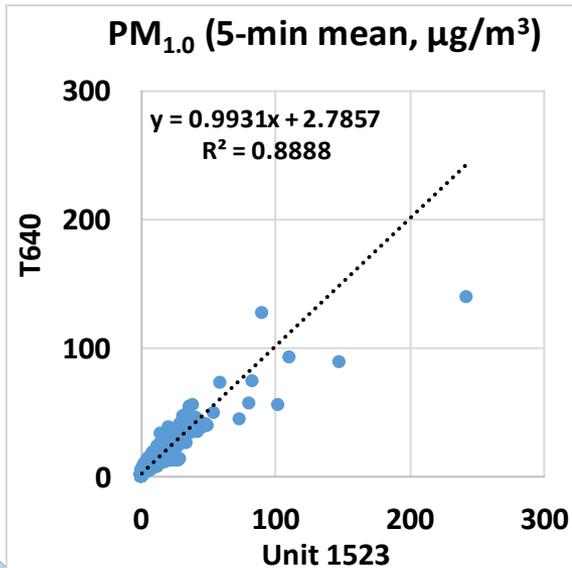
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM GRIMM data ($0.89 < R^2 < 0.90$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM GRIMM
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM GRIMM



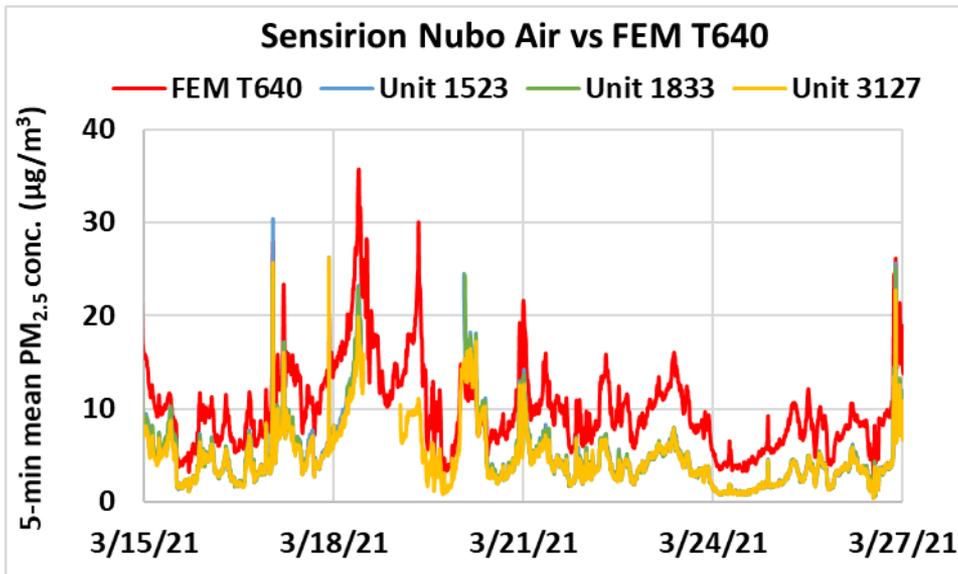
Sensirion Nubo Air vs T640 (PM_{1.0}; 5-min mean)



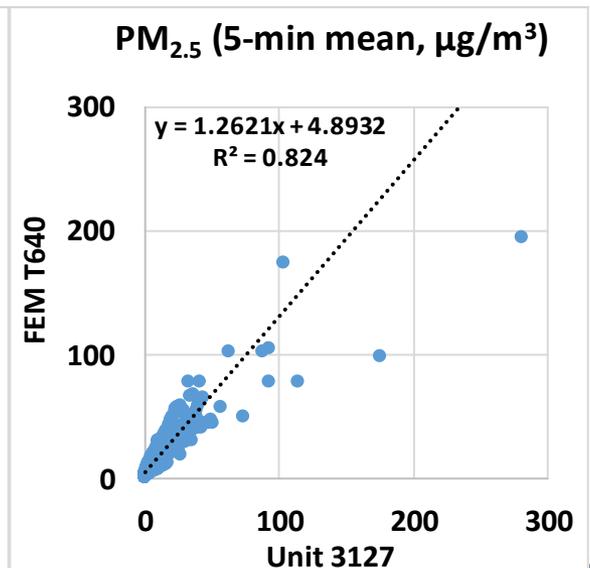
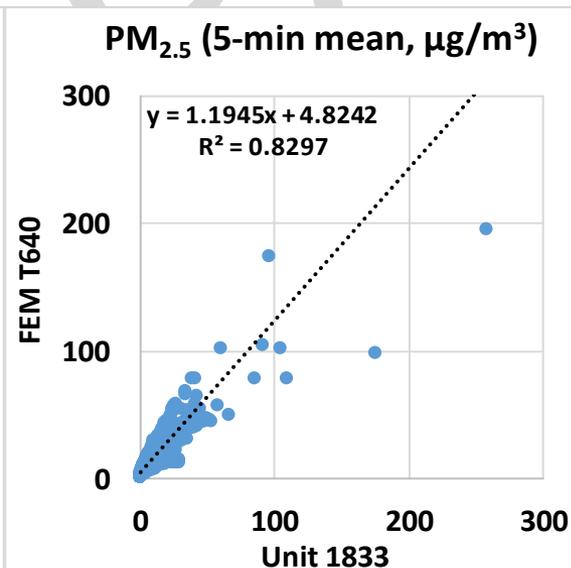
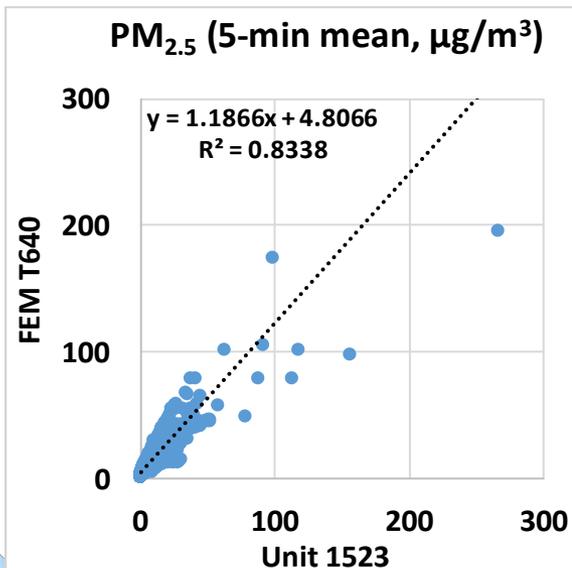
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding T640 data ($0.85 < R^2 < 0.89$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by T640
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by T640



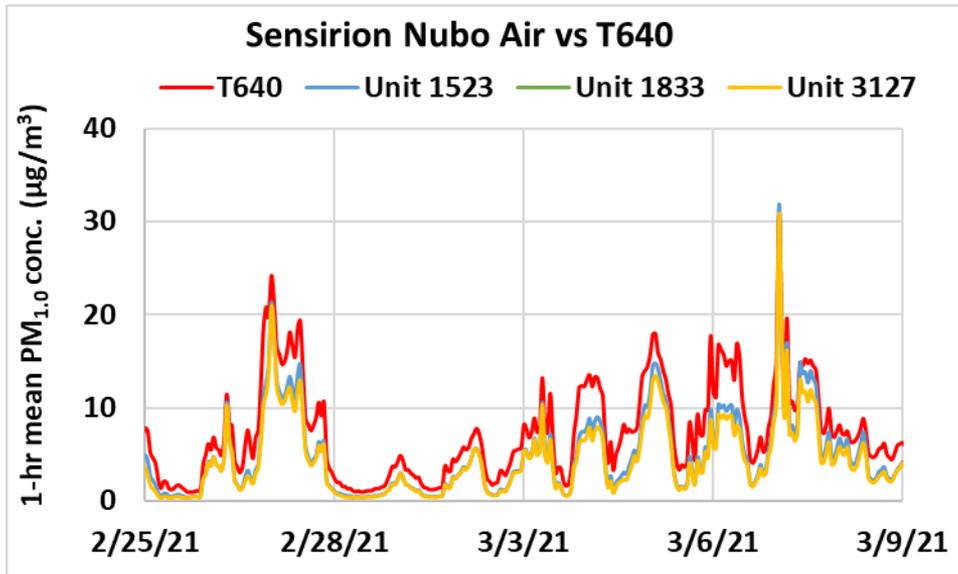
Sensirion Nubo Air vs FEM T640 (PM_{2.5}; 5-min mean)



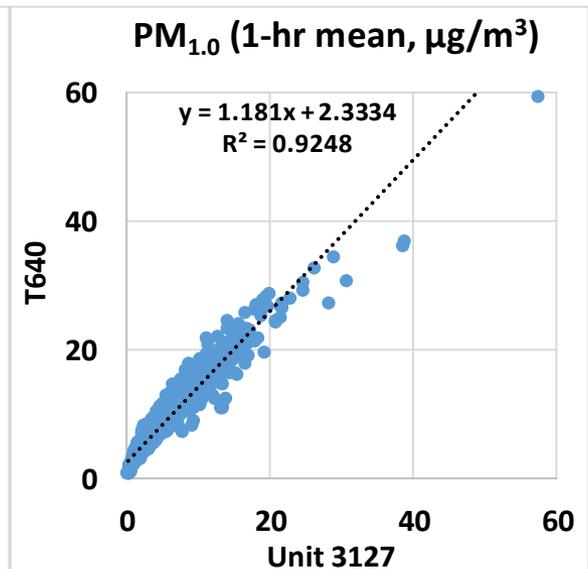
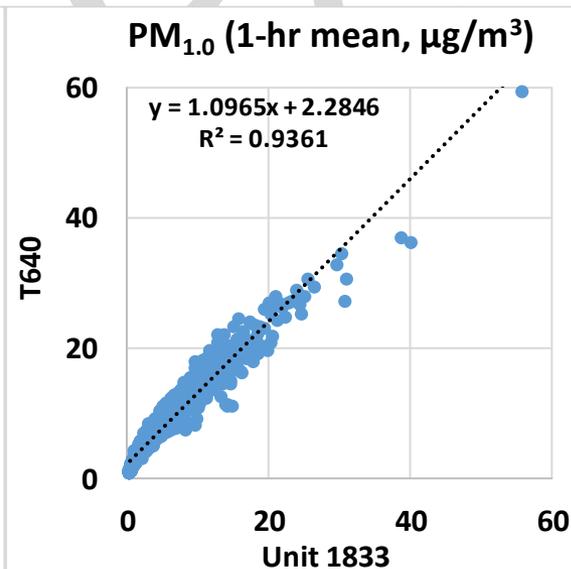
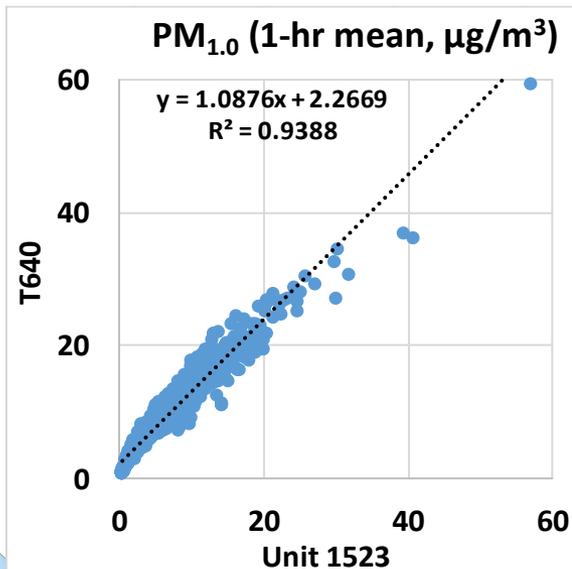
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM T640 data ($0.82 < R^2 < 0.84$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM T640
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM T640



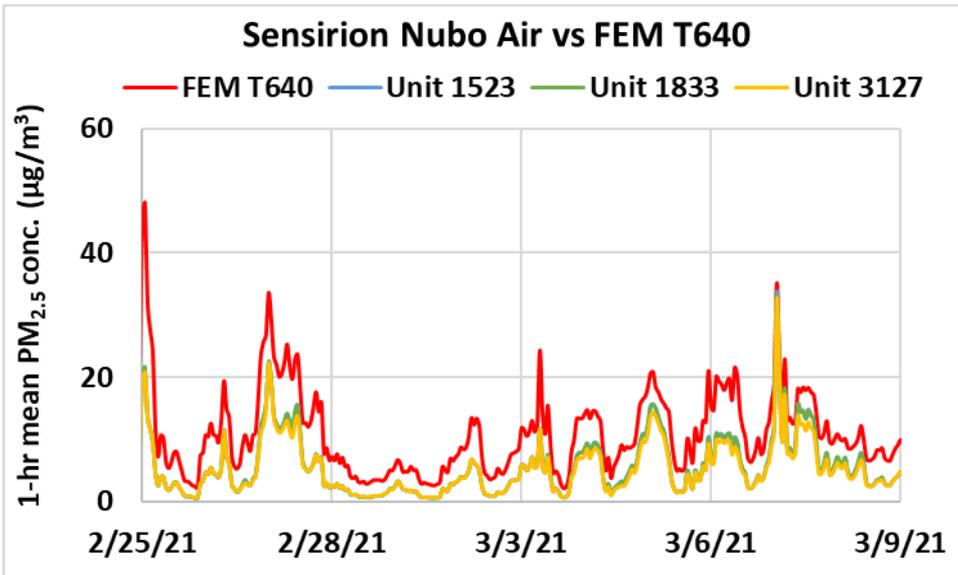
Sensirion Nubo Air vs T640 (PM_{1.0}; 1-hr mean)



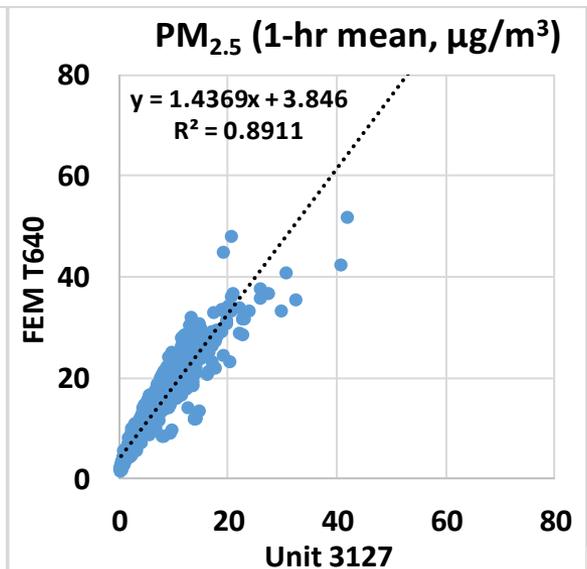
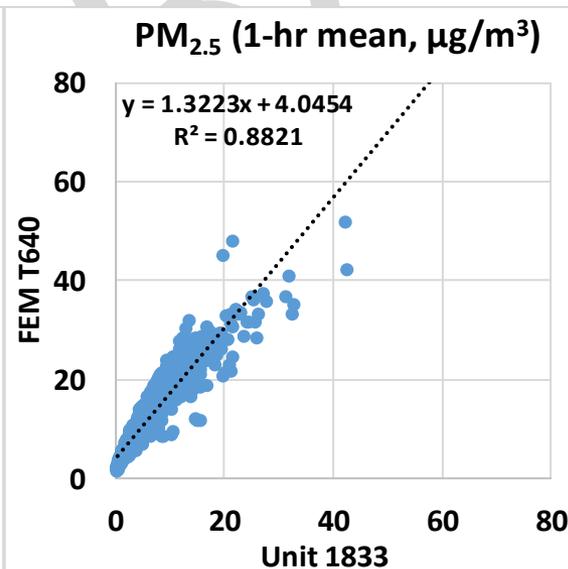
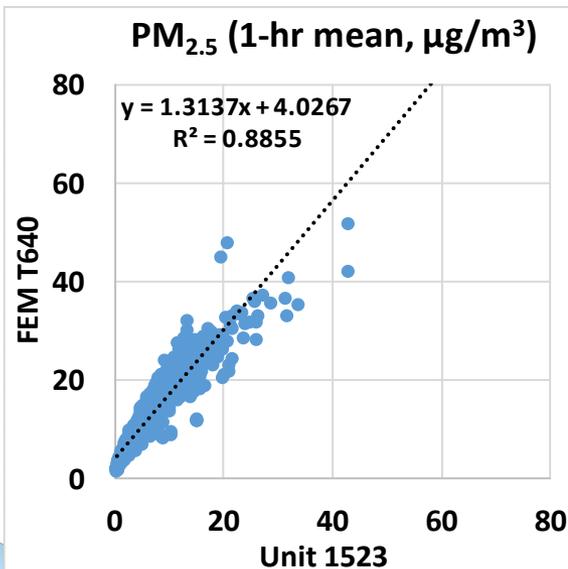
- The Sensirion Nubo Air sensors showed very strong correlations with the corresponding T640 data ($0.92 < R^2 < 0.94$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by T640
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by T640



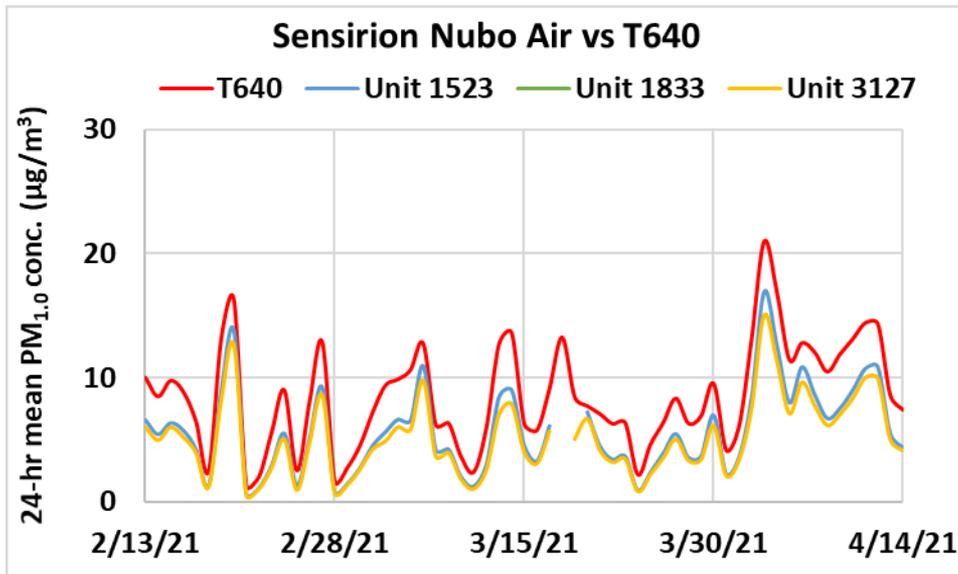
Sensirion Nubo Air vs FEM T640 (PM_{2.5}; 1-hr mean)



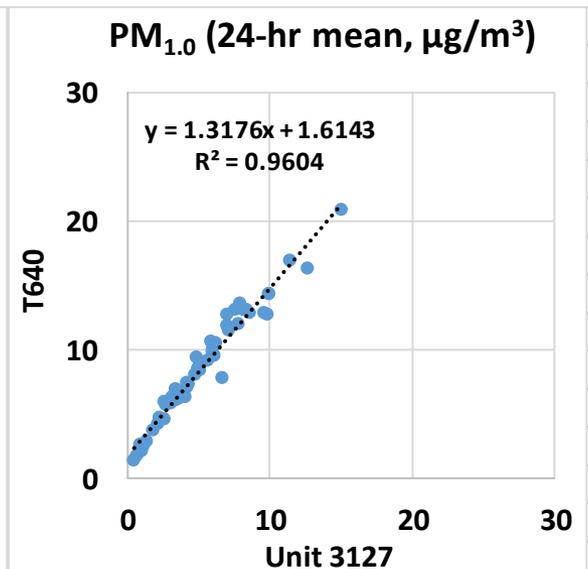
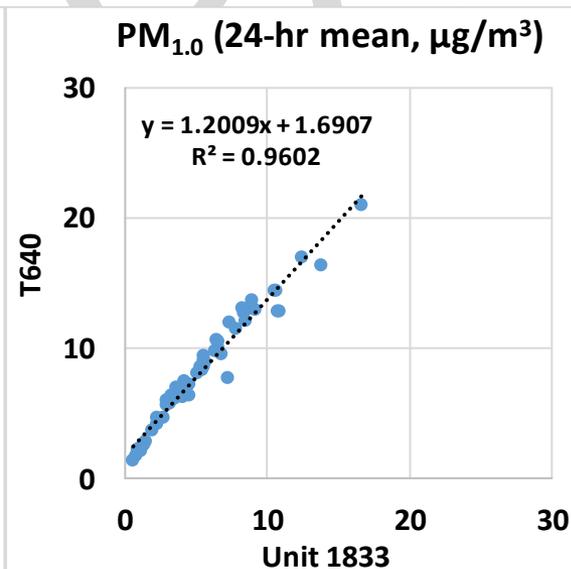
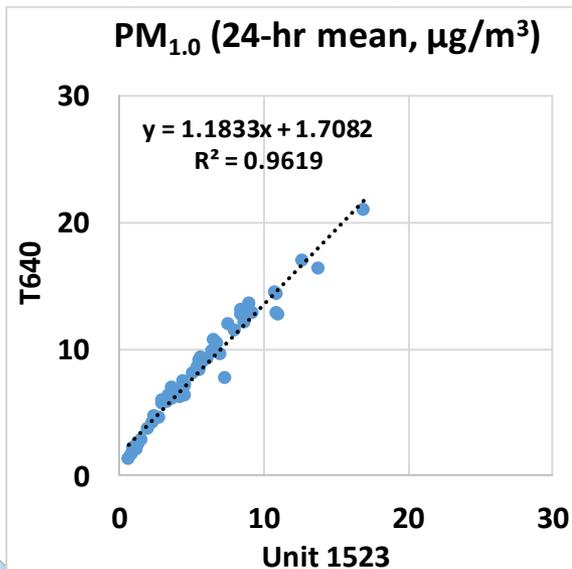
- The Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM T640 data ($0.88 < R^2 < 0.90$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM T640
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM T640



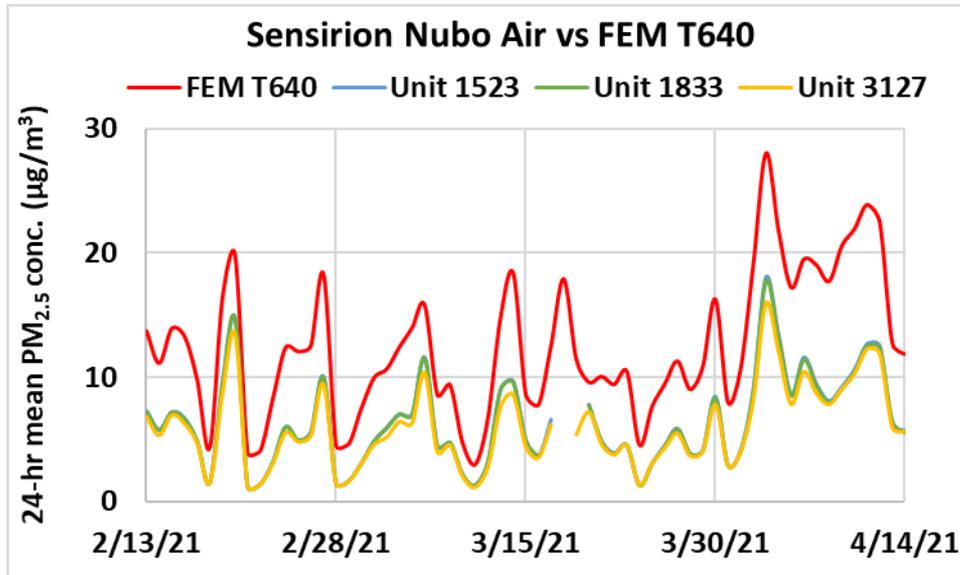
Sensirion Nubo Air vs T640 (PM_{1.0}; 24-hr mean)



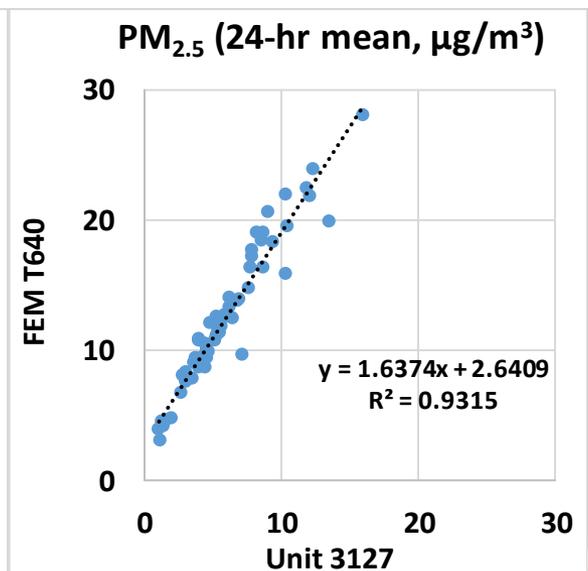
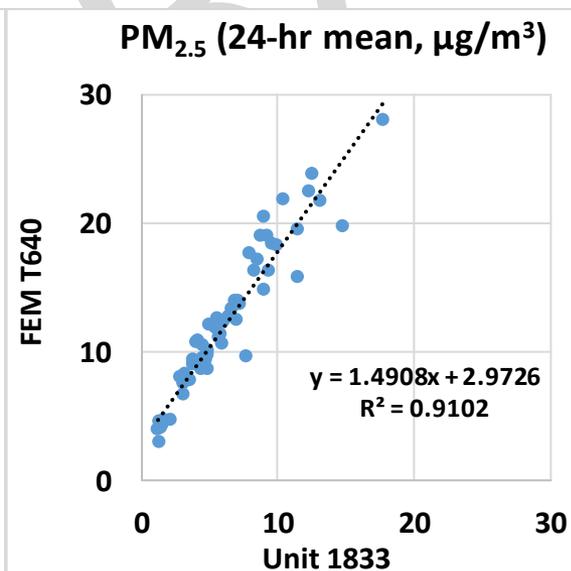
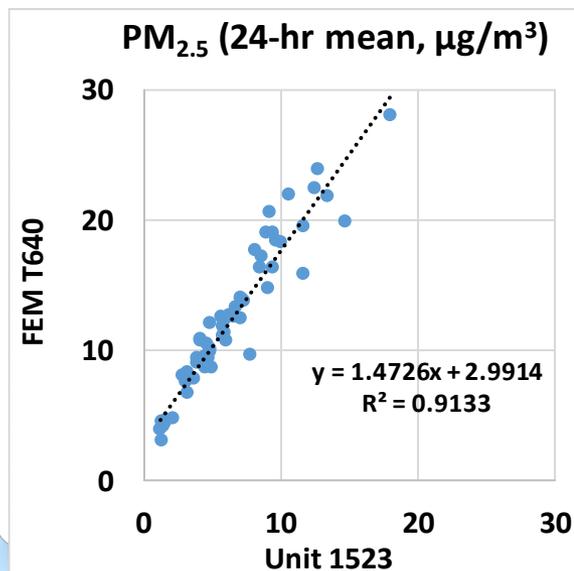
- The Sensirion Nubo Air sensors showed very strong correlations with the corresponding T640 data ($0.96 < R^2 < 0.97$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{1.0} mass concentrations as measured by T640
- The Sensirion Nubo Air sensors seemed to track the PM_{1.0} diurnal variations as recorded by T640



Sensirion Nubo Air vs FEM T640 (PM_{2.5}; 24-hr mean)



- The Sensirion Nubo Air sensors showed very strong correlations with the corresponding FEM T640 data ($0.91 < R^2 < 0.94$)
- Overall, the Sensirion Nubo Air sensors underestimated the PM_{2.5} mass concentrations as measured by FEM T640
- The Sensirion Nubo Air sensors seemed to track the PM_{2.5} diurnal variations as recorded by FEM T640



Summary

	Average of 3 Sensors, PM _{1.0}		Sensirion Nubo Air vs GRIMM & T640, PM _{1.0}						GRIMM & 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	5.56	5.44	0.77 to 0.89	0.99 to 1.08	2.7 to 3.0	-3.4 to -2.8	2.9 to 3.5	3.4 to 4.6	8.5 to 8.7	5.9 to 6.4	0.4 to 139.9
1-hr	5.54	4.86	0.87 to 0.94	1.09 to 1.26	2.0 to 2.3	-3.4 to -2.8	2.8 to 3.5	3.1 to 4.3	8.5 to 8.7	5.6 to 6.2	0.4 to 59.2
24-hr	5.50	3.33	0.91 to 0.96	1.18 to 1.35	1.6 to 1.7	-3.4 to -2.8	2.8 to 3.4	2.9 to 3.8	8.5 to 8.7	4.2 to 4.4	1.0 to 21.0

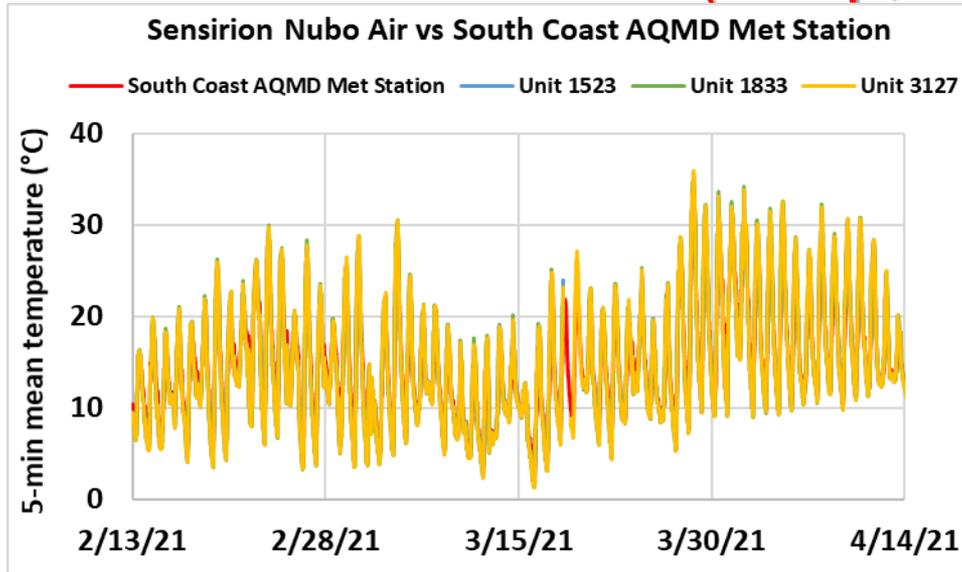
	Average of 3 Sensors, PM _{2.5}		Sensirion Nubo Air vs FEM GRIMM & FEM T640, PM _{2.5}						FEM GRIMM & FEM T640 (PM _{2.5} , µg/m ³)		
	Average (µg/m ³)	SD (µg/m ³)	R ²	Slope	Intercept	MBE ¹ (µg/m ³)	MAE ² (µg/m ³)	RMSE ³ (µg/m ³)	Ref. Average	Ref. SD	Range during the field evaluation
5-min	6.29	5.77	0.73 to 0.83	1.11 to 1.26	4.4 to 4.9	-6.5 to -5.1	5.2 to 6.5	6.4 to 7.4	11.6 to 12.5	7.5 to 7.7	0.7 to 195.3
1-hr	6.26	5.14	0.84 to 0.89	1.26 to 1.44	3.3 to 4.0	-6.5 to -5.1	5.2 to 6.5	6.1 to 7.2	11.6 to 12.5	7.3 to 7.4	0.8 to 82.6
24-hr	6.23	3.53	0.89 to 0.93	1.29 to 1.64	2.6 to 3.2	-6.4 to -5.1	5.1 to 6.4	5.5 to 6.9	11.6 to 12.5	5.0 to 5.6	2.3 to 28.0

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).

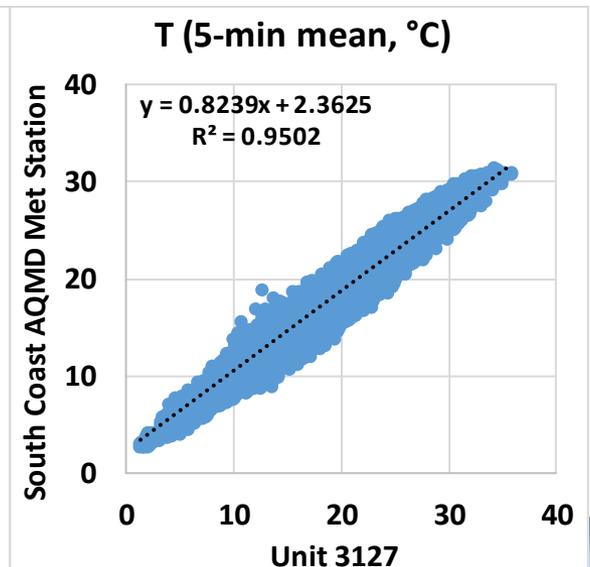
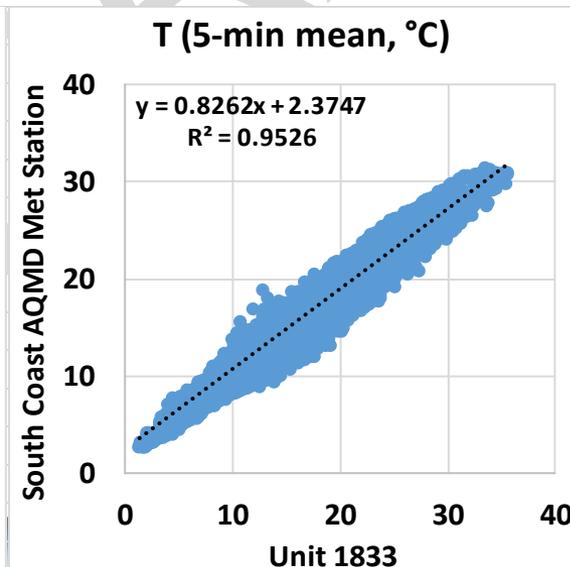
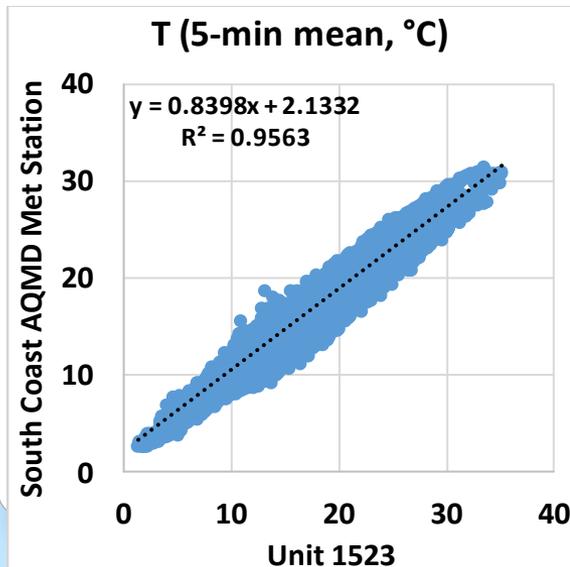
² Mean Absolute Error (MAE): the absolute difference between the sensors and the reference instruments. The larger MAE values, the higher measurement errors as compared to the reference instruments.

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

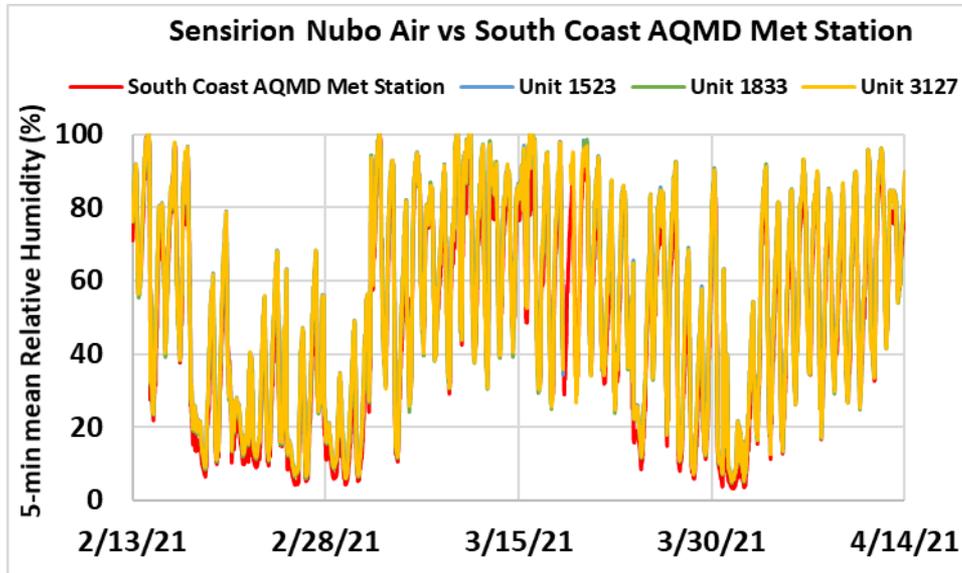
Sensirion Nubo Air vs South Coast AQMD Met Station (Temp; 5-min mean)



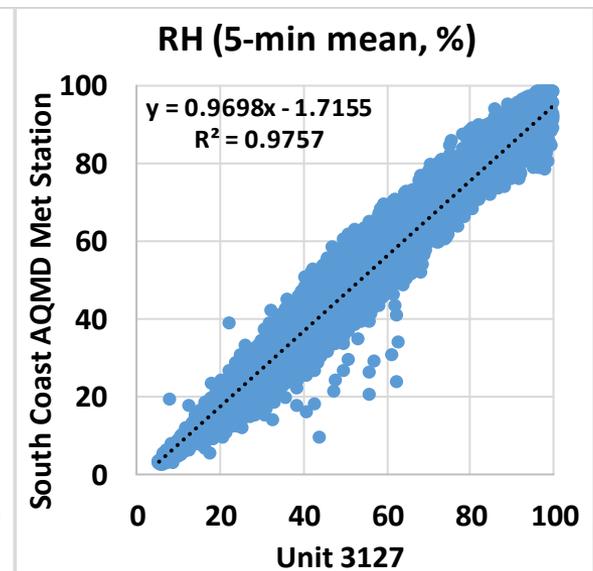
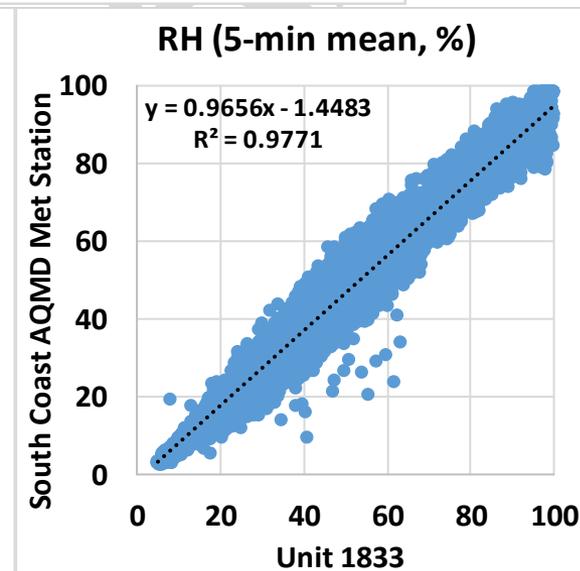
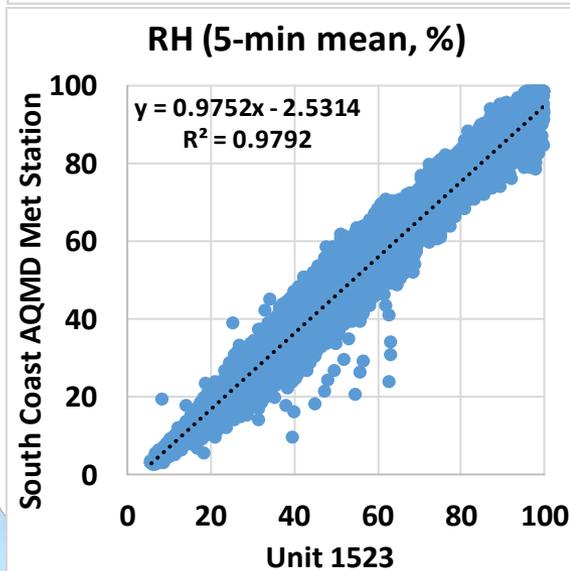
- Sensirion Nubo Air temperature measurements showed very strong correlations with the corresponding South Coast AQMD Met Station data ($R^2 \sim 0.95$)
- Overall, the Sensirion Nubo Air temperature measurements overestimated the corresponding South Coast AQMD Met Station data
- The Sensirion Nubo Air sensors seemed to track well the temperature diurnal variations as recorded by South Coast AQMD Met Station



Sensirion Nubo Air vs South Coast AQMD Met Station (RH; 5-min mean)



- Sensirion Nubo Air RH measurements showed very strong correlations with the corresponding South Coast AQMD Met Station data ($R^2 \sim 0.98$)
- Overall, the Sensirion Nubo Air RH measurements underestimated the corresponding South Coast AQMD Met Station data
- The Sensirion Nubo Air sensors seemed to track well the RH diurnal variations as recorded by South Coast AQMD Met Station



Discussion

- The three **Sensirion Nubo Air** sensors' data recovery from units 1523, 1833 and 3127 was ~100%, 97% and 99% respectively, for PM_{1.0} and PM_{2.5} measurements
- The intra-model variability was ~ 0.23, and 0.20 µg/m³ for PM_{1.0}, and PM_{2.5}, respectively
- Very strong correlations between GRIMM and T640 for PM_{1.0} mass concentration measurements ($R^2 \sim 0.95$, 1-hr mean)
- Very strong correlations between FEM GRIMM and FEM T640 for PM_{2.5} mass concentration measurements ($R^2 \sim 0.92$, 1-hr mean)
- PM_{1.0} mass concentration measurements measured by Sensirion Nubo Air sensors showed strong to very strong correlations with the corresponding GRIMM and T640 data ($0.86 < R^2 < 0.94$, 1-hr mean). The sensors underestimated PM_{1.0} mass concentrations as measured by GRIMM and T640
- PM_{2.5} mass concentration measurements measured by Sensirion Nubo Air sensors showed strong correlations with the corresponding FEM GRIMM and FEM T640 data ($0.83 < R^2 < 0.90$, 1-hr mean). The sensors underestimated PM_{2.5} mass concentrations as measured by FEM GRIMM and FEM 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