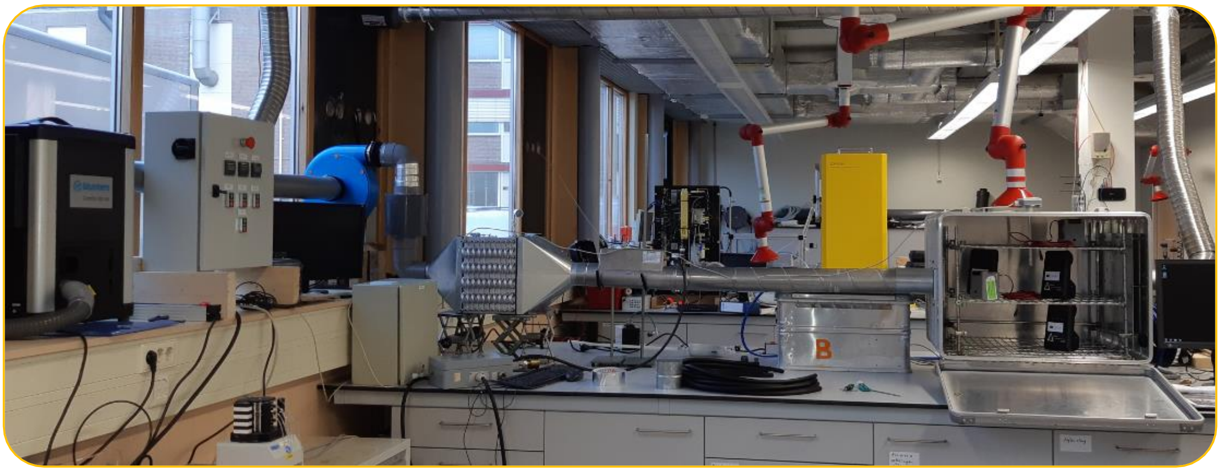
Evaluation of the laboratory testing of particulate matter sensor systems

Author: Daniëlle van Dinther



1 Index

2 Introduction

This report describes the lab comparison of several low-cost PM sensors. Full details of the testing are provided in the test protocol (https://vaquums.eu/sensor-db/tests/protocols/life-vaquums_testprotocol_final.pdf)

The PM-sensors were compared to **one reference systems**:
An 'equivalent' automatic optical PM-monitor (Fidas Palas 200) measuring at a high time resolution (5-min averages) and operating according to EN16450;

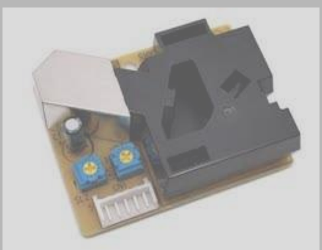
For each sensor type we discuss the following points:

a. **Linearity of the response:** Testing the linearity between the sensors and the reference system was done by looking at regression statistics during a ramping experiment with constant temperature and relative humidity settings.
b. **Accurary**: was assessed by comparing the average sensor response to that of the reference system during the ramping experiment (given in %).
c. **Data recovery: was calculated as the** amount of data points (given in %) recovered by the sensor unit during the lab tests.
d. **Effect of temperature and relative humidity: was visibly inspected by** making a scatter plot of the sensors response against the reference system colour coded by temperature and relative humidity.

8 Types of sensors were included in the lab tests (see

Table *1*). However, the Shinyei PPD42NS and the Alphasense OPC-N2 were excluded from this report due to substantial technical problems.

Table 1: PM-sensors that were tested.

Honeywell **HPMA** 115S0 	**Dylos** DC1700 	Nova Fitness **SDS**011 
Plantower PMS7003 	**Winsen** ZH03B 	Shinyei **PPD**60PV 
(Shinyei PPD42NS) 	*(Alphasense OPC-N2)* 	

3 PM sensor lab testing setup

3.1 Experimental methods

TNO used a PALAS RBG 100 system for generating a range of PM-concentrations in the test box. A powder (in this case ISO 12103-1, test dust made from Arizona desert sand dust) is filled into a cylinder. A feed piston is used to press the powder up in the cylinder while a dispersion brush on top of the cylinder brushes off the powder.

3.2 Exposure chamber

TNO used an exposure chamber (*Figure 1*) of sufficient capacity to accommodate several sensors simultaneously (inner dimensions 57x75x55 cm, DxWxH). The sensors were placed on a grid 2.5 cm above the lower manifold, above this lower grid two grids are placed around 20 cm apart.

Figure 1: Exposure box used for PM testing with the three grids visible

An equivalent monitor, in this case a Palas Fidas 200, measures the concentration of the generated PM in the exposure chamber and is used as the reference system. The sample inlet of the reference method is positioned in the center of the chamber. In order to test the homogeneity of PM within the chamber tests were carried out switching the inlet in different spots in the chamber. The test showed that the PM was homogeneously distributed within the chamber. The inlet flow is controlled both in temperature and relative humidity in order to reach the desired conditions inside the chamber. Due to the electronic components next to each sensor the temperature in the chamber is higher and can vary with the air flow through the chamber. In order to limit the temperature effect from the sensors and ensure sufficient space in between the sensors the experiments were carried out in two batches.

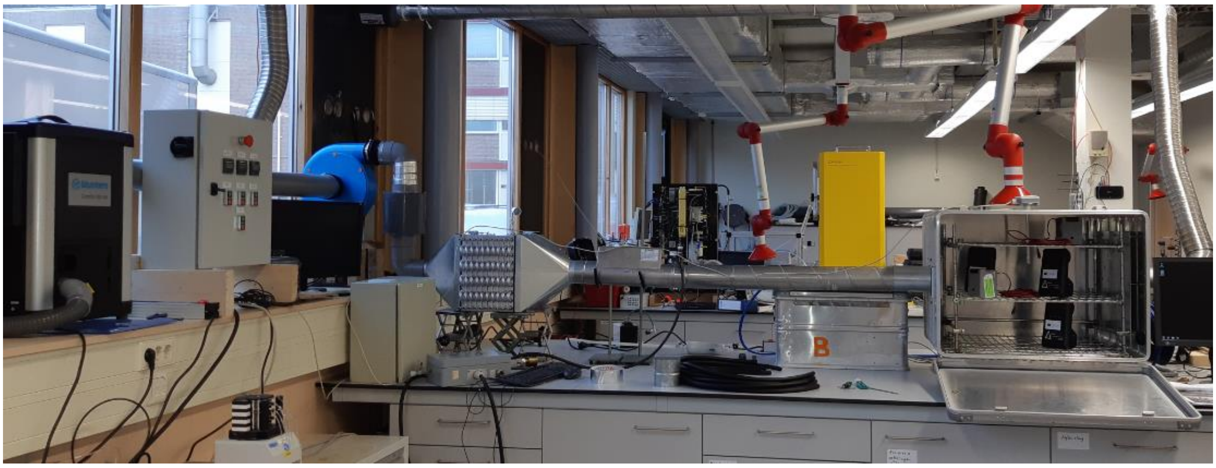


Figure 2 complete experimental setup for PM lab testing

3.3 Reference analyzer

The equivalent PM analyser used to measure PM concentrations in the laboratory evaluation was a Palas Fidas 200 analyser (Figure 3). The Fidas 200 is an aerosol spectrometer developed specifically for regulatory air pollution control. It continuously analyzes the fine dust particles present in the ambient air in the size range 180 nm – 18 µm and calculates simultaneously the immission values PM_{10} and $PM_{2.5}$ to be monitored by law. At the same time PM_1, PM_4, PM_{total} (up to 18 µm), the particle number concentration Cn, and the particle size distribution are calculated and recorded.

Figure 3: Palas Fidas 200 reference analyser

The Fidas 200 utilizes the acknowledged principle of single particle light scattering size analysis and is equipped with an LED light source of high intensity (dp,min = 180 nm). The sampling system of the Fidas 200 operates with a volume flow of approximately 0.3 m^3/h.

The actual aerosol sensor is an optical aerosol spectrometer which determines the particle size using Lorenz-Mie scattered light analysis of single particles. The particles travel individually through an optically confined measurement volume which is homogeneously illuminated with polychromatic light. Every particle generates a scattered light impulse that is detected at an angle between 85° and 95°. The particle number is determined based on the number of scattered light impulses. Particle size is derived from the level of a scattered light impulse.

Precise optics, high light output from the polychromatic LED used, and powerful signal processing electronics using logarithmic A/D conversion allow detection of particles down to 180 nm diameter. The detection of small particles, which can be found in high concentration in particular close to roads, is of importance, e.g. for the correct determination of $PM_{2.5}$.

4 Laboratory testing procedure for PM sensors

4.1 Preparation

The reference instrument, as described earlier, was outside the climate room (because of size and optimal performance of the instrument) and the sample tube was insolated (outside the climate room). Three LabJack EI1034 were placed inside the exposure box (one on each grid) to measure the temperature inside the box. Furthermore an EE210 E + E elektronik measured the temperature and humidity in the center of the box. All PM sensors were placed as described by the manufacturer in order to ensure that air flow through the sensor was possible.

Each PM sensor had its own power cord(s). Sensors were switched on at least an hour before the test (and the data logging) began. Data was send using Wi-Fi and collected on two laptops. When a PM sensor was malfunctioning the power supply (which were labelled) was unplugged to try and retrieve the signal.

The testing of the sensors was done in two sessions. In the first session the three identical PM sensors (i.e. same make and model) of Nova fitness (SDS011), Shinyei (both PPD42 and PPD60), Honeywell (HPMA) and Dylos (1700) were tested. During the second session the three PM sensors of Plantower (PMS7003), Winsen (SH03A), and Alphasense (OPC-N2) were tested.

4.2 Standard procedure

The goal was to evaluate the sensor performance in different concentration ranges at various temperatures and relative humidities. Results from these experiments were used to calculate performance parameters such as accuracy and linear correlation as defined above. For the testing of the PM sensors the temperature and relative humidity settings had to be set manually therefore the duration of each setting is not constant.

The testing procedure needed 28 steps. The order of steps is given in *Table 2*, *Table 3*, *Figure 4* and *Figure 5*.

Table 2: Temperature, humidity and average PM concentration during the steps for batch 1.

Step nr	Duration (hh:mm)	T (°C)	RH (%)	PM_1 ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_4 ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	PM_{total} ($\mu g\ m^{-3}$)
1	14:20	30	20	8	38	113	307	497
2	2:35	30	50	18	86	263	751	1266
3	1:45	35	80	18	88	268	781	1297
4	14:10	30	20	0	0	0	0	0
5	19:40	25	20	9	46	153	510	954
6	15:50	35	20	18	88	260	726	1092
7	2:00	35	80	28	136	385	1016	1447
8	1:50	35	50	26	123	348	907	1265
9	1:50	25	50	27	129	369	975	1405
10	2:00	15	50	7	38	129	398	646
11	5:30	15	20	16	77	230	632	955
12	1:50	15	50	26	133	409	1212	1955

Table 3: Temperature, humidity and average PM concentration during the steps for batch 2.

Step nr	Duration (hh:mm)	T (°C)	RH (%)	PM_1 ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_4 ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	PM_{total} ($\mu g\ m^{-3}$)
1	18:50	15	30	0	0	0	0	1
2	2:25	15	50	26	156	552	1815	3060
3	1:00	15	80	31	166	561	1817	3036
4	14:15	15	20	24	126	403	1267	2109
5	9:09	15	20	1	4	16	61	105
6	2:15	15	80	5	32	118	401	653
7	1:50	15	50	3	19	67	206	323
8	2:10	15	20	16	84	273	846	1364
9	15:30	25	20	23	119	388	1248	2109
10	1:50	25	50	30	163	532	1649	2693
11	2:10	35	80	28	147	484	1556	2592
12	2:50	35	50	24	126	414	1345	2242
13	13:00	35	20	25	132	440	1462	2523
14	15:50	15	20	15	83	292	1025	1858
15	2:00	15	50	16	87	303	1063	1963
16	3:40	15	80	8	42	146	512	920

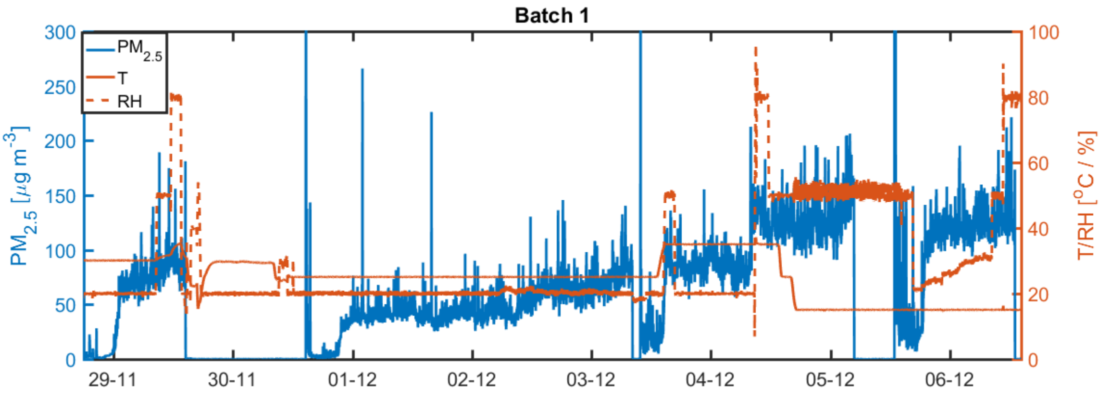


Figure 4: Overview of $PM_{2.5}$, T and RH for the test protocol of batch 1.

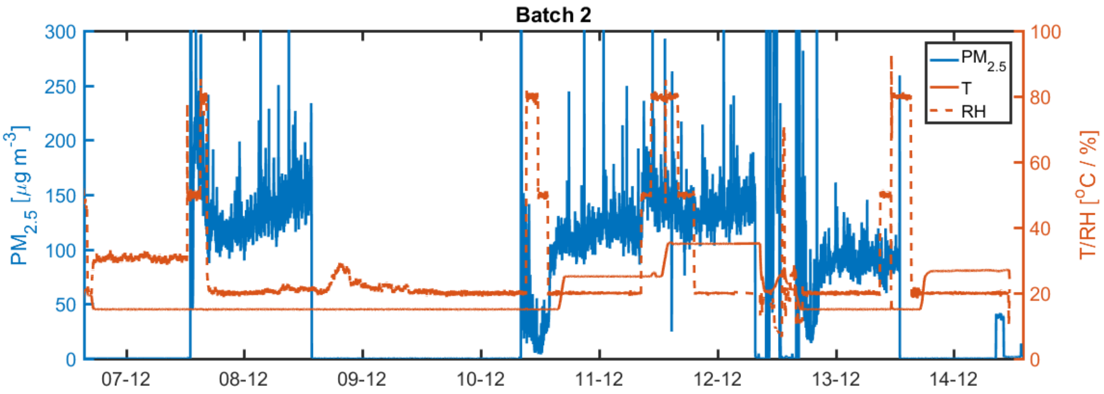


Figure 5: Overview of $PM_{2.5}$, T and RH for the test protocol of batch 2.

For both batches the sensors were tested when there was no PM present in the room. For batch 1 this occurred in step number 4 and for batch 1 in step number 1. For the other steps the PM - concentrations varied by itself as a consequence of the generation of PM. *Table 2* and *Table 3* give the PM concentrations measured by the Fidas for different steps. The RH was fixed at 20%, 50% and 80%. For PM it was decided to have lower RH values than for O_3 and NO_2 since some PM sensors have problems with very low RH concentrations. Due to the heat production by the sensors itself, it was not possible to fix the box at a very low temperature. Therefore, the lowest temperature setting was fixed at 15°C. Other temperatures at which the box was fixed during the steps were 25, 30 and 35°C. For batch 1 also some test were undertaken with a fixed temperature of 30°C. However, since this was reasonably close to 25°C is was decided to set the maximum fixed temperature to 35°C.

Concentration range

The generated $PM_{2.5}$ concentrations ranged from a few µg/m^3 to 150 µg/m^3. These levels represent a typical range of hourly PM-concentrations in Europe. The generated PM_{10} concentrations ranged from a few µg/m^3 to 1500 µg/m^3. The upper limit is higher than the typical upper range of hourly PM-concentrations in Europe.

Particle size

In *Table 2* and *Table 3* the average PM_1, $PM_{2.5}$, PM_4, PM_{10} and PM_{total} measured by the Fidas in the different steps for batch 1 and 2 are mentioned. The distribution along these PM sizes is more or less constant along the experiment. About 1% of the total PM concentration is caused by particle sizes below 1 µm. Around 4% by particles in between size 1 and 2.5 µm. Particle in between size 2.5 and 4 contribute to about 13% of PM_{total}. And particles in between 4 and 10 µm, as well as those above 10 µm, contribute each about 41% to the PM_{total} signal.

This size distribution is significantly different from typical ambient aerosol (with has relatively much more PM_1 and $PM_{2.5}$). Since we assume that most cheap PM-sensor are probably internally calibrated based on 'average ambient aerosol' this coarser particle distribution can have a significant effect on certain test parameters. However is does allow us to have a better understanding of the true capability of these cheap PM sensor to actually measure coarser PM (between 2.5 and 10 µm).

Effect of T and RH

The temperature and relative humidity parameters vary between a low, medium and high level; in total there are 9 different combinations (at a fixed concentration level). *Table 4* shows the set points for both T and RH:

Table 4: 3 levels of T and RH during the PM experiment

	T	RH
	°C	%
low	15	20
medium	25	50
high	35	80

5 Summary of experiments

Linearity

Table 5 shows the regression statistics of the sensor units with the reference system during the ramping experiment given constant temperature and relative humidity. For $PM_{2.5}$ we see a high linearity (with R^2 above 0.90) for the Honeywell, Dylos, Nova Fitness and the Shinyei PPD60. Note that the Shinyei sensors were calibrated with this dataset, since they are not calibrated by the manufacturer. Only the Winsen showed less linearity for $PM_{2.5}$ for two of the three units, with more scattering with R^2-values of 0.40 and 0.42 (the one unit with a high linearity has an R^2 of 0.90). For PM_{10} a high linearity (R^2 above 0.90) is found for the Honeywell, Dylos and Nova Fitness sensor units. The PM_{10} of the Plantower shows a moderate linearity with R^2-values of 0.77 and 0.78. Also the Winsen shows a moderate linearity with the reference system with R^2-values between 0.72 and 0.82.

Looking at the slope of the sensor output closest to one is the Shinyei PPD60 (0.94 and 0.98). However, this is to be expected since the ramping experiment was used for calibration. Excluding this sensor the best fit to the reference system for $PM_{2.5}$ is of the Dylos (with slopes of 1.09 and 1.10). The other sensor all underestimate the $PM_{2.5}$-values by more than 50% (with slopes below 0.5). All sensors underestimate the PM_{10}-values. The Dylos was closest to the value of the reference system with slopes of 0.41 and 0.44. The other sensors all strongly underestimate the PM_{10}-values with slopes all below 0.1.

Table 5: Linear regression statistics found during the ramping experiment.

Sensor unit	PM2.5			PM10		
	Slope	Intercept	R^2	Slope	Intercept	R^2
Honeywell-2	0.45	0.53	0.99	0.056	2.0	0.97
Honeywell-3	0.39	0.39	0.99	0.049	1.7	0.98
Honeywell-4	0.38	0.20	0.98	0.047	1.5	0.97
Dylos-3	1.09	1.8	0.99	0.41	6.4	0.98
Dylos-4	1.10	2.0	0.99	0.44	7.1	0.97
Nova Fitness-1	0.18	0.49	0.99	0.086	0.89	0.98
Nova Fitness-2	0.16	0.60	0.99	0.071	0.61	0.98
Nova Fitness-3	0.16	0.44	0.95	0.074	0.76	0.94
Plantower-2	0.29	-1.7	0.93	0.032	1.0	0.77
Plantower-3	0.29	-1.3	0.93	0.027	0.28	0.77
Plantower-4	0.27	-2.3	0.93	0.030	-0.23	0.78
Winsen-2	0.12	14	0.42	0.019	12	0.72
Winsen-3	0.14	18	0.40	0.024	16	0.72
Winsen-4	0.22	2.5	0.91	0.027	3.6	0.82
PPD60-1[1]	0.94	1.4	0.98			
PPD60-3[1]	0.98	0.98	0.97			

<u>Accuracy</u>

The accuracy states how close the PM-concentration given by the sensor units is to the reference system. An accuracy of 100% would mean that the average PM concentration of the senor unit is exactly the same as that of the reference system. The accuracy was calculated given the different temperature and relative humidity settings. *Table 6* shows the average accuracy of all the setting (excluding the setting where the PM-concentrations were 0 µg m^{-3}).

Table 6: Average accuracy (in %) of the sensor units (excluding the setting were PM=0 µg m^{-3}) for the different PM classes.

Sensor unit	PM_1 (%)	$PM_{2.5}$ (%)	PM_{10} (%)
Honeywell-2		46	6
Honeywell-3		48	5
Honeywell-4		47	6
Dylos-3		90	43
Dylos-4		89	46
Nova Fitness-1		19	9
Nova Fitness-2		17	7
Nova Fitness-3		26	13
Plantower-2	66	27	4
Plantower-3	73	28	3
Plantower-4	62	21	3
Winsen-2[2]	86	22	3
Winsen-3[2]	86	25	3
Winsen-4[2]	86	21	3
PPD60-1[1]		70	
PPD60-3[1]		85	

[1] Shinyei PPD60 units were calibrated with the data of the ramping experiment using a quadratic function.

[2] For Winsen the accuracies was much lower for setting 15 and 16, which were therefore excluded in the averages.

From *Table 6* it is clear that the accuracy are all below 100%, which means all sensors underestimate the PM-concentrations. This is especially the case for PM_{10}, were are accuracy are below 50% (i.e., PM_{10} is underestimated by more than 50%). The fact that the accuracies are lower for PM_{10} than $PM_{2.5}$, indicates the sensors have problems capturing particle sizes between 2.5 and 10 µm. The highest (and therefore closest to the reference instrument) accuracies are achieved by the Dylos (around 90% for $PM_{2.5}$ and around 45% for PM_{10}). It is remarkable that the Shinyei PPD60 sensors are calibrated during the ramping experiment using the same dust as for the other lab experiment but still $PM_{2.5}$ is underestimated (with accuracies of 70 and 85%).

Data availability

Table 7: Data availability (in %) of the sensor units for the different PM classes.

Sensor unit	Data availability
Honeywell-2	100
Honeywell-3	100
Honeywell-4	100
Dylos-3	99
Dylos-4	100
Nova Fitness-1	46
Nova Fitness-2	100
Nova Fitness-3	100
Plantower-2	95
Plantower-3	95
Plantower-4	95
Winsen-2	95
Winsen-3	95
Winsen-4	95
PPD60-1	99
PPD60-3	87

Laboratory Evaluation
Honeywell HPMA115S sensor

Manufacturer: Honeywell
Link to website manufacturer

Link to test protocol

6 Honeywell HPMA115S0 PM sensor

Three **Honeywell HPMA115S0** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. These sensors have also been tested in the field (at Borgerhout station).

Honeywell HPMA115S0:

- Particle counter
- Unit measures $PM_{2.5}$ & PM_{10}
- Time resolution: 1 minute
- Units IDs: HPMA-2, HPMA-3, HPMA-4.

Reference instrument

- FIDAS 200S
- Time resolution: 2 minutes

Different settings and PM concentrations

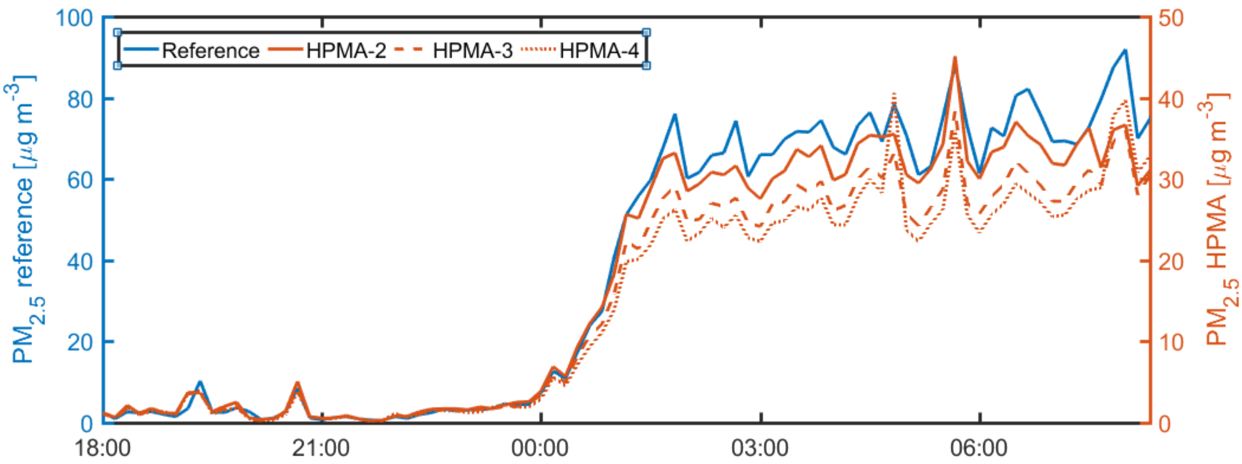
Dylos sensors were evaluated in batch 1

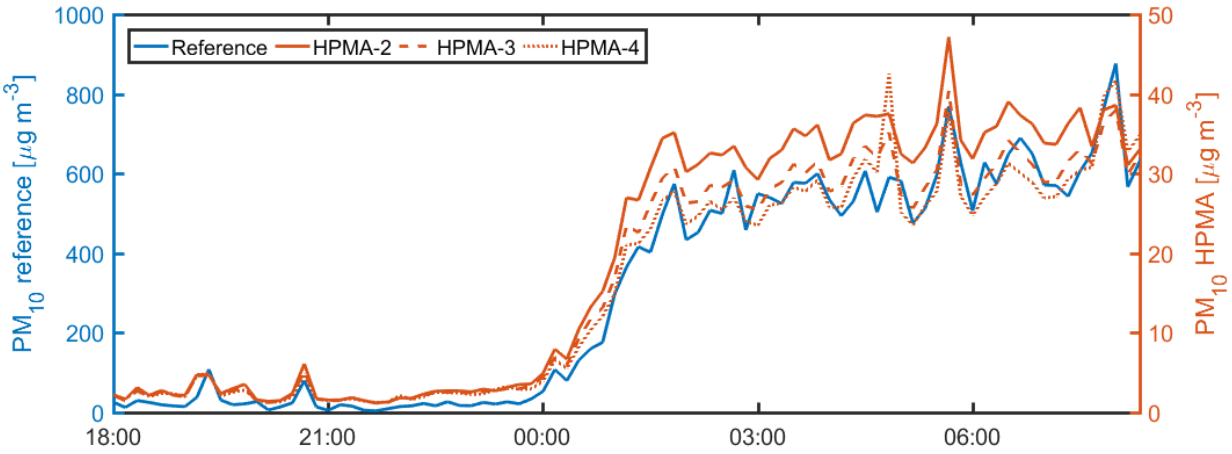
Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	30	20	8	38	113	307	497
2	30	50	18	86	263	751	1266
3	35	80	18	88	268	781	1297
4	30	20	0	0	0	0	0
5	25	20	9	46	153	510	954
6	35	20	18	88	260	726	1092
7	35	80	28	136	385	1016	1447
8	35	50	26	123	348	907	1265
9	25	50	27	129	369	975	1405
10	15	50	7	38	129	398	646
11	15	20	16	77	230	632	955
12	15	50	26	133	409	1212	1955

For the details about the laboratory protocol followed here, consult our [test protocol].

6.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Honeywell units on the right y-axis.



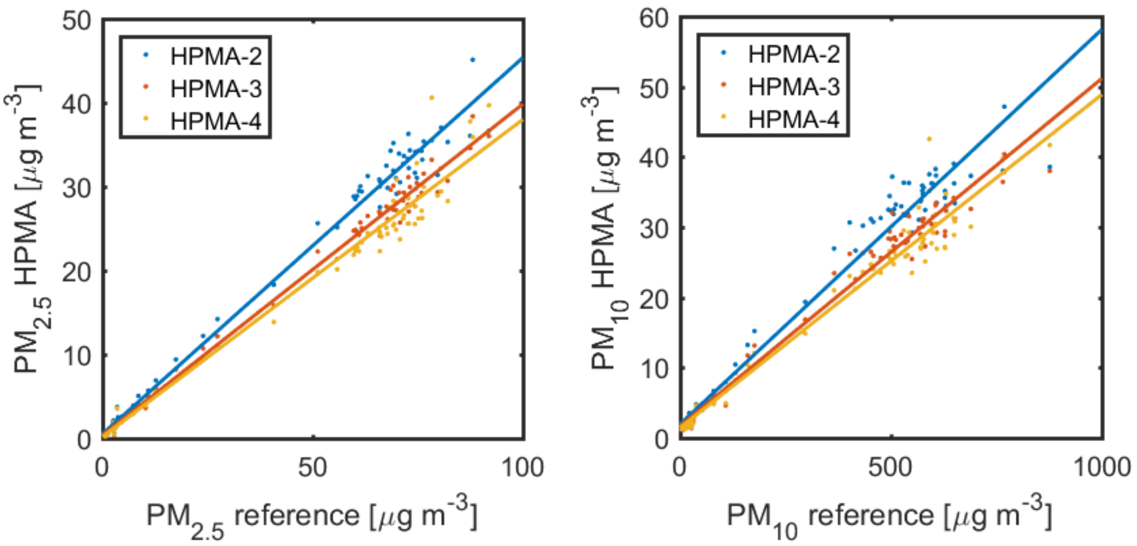


- All HPMA units track well with the $PM_{2.5}$ and PM_{10} concentration changes as measured by the FIDAS reference.

- All units underestimate the FIDAS $PM_{2.5}$ and PM_{10} reference concentration.

6.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.



Unit	PM2.5			PM10		
	Slope	Intercept	R^2	Slope	Intercept	R^2
2	0.45	0.53	0.99	0.056	2.0	0.97
3	0.39	0.39	0.99	0.049	1.7	0.98
4	0.38	0.20	0.98	0.047	1.5	0.97

- In the concentration range of 0-100 µg m^{-3} for $PM_{2.5}$ and 0-1000 µg m^{-3} for PM_{10}, the three HPMA units show a very good correlation with the corresponding FIDAS data ($R^2 \geq 0.97$) at 30°C and 20% RH. Especially for units HPMA-2 and HPMA-3 for $PM_{2.5}$ (R^2=0.99)

- The slope of the regression equations is reasonably low for $PM_{2.5}$ between 0.38 and 0.45 and very low for PM_{10} 0.047 and 0.056.

6.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit	PM2.5			PM10		
Setting	2	3	4	2	3	4
1	46	40	38	6	6	5
2	41	79	46	5	9	5
3	43	40	43	5	5	5
4	0	$-6.3*10^3$	0	$2.7*10^3$	$-5.0*10^3$	$-2.7*10^3$
5	47	45	48	5	4	5
6	46	43	46	6	5	6
7	40	39	46	6	2	6
8	42	42	49	6	6	7
9	41	40	24	6	5	5
10	50	45	48	5	5	5
11	47	43	44	6	6	6
12	59	74	83	7	6	7

- On average, the units show reasonably low accuracy when compared to the FIDAS. For $PM_{2.5}$ the sensors' accuracies are between 24% and 83% (excluding setting 4 where PM=0 µg m^{-3}). For PM_{10} the sensors' accuracies are lower between 4% and 7% (excluding setting 4 where PM=0 µg m^{-3}).

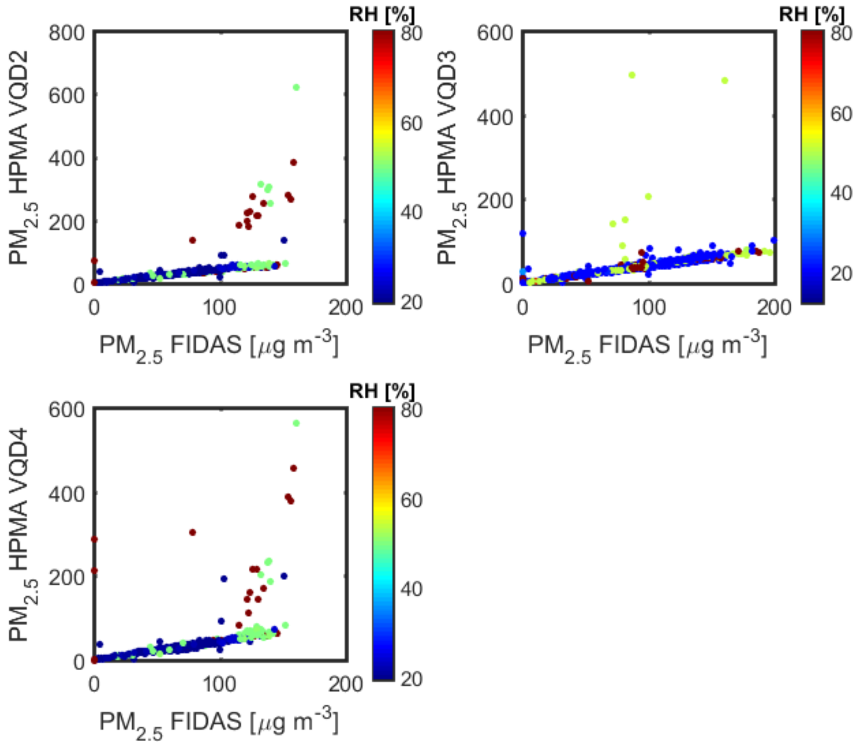
6.4 Data recovery and coefficients of variation

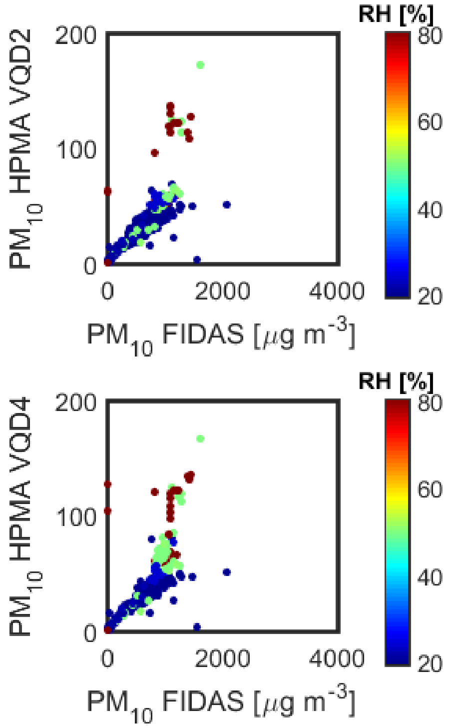
- Data recovery was 100% for all the units.

6.5 Climate susceptibility

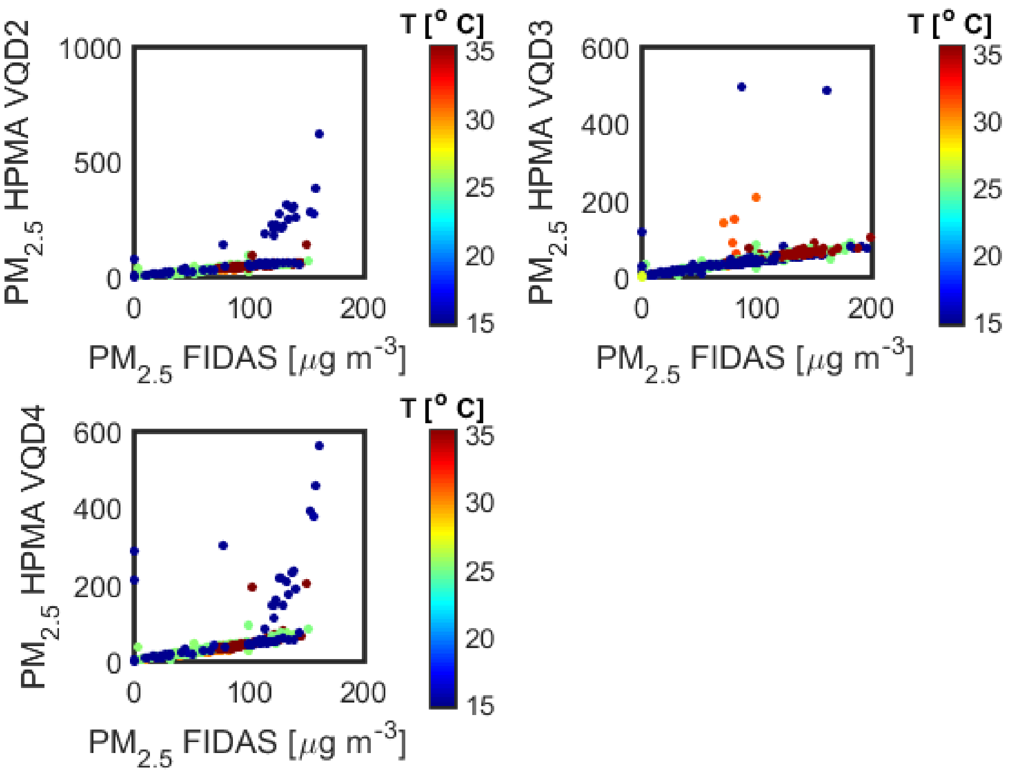
The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.

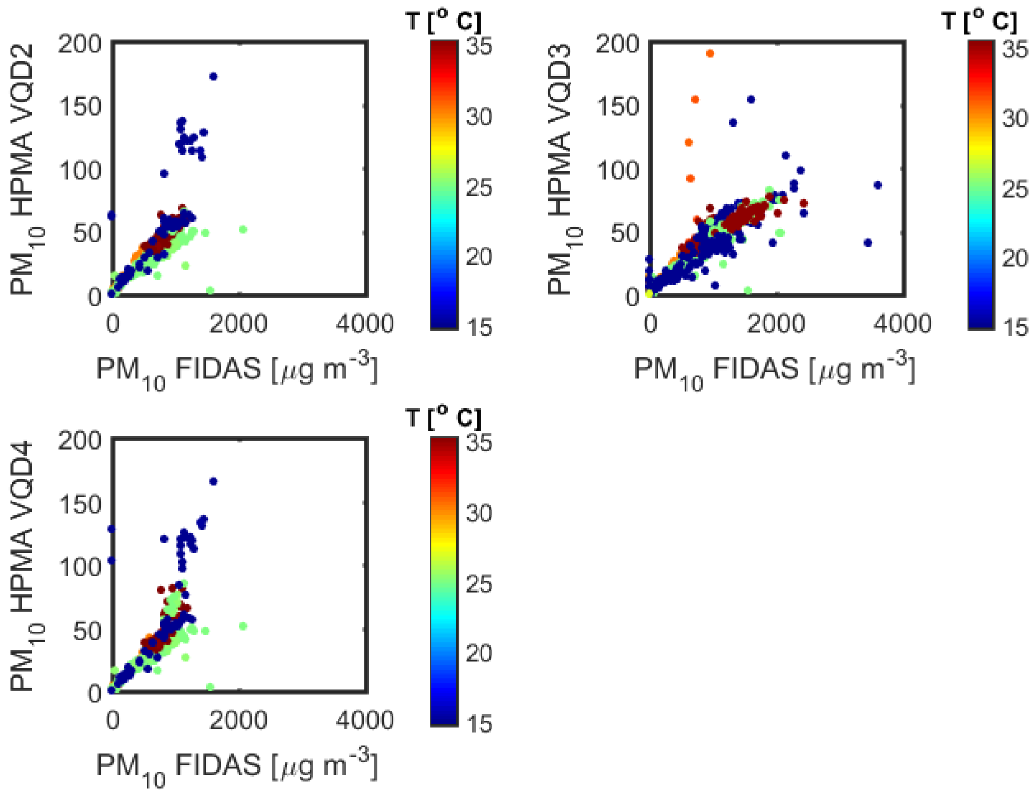
For relative humidity sensors VQD2 and VQD4 are influenced with more scatter and a higher overestimation at higher humidity's. Sensor VQD3 seems less affected by relative humidity's, although for PM_{10} there is more scatter for relative humidity's of 50%.





The three sensors does not seem to be influenced significantly by temperature.





6.6 Summary

- **Accuracy**: The accuracy for the three HPMA units was reasonably low especially for PM_{10} (around 45% for $PM_{2.5}$ and around 7% for PM_{10}), but reasonably stable.

- **Data recovery** for the three HPMA units was excellent with values of 100% for all of them.

- **Linearity of sensor response**: HPMA units showed very good linear correlation (≥0.97) with the corresponding FIDAS measurements for $PM_{2.5}$ (between 0-100 µg m^{-3}) and PM_{10} (between 0-1000 µg m^{-3}).

- **Climate susceptibility**: All three units are susceptible to higher RH values (≥50%) for both $PM_{2.5}$ and PM_{10}.

Laboratory Evaluation
Dylos DC1700 sensor

Manufacturer: Dylos

[Link to website manufacturer]

[Link to test protocol]

7 Dylos DC1700

Three **Dylos DC1700** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. However, one unit (Dylos-2) had problems with the power supply and could therefore not be tested. These sensors have also been tested in the field (at Borgerhout station).

Dylos DC1700:

- Particle counter
- Unit measures $PM_{2.5}$ & PM_{10}
- Time resolution: 1 minute
- Units IDs: Dylos-2 (not working), Dylos-3, Dylos-4.

Reference instrument

- FIDAS 200S

- Time resolution: 2 minutes

<u>Different settings and PM concentrations</u>

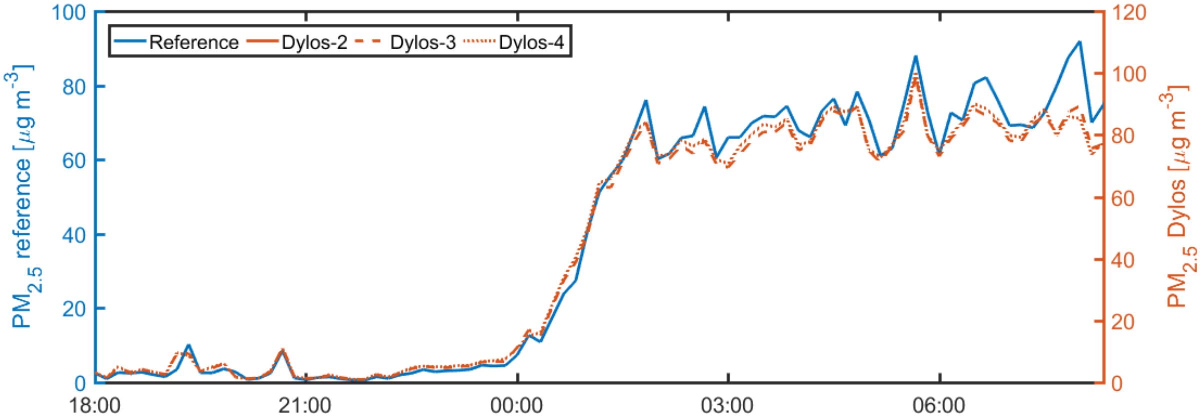
Dylos sensors were evaluated in batch 1

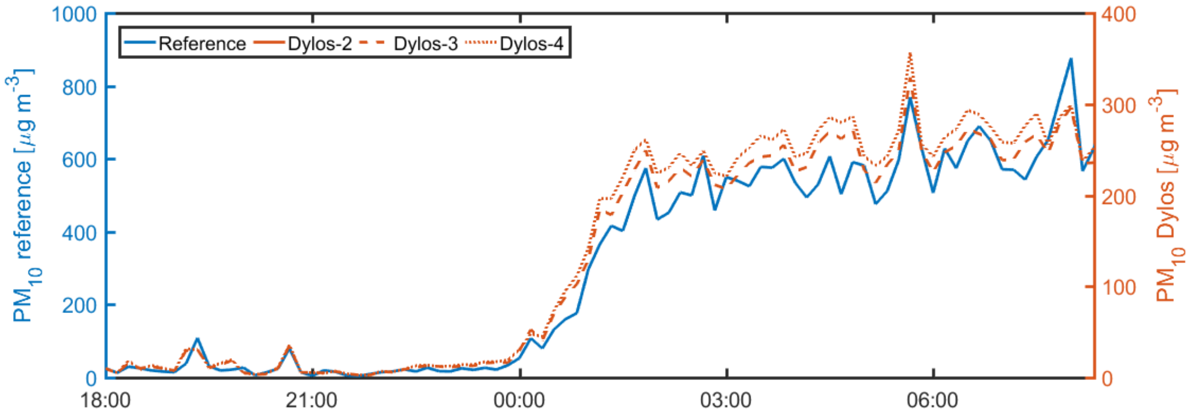
Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	30	20	8	38	113	307	497
2	30	50	18	86	263	751	1266
3	35	80	18	88	268	781	1297
4	30	20	0	0	0	0	0
5	25	20	9	46	153	510	954
6	35	20	18	88	260	726	1092
7	35	80	28	136	385	1016	1447
8	35	50	26	123	348	907	1265
9	25	50	27	129	369	975	1405
10	15	50	7	38	129	398	646
11	15	20	16	77	230	632	955
12	15	50	26	133	409	1212	1955

For the details about the laboratory protocol followed here, consult our test protocol.

7.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Dylos units on the right y-axis!

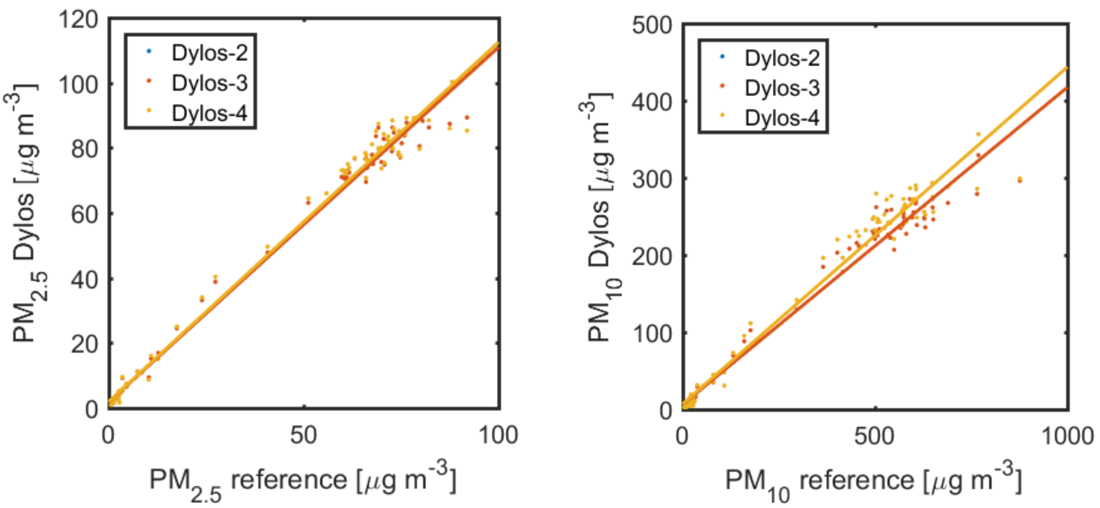




- All Dylos units track well with the $PM_{2.5}$ and PM_{10} concentration changes as measured by the FIDAS reference.
- All units somewhat underestimate the FIDAS $PM_{2.5}$ and PM_{10} reference concentration.

7.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.



Unit	$PM_{2.5}$			PM_{10}		
	Slope	Intercept	R^2	Slope	Intercept	R^2
3	1.09	1.8	0.99	0.41	6.4	0.98
4	1.10	2.0	0.99	0.44	7.1	0.97

- In the concentration range of 0-100 µg m^{-3} for $PM_{2.5}$ and 0-1000 µg m^{-3} for PM_{10}, the three Dylos units show a very good correlation with the corresponding FIDAS data ($R^2 \geq 0.97$) at 30°C and 20% RH. Especially for $PM_{2.5}$ (R^2=0.99)

- The slope of the regression equations is close to 1 for $PM_{2.5}$ (1.09 and 1.10) and reasonably low for PM_{10} 0.41 and 0.44.

7.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit / Setting	PM2.5 3	PM2.5 4	PM10 3	PM10 4
1	86	84	43	46
2	98	97	36	37
3	95	98	36	35
4	91	61	32	21
5	82	84	39	40
6	94	97	36	40
7	97	95	39	39
8	94	98	42	44
9	89	83	49	58
10	81	83	50	53
11	79	76	57	63
12	NaN	88	NaN	NaN

- For $PM_{2.5}$ the units show reasonably good accuracy when compared to the FIDAS (in between 76 and 98%, excluding setting 4 where PM=0 µg m^{-3}). For PM_{10} the sensors' accuracies are lower in between 35% and 63% (excluding setting 4 where PM=0 µg m^{-3}).

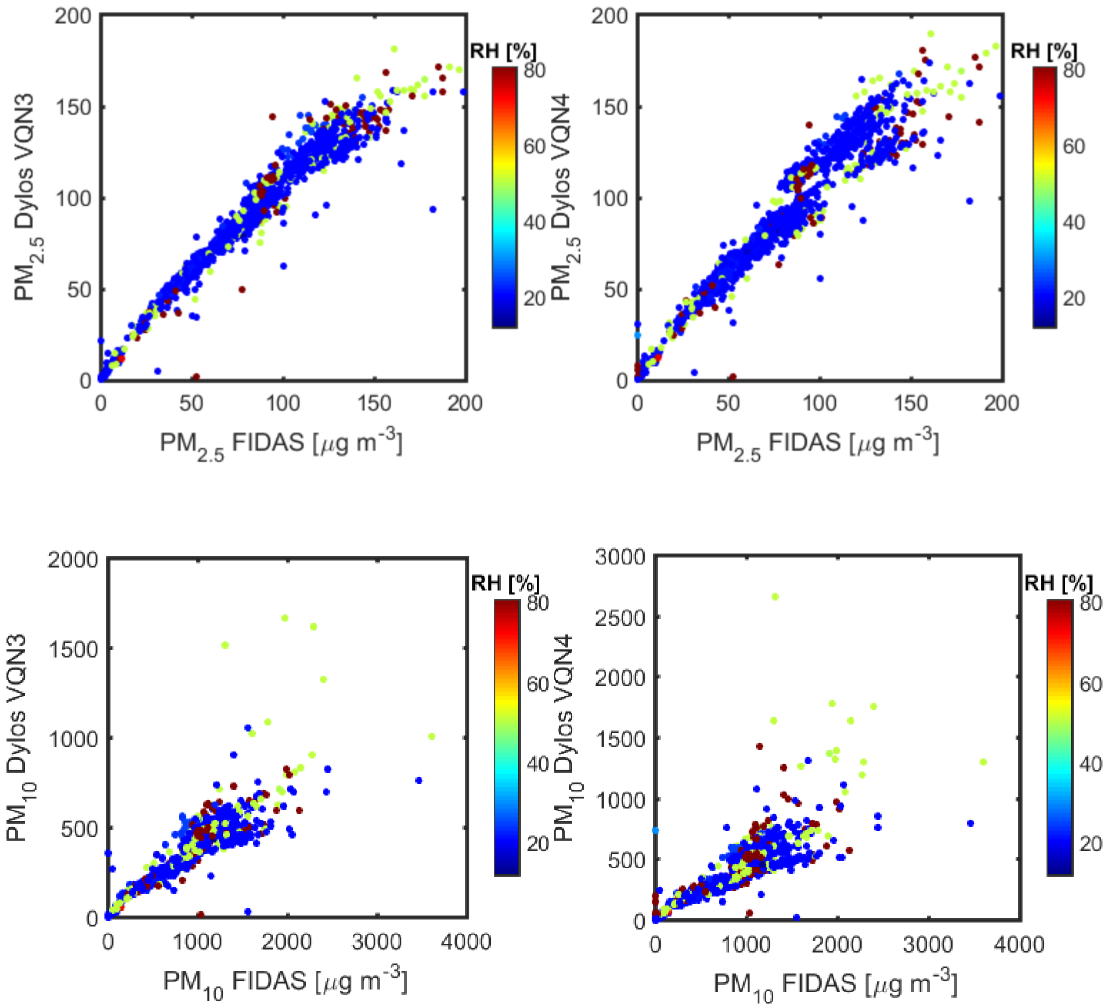
7.4 Data recovery and coefficients of variation

- Data recovery was 100% for unit Dylos-4 and 99% for Dylos-3. Unit Dylos-2 could not be tested due to power issues.

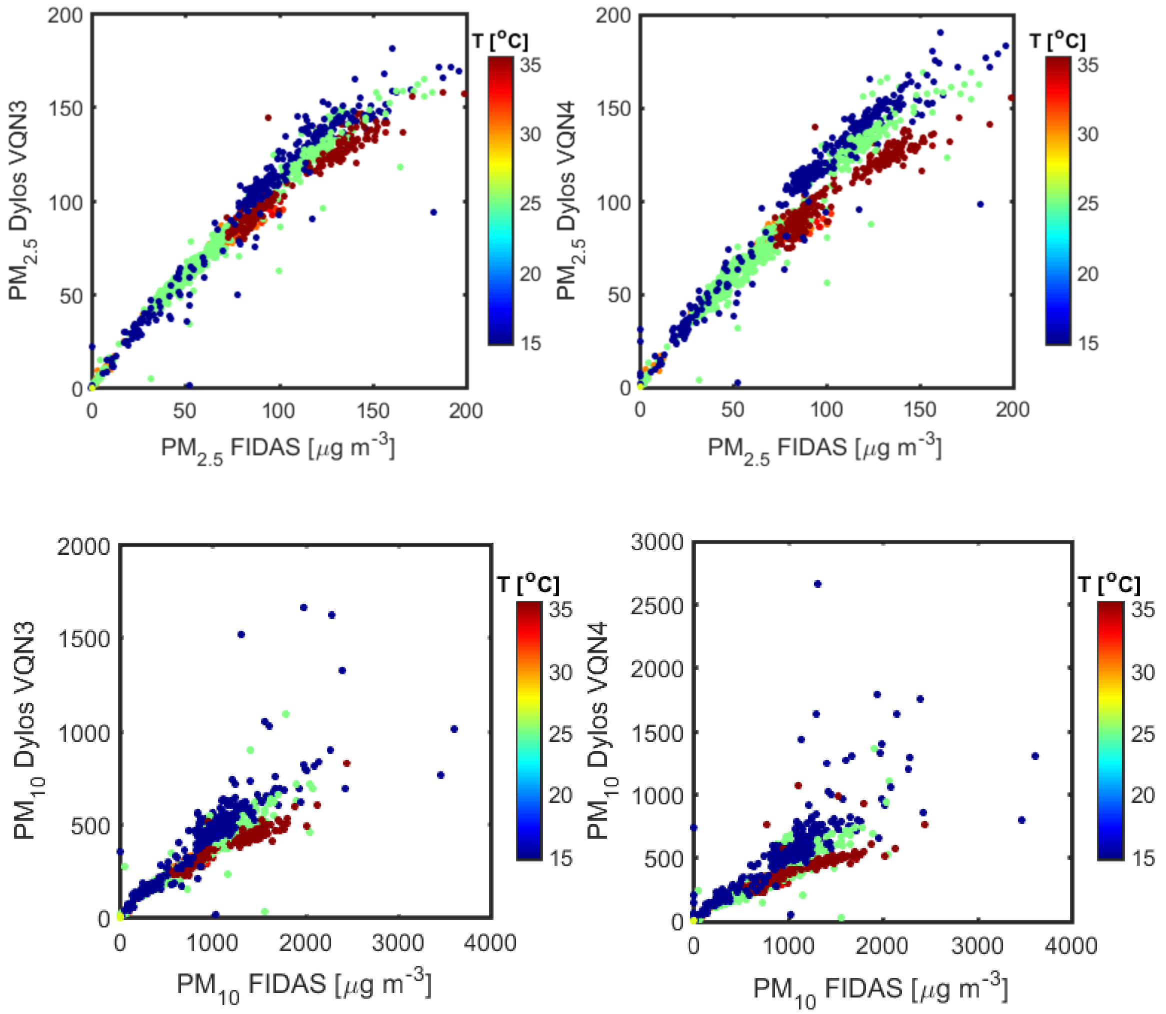
7.5 Climate susceptibility

The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.

The sensors are not strongly influenced by relative humidity.



The sensors are influenced by temperature. In the figure below it can be seen that the PM concentrations (both for $PM_{2.5}$ and PM_{10}) are lower at higher temperatures. This is the case for both tested sensors.



7.6 Summary

- **Accuracy**: The accuracy for the two Dylos units for $PM_{2.5}$ was reasonably good (in between 76 and 98%). For PM_{10} the accuracies were lower and between 35% and 63%.

- **Data recovery** for the two Dylos units was very good with values of 99 and 100%.

- **Linearity of sensor response**: The Dylos units showed very good linear correlation (≥0.97) with the corresponding FIDAS measurements for $PM_{2.5}$ (between 0-100 µg m^{-3}) and PM_{10} (between 0-1000 µg m^{-3}).

- **Climate susceptibility**: All three units were somewhat susceptible to temperature, especially for PM_{10}.

Laboratory Evaluation
Nova Fitness SDS011 sensor

Manufacturer: Nova Fitness
Link to website manufacturer

Link to test protocol

8 Nova Fitness SDS011

Three **Nova Fitness SDS011** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. These sensors have also been tested in the field (at Borgerhout station).

Nova Fitness SDS011:

- Particle counter
- Unit measures $PM_{2.5}$ & PM_{10}
- Time resolution: 1 minute
- Units IDs: SDS011-1, SDS011-2, SDS011-3.

Reference instrument

- FIDAS 200S
- Time resolution: 2 minutes

Different settings and PM concentrations

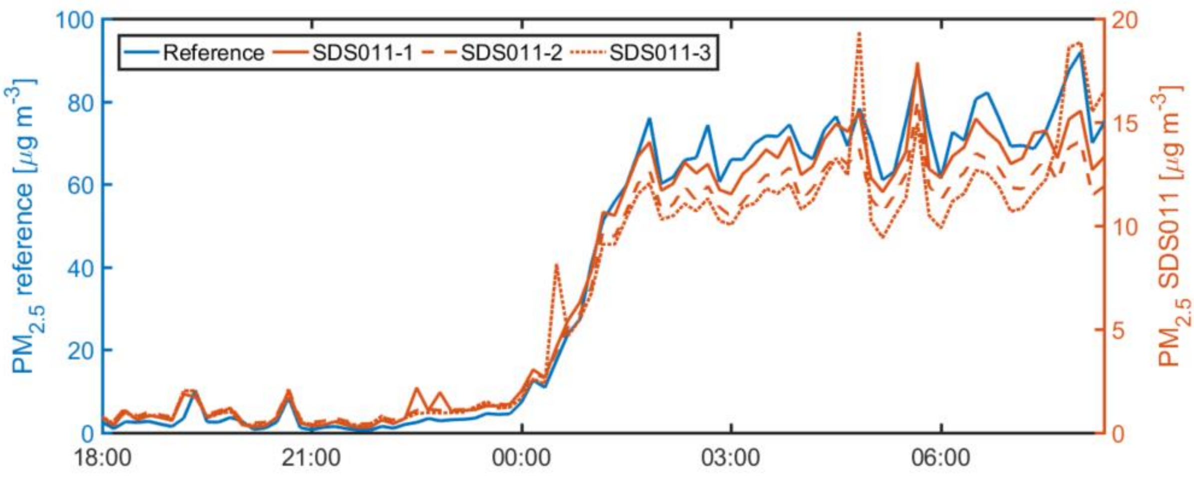
Nova Fitness sensors were evaluated in batch 1

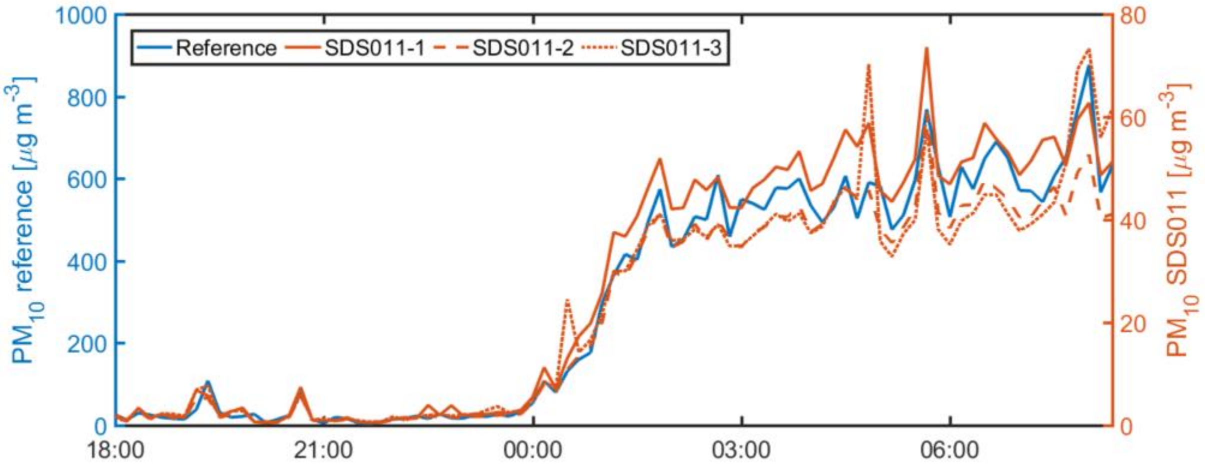
Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	30	20	8	38	113	307	497
2	30	50	18	86	263	751	1266
3	35	80	18	88	268	781	1297
4	30	20	0	0	0	0	0
5	25	20	9	46	153	510	954
6	35	20	18	88	260	726	1092
7	35	80	28	136	385	1016	1447
8	35	50	26	123	348	907	1265
9	25	50	27	129	369	975	1405
10	15	50	7	38	129	398	646
11	15	20	16	77	230	632	955
12	15	50	26	133	409	1212	1955

For the details about the laboratory protocol followed here, consult our [test protocol].

8.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Nova Fitness units on the right y-axis.

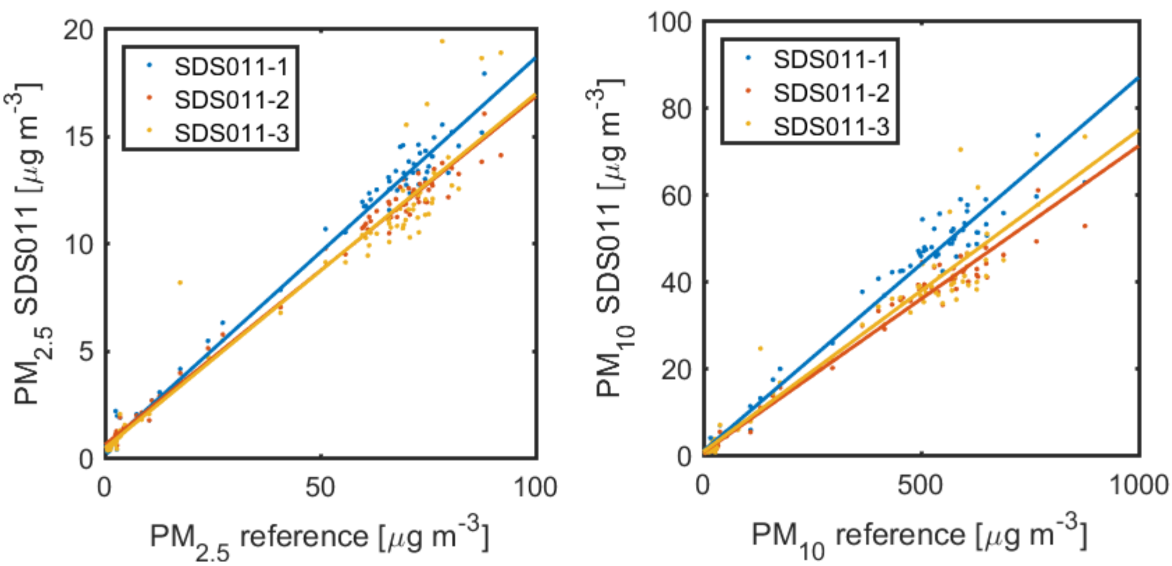




- All SDS011 units track well with the $PM_{2.5}$ and PM_{10} concentration changes as measured by the FIDAS reference.
- All units underestimate the FIDAS $PM_{2.5}$ and PM_{10} reference concentration.

8.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.



Unit	PM2.5			PM10		
	Slope	Intercept	R^2	Slope	Intercept	R^2
1	0.18	0.49	0.99	0.086	0.89	0.98
2	0.16	0.60	0.99	0.071	0.61	0.98
3	0.16	0.44	0.95	0.074	0.76	0.94

- In the concentration range of 0-100 µg m^{-3} for $PM_{2.5}$ and 0-1000 µg m^{-3} for PM_{10}, the three SDS011 units show a very good correlation with the corresponding FIDAS data ($R^2 \geq 0.94$) at 30°C and 20% RH. Especially for units SDS011-1 and SDS011-2 ($R^2 \geq 0.98$)

- The slope of the regression equations is low for $PM_{2.5}$ between 0.16 and 0.18 and very low for PM_{10} 0.071 and 0.086.

8.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit	PM2.5			PM10		
Setting	1	2	3	1	2	3
1	19	18	18	9	7	8
2	17	16	22	8	7	9
3	18	17	20	8	7	8
4	26	-621	64	10	-86	49
5	NaN	16	22	NaN	6	8
6	17	17	22	7	7	10
7	19	18	24	9	8	11
8	21	18	24	11	8	12
9	23	17	24	12	8	12
10	21	16	19	10	7	8
11	20	15	17	10	7	8
12	NaN	NaN	77	NaN	NaN	45

- On average, the units show low accuracy when compared to the FIDAS. For $PM_{2.5}$ the sensors' accuracies are between 15% and 24% (excluding setting 4 where PM=0 µg m^{-3}). For PM_{10} the sensors' accuracies are lower between 7% and 15% (excluding setting 4 where PM=0 µg m^{-3} and setting 12 where PM is extremely high PM_{total}=1955 µg m^{-3}).

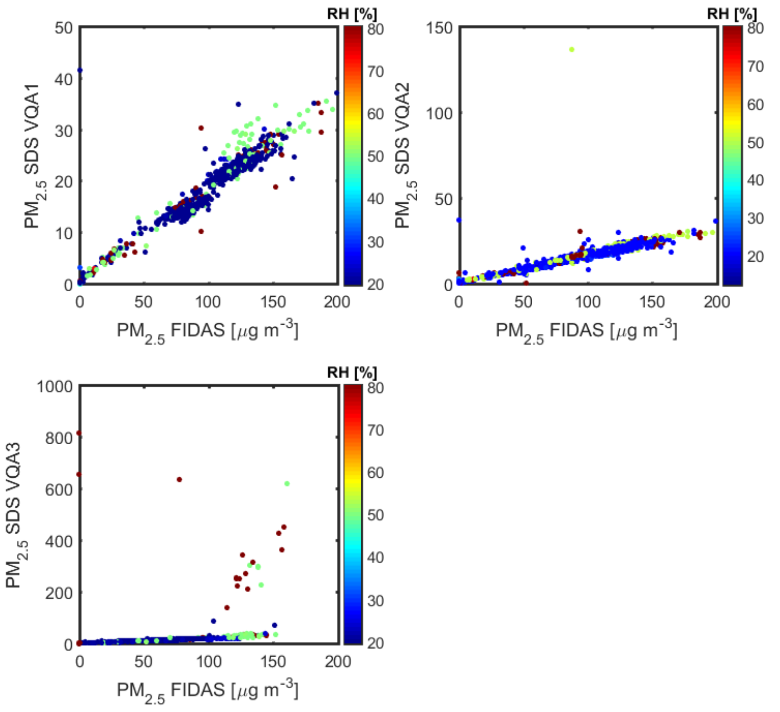
8.4 Data recovery and coefficients of variation

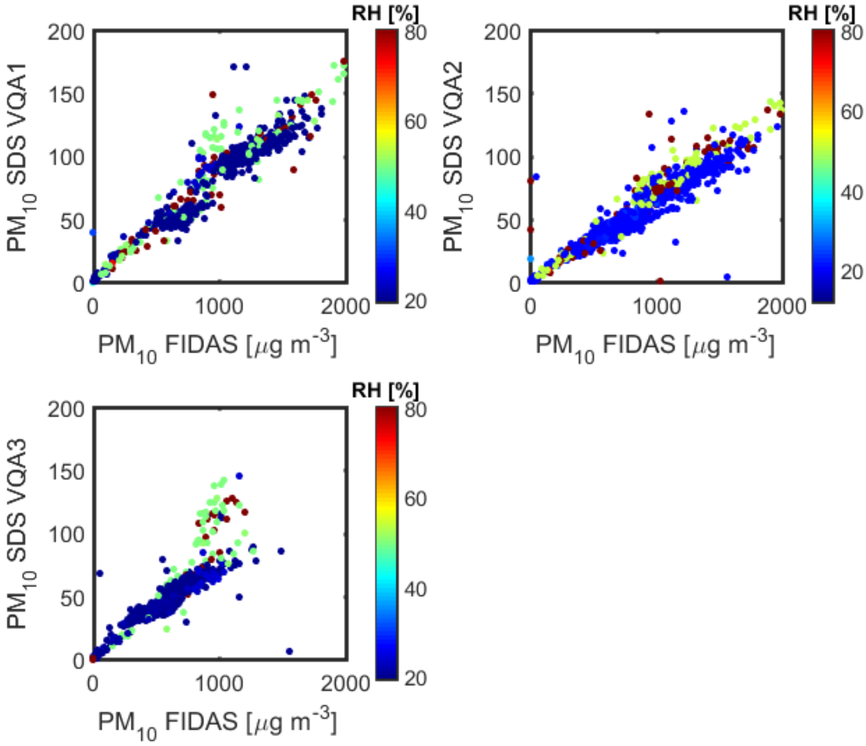
- Data recovery was 100% for the units 2 and 3. For unit 1 the data recovery was only 46%.

8.5 Climate susceptibility

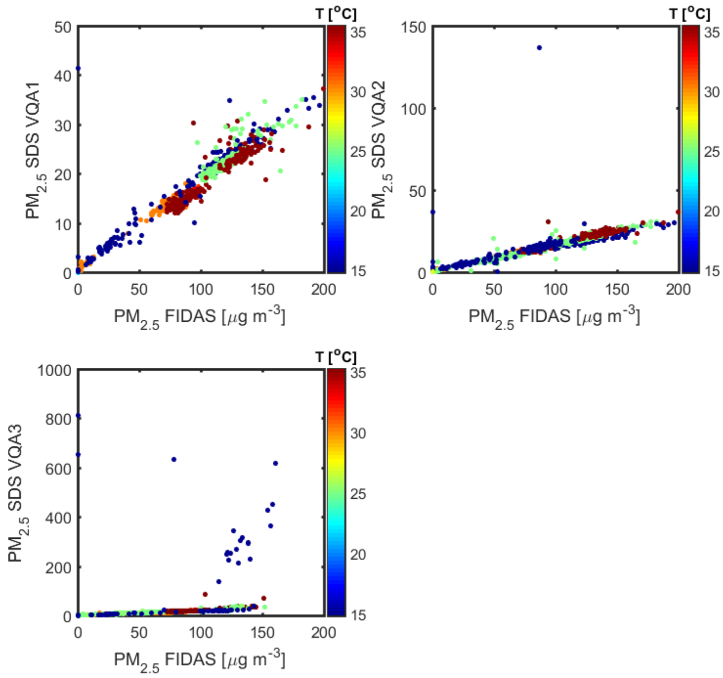
The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.

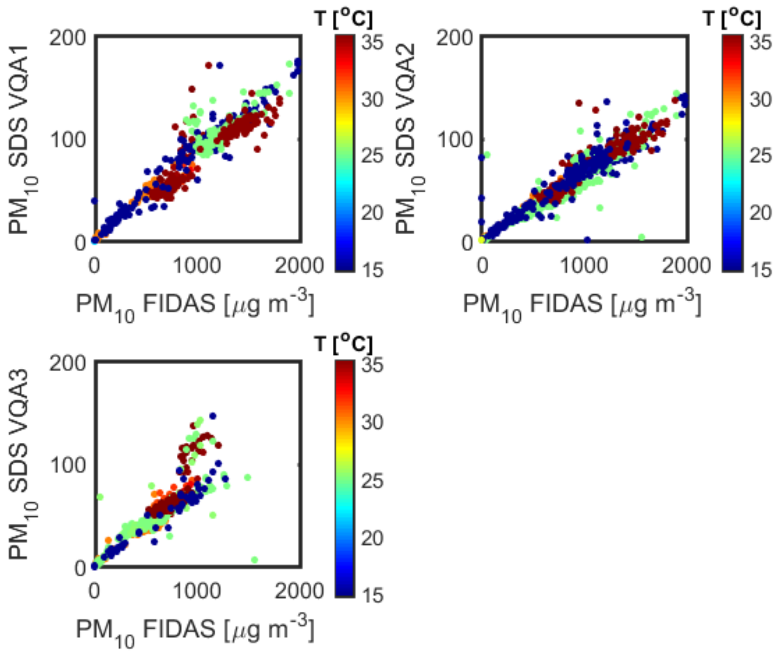
For relative humidity sensor VQA3 is influenced for PM10 with more scatter and a higher overestimation with higher humidity’s.





The sensors are during the testing not very susceptible for changes in temperature. Only for PM_{10} of sensor VQA3 there is some more scatter visible at higher temperatures, but this seems to be driven by relative humidity and not temperature.





8.6 Summary

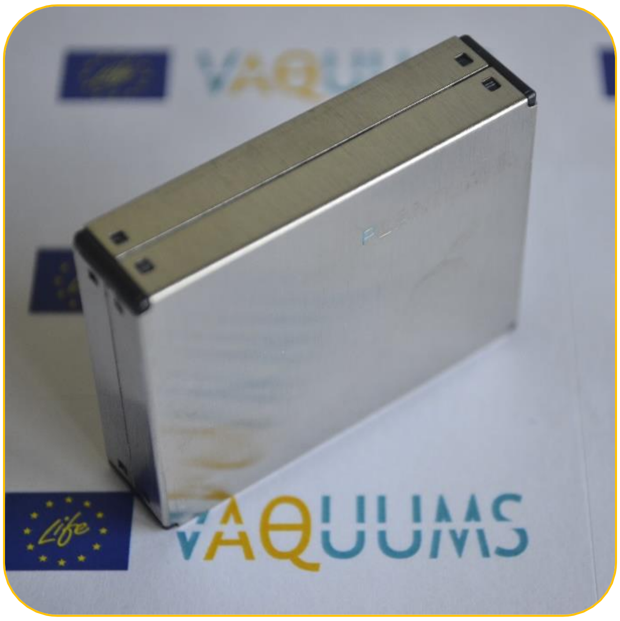
- **Accuracy**: The accuracy for the three SDS011 units was low especially for PM_{10} (around 20% for $PM_{2.5}$ and around 10% for PM_{10}), but reasonably stable.

- **Data recovery** for two SDS011 units was 100%, for unit 1 the data recovery was 46%.

- **Linearity of sensor response**: SDS011 units showed very good linear correlation (≥0.94) with the corresponding FIDAS measurements for $PM_{2.5}$ (between 0-100 µg m^{-3}) and PM_{10} (between 0-1000 µg m^{-3}).

- **Climate susceptibility**: One of the units is susceptible to RH when it is 50% or higher.

Laboratory Evaluation
Plantower PMS 7003 sensor



Manufacturer: Plantower
Link to website manufacturer

Link to test protocol

9 Plantower PMS 7003

Three **Plantower PMS 7003** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. These sensors have also been tested in the field (at Borgerhout station).

Plantower PMS 7003:

- Particle counter
- Unit measures PM_1, $PM_{2.5}$ & PM_{10}
- Time resolution: 1 minute
- Units IDs: Plantower-1, Plantower-2, Plantower-3.

Reference instrument

- FIDAS 200S
- Time resolution: 2 minutes

Different settings and PM concentrations

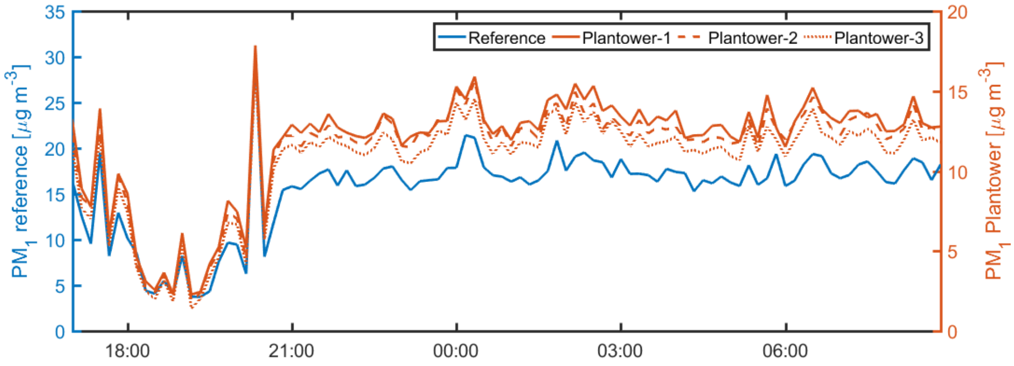
Plantower sensors were evaluated in batch 2

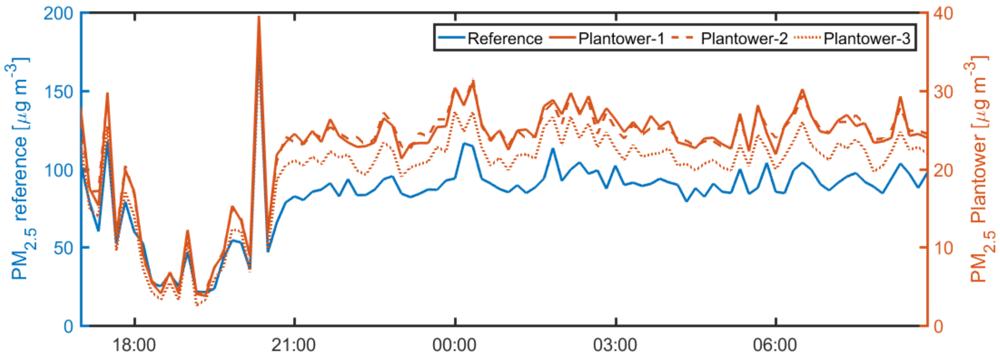
Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	15	30	0	0	0	0	1
2	15	50	26	156	552	1815	3060
3	15	80	31	166	561	1817	3036
4	15	20	24	126	403	1267	2109
5	15	20	1	4	16	61	105
6	15	80	5	32	118	401	653
7	15	50	3	19	67	206	323
8	15	20	16	84	273	846	1364
9	25	20	23	119	388	1248	2109
10	25	50	30	163	532	1649	2693
11	35	80	28	147	484	1556	2592
12	35	50	24	126	414	1345	2242
13	35	20	25	132	440	1462	2523
14	15	20	15	83	292	1025	1858
15	15	50	16	87	303	1063	1963
16	15	80	8	42	146	512	920

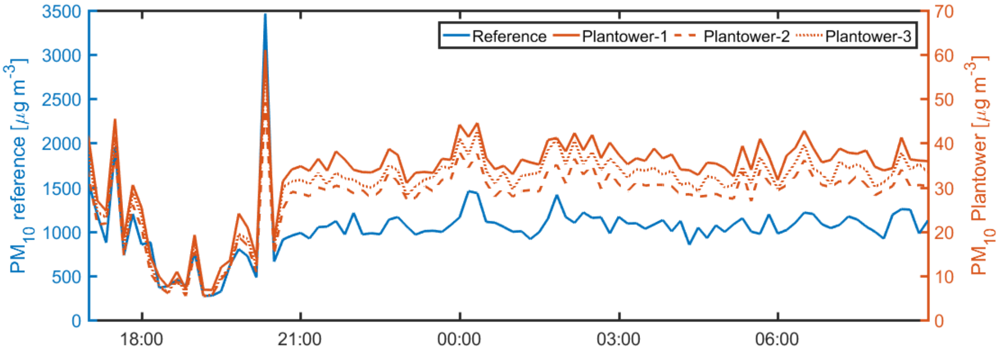
For the details about the laboratory protocol followed here, consult our test protocol.

9.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Plantower units on the right y-axis.



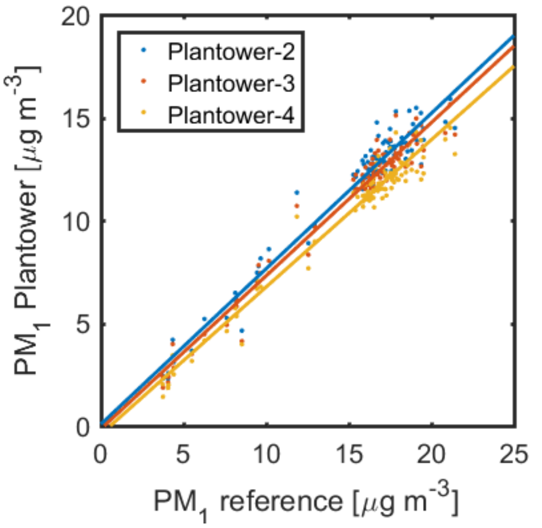


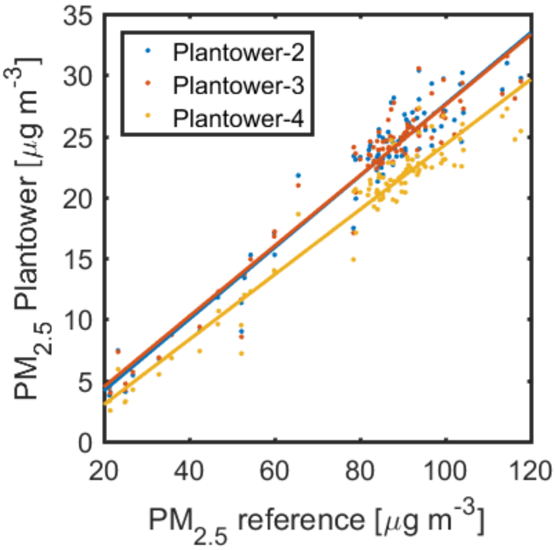


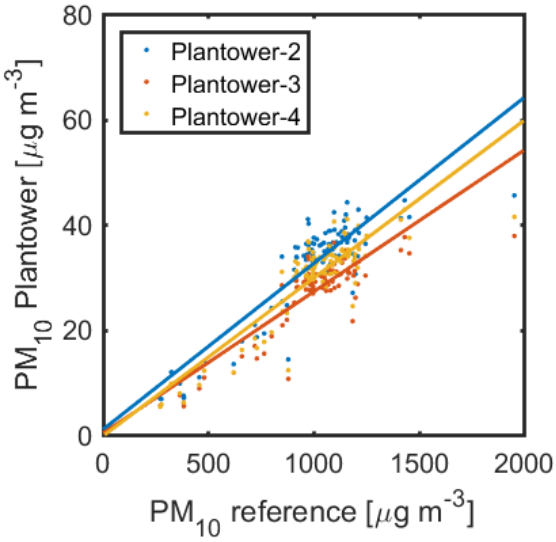
- All Plantower units track well with the PM_1, $PM_{2.5}$ and PM_{10} concentration changes as measured by the FIDAS reference.
- All units underestimate the FIDAS $PM_{2.5}$ and PM_{10} reference concentration. The PM_1 concentration of the units are more comparable to that of the FIDAS.

9.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.







Unit	PM_1			$PM_{2.5}$			PM_{10}		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
2	0.76	0.079	0.95	0.29	-1.7	0.93	0.032	1.0	0.77
3	0.74	-0.15	0.96	0.29	-1.3	0.93	0.027	0.28	0.77
4	0.72	-0.4	0.96	0.27	-2.3	0.93	0.030	-0.23	0.78

- In the concentration range of 0-25 μg m^{-3} for PM_1, 0-150 μg m^{-3} for $PM_{2.5}$, and 0-2000 μg m^{-3} for PM_{10}, the three Plantower units show a good correlation with the corresponding FIDAS data ($R^2 \geq 0.72$) at 15°C and 20% RH. Especially for PM_{10} the correlation was good ($R^2 \geq 0.95$).
- The slope of the regression equations is just below 1 for PM_1 (0.72-0.76), is low for $PM_{2.5}$ (0.27-0.29 for all units) and very low for PM_{10} (0.027 and 0.032).

9.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit	PM_1			$PM_{2.5}$			PM_{10}		
Setting	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	-35453	-35531	-135450	-23277	-40757	-37904	-274	-705	-363
2	68	72	64	25	31	23	3	4	3
3	60	78	54	22	30	19	3	3	3
4	62	82	59	23	32	21	3	4	3
5	NaN	NaN	72	NaN	NaN	NaN	NaN	NaN	NaN
6	63	78	55	22	31	17	3	3	2
7	47	55	51	14	19	15	2	2	2
8	62	83	62	22	32	22	3	4	3
9	55	79	68	20	30	23	3	4	3
10	61	63	62	22	24	22	3	3	3
11	64	65	59	23	24	21	3	3	3
12	61	68	58	21	25	20	3	3	3
13	NaN	NaN	59	NaN	NaN	NaN	NaN	NaN	NaN
14	76	73	69	27	27	24	3	3	3
15	90	85	75	53	40	29	8	5	5
16	85	66	58	51	25	20	7	3	2

- On average, the units show reasonable accuracy for PM_1 when compared to the FIDAS (in between 54 and 90%, excluding setting 1 where PM=0 µg m^{-3}). For $PM_{2.5}$ the sensors' accuracies are lower between 14% and 51% (excluding setting 1 where PM=0 µg m^{-3}). For PM_{10} the sensors' accuracies are even lower between 2 and 8% (excluding setting 1 where PM=0 µg m^{-3}).

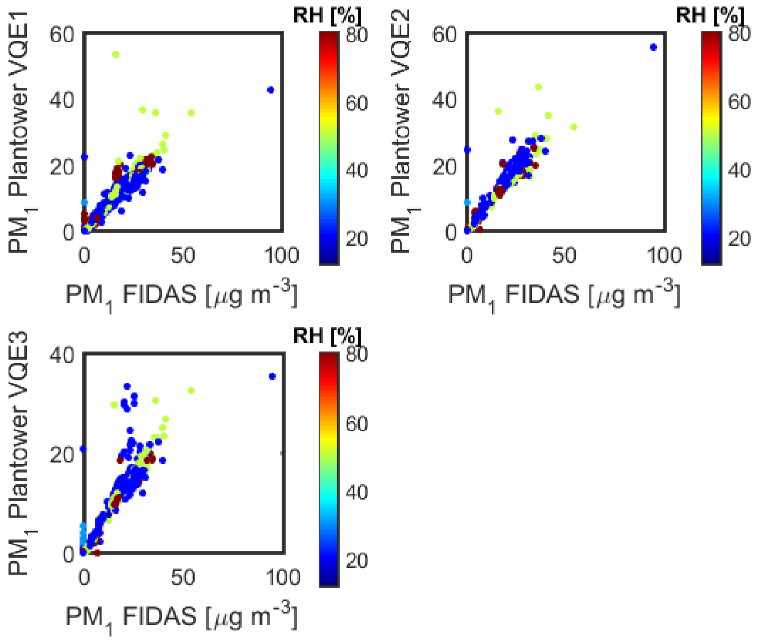
9.4 Data recovery

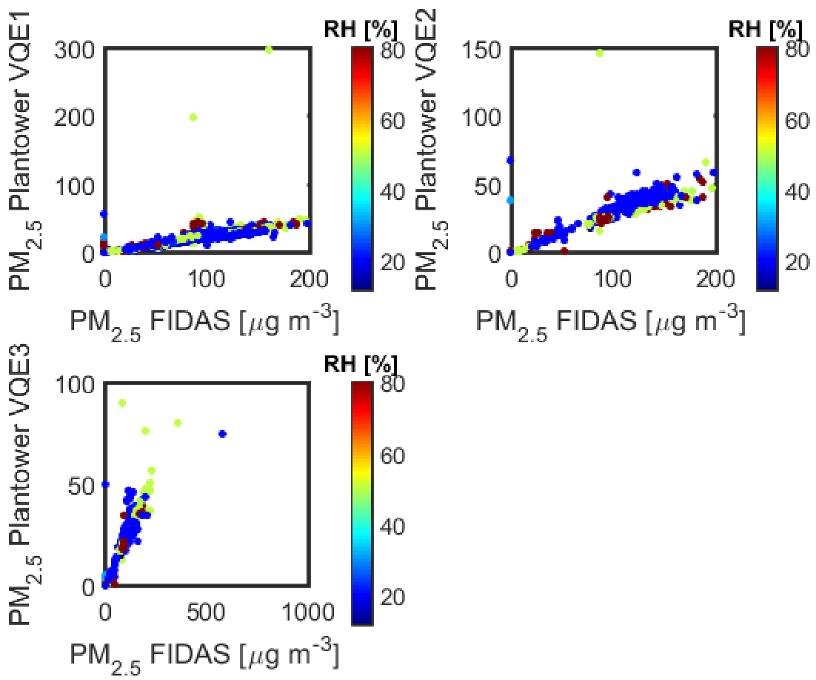
- Data recovery was 95% for all the units.

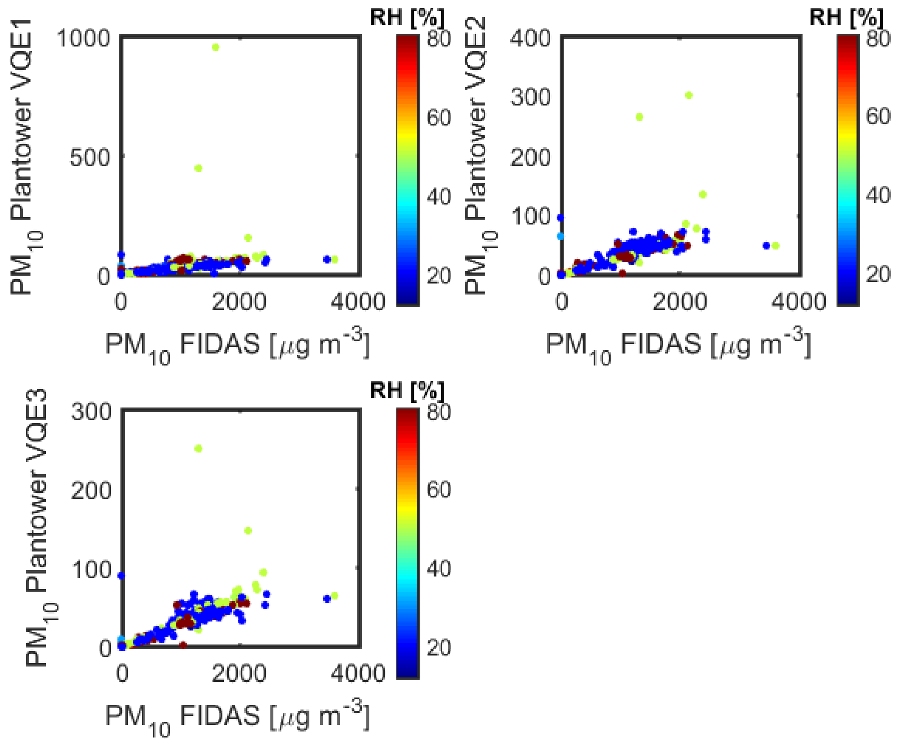
9.5 Climate susceptibility

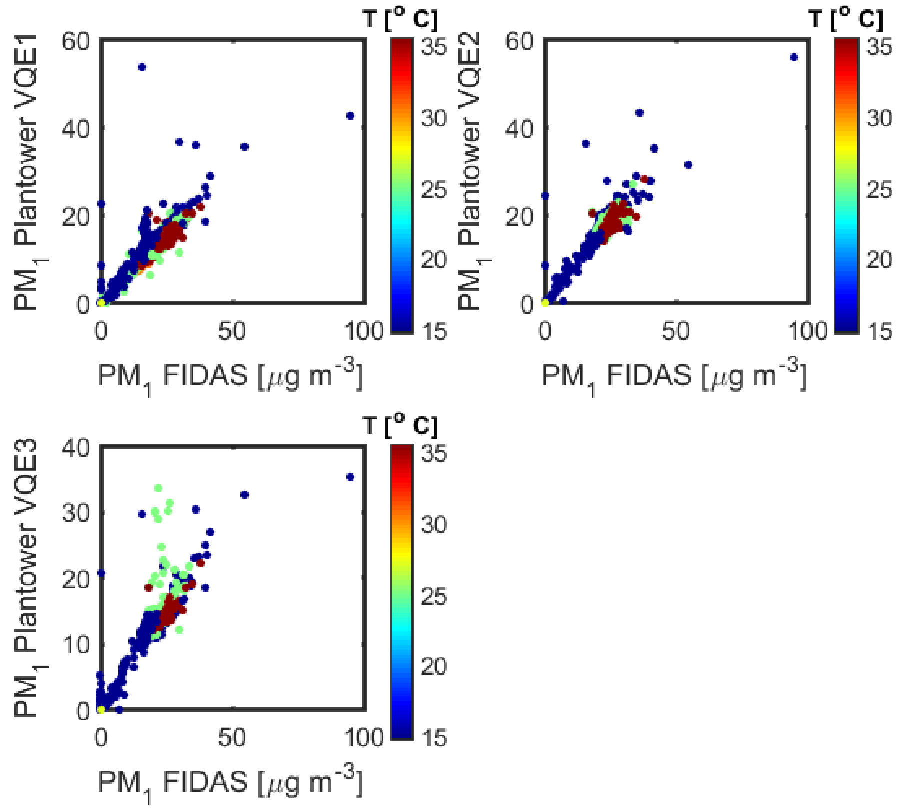
The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.

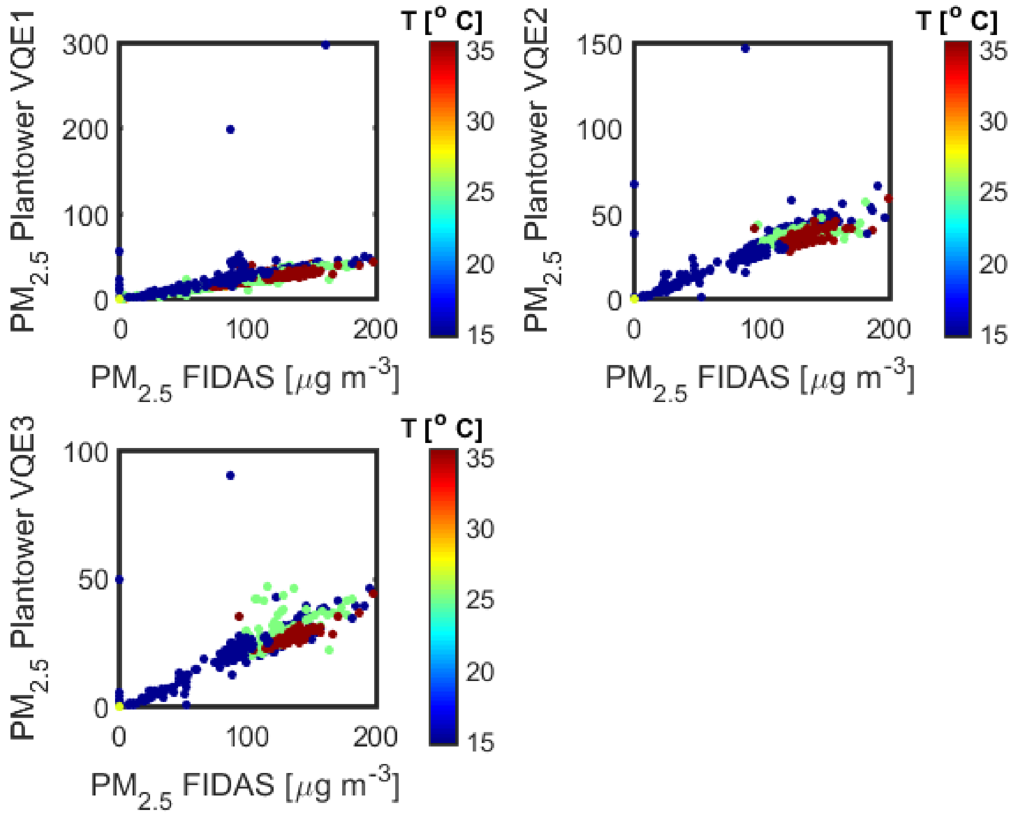
The sensor are somewhat influenced by relative humidity with more scatter for higher humidity's. Sensor VQE3 shows more scatter and higher values of PM_1, when the temperature is 25°C.

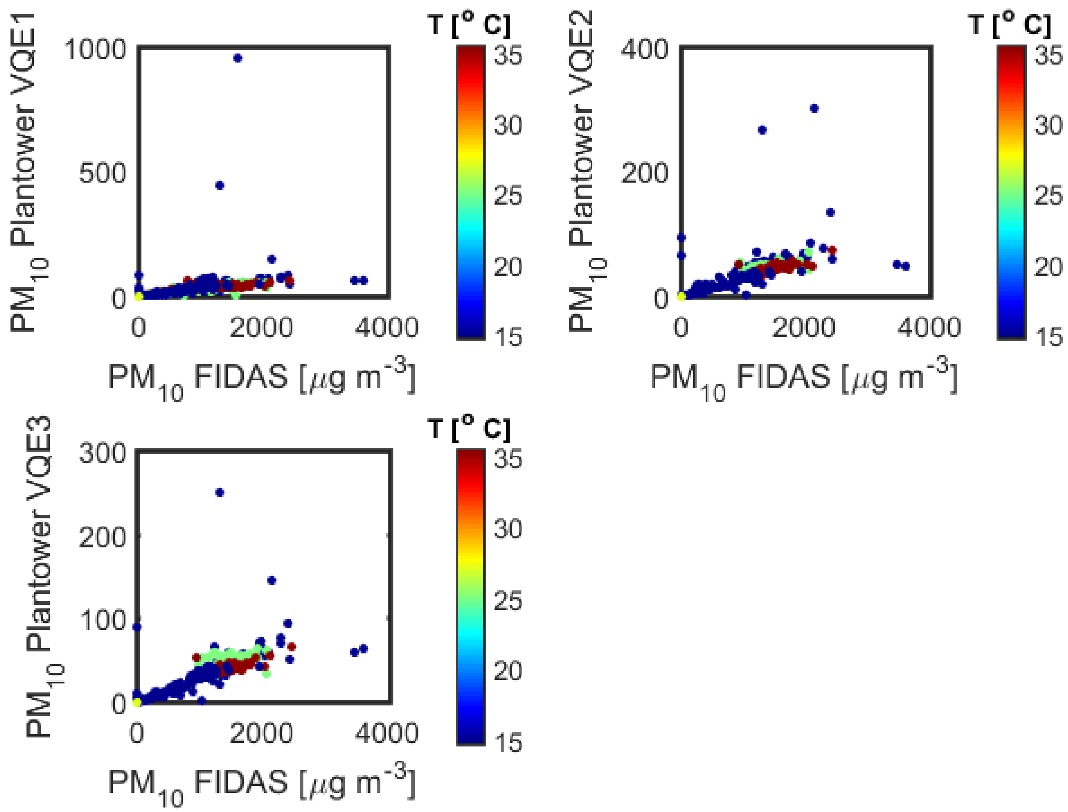





PM$_{10}$ Plantower VQE1
PM$_{10}$ Plantower VQE2
PM$_{10}$ Plantower VQE3
PM$_{10}$ FIDAS [μg m^{-3}]
RH [%]


PM$_1$ Plantower VQE1
PM$_1$ Plantower VQE2
PM$_1$ Plantower VQE3
PM$_1$ FIDAS [μg m^{-3}]
T [^{o} C]


PM2.5 Plantower VQE1
PM2.5 FIDAS [μg m-3]
PM2.5 Plantower VQE2
PM2.5 FIDAS [μg m-3]
PM2.5 Plantower VQE3
PM2.5 FIDAS [μg m-3]
T [o C]


PM10 Plantower VQE1
PM10 FIDAS [μg m-3]
PM10 Plantower VQE2
PM10 FIDAS [μg m-3]
PM10 Plantower VQE3
PM10 FIDAS [μg m-3]
T [o C]

9.6 Summary

- **Accuracy**: The accuracy for the three Plantower units was reasonable for PM_1 (in between 54 and 90%). For $PM_{2.5}$ the accuracies are lower and for PM_{10} they are very low.

- **Data recovery** for the three Plantower units was good with all values of 95%.

- **Linearity of sensor response**: Plantower units showed very good linear correlation for PM_1 ($R^2 \geq 0.95$) with the corresponding FIDAS measurements. For $PM_{2.5}$ the linearity was reasonably good ($R^2=0.93$ for all units). For PM_{10} the linearity was moderate with R^2 values of around 0.77.

- **Climate susceptibility**: All three units are somewhat susceptible to higher RH values (≥50%) for all PM values. One unit is for PM_1 also sensitive to T.

Laboratory Evaluation
Winsen ZH03B sensor

Manufacturer: Winsen
[Link to website manufacturer]
[Link to test protocol]

10 Winsen ZH03B

Three **Winsen ZH03B** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. These sensors have also been tested in the field (at Borgerhout station).

Winsen ZH03B:

- Particle counter
- Unit measures $PM_{2.5}$ & PM_{10}
- Time resolution: 1 minute
- Units IDs: Winsen-1, Winsen-2, Winsen -3.

Reference instrument

- FIDAS 200S
- Time resolution: 2 minutes

Different settings and PM concentrations

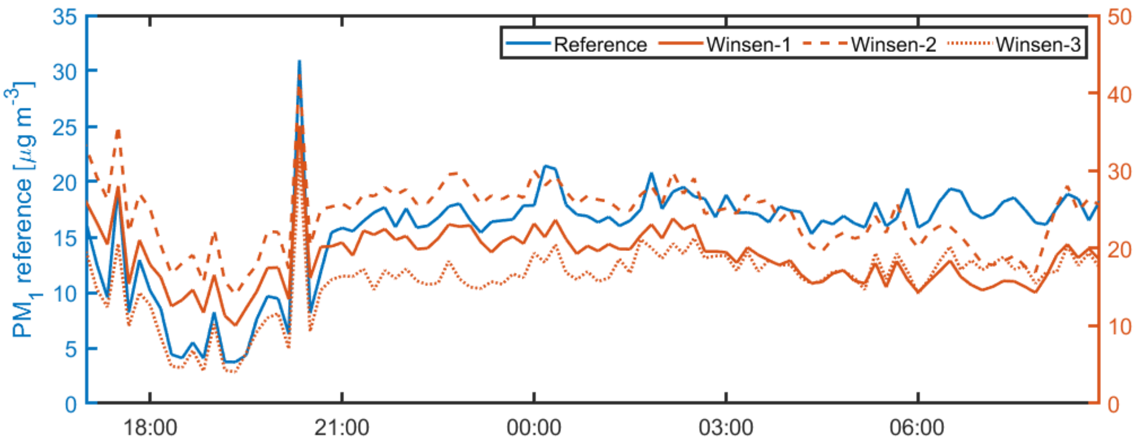
Winsen sensors were evaluated in batch 2

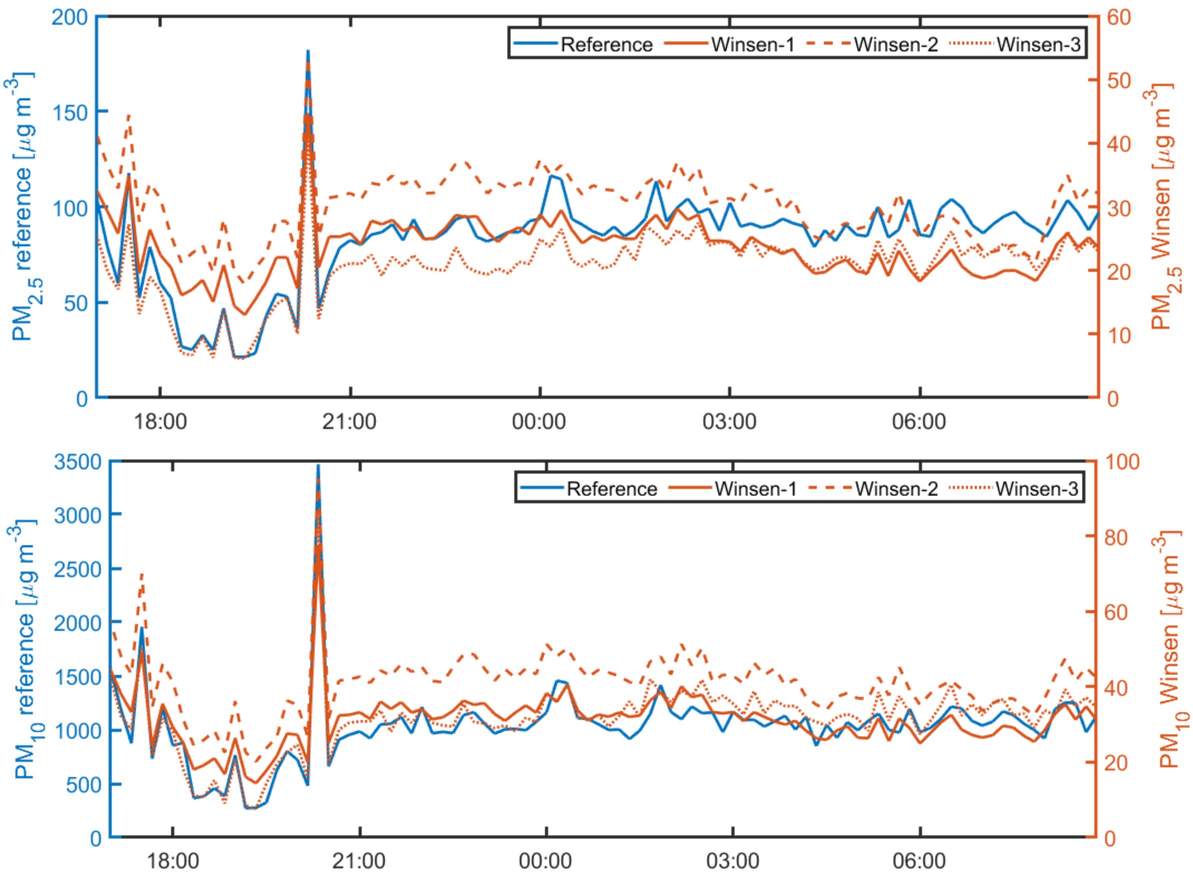
Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	15	30	0	0	0	0	1
2	15	50	26	156	552	1815	3060
3	15	80	31	166	561	1817	3036
4	15	20	24	126	403	1267	2109
5	15	20	1	4	16	61	105
6	15	80	5	32	118	401	653
7	15	50	3	19	67	206	323
8	15	20	16	84	273	846	1364
9	25	20	23	119	388	1248	2109
10	25	50	30	163	532	1649	2693
11	35	80	28	147	484	1556	2592
12	35	50	24	126	414	1345	2242
13	35	20	25	132	440	1462	2523
14	15	20	15	83	292	1025	1858
15	15	50	16	87	303	1063	1963
16	15	80	8	42	146	512	920

For the details about the laboratory protocol followed here, consult our test protocol.

10.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Winsen units on the right y-axis.



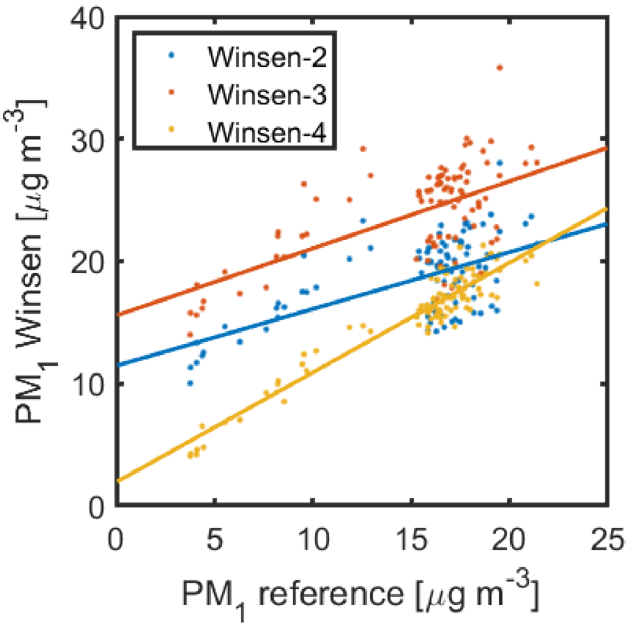


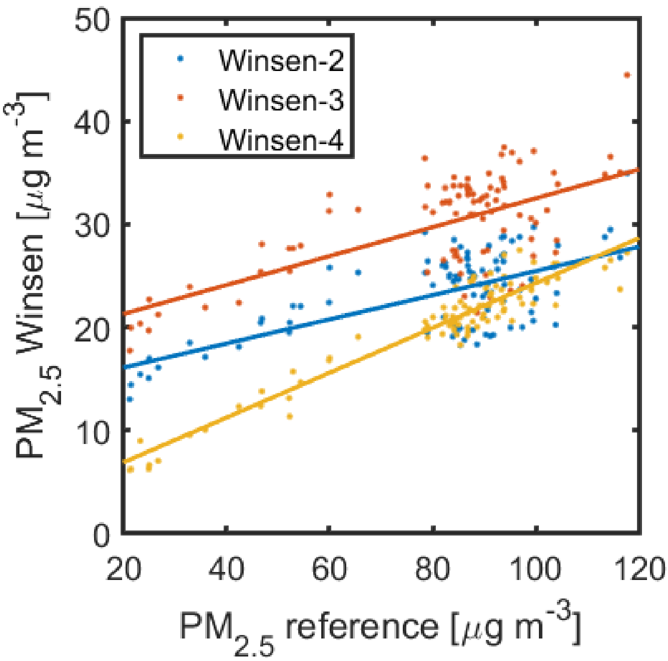
Note: Reference on left y-axis and Winsen units on right y-axis.

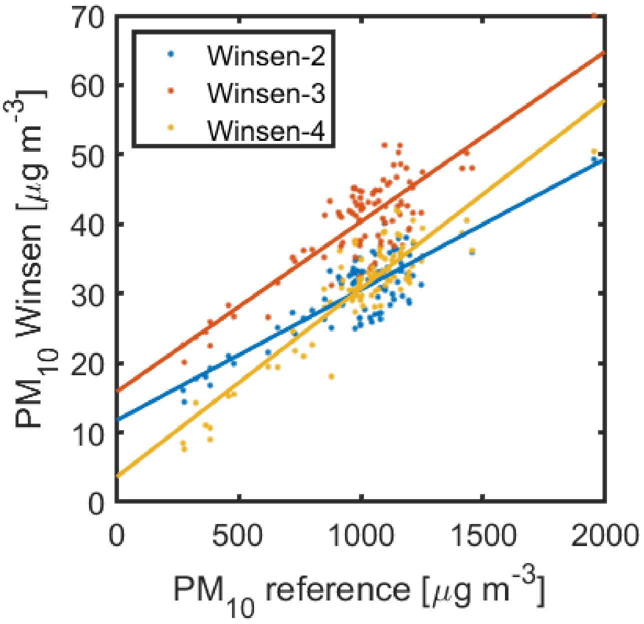
- All Winsen units track well with the PM_1, $PM_{2.5}$ and PM_{10} concentration changes as measured by the FIDAS reference.
- All units underestimate the FIDAS PM_1, $PM_{2.5}$ and PM_{10} reference concentration.

10.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.







Unit	PM_1			$PM_{2.5}$			PM_{10}		
	Slope	Inter-cept	R^2	Slope	Inter-cept	R^2	Slope	Inter-cept	R^2
2	0.46	11	0.37	0.12	14	0.42	0.019	12	0.72
3	0.55	16	0.35	0.14	18	0.40	0.024	16	0.72
4	0.89	2.0	0.90	0.22	2.5	0.91	0.027	3.6	0.82

- In the concentration range of 0-2000 µg m^{-3} for PM_{10}, the three Winsen units show a moderate correlation with the corresponding FIDAS data ($R^2 \geq 0.72$) at 15°C and 20% RH. For $PM_{2.5}$ the fit is good for one unit 4 ($R^2=0.91$), but the other two have a much lower R^2 (0.40 and 0.42). Also for PM_1 the fit of unit 4 with the reference is reasonable good ($R^2=0.90$), while for the other units it is much lower (R^2 of 0.35 and 0.37).

- The slope of the regression equations is somewhat low for PM_1 (0.46-0.89), low for $PM_{2.5}$ (0.12-0.22) and very low for PM_{10} (0.019-0.027).

10.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit	PM_1			$PM_{2.5}$			PM_{10}		
Setting	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
2	94	72	95	23	28	23	3.3	4.1	3.6
3	91	100	87	21	23	20	3.0	3.5	2.9
4	86	96	84	21	24	21	3.1	3.6	3.0
5	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
6	96	90	100	23	26	24	2.5	3.3	3.2
7	85	99	80	24	27	23	2.6	3.3	2.6
8	85	98	80	21	25	20	3.0	3.8	2.9
9	83	93	75	20	23	19	2.8	3.3	2.6
10	84	88	83	19	21	19	2.8	3.2	2.9
11	80	84	81	19	20	19	2.6	2.9	2.6
12	80	85	80	19	20	19	2.6	2.9	2.6
13	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
14	79	44	98	28	37	25	3.0	4.0	3.0
15	-36	-159	-197	52	79	85	6.3	8.8	11
16	75	-84	-16	29	64	54	3.1	7.9	13

- For PM_1 the accuracies of the sensor are reasonable for settings 2 to 12 (in between 72 and 100%), although somewhat lower than the reference. However, for the last two settings the accuracies become negative (PM_1 concentrations are higher for sensors than for reference). The accuracy for all unit for $PM_{2.5}$ is in general low (in between 19 and 85%). For PM_{10} the sensors' accuracies are even lower between 2 and 13%.

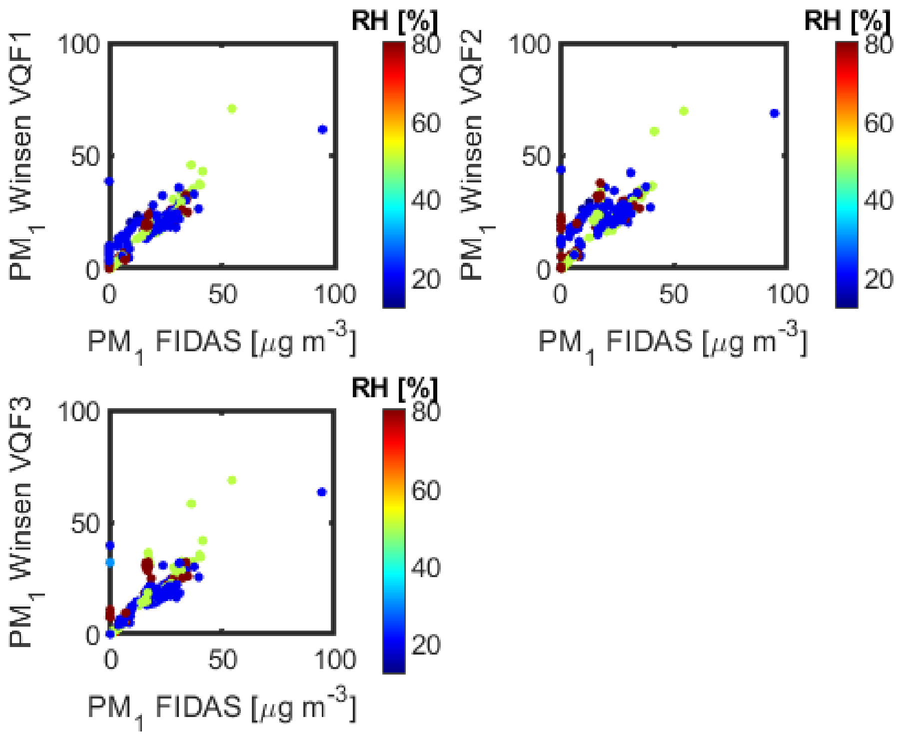
Data recovery

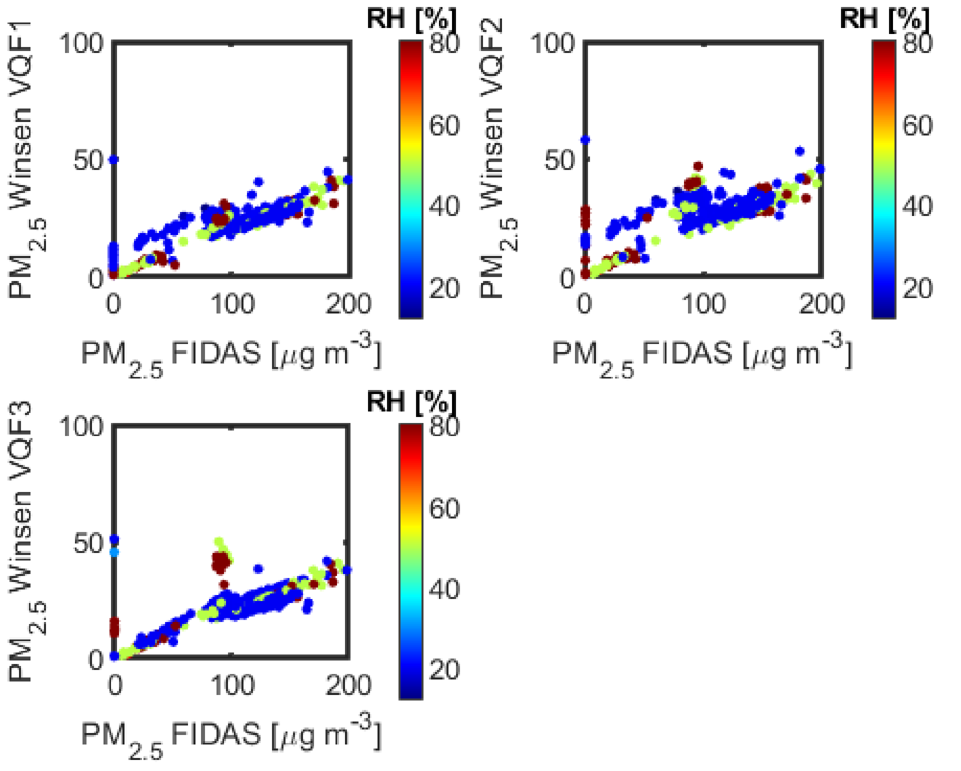
- Data recovery was 95% for all the units.

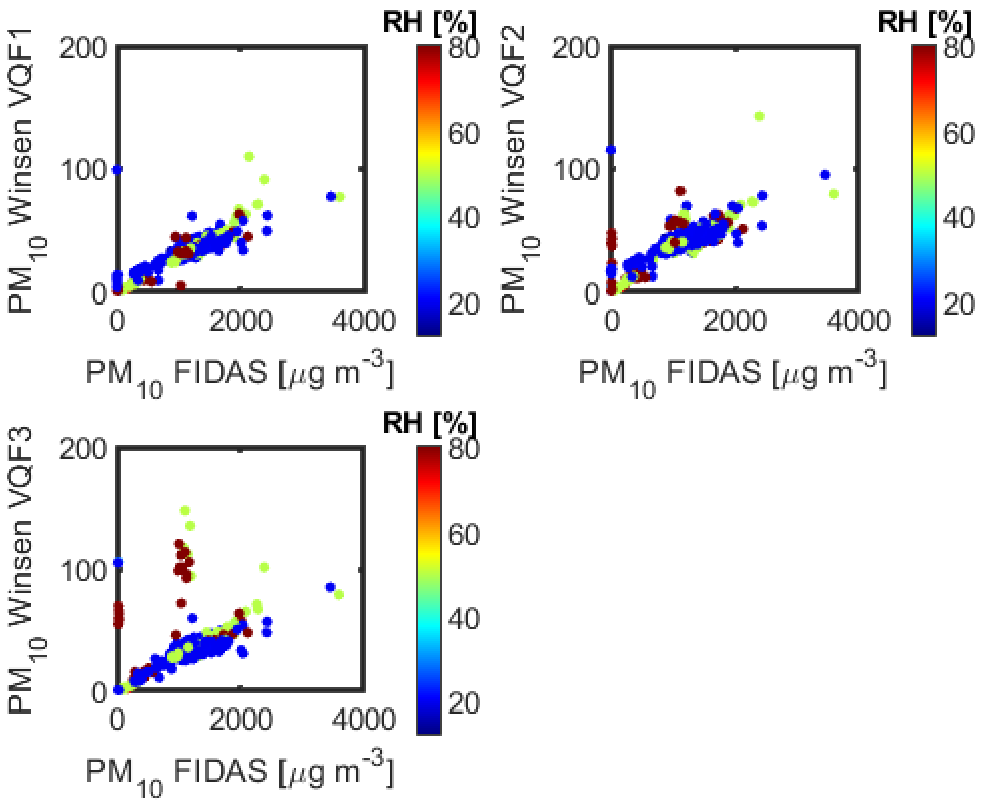
10.4 Climate susceptibility

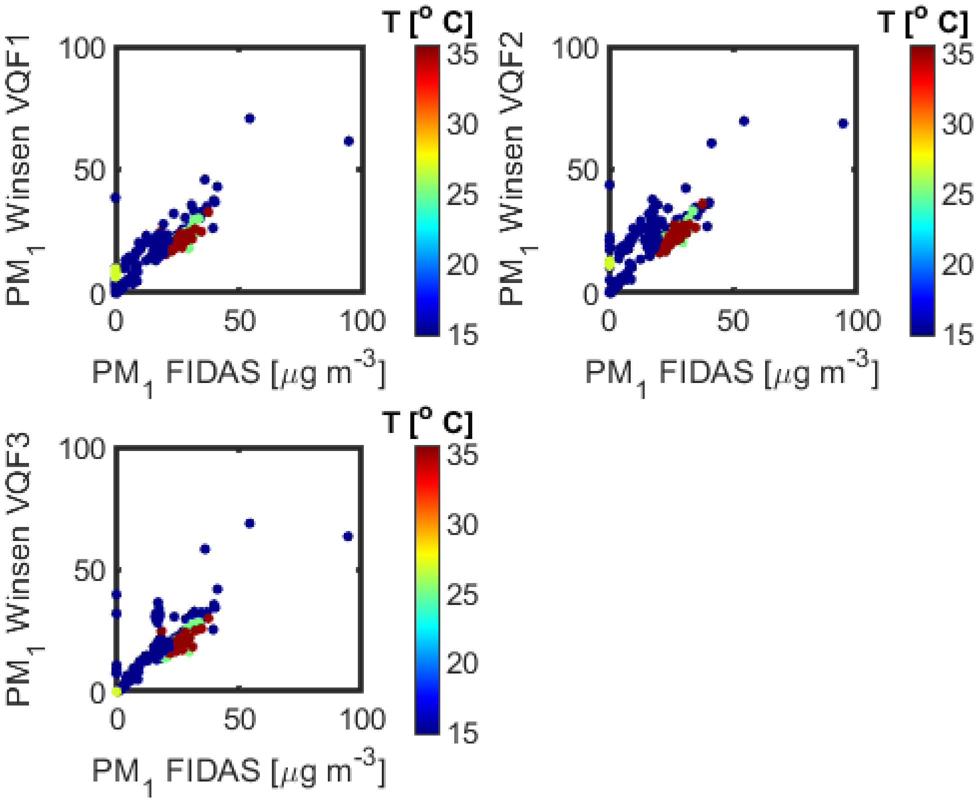
The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.

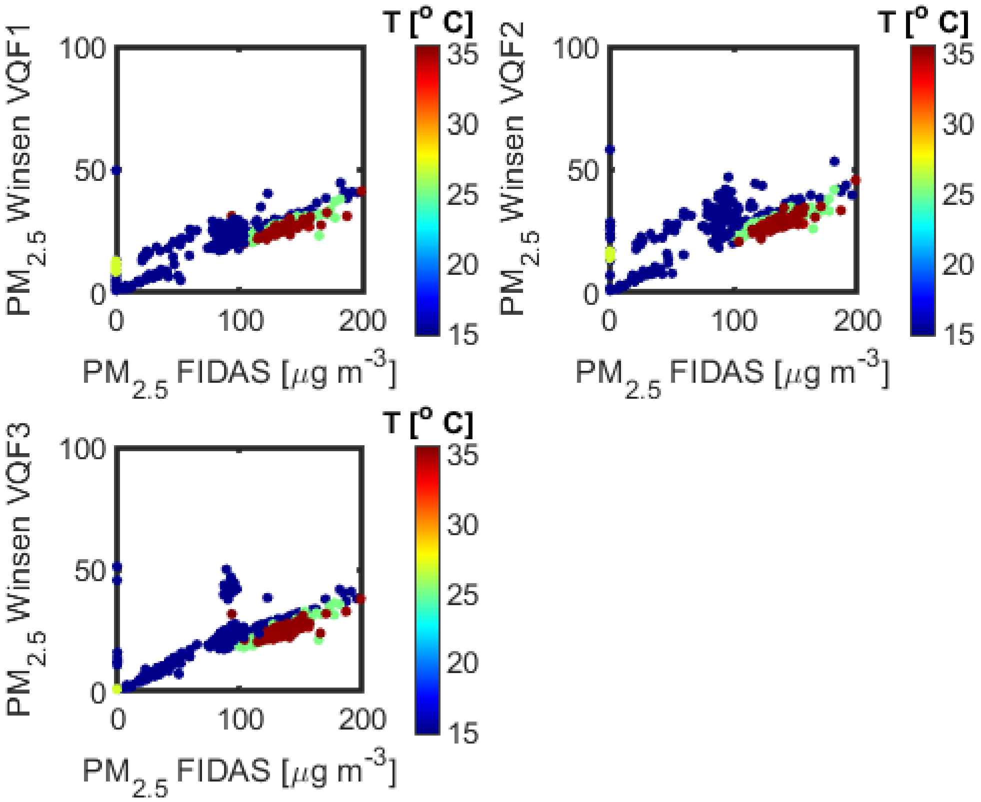
There was one outlier for all three sensor for all PM sizes, which is not included in the figures. For relative humidity only PM_{10} of sensor VQF3 is sensitive, with higher values and more scatter with higher relative humidity's. The sensors do not show any sensitivity to a change in temperature.

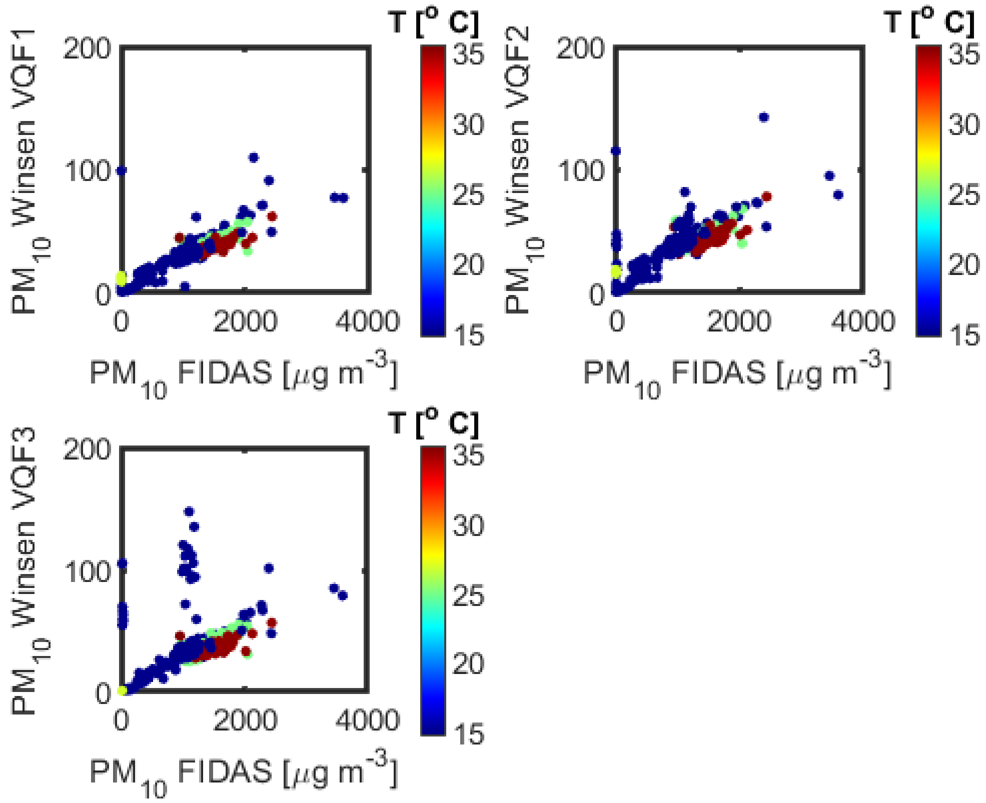



PM$_{2.5}$ Winsen VQF1
PM$_{2.5}$ Winsen VQF2
PM$_{2.5}$ Winsen VQF3
PM$_{2.5}$ FIDAS [μg m^{-3}]
RH [%]
0
50
100
200
20
40
60
80


PM$_{10}$ Winsen VQF1
PM$_{10}$ Winsen VQF2
PM$_{10}$ Winsen VQF3
PM$_{10}$ FIDAS [μg m^{-3}]
RH [%]
0
100
200
2000
4000
20
40
60
80


PM1 Winsen VQF1
PM1 Winsen VQF2
PM1 Winsen VQF3
PM1 FIDAS [μg m-3]
T [o C]
0
50
100
15
20
25
30
35


PM2.5 Winsen VQF1
PM2.5 Winsen VQF2
PM2.5 Winsen VQF3
PM2.5 FIDAS [μg m-3]
T [o C]
0
50
100
200
15
20
25
30
35


T [° C]
35
30
25
20
15
200
100
0
0
2000
4000
PM_{10} Winsen VQF1
PM_{10} FIDAS [μg m^{-3}]
PM_{10} Winsen VQF2
PM_{10} Winsen VQF3

10.5 Summary

- **Accuracy**: The accuracy for the three Winsen units was reasonable good for PM1 in between 72 and 100%, only for the last three settings more discrepancy occurred. For $PM_{2.5}$ it was reasonable low for $PM_{2.5}$ (in between 19 and 85% and in general around 25%). For PM_{10} the accuracies were very low (in between 2 and 13 %).

- **Data recovery** for the three Winsen units was good with all values of 95%.

- **Linearity of sensor response**: The Winsen units for PM_1 showed a relatively poor linearity with the reference, expect for one (with R^2 values of 0.35, 0.37 and 0.90). For PM10 the units showed a reasonable good linear correlation with the reference (R^2=0.72-0.91). For $PM_{2.5}$ the linearity was relatively low, expect for one unit (R^2=of 0.40, 0.42 and 0.91). Unit 3 (Winsen-4) had clearly a better linearity with the reference than the other 2 units.

- **Climate susceptibility**: Only one unit showed for PM_{10} a sensitivity with higher relative humidity's (≥50%). For temperature all three units did not show susceptibility.

Laboratory Evaluation
Shinyei PPD60 sensor

Manufacturer: Shinyei Technology
[Link to website manufacturer]v

[Link to test protocol]

11 Shinyei PPD60

Three **Shinyei PPD60** sensors have been evaluated in the TNO Testing Laboratory under controlled PM concentrations, temperatures and relative humidity's. These sensors have also been tested in the field (at Borgerhout station). For unit 4 unfortunately no data was retrieved during the lab testing, so this unit could not be evaluated.

Note the Shinyei PPD60 are not calibrated by the manufacturer. Thus the ramping experiment in the lab was used to calibrate the sensors. The sensors were calibrated using the following equation $y = a \cdot x^2 + b \cdot x$. The fit of the data to this function was very high, with R^2-values above 0.99 and RMSE values from 0.53 to 0.60 µg m^{-3}. However, this calibration did lead to a upper limit of the calibration range for unit 1 up to 78 µg m^{-3} and 87 µg m^{-3} for unit 3. Above these values no estimates of the $PM_{2.5}$ values can be given.

Shinyei PPD60:

- Particle counter
- Unit measures $PM_{2.5}$
- Time resolution: 1 minute
- Units IDs: PPD60-1, PPD60-3, PPD60-4.

Reference instrument

- FIDAS 200S

- Time resolution: 2 minutes

<u>Different settings and PM concentrations</u>

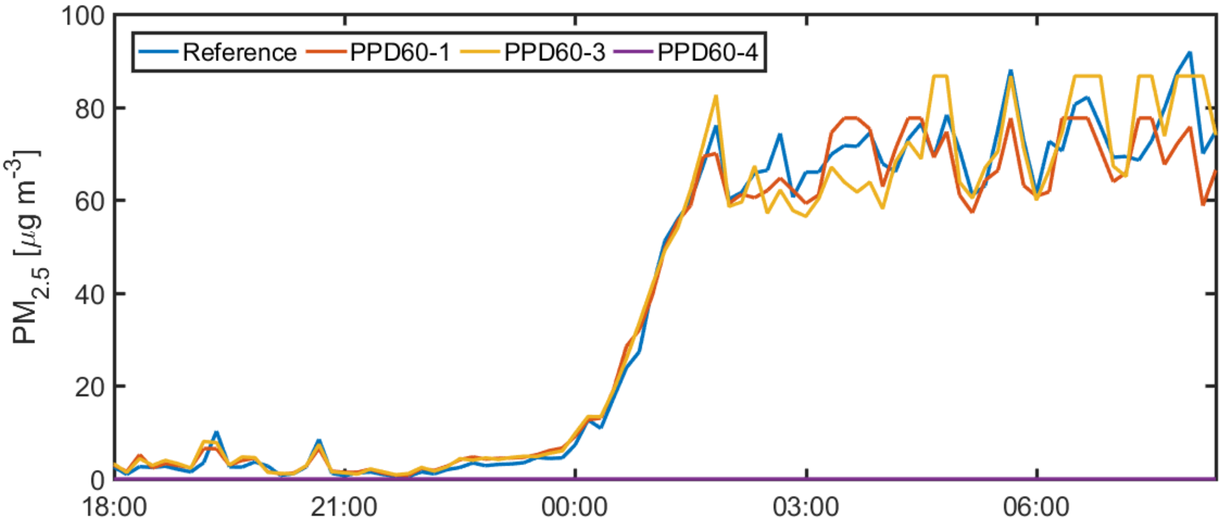
Shinyei PPD60 sensors were evaluated in batch 1

Setting nr	T [oC]	RH [%]	PM1 [µg m-3]	PM2.5 [µg m-3]	PM4 [µg m-3]	PM10 [µg m-3]	PMtotal [µg m-3]
1	30	20	8	38	113	307	497
2	30	50	18	86	263	751	1266
3	35	80	18	88	268	781	1297
4	30	20	0	0	0	0	0
5	25	20	9	46	153	510	954
6	35	20	18	88	260	726	1092
7	35	80	28	136	385	1016	1447
8	35	50	26	123	348	907	1265
9	25	50	27	129	369	975	1405
10	15	50	7	38	129	398	646
11	15	20	16	77	230	632	955
12	15	50	26	133	409	1212	1955

For the details about the laboratory protocol followed here, consult our test protocol.

11.1 Ramping experiment: $PM_{2.5}$ and PM_{10} versus Reference

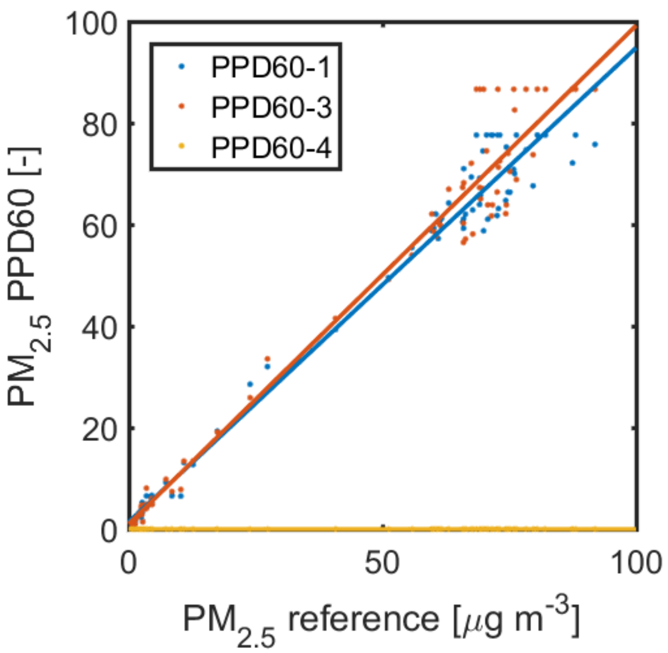
The ramping experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means. Note that the measurements of the reference are shown on the left y-axis and the measurements of the Shinyei PPD60 units on the right y-axis.



- Unit PPD60-4 did not retrieve any data (only zeros were recorded, despite turning the power off and on).
- The two remaining units (PPD60-1 and PPD60-3) both show the same pattern as the reference monitor.
- Due to the calibration undertaken with this dataset the $PM_{2.5}$ of the sensors and reference monitor are similar.

11.2 Linearity

The linearity experiment was conducted at 30°C and 20% relative humidity (setting 1) with 10-minte means.



Unit	PM2.5		
	Slope	Intercept	R^2
1	0.94	1.4	0.98
3	0.98	0.98	0.97

- In the concentration range of 0-100 µg m^{-3} for $PM_{2.5}$, the two PPD60 units show a good correlation with the corresponding FIDAS data ($R^2 \geq 0.97$) at 30°C and 20% RH.
- The slope of the regression equations is close to one for $PM_{2.5}$ (0.94 and 0.98), which is to be expected since this dataset was used for calibration.

11.3 Accuracy

The accuracy was calculated under the different temperature, relative humidity and PM settings described under point 1.

Unit	PM2.5	
Setting	1	3
1	97	99
2	82	96
3	84	90
4	-38	-288
5	68	91
6	62	NaN
7	58	NaN
8	63	70
9	60	67
10	69	99
11	73	85
12	58	65

- On average, the units show a reasonable good accuracy when compared to the FIDAS. For $PM_{2.5}$ the sensors' accuracies are between 58% and 99% (excluding setting 4 where PM=0 µg m^{-3}).

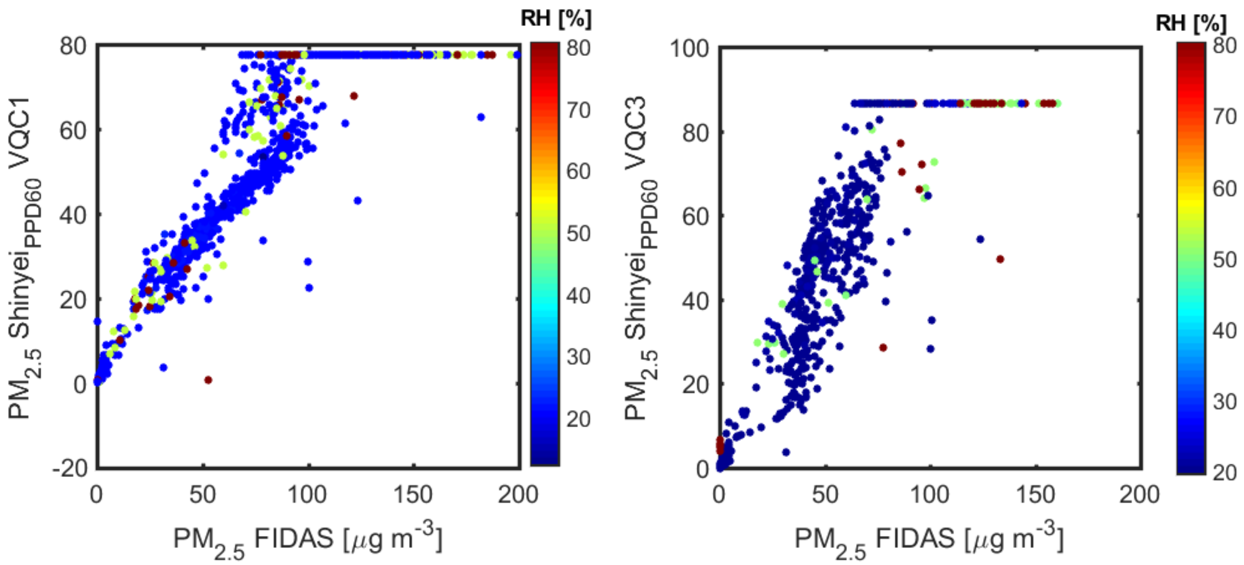
- The accuracy does decrease over time with values starting close to 100% and during the last setting the values were closer to 60%. This is probably partly due to higher $PM_{2.5}$ values (>100 µg m^{-3}) generated during setting 7, 8, 9, and 12, where this sensor cannot distinguish the absolute values.

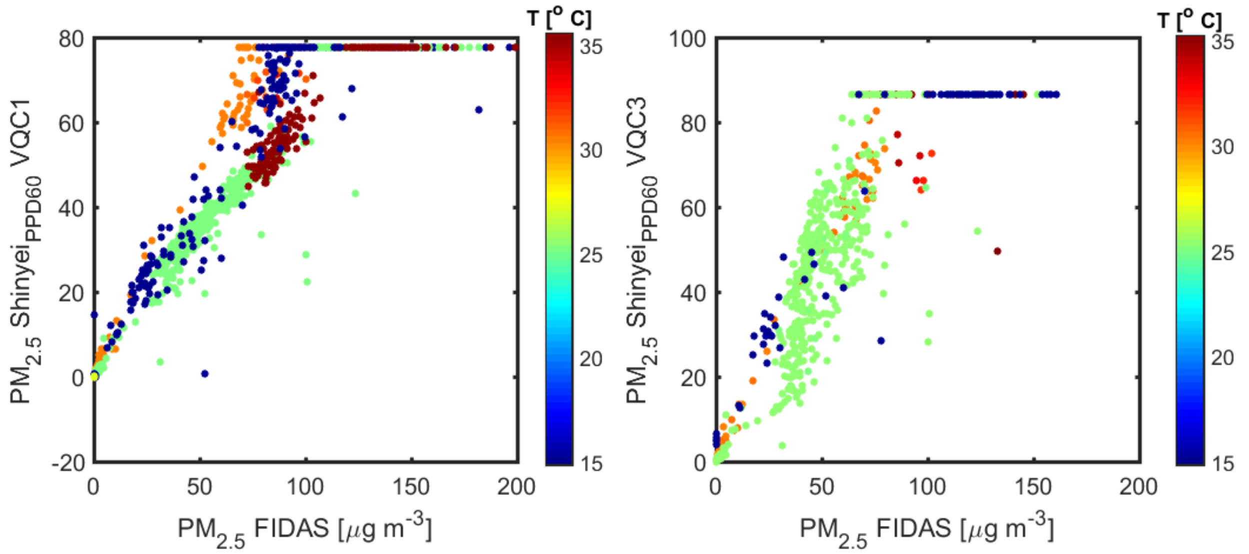
11.4 Data recovery

- Data recovery was 99% and 87% for the units 1 and 3 respectively. Unit 4 had a data recovery of 0%, since it only registered PM values of 0 µg m^{-3}.

11.5 Climate susceptibility

The influence of temperature and relative humidity was studied at temperatures of 15°C, 25°C and 35°C and a relative humidity of 20%, 50% and 80%.





Note due to the 2nd order quadratic calibration the sensors are unable to distinguish higher $PM_{2.5}$ values (78 µg m^{-3} for VQC1 and 87 µg m^{-3} for VQC3).

11.6 Summary

- **Accuracy**: The accuracy for the two PPD60 units was reasonably good (around 80% for $PM_{2.5}$). However, for settings where the average $PM_{2.5}$ values were above 100 µg m^{-3} the accuracy dropped to 60%.

- **Data recovery** was good for two units with values of 99% and 87%. Unit 4 had a data recovery of 0%, since it only registered PM values of 0 µg m^{-3}.

- **Linearity of sensor response**: The linearity of the two units was good with R^2 ≥0.97. However, for higher $PM_{2.5}$ values (>60 µg m^{-3} measured by the FIDAS) the sensitivity decreases.

- **Climate susceptibility**: The two units showed a slight susceptibility for temperature.