PurpleAir PA-II Temperatures and RH compared to measured indoor and outdoor values

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PurpleAir PA-II monitors are warmer than the surrounding air, perhaps due to the waste energy used to operate the fan and the two laser sensors. The warmer air also results in reduced relative humidity (RH). Here we examine how temperatures and RH estimates reported by PurpleAir PA-II monitors are related to observed collocated research-grade temperature-RH dataloggers.

Indoor data

Over the years 2019-2020, two PA-II monitors were operated inside a home beginning Jan 10, 2019. Two additional PA-II monitors were bought in June of 2020 and operated outside the house, one beginning in June, 2020, and the other in September, 2020. Values have been recorded through Dec 31, 2020.

Over this same period, two Hobo monitors (indoors: HOBO UX-90-001; outdoors: HOBO Pro V2 Model U23-001) collected Temperature and RH data indoors (for the full two years) and outdoors (for the last 6 months). The Hobo monitors are said to be accurate to within 0.2 ^{o}C (0.38 oF) and 3.5 % RH. (https://www.onsetcomp.com/products/data-loggers/rx2105). The Bosch BME device within the PurpleAir monitors claims an accuracy of 1.0 C (1.8 F) and 3% RH. (See Appendix for brief discussion of the maximum variation one might expect in comparing the two devices). The indoor T & RH data have been analyzed over the period from Jan 10, 2019 to June 12, 2020. About 400,000 2-minute average temperature measurements were collected by the PurpleAir and Hobo monitors. Some losses of the RH measurements occurred and only 360,000 paired Hobo and PurpleAir measurements were collected (Table 1).

Table 1. PurpleAir Temperature (^{o}F) and RH (%) compared to measured values inside a home over 18 months.

	N	Mean	SD	SE	Min	10th	25th	Median	75th	90th	Max
Matched Temperatures											
Measured indoor temperature (^{o}F)	407148	72.05	3.83	0.01	54.6	67.4	69.6	71.9	74.2	77.3	85.9
Mean PurpleAir temperature (^{o}F)	407148	80.62	3.80	0.01	60.5	76	78	80.5	83	85.5	95
Matched RH											
Hobo RH 2-min avg %	363746	46.88	4.76	0.01	23.5	40.3	43.7	47.4	50.3	52.5	63.3
Mean PA RH	363746	30.66	3.33	0.01	17	26	28.5	31	33	34.5	39.5

PurpleAir mean temperatures averaged about 8.6 degrees (Fahrenheit) greater than ambient indoor temperatures, whereas the PurpleAir mean indoor RH values were about 16.2 percentage

points below ambient indoor RH. However, the differences between the two instruments were not constant. They showed a gradient with increasing ambient T and RH values.

Indoor temperature

From the table, the mean temperature differences were quite small, ranging from about 6 ^{o}F at the very lowest indoor temperatures (54.6 ^{o}F) to about 9 ^{o}F at the highest indoor temperatures (86 ^{o}F). However, graphing all measured temperatures show that there is a moderately wide uncertainty band around the regression parameters (Figure 1). For example, at a PurpleAir temperature reading of 70 ^{o}F, the best estimate of the actual indoor temperature is 62 ^{o}F, but Figure 1 shows a range of 60-64 ^{o}F. Indeed, for any given PurpleAir temperature in the range from 65-95 ^{o}F, the 95% range of actual indoor temperatures is generally ± 2 ^{o}F (or ± 1 ^{o}C) around the estimated value shown in the "Indoor Temperature" column. These are *not* measurement errors, since the two thermometers are accurate to within 0.2 degrees Celsius. Rather, it must be that some aspects of the environmental conditions within the PurpleAir PA-II monitor have an effect on the measured temperature. We will explore this idea below.

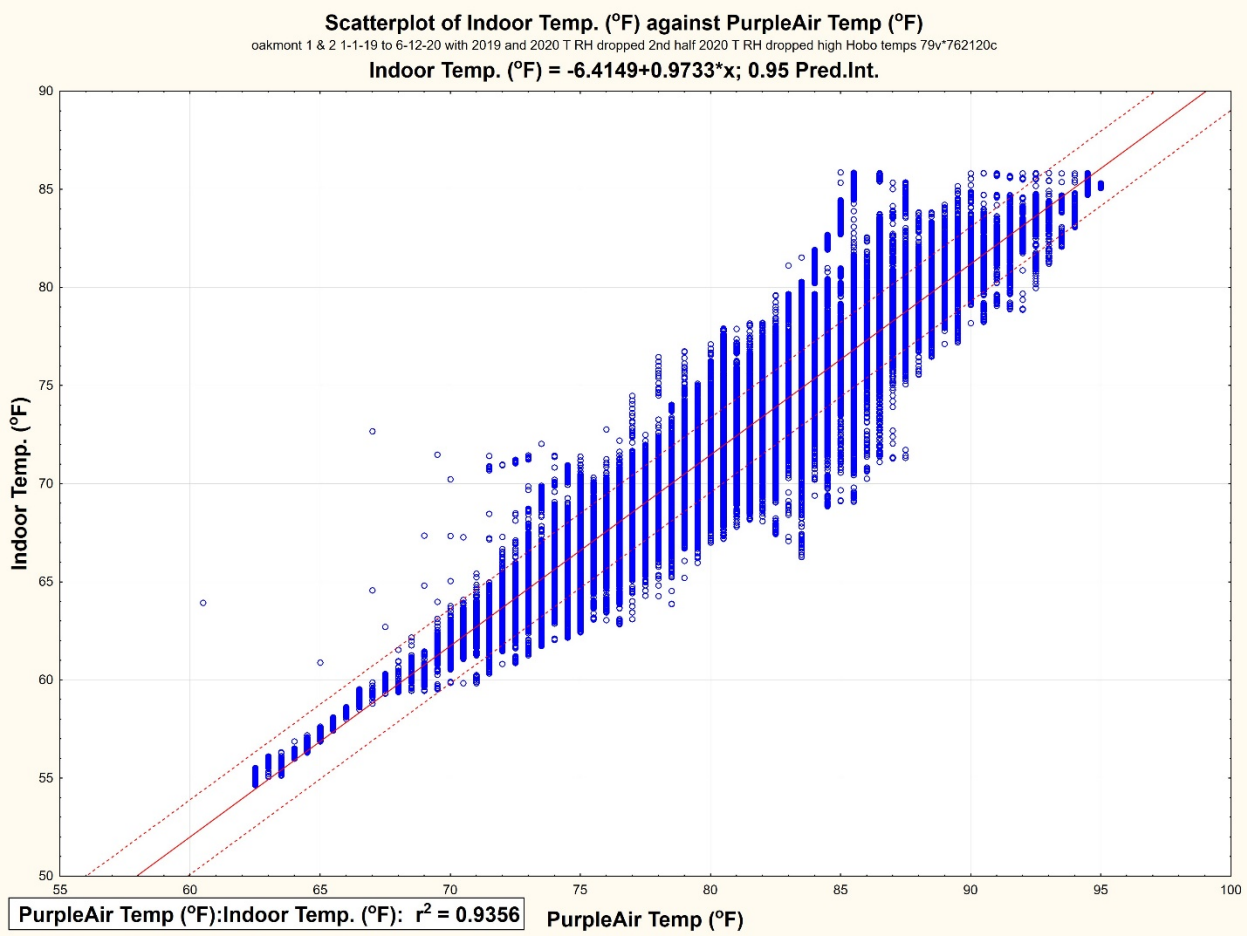

Figure 1. Regression of Indoor Air Measured Temperatures (°F) on observed PurpleAir indoor temperatures (°F). Dashed lines enclose 95% of the data.

For persons preferring to work with the Celsius scale, a similar regression is provided (Figure 2).

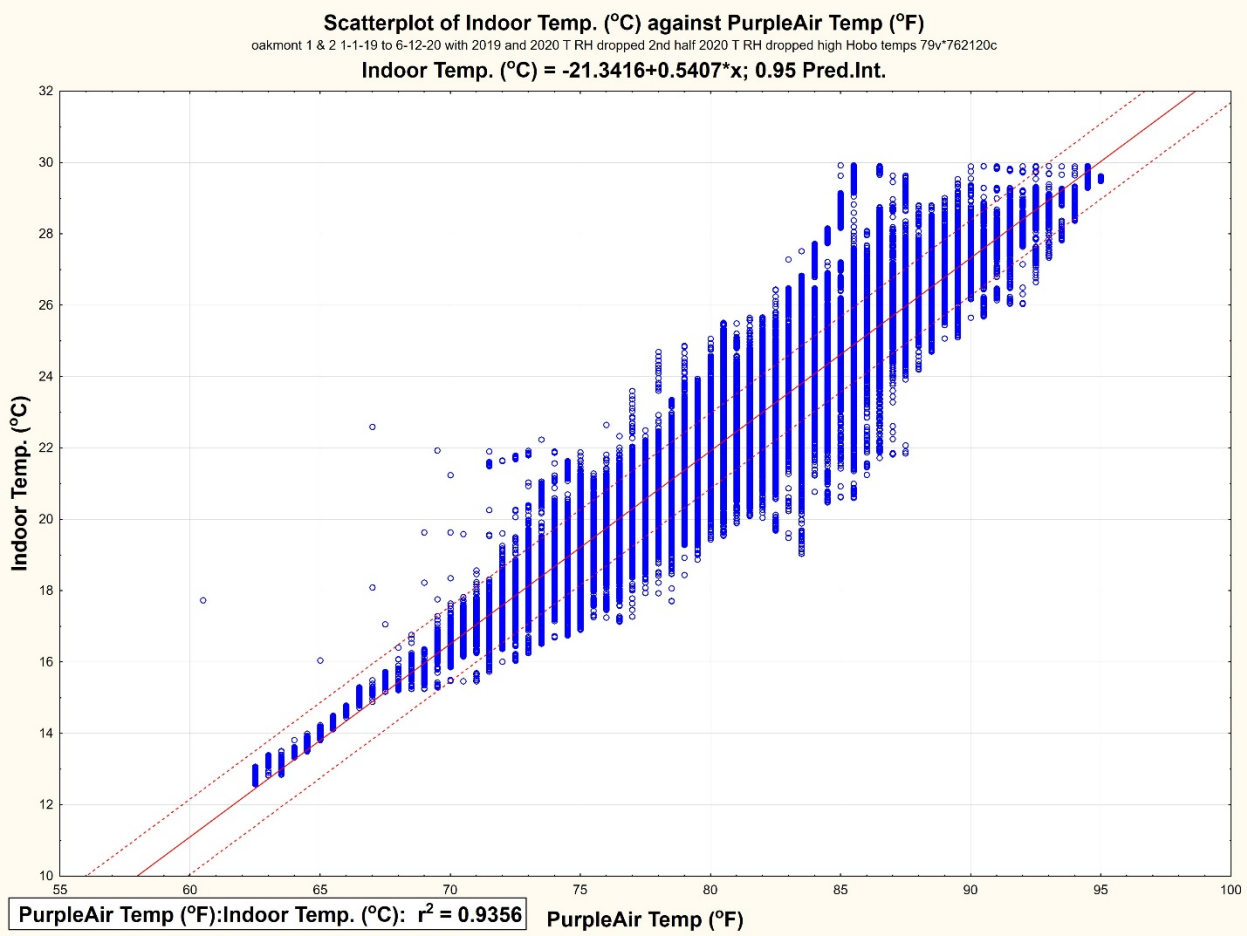

Figure 2. Regression of Indoor Air Measured Temperatures (°C) on observed PurpleAir indoor temperatures (°F).

Table 2 shows the range of estimated indoor temperatures (both °C and °F) for selected PurpleAir temperatures (°F).

PurpleAir Temp. (°F)	Indoor Temp. (°F)	Difference (°F)	95% Range (°F)	Indoor Temp. (°C)	Difference (°C)	95% Range (°C)
65	56.8	8.2	55-59	14.5	4.5	13.5-15.5
70	61.7	8.3	60-64	17.2	4.6	16-18
75	66.6	8.4	65-69	19.9	4.7	19-21
80	71.4	8.6	69-73	22.6	4.8	21-23
85	76.3	8.7	74-78	25.3	4.8	24-26
90	81.2	8.8	79-83	28.0	4.9	27-29
95	86.0	9.0	84-88	30.7	5.0	30-32

As can be seen from Table 2, the increase in PurpleAir temperatures compared to actual indoor temperatures is almost constant at about 8.6 °F or about 4.8 °C. ***So an acceptable interpretation of PurpleAir indoor temperature readings would be that they are reading between 8 and 9 °F (4.5-5 °C) above the true indoor room temperature*** (Figure 3).

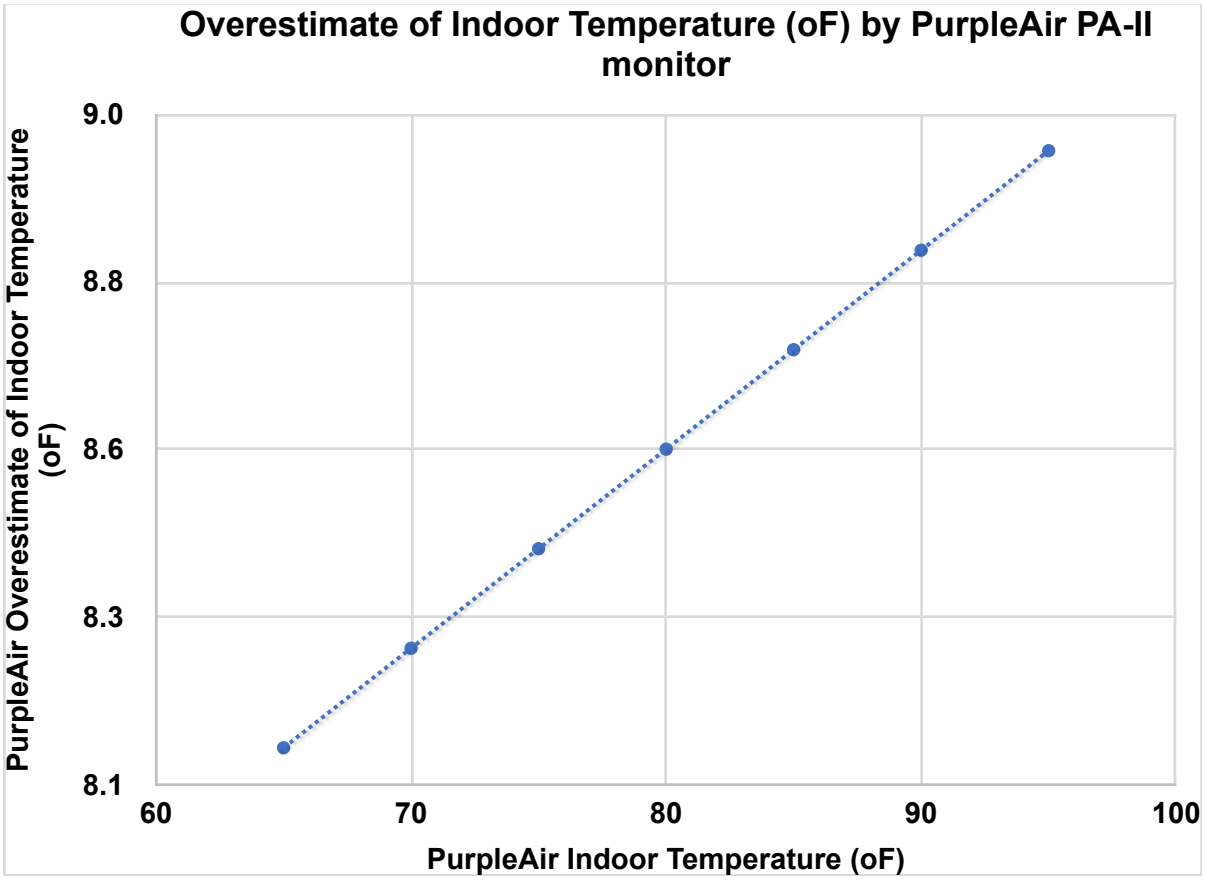

Figure 3. Overestimate of PurpleAir PA-II Indoor Temperature

Indoor Relative Humidity

Because of the increased temperature within PurpleAir PA-II monitors, the air inside can hold more water vapor, and therefore the relative humidity RH falls. A regression of measured indoor RH on RH readings from the PurpleAir PA-II monitor is provided (Figure 4).

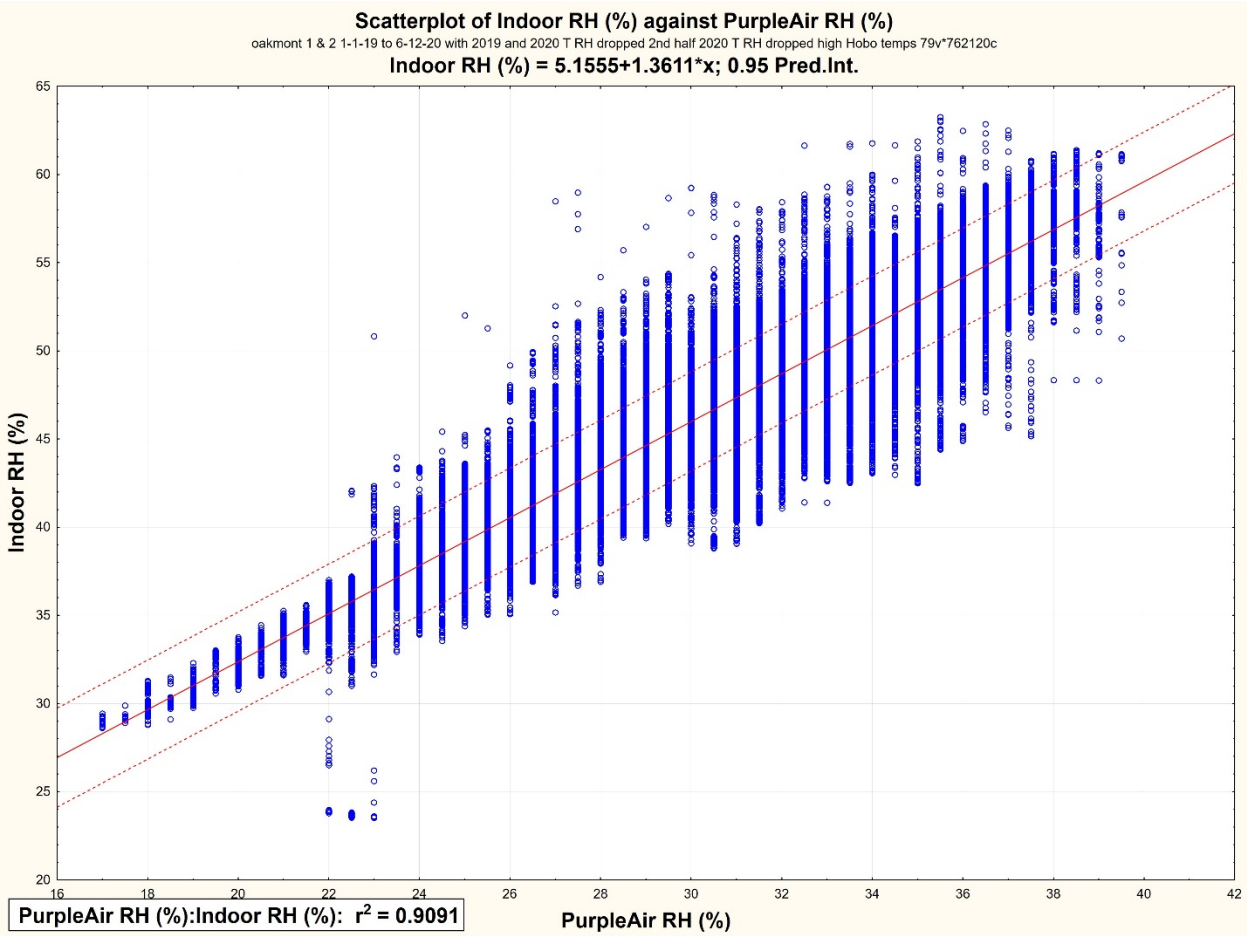

Figure 4. Indoor air RH (%) measured by the HOBO datalogger is regressed on the PurpleAir measurements.

The decline is on the order of 16 percentage points, as shown in Table 3. The decline varies from about -13 percentage points at low RH to -19 percentage points at high RH. As shown in Table 3, the variation of estimated RH from an RH PurpleAir estimate is on the order of ± 3%.

For example, at 30% RH as estimated by the PurpleAir PA-II monitor, the best estimate of the true indoor RH is 46%, but HOBO measurements range between 43% and 49%. Both the HOBO and Bosch BME instruments report an error of about 3-3.5%, so this observed range is to be expected based on the known accuracy of the two instruments.

Table 3. Measured indoor RH compared to RH readings from PurpleAir PA-II monitor.

PurpleAir RH (%)	Indoor RH (%)	Difference (%)	Range (%)
22	35.1	-13.1	32-38
26	40.5	-14.5	37.5-43.5
30	46.0	-16.0	43-49
34	51.4	-17.4	48.5-54.5
38	56.9	-18.9	54-60

The underestimate of indoor RH averages -16% and varies from -13% to -19% (Figure 5).

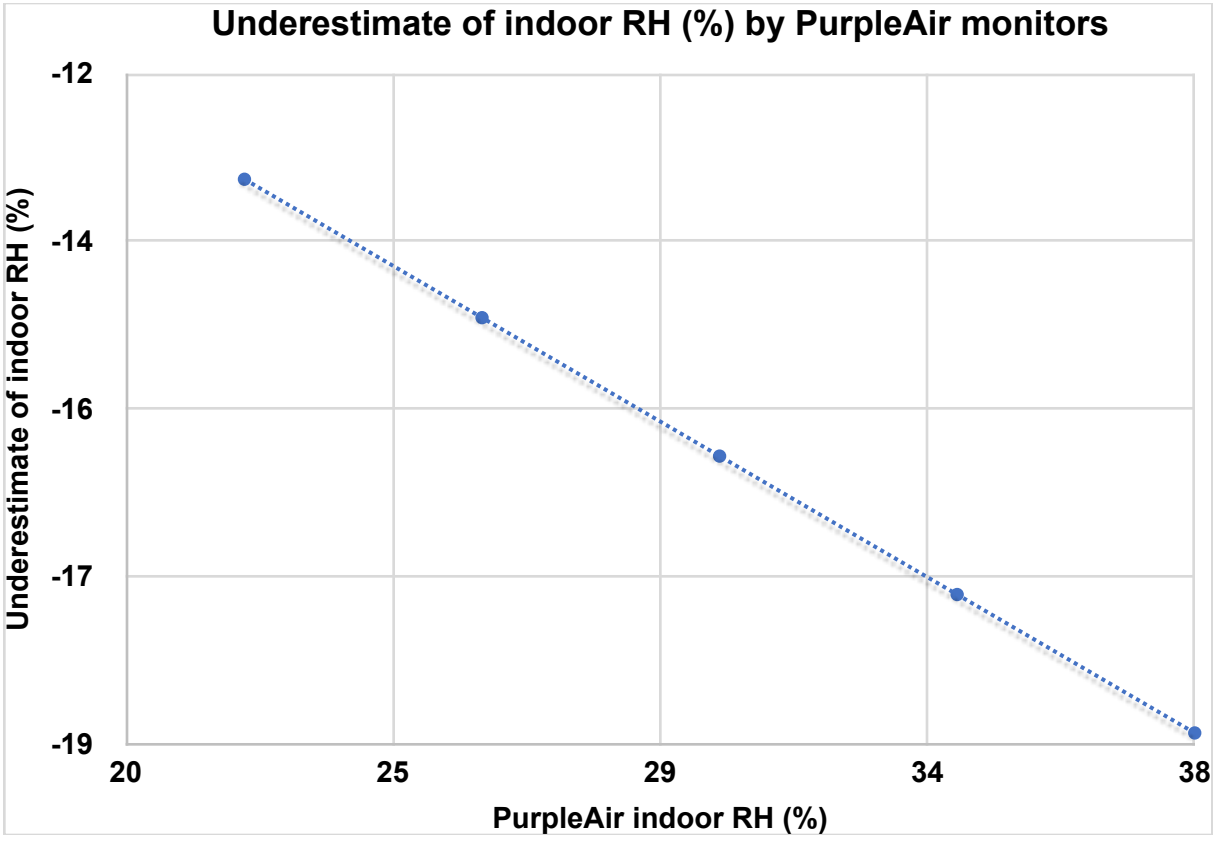

Figure 5. Underestimate of Indoor RH by PurpleAir PA-II monitors

Summarizing these indoor relationships, PurpleAir PA-II temperatures, on average, will be 8.6 °F higher than room temperatures, and PurpleAir PA-II RH values will be, on average, about 16 percentage points below room RH values.

Outdoor data

The greater range of T and RH outdoors will extend these relationships. Nine months of outdoor data were collected from July 2, 2020 through March 31, 2021 in the back yard of the same Santa Rosa house providing the indoor data. The mean temperature difference (Delta T) is about the same as for indoor air at about 8 °F, but the mean RH difference is much larger, at about -27% (Table 4).

Table 4. PurpleAir Temperature and RH compared to ambient values outside a home over 9 months.

Statistics (N = 110229)	HOBO T (°F)	HOBO RH (%)	PurpleAir T (°F)	PurpleAir RH (%)	Delta T (PA - HOBO) (°F)	Delta RH (PA - HOBO) (%)
Mean	59.0	71.1	66.9	44.2	7.9	-26.9
Std. Dev.	14.1	22.7	13.6	15.2	2.6	8.7
Std. Err.	0.042	0.068	0.041	0.046	0.008	0.026
Min	28.7	9.9	37	2.9	-5.3	-60.0
10th Percentile	41.7	37.2	50	22.4	4.7	-36.0
Lower quartile	49.0	52.5	57	32.0	6.7	-33.7
Geom. mean	57.4	66.5	66	40.8		
Median	56.4	76.1	65	46.5	7.8	-29.4
Upper quartile	68.1	91.6	76	58.0	9.1	-20.1
90th Percentile	80.3	96.8	87	62.0	11.3	-13.7
Max	105.0	100.0	104	70.7	18.6	1.9

Outdoor Temperature

The outdoor PurpleAir temperature is strongly related to outdoor temperature as measured by the HOBO thermometer (R^2 = 97%) with a nearly constant difference of 8 ± 1 °F (Figure 6). However, this mean difference is accompanied by a considerable uncertainty range (Figure 7). For example, a PurpleAir reading of 60 °F might be associated with HOBO readings varying between about 45 and 55 °F. Again, this is not a measurement error, since both instruments can

measure temperatures to within 0.2 degrees Celsius, but rather an indication that other variables may have an effect on the temperature reading within the PurpleAir monitor.

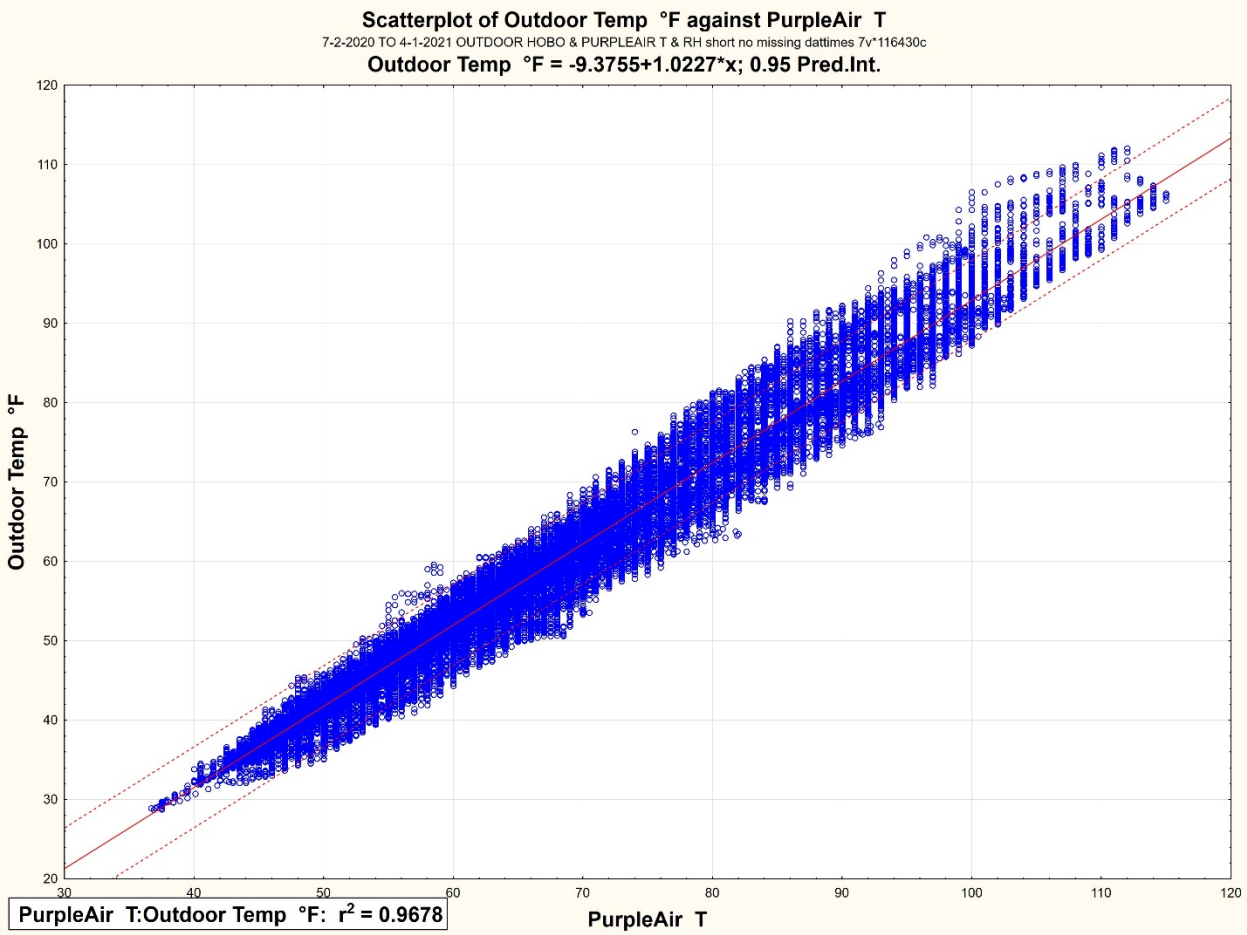

Figure 6. Regression of Measured Outdoor Temperature (°F) on outdoor PurpleAir PA-II temperature reading (°F).

To estimate the outdoor temperature in degrees Celsius, Figure 7 provides the relationship.

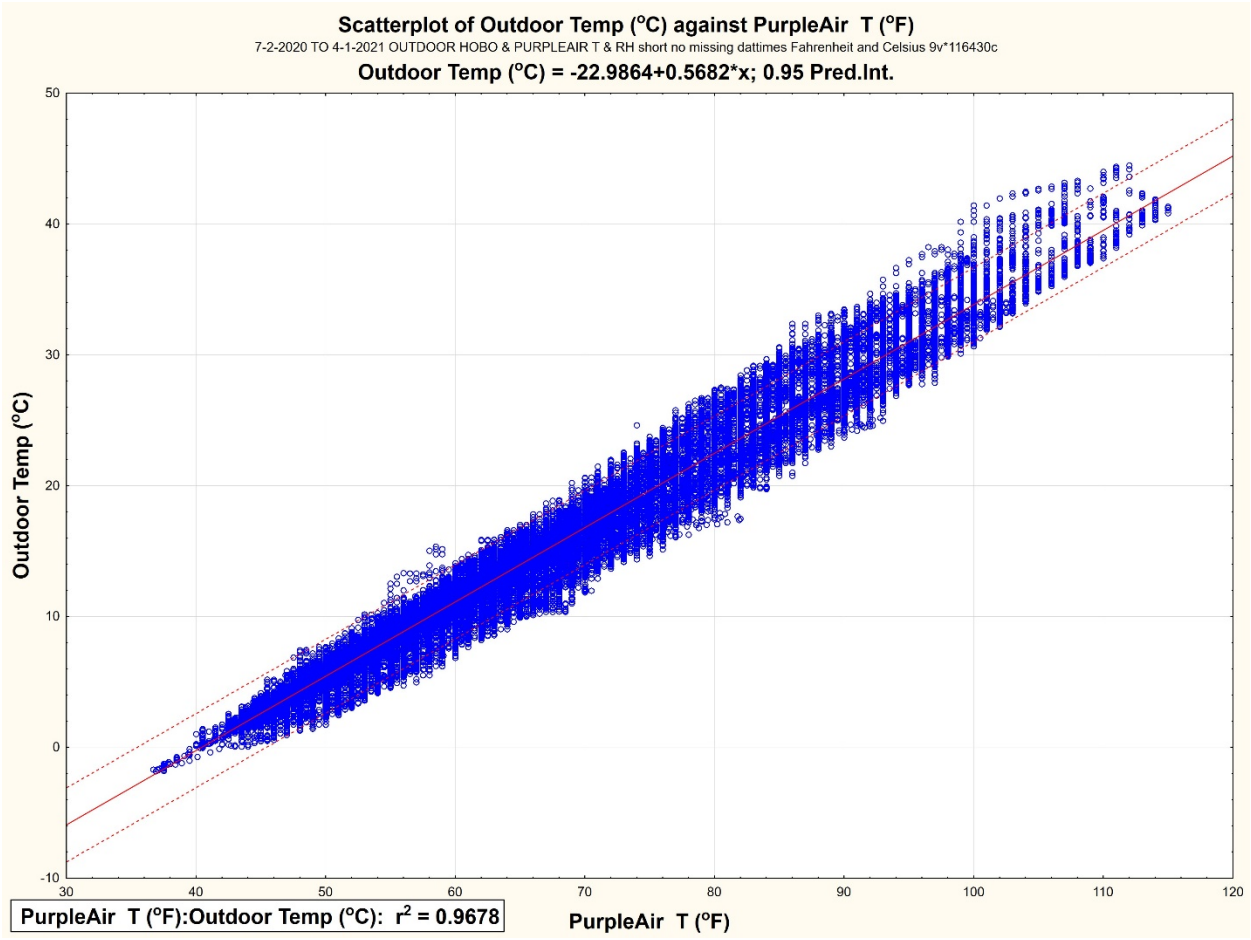

Figure 7. Regression of Measured Outdoor Temperature (°C) on outdoor PurpleAir PA-II temperature reading (°F).

Table 5. Best estimates and range of outdoor temperatures (°F and °C) for selected PurpleAir temperatures (°F).

PurpleAir outdoor T (°F)	Best Estimate of Outdoor T (°F)	Difference (°F)	Range (°F)	Best Estimate of Outdoor T (°C)	Difference (°C)
40	31.5	8.5	30-36	-0.3	4.7
50	41.8	8.2	36-46	5.4	4.6
60	52.0	8.0	46-56	11.1	4.5
70	62.2	7.8	55-66	16.8	4.3
80	72.4	7.6	66-76	22.5	4.2
90	82.7	7.3	76-86	28.2	4.1
100	92.9	7.1	87-98	33.8	3.9

There is a very slow change in the mean difference between the temperature measurements, merely dropping from 8.5 ºF (4.7 ºC)at the lowest temperature to 7.1 ºF (3.9 ºC) at the highest temperature (Figure 8).

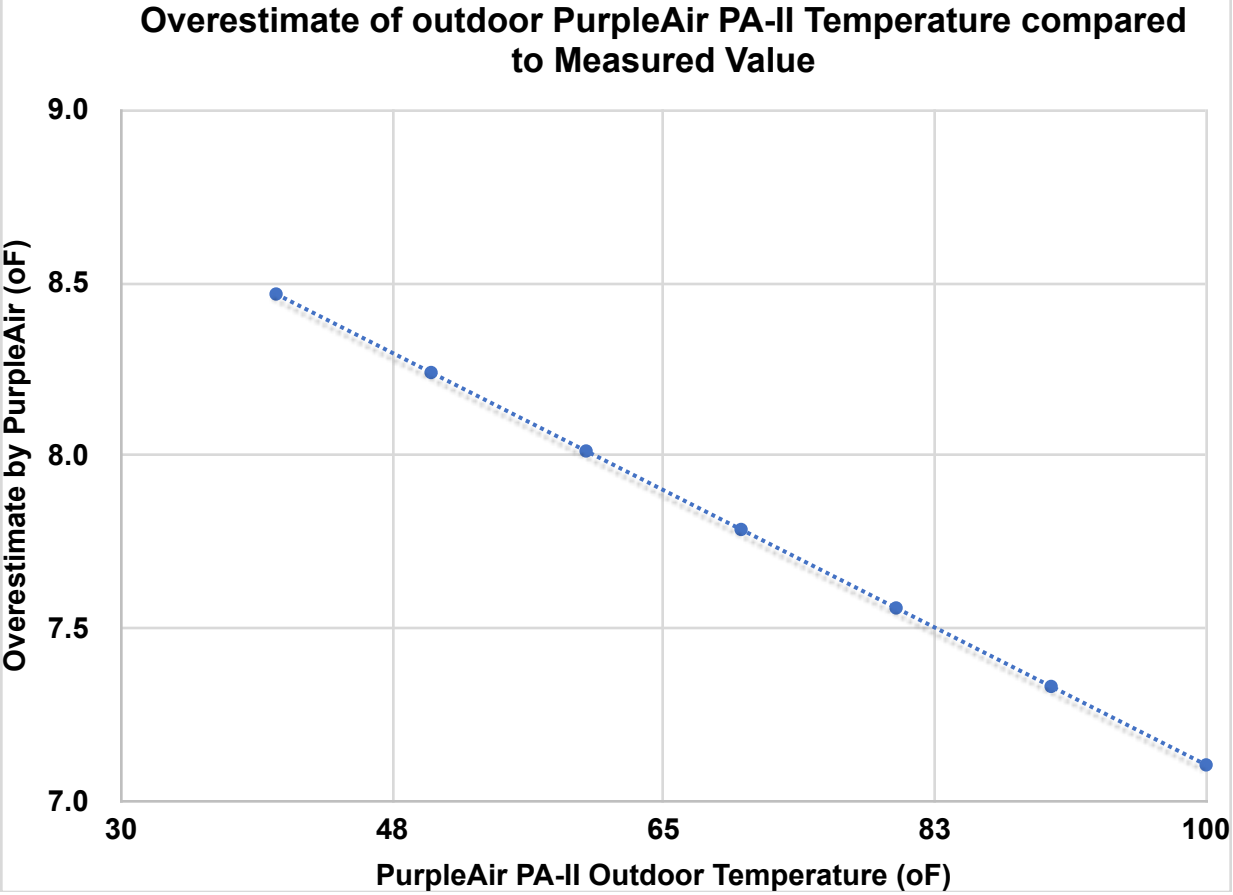

Figure 8. PurpleAir PA-II Overestimate of Outdoor Temperature

Summarizing the outdoor temperature findings, the overestimate of the PurpleAir PA-II averages 7.9 ºF and varies between about 7.1 ºF and 8.5 ºF.

Relative Humidity

PurpleAir outdoor RH is compared to the HOBO readings (Figure 9).

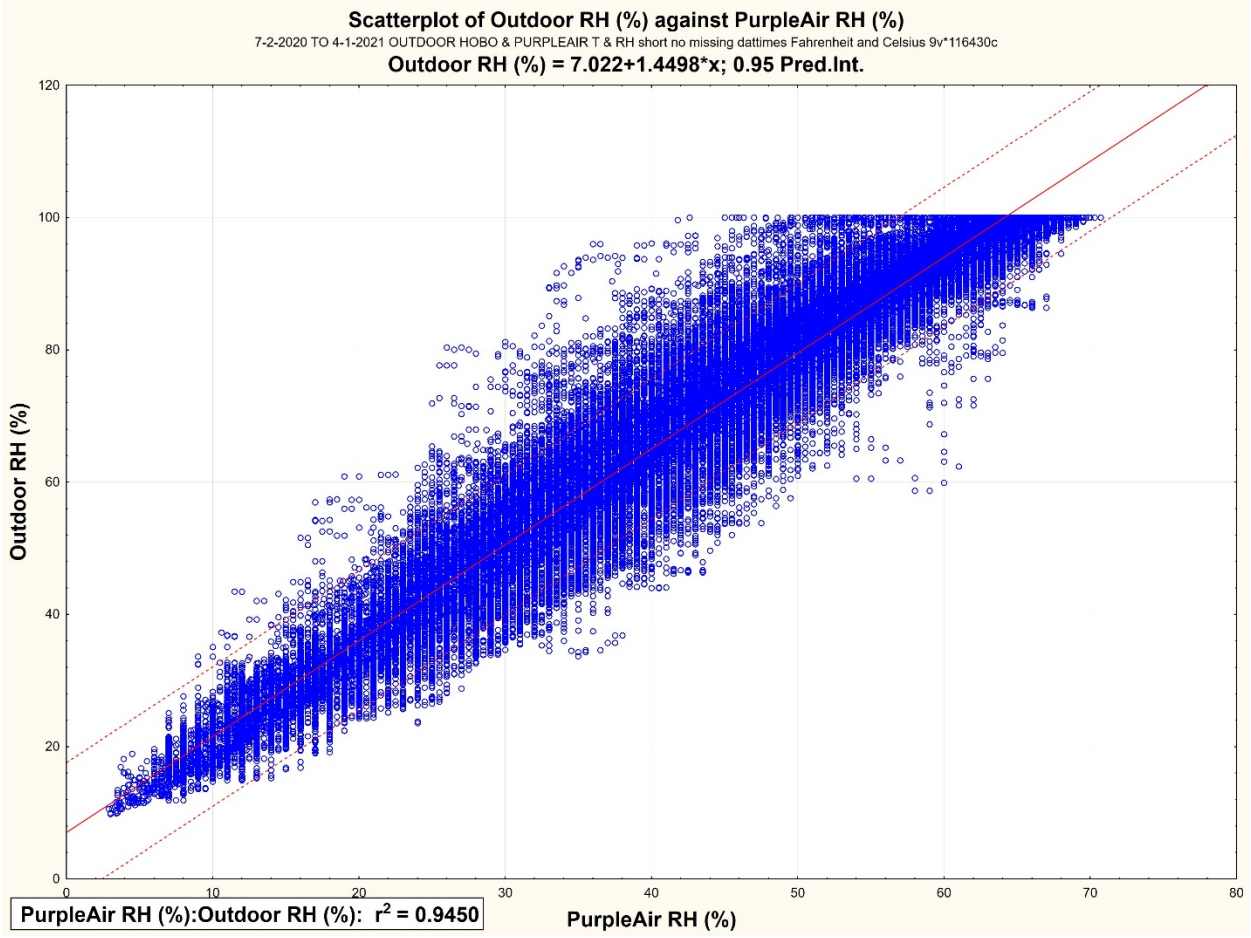

Figure 9. Measured outdoor RH (%) is regressed on the PurpleAir RH readings.

There is a strong relationship (R^2 = 94.5%) but with considerable variation. For example, at a PurpleAir reading of outdoor RH of 20%, the measured outdoor RH varies between about 20% and 40%. When it is raining (outdoor RH = 100%) the outdoor PurpleAir monitor varies only between about 50% and 70%.

The best estimates and range of observed outdoor RH based on PurpleAir measurements are provided in Table 6. The mean difference (PurpleAir – HOBO) varies from -11.5 percentage points at a measured outdoor RH of 20% to about − 37 percentage points at 100 % RH.

Table 6. Best estimates and range of RH outdoor measurements for selected PurpleAir RH measurements.

PurpleAir outdoor RH (%)	Best estimate of Measured outdoor RH (%)	Difference (%)	Range (%)
10	21.5	-11.5	12-28
20	36.0	-16.0	24-46

30	50.5	-20.5	38-62
40	65.0	-25.0	48-72
50	79.5	-29.5	68-88
60	94.0	-34.0	84-100

The difference between PurpleAir and HOBO outdoor RH as a function of PurpleAir outdoor RH is shown (Figure 10).

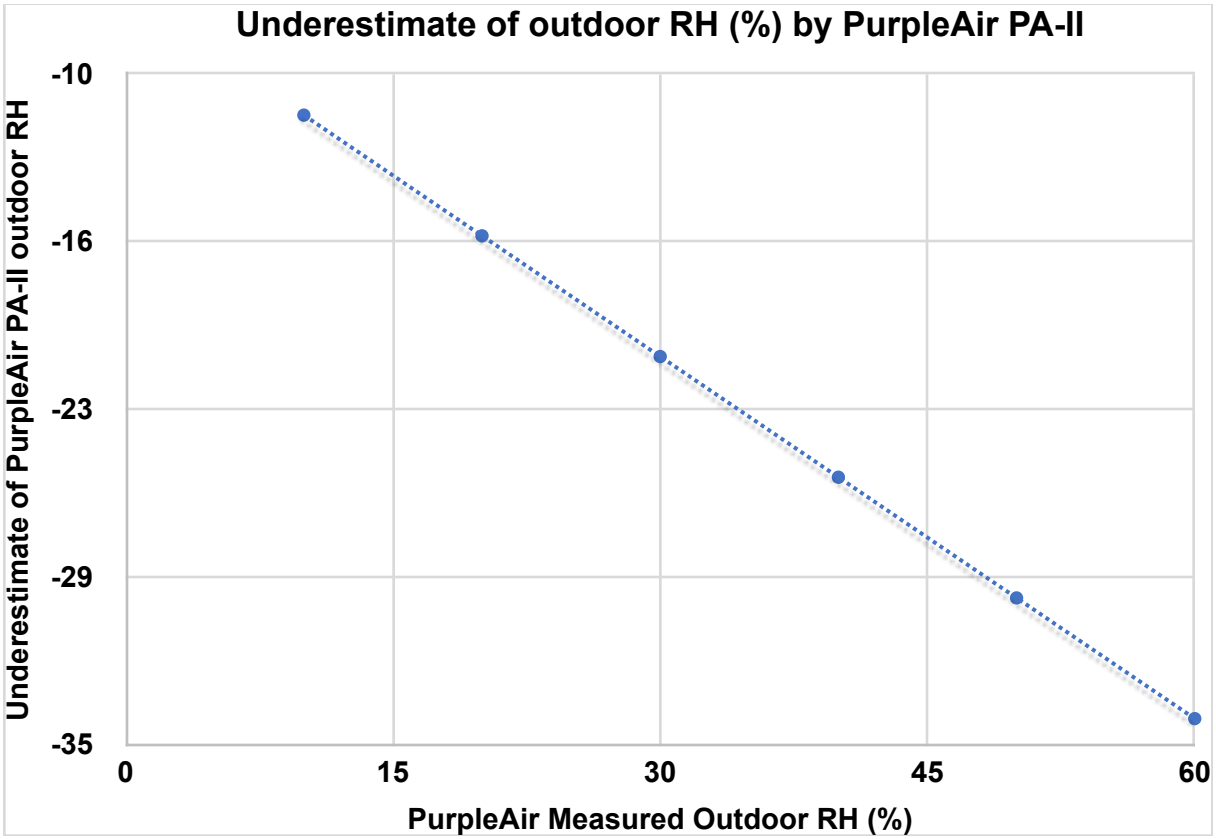

Figure 10. Underestimate of PurpleAir PA-II outdoor RH at selected PurpleAir RH values.

Summarizing the outdoor measurements of RH by the HOBO and PurpleAir PA-II monitors, the ***PurpleAir PA-II monitors underestimate outdoor RH by a mean value of -27 percentage points, ranging from about -11 percentage points at low outdoor values to -37 percentage points at the highest outdoor values.***

However, the difference in readings at any particular outdoor RH varies quite a bit across the 95% of PurpleAir PA-II values at any given RH as measured by the HOBO instrument. The full range varies between about 16 and 24 percentage points as shown in Table 6. Taking half of this range as an estimate of the uncertainty, the uncertainty ranges from about 8 to about 12 percentage points. This range is not completely due to erroneous readings, since both thermometers have excellent accuracy and can predict RH values to within 3%. (Please check the Appendix for a discussion of the maximum range expected from these values. The observed range here is larger than that maximum.) Rather, the excess observed variation must be related to changing conditions within the PurpleAir monitor. That is, there must be some interferents within the PA-II monitor that affect the reading of the T-RH sensor within. A simple multiple regression of PA RH on HOBO RH finds at least 4 variables that have highly significant ($p<0.0001$) effects (Table 7).

Table 7. Multiple regression of PA RH on HOBO RH with three possible interferents—date, Temperature, PM2.5. (Red typeface indicates significant effect)

	Regression Summary for Dependent Variable: RH3 outdoors (Oakmont 6-18-20 to1-14-22 with LOD calculations and indoor-generated) R= .96667177 R²= .93445431 Adjusted R²= .93445220 F(4,124282)=4430E2 p<0.0000 Std.Error of estimate: 3.8772					
N=124287	b*	Std.Err. of b*	b	Std.Err. of b	z	p-value
Intercept			347.3779	12.58825	27.5954	0.000000
date	-0.028710	0.001007	-0.0081	0.00028	-28.5047	0.000000
Hobo Outdoor Temp	0.065766	0.001630	0.0682	0.00169	40.3464	0.000000
Hobo Outdoor RH	1.024704	0.001350	0.6800	0.00090	759.1405	0.000000
Mean 2 & 3 PM2.5 CF3 OUTDOORS	-0.006593	0.000738	-0.0048	0.00054	-8.9390	0.000000

The "date" variable might indicate instrumental drift over time, which appeared to have a small but significant negative effect on measured RH. The outdoor temperature had a slightly stronger and still significant positive effect. Increased particle numbers in the monitor were associated, again significantly, with a negative effect on RH.

A proper analysis could consider these and possibly other variables, and would carefully consider correlations in the independent variables to arrive at a more robust estimate of why the uncertainty band has the width observed.

I have no PA-I monitors, so cannot comment on whether similar results may be observed for those monitors. However, one study (Wallace and Zhao, 2023) compared the PA-I monitors with a single Plantower PMS 1003 sensor to PA-II monitors with two Plantower 5003 sensors and found the two monitors had precisely the same calibration factors (CF 3.4) for PM2.5 estimates, so at least there is that similarity. However, it is likely that the single sensor puts out less heat than two sensors, so the temperature and RH differences of the PA-I monitor might be smaller than those observed for the PA-II monitor.

Reference

1. Wallace, L. Zhao, T. and Klepeis, N.E.. Calibration of PurpleAir PA-I and PA-II monitors using daily mean PM2.5 concentrations measured in California, Washington, and Oregon from 2017

to 2021. *Sensors* **2022, 22**, 4741. https://doi.org/10.3390/ s22134741 https://pubmed.ncbi.nlm.nih.gov/35808235/

Appendix.

The Bosch BME manual https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bme680-ds001.pdf states that the RH "accuracy tolerance" is ± 3%. The BME temperature "absolute accuracy" is said to be ± 0.5 °C (0.9 °F) at a temperature of 25 °C, but ± 1.0 °C (1.8 °F) at temperatures in the range of 0-65 °C.

The HOBO UX-100 data logger manual https://www.onsetcomp.com/sites/default/files/resources-documents/16209-H%20UX100-003%20Manual.pdf claims a temperature accuracy of ± 0.21 C (±0.38 F) for a range of 0-50 C
The HOBO RH sensor states an accuracy of ± 3.5% from Rh of 25% to 85% but ± 5% outside that range.

So at a temperature of 70 °F, the BME might read anywhere between 68.2 and 71.8 °F, whereas the HOBO might read anywhere between 69.8 and 70.2 °F. This means comparing the two monitors could result in a temperature variation (Delta T) of as much as (71.8-69.8 = 2.0 °F (or 70.2-68.2)=2.0 °F)).

At an RH of 30%, the BME might read between 27 and 33%, while the HOBO might read anywhere between 26.5% and 33.5%. Comparing the two (Delta RH) could then result in a maximum swing of (33-26.5 = 6.5% RH or 33.5-27 = 6.5 % RH).

These considerations are for the BME being outside the PurpleAir monitor. The changed conditions inside the monitor (higher temperature, lower RH) would then just add to this variation.