AirGradient OpenAir
Temperature and RH correction

20th March 2024, Dr. Anika Krause

Temperature correction

- The problem
- The reason
- Can we correct for it?
- The solution
- How well does it work?

RH correction

Outlook

The problem

25°C   25°C

-5°C   -11°C

Temperature error at low temperatures

Impact of sensor position

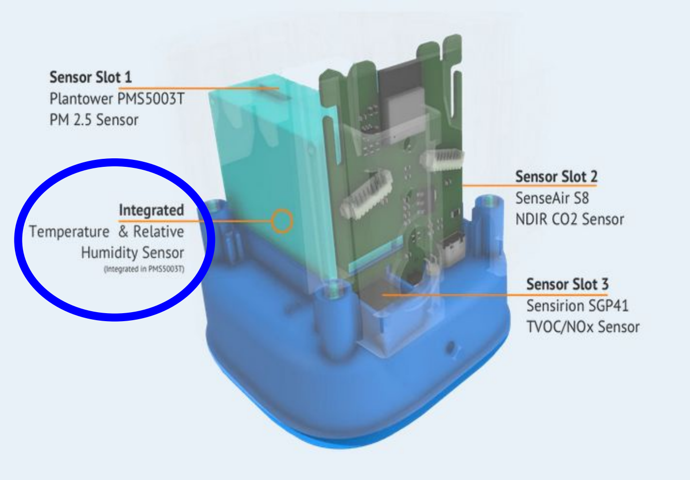
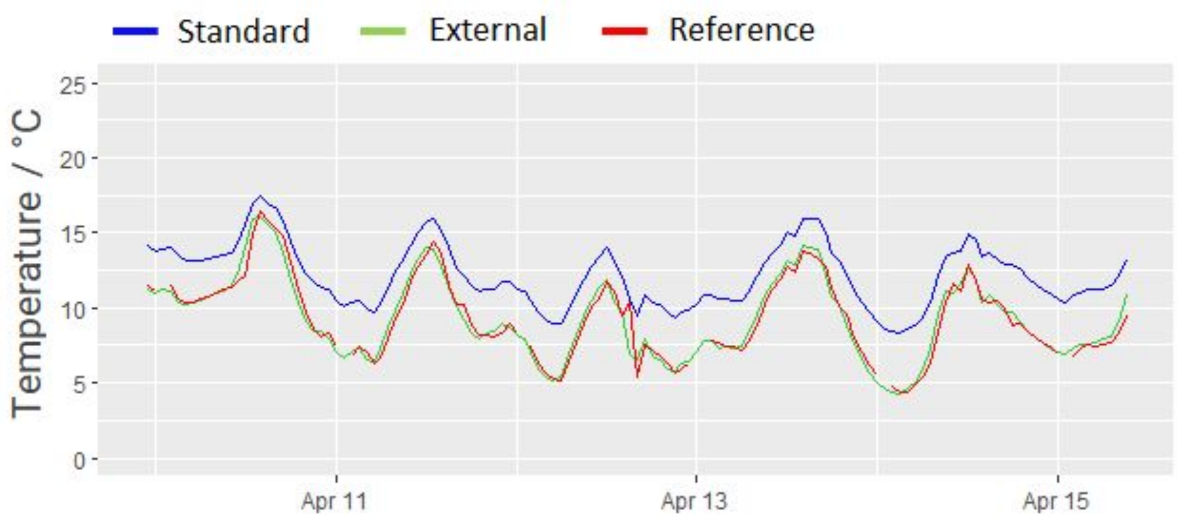


Fig. 1: *The temperature sensor is integrated in the PM module of the AirGradient monitor.*

Impact of sensor position - experiment

Fig. 1: *The temperature sensor is integrated in the PM module of the AirGradient monitor. To test the impact of the sensor position, an additional sensor was added outside of the monitor box. Both sensors were compared to a reference device.*

Impact of sensor position - experiment



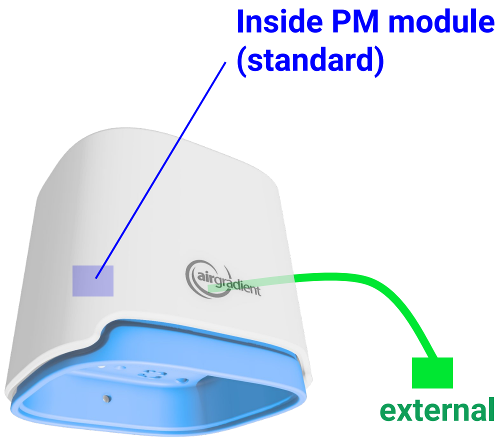


***Fig. 2:** Measurements of the temperature sensor integrated inside the PM module (blue) and outside of the monitor box (green) compared to reference measurements (red).*

Impact of sensor position - experiment

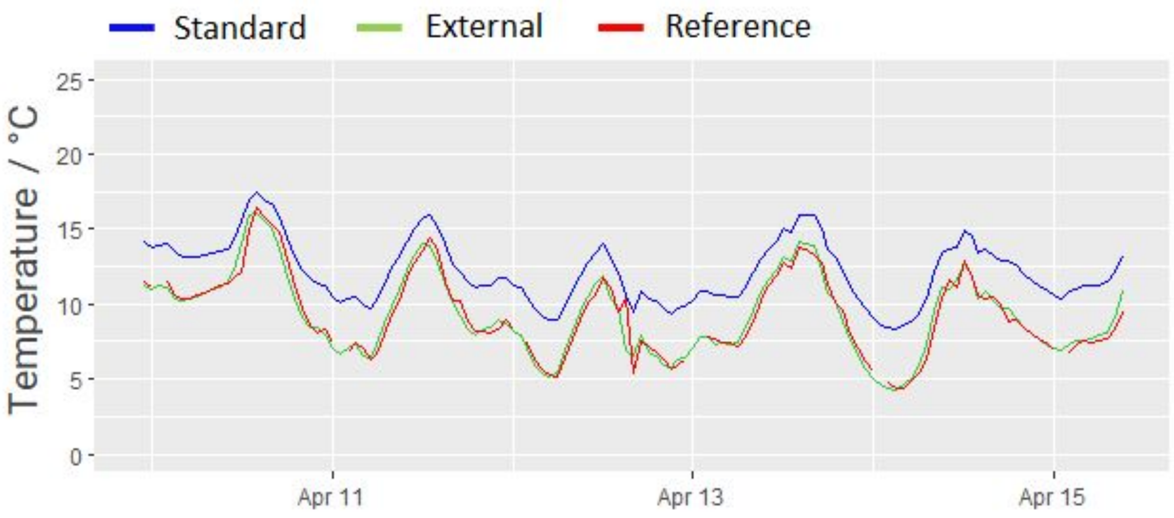


***Fig. 2:** Measurements of the temperature sensor integrated inside the PM module (blue) and outside of the monitor box (green) compared to reference measurements (red).*

Temperature sensor itself is accurate
→ Deviation is due to sensor position

BUT

- Integration into PM module allows more accurate PM readings

- Internal temperature correlates well with external
→ Can be corrected?

Reproducibility analysis

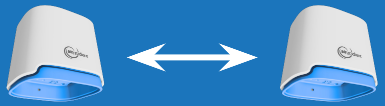
Is the temperature error consistent?

OR

Monitor 1	-5°C	-11°C
Monitor 2	-5°C	-11°C
Monitor 3	-5°C	-11°C
Monitor 4	-5°C	-11°C
Monitor 5	-5°C	-11°C

Monitor 1	-5°C	-11°C
Monitor 2	-15°C	-11°C
Monitor 3	-1°C	-11°C
Monitor 4	-9°C	-11°C
Monitor 5	-6°C	-11°C

Monitor-monitor agreement



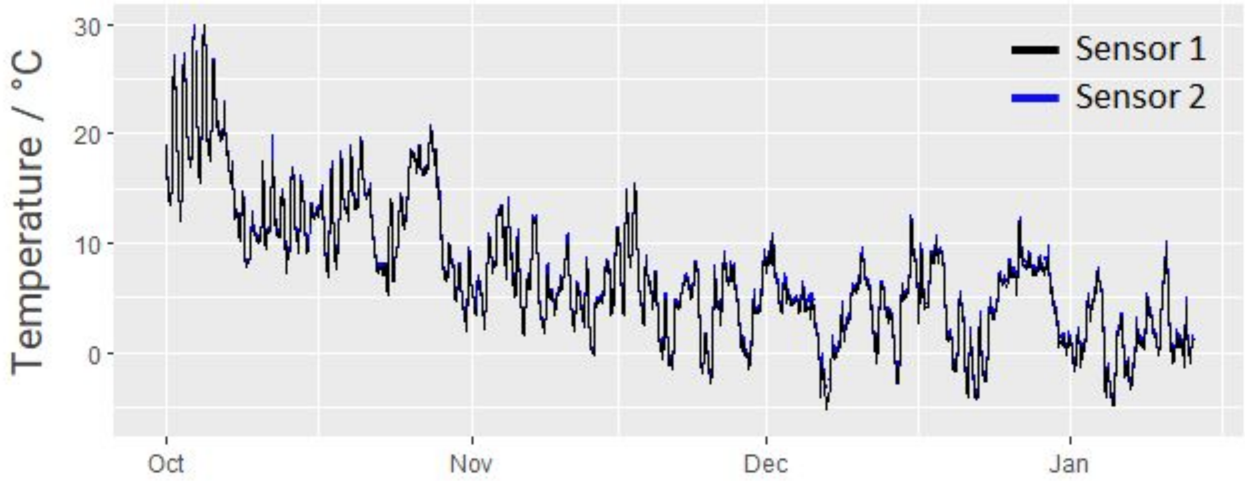
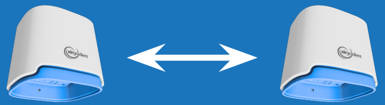


Fig.3: *Two co-located OpenAir monitors in Ottawa, Canada. Time plot of the two temperature measurements.*

Monitor-monitor agreement



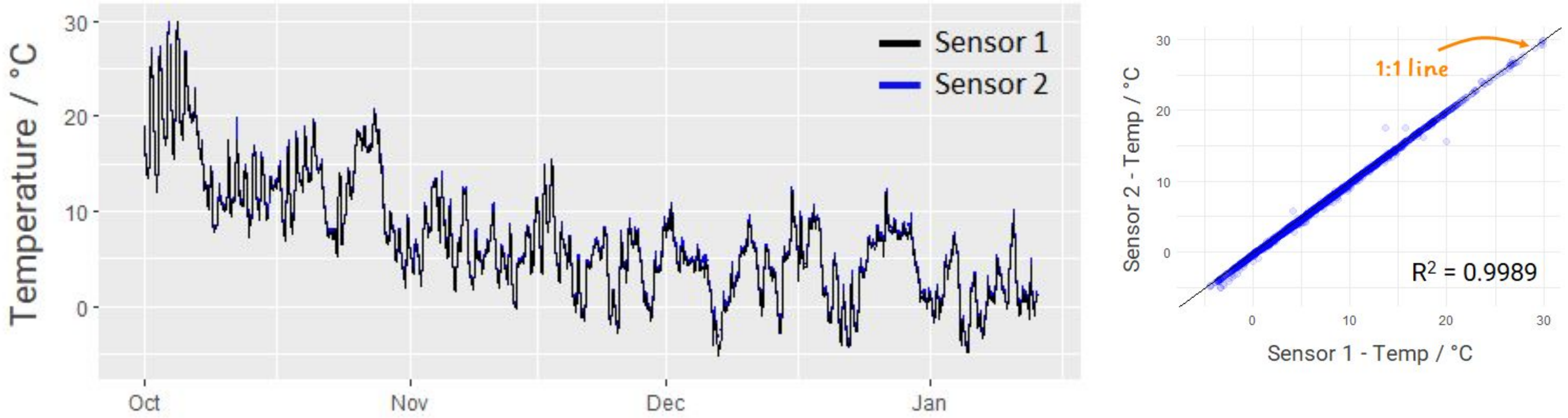
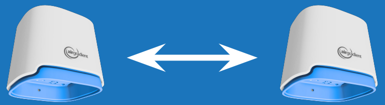


Fig.3: *Two co-located OpenAir monitors in Ottawa, Canada. Left: Time plot of the two temperature measurements. Right: Scatterplot between the two sensors.*

- **Scatterplot:** The closer the data points to the 1:1 line, the higher the agreement between the sensors
- **R^2 -** measure of the linear correlation. **Ideal agreement:** $R^2 = 1$

You can find more information about sensor performance evaluation in our blog or youtube channel.

Average difference between two sensors



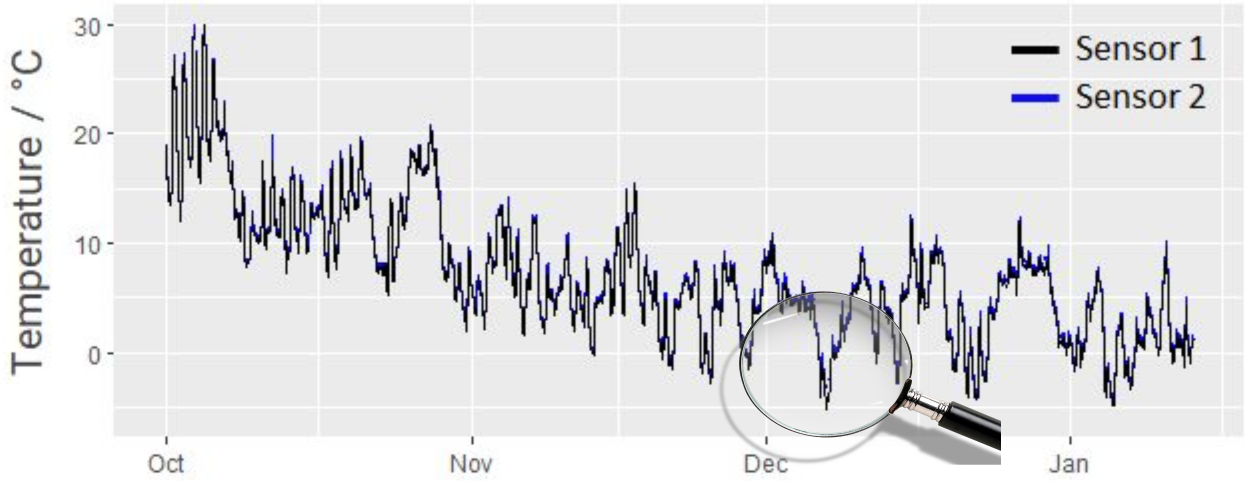
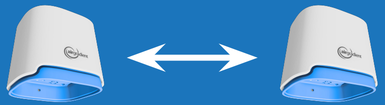


Fig.3: *Two co-located OpenAir monitors in Ottawa, Canada. Left: Time plot of the two temperature measurements.*

Average difference between two sensors



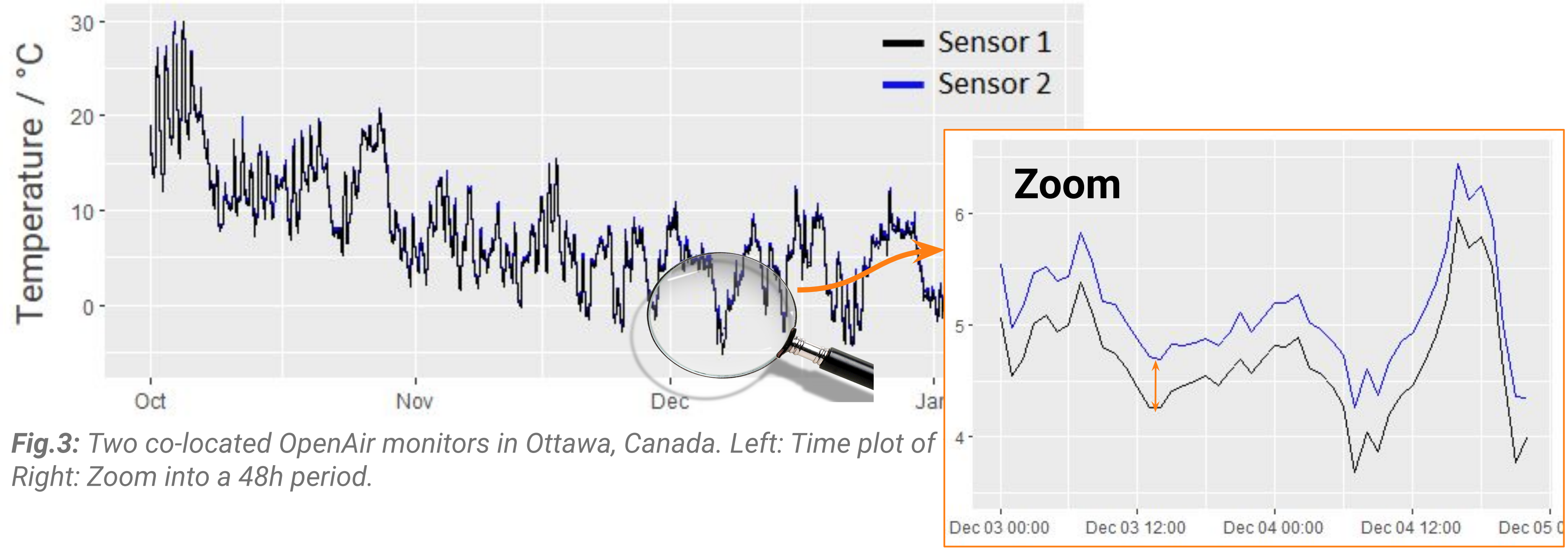
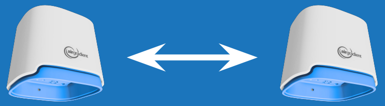


Fig.3: *Two co-located OpenAir monitors in Ottawa, Canada. Left: Time plot of*
Right: Zoom into a 48h period.

Average difference between two sensors



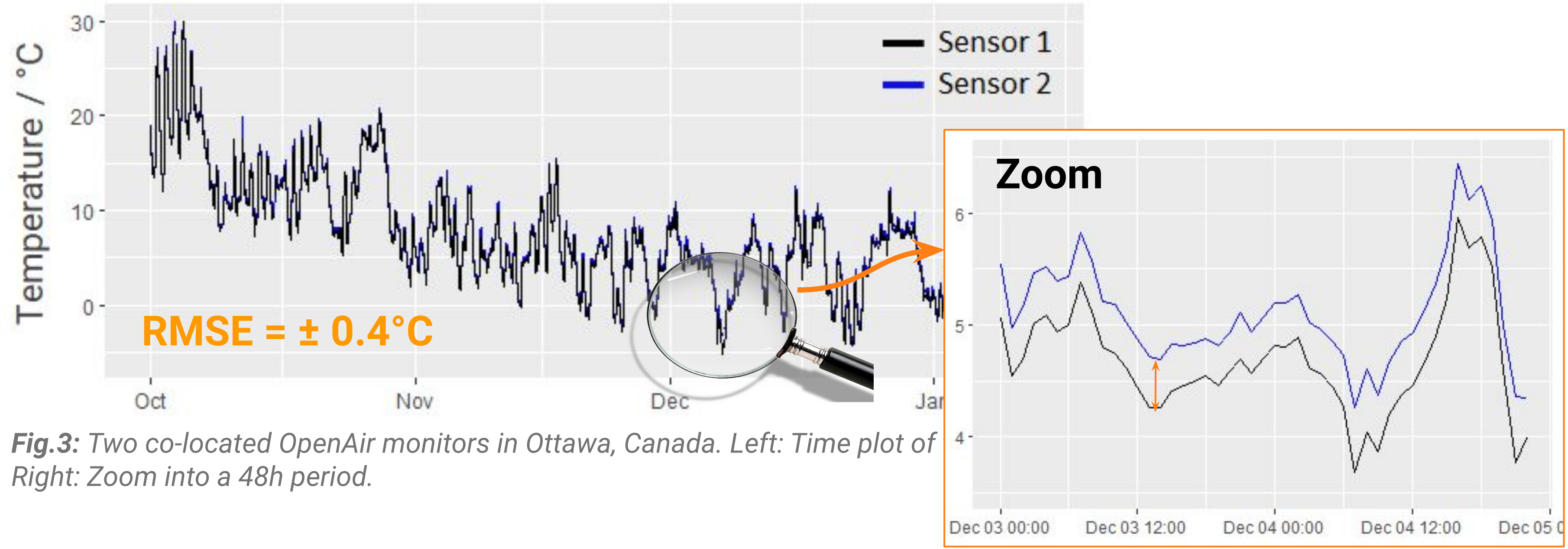
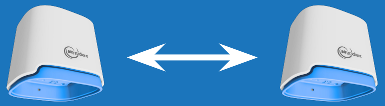
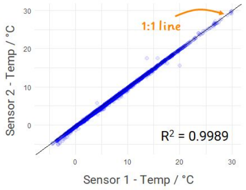


Fig.3: *Two co-located OpenAir monitors in Ottawa, Canada. Left: Time plot of*
Right: Zoom into a 48h period.

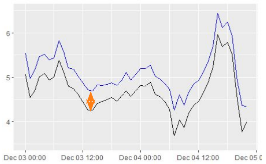
Root Mean Square Error (RMSE) - Measure for average difference between two measurements

Monitor-monitor agreement: Conclusion Ottawa





✔ High linearity (R^2 > 0.99)



✔ Small difference between sensor readings (RMSE = 0.4°C)

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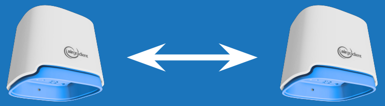

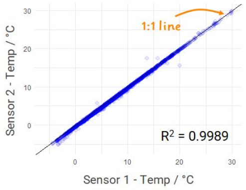

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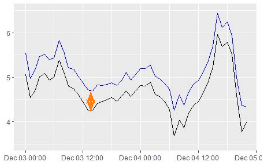
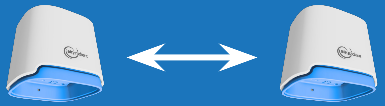


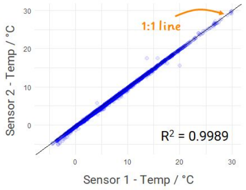
✔ Small difference between sensor readings (RMSE = 0.4°C)

High reproducibility.

If we can correct the temperature readings for one monitor, it will also work with the other.

Monitor-monitor agreement: Conclusion Ottawa





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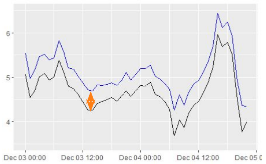

✔ Small difference between sensor readings (RMSE = 0.4°C)

Only one monitor pair

High reproducibility.

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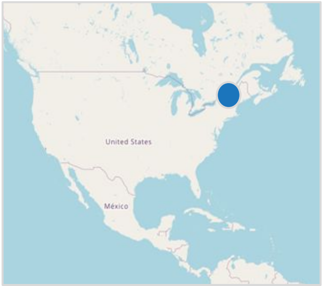


Only one location

Co-location Project

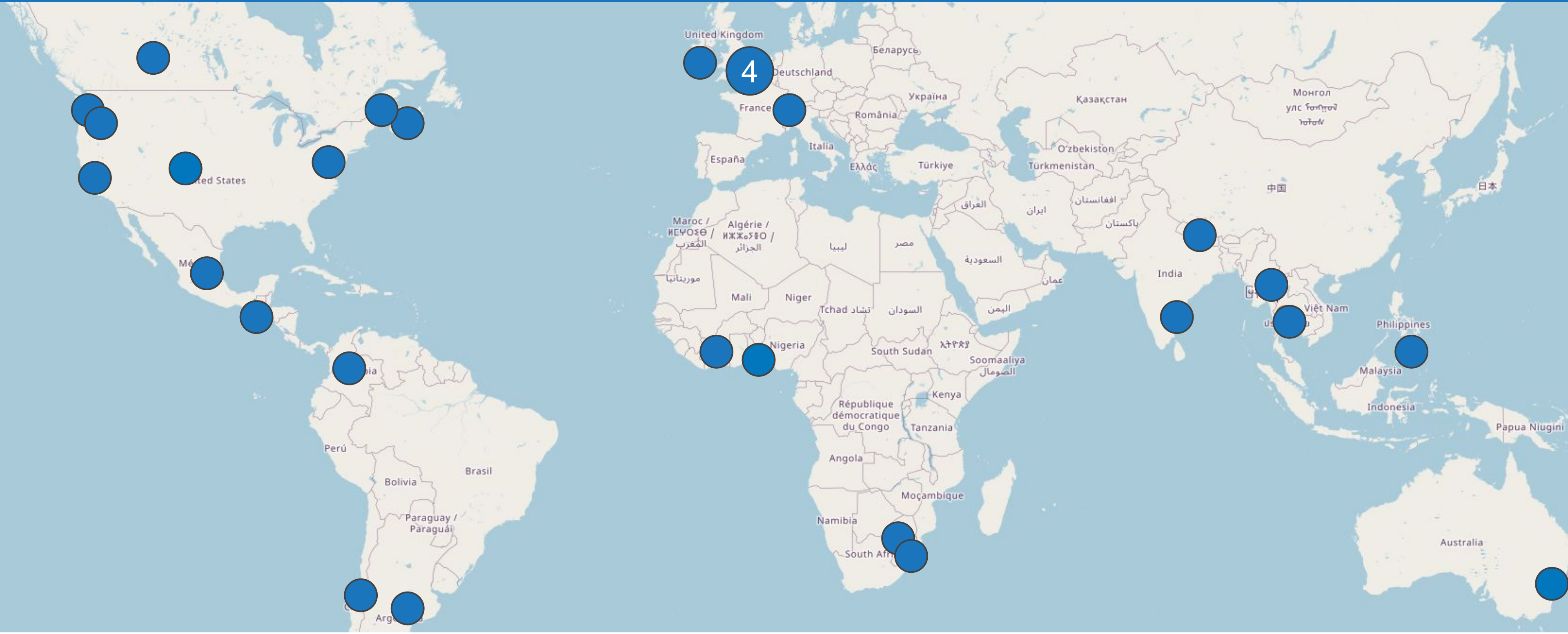


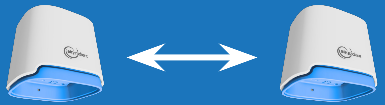
Fig. 4: Co-location sites of the AirGradient outdoor monitor (Open Air)

Co-location Project

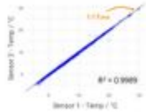
- Performance testing in > 25 different locations
- Large scientific network
- Reproducibility analysis and comparison with certified reference instruments

University of Birmingham
NARIT
Environment and Climate Change Canada
northwest Clean Air agency
Columbia University
Imperial College London
Clean Air Asia
SEEN
NWU
Empa
fhi360
SEI
Citizen Science Global Partnership
University of Cambridge
Sri Ramachandra Institute of Higher Education and Research
openaq
Universidad Nacional Autónoma de México
AFRI-SET

Reproducibility analysis across co-location sites



Monitor-monitor agreement: Fazit Ottawa



✔ High linearity ($R^2 > 0.99$)

✔ Small difference between sensor readings (RMSE = 0.4°C)

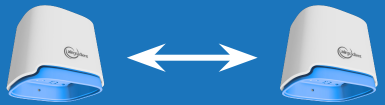
Only one monitor pair

High reproducibility.
If we can correct the temperature readings for one monitor, it will also work with the other.

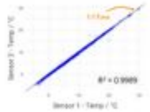
Only one location

Do analysis for more co-location sites

Reproducibility analysis across co-location sites



Monitor-monitor agreement: Fazit Ottawa



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✔ Small difference between sensor readings (RMSE = 0.4°C)

Only one monitor pair

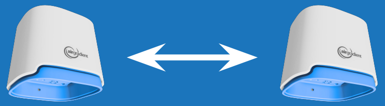
High reproducibility.
If we can correct the temperature readings for one monitor, it will also work with the other.

Only one location

Compare more than two monitors
→ average R^2 and RMSE

Do analysis for more co-location sites

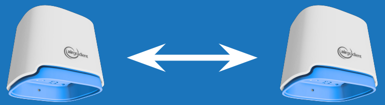
Reproducibility analysis



City	Country	Mean R^2	Mean RMSE / °C
Anacortes	USA	0.98	± 0.63
Bellingham	USA	0.99	± 0.63
Chennai	India	1.00	± 0.24
Chiang Mai	Thailand	0.99	± 0.63
Duebendorf	Switzerland	1.00	± 0.14
Guatemala City	Guatemala	0.99	± 0.65
London (Marylebone Road)	UK	1.00	± 0.30
London (Honor Oak Park)	UK	0.99	± 0.61
Ottawa	Canada	1.00	± 0.41
Cambridge	UK	1.00	± 0.28
Vanderbijlpark	South Africa	1.00	± 0.52

Table 1: *Reproducibility of AirGradient temperature measurements. Performance characteristics are averaged over all sensors in each location.*

Reproducibility analysis



City	Country	Mean R^2	Mean RMSE / °C
Anacortes	USA	0.98	± 0.63
Bellingham	USA	0.99	± 0.63
Che[illegible]	[illegible]	[illegible]	[illegible]
Chi[illegible]	[illegible]	[illegible]	[illegible]
Due[illegible]	[illegible]	[illegible]	[illegible]
Gua[illegible]	[illegible]	[illegible]	[illegible]
London (Marylebone Road)	UK	[illegible]	[illegible]
London (Honor Oak Park)	UK	0.99	± 0.61
Ottawa	Canada	1.00	± 0.41
Cambridge	UK	1.00	± 0.28
Vanderbijlpark	South Africa	1.00	± 0.52

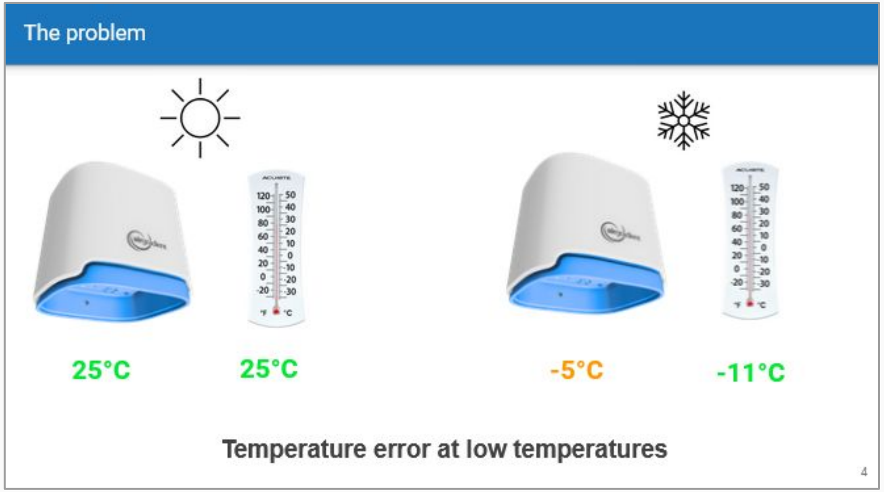
CONCLUSION

Excellent agreement between AirGradient monitors

→ temperature error can be corrected for

Table 1: *Reproducibility of AirGradient temperature measurements. Performance characteristics are averaged over all sensors in each location.*

Temperature correction



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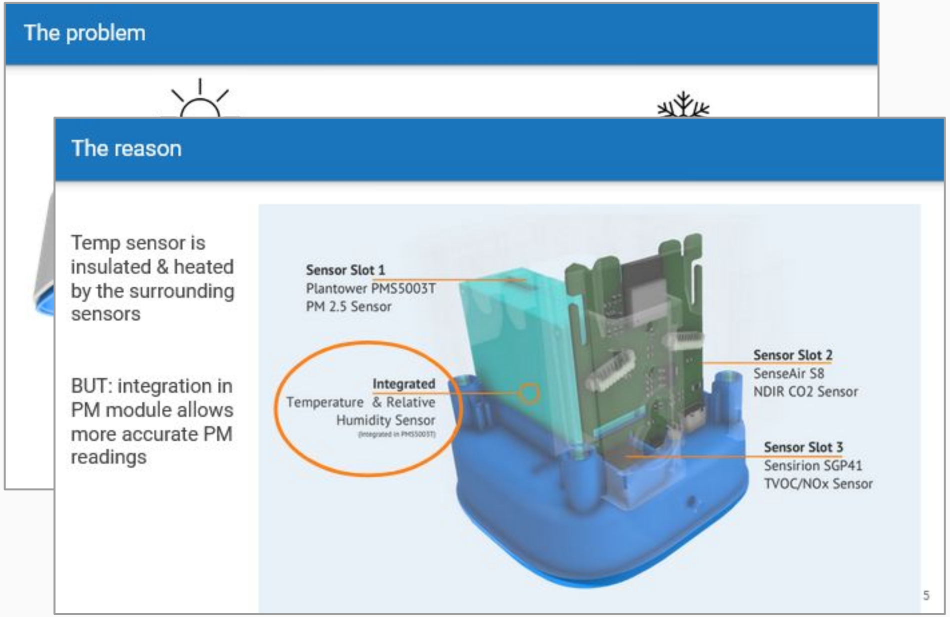
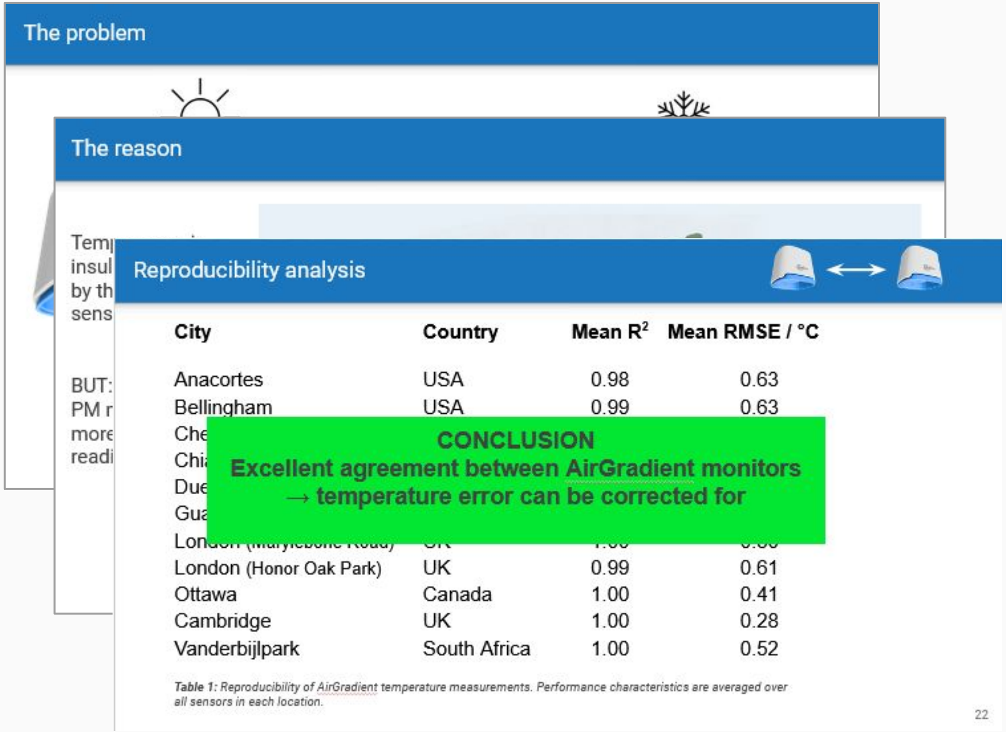
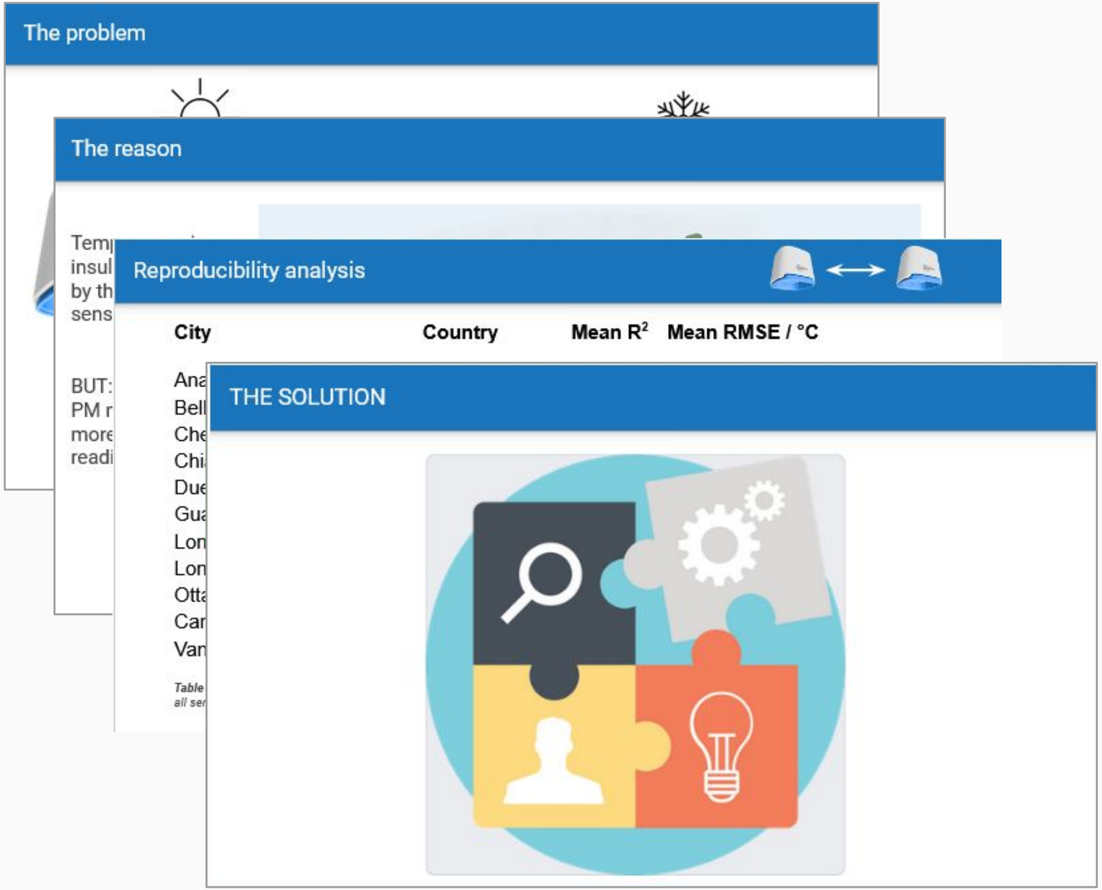


Temperature correction



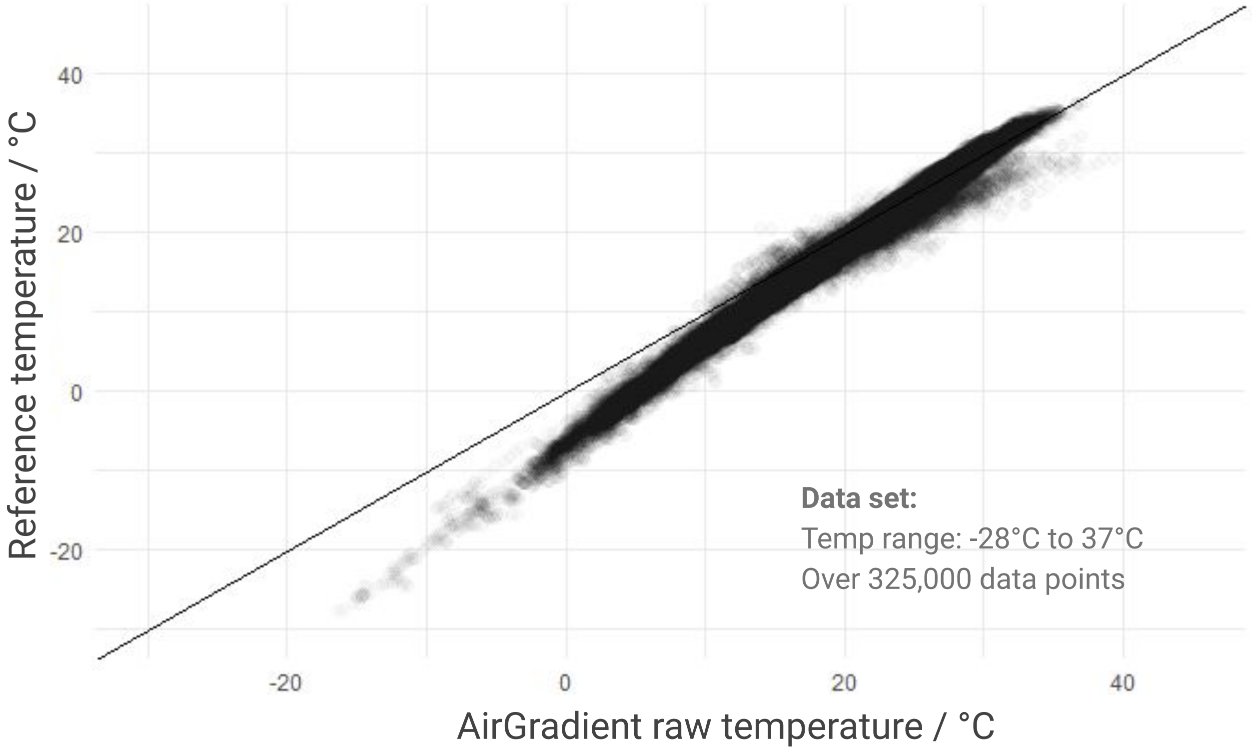
Temperature correction



Comparison with reference

Compare monitor readings with reference

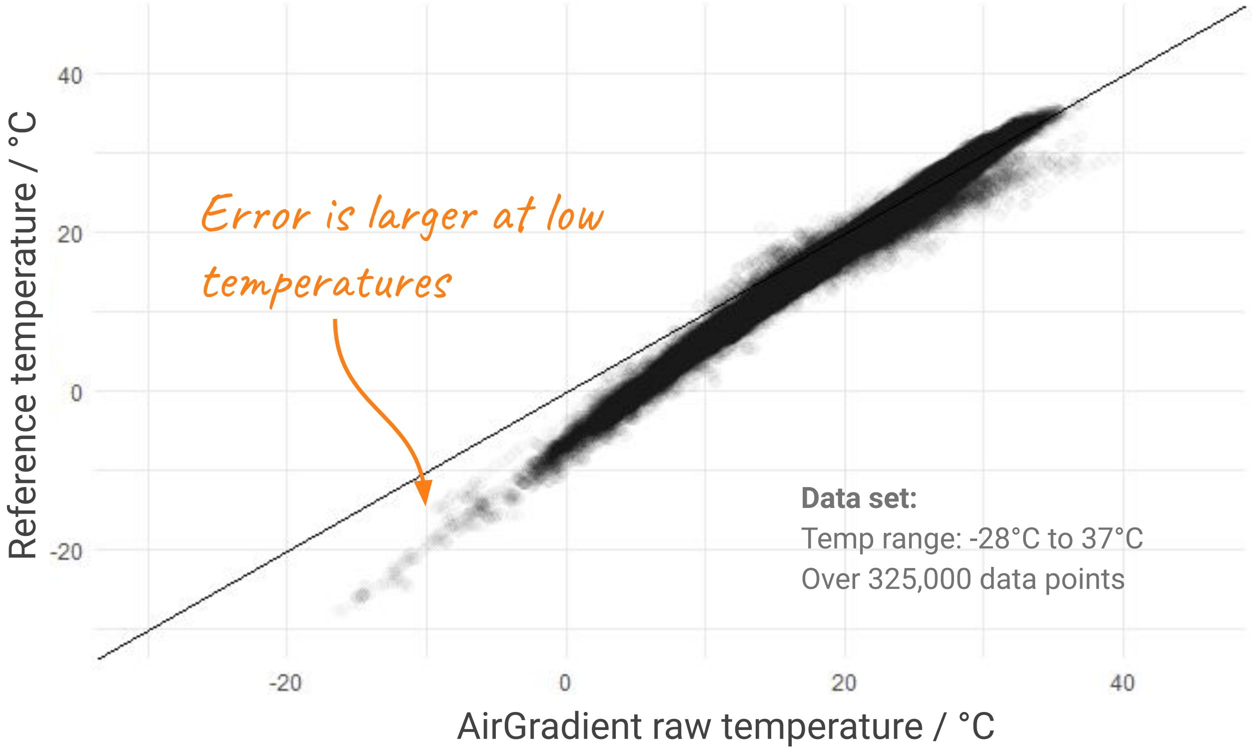
Comparison with reference



Compare monitor readings with reference

***Fig. 5:** Scatterplot of AirGradient temperature measurements and their corresponding reference values across multiple locations (Bellingham, USA; Chennai, India; Cambridge, UK; Edmonton, Canada; Copenhagen, Denmark).*

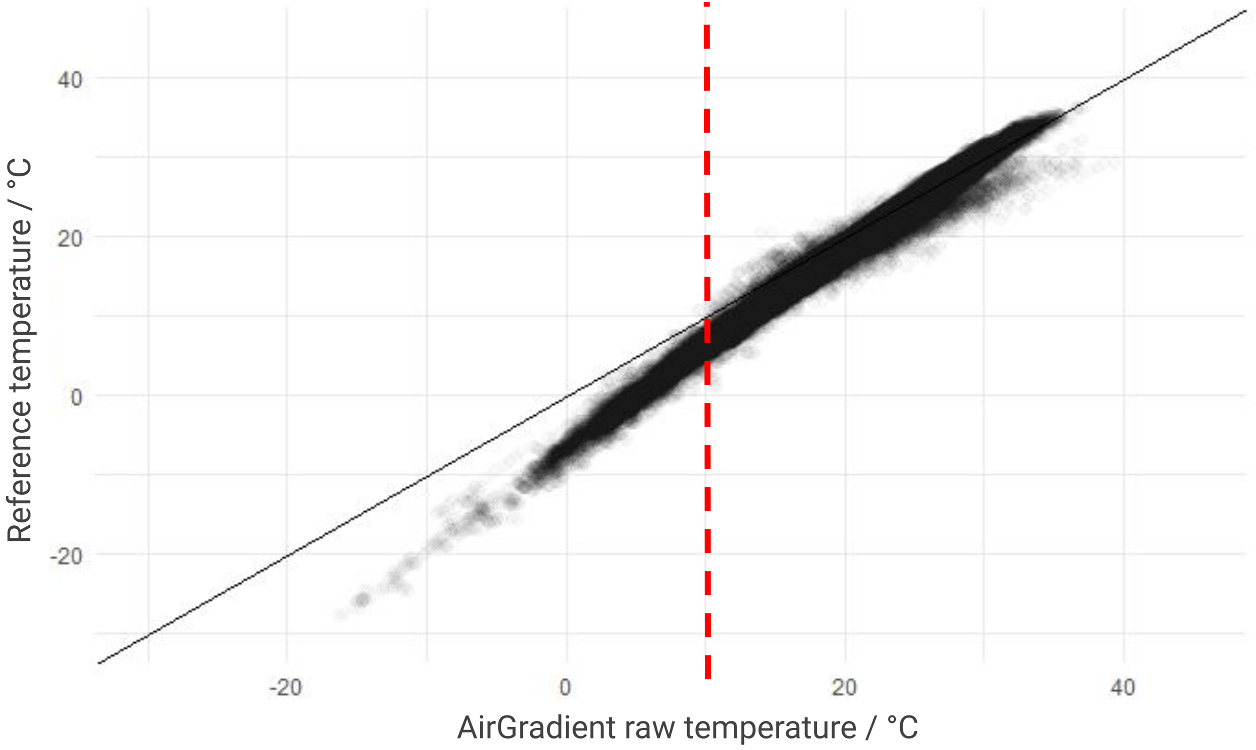
Comparison with reference



Compare monitor readings with reference

Fig. 5: Scatterplot of AirGradient temperature measurements and their corresponding reference values across multiple locations (Bellingham, USA; Chennai, India; Cambridge, UK; Edmonton, Canada; Copenhagen, Denmark).

The Solution



Calibration procedure

- Split into 2 ranges:
  > 10 degrees
  < 10 degrees

- Perform a separate linear calibration for each temp range

Fig. 5: *Scatterplot of AirGradient temperature measurements and their corresponding reference values across multiple locations (Bellingham, USA; Chennai, India; Cambridge, UK; Edmonton, Canada; Copenhagen, Denmark).*

The Solution

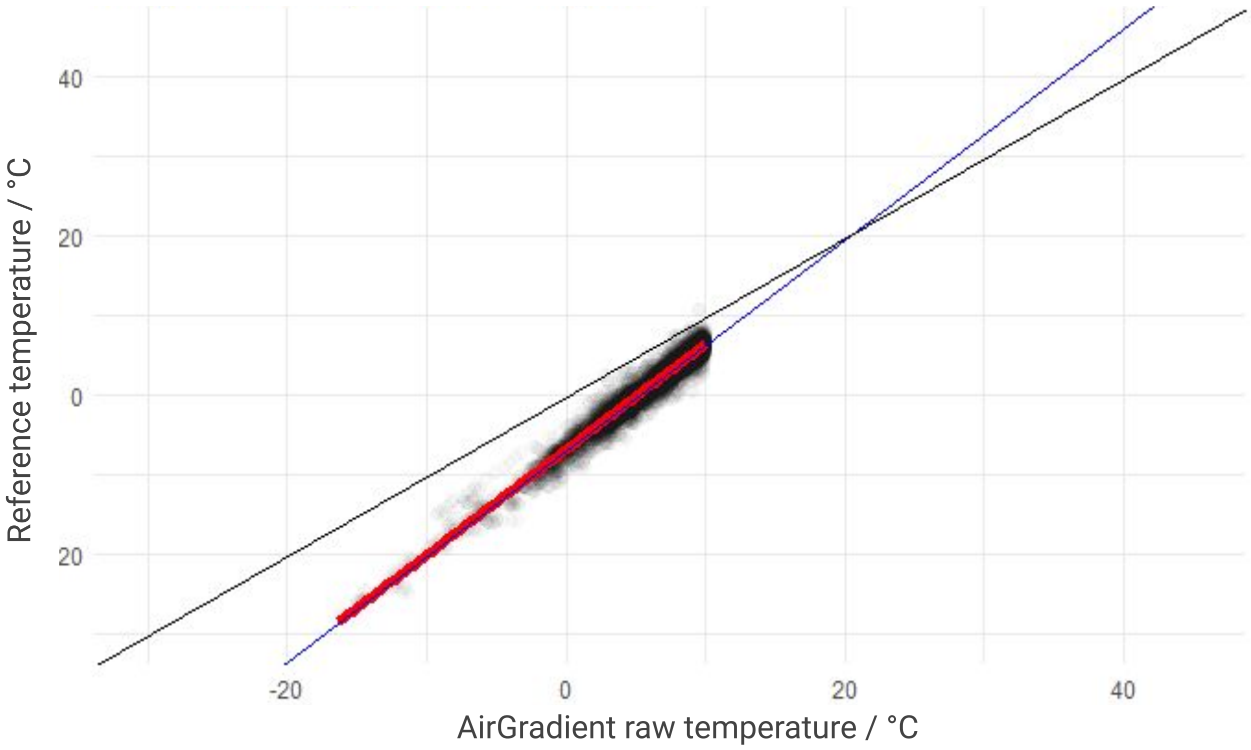


Fig. 5a: *Scatterplot of AirGradient temperature measurements and their corresponding reference values below 10°C.*

Calibration parameters

Low temperatures
< 10 °C

Calibr. = raw *1.327 - 6.738

slope a intercept b

The Solution

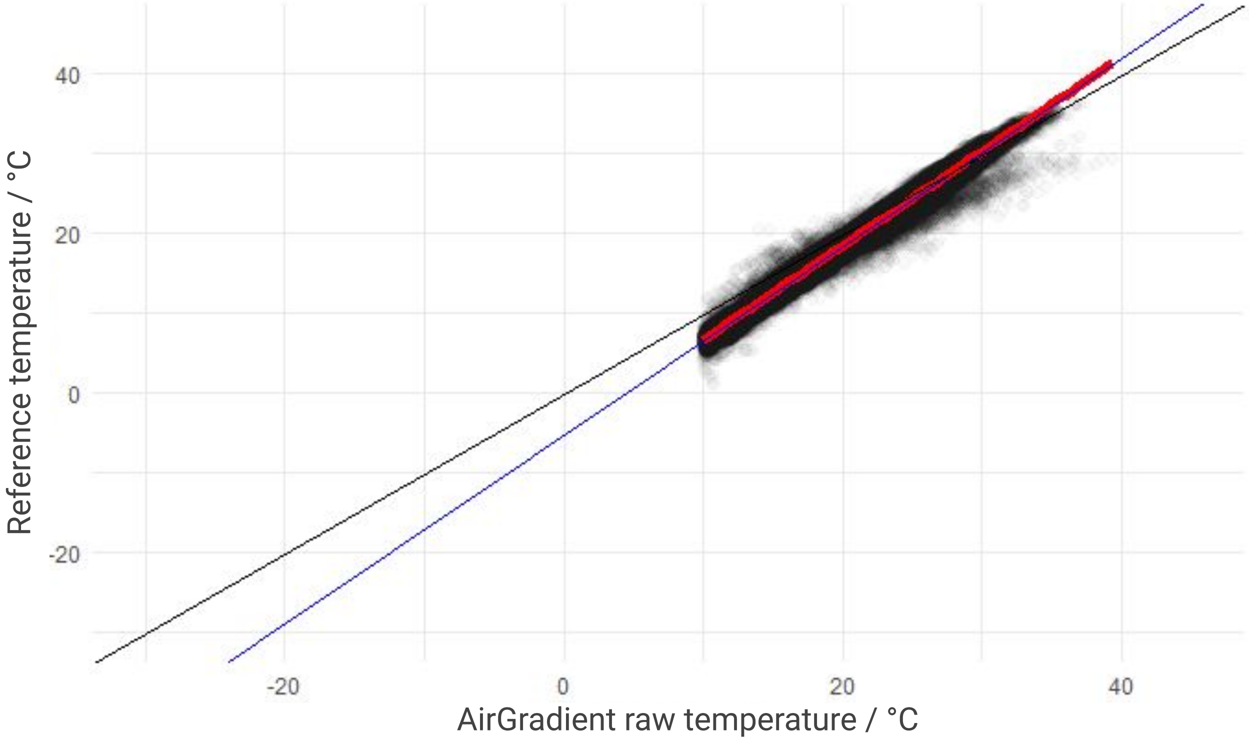


__Fig. 5b:__ Scatterplot of AirGradient temperature measurements and their corresponding reference values above 10°C.

Calibration parameters

High temperatures
> 10 °C

Calibr. = raw *1.181 - 5.112

slope a intercept b

The Solution: Raw vs. calibrated

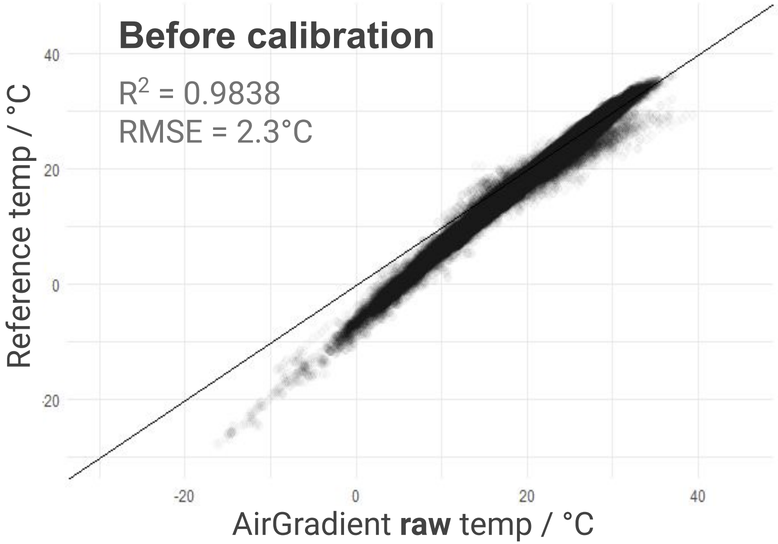


***Fig. 5:** Raw AirGradient vs reference.*

Correction code (R script):

```
data$temp_ag_cal <- ifelse(data$temp_degc_ag < 10,
                           data$temp_degc_ag*1.327 - 6.738,
                           data$temp_degc_ag*1.181 - 5.112)
```

The Solution: Raw vs. calibrated

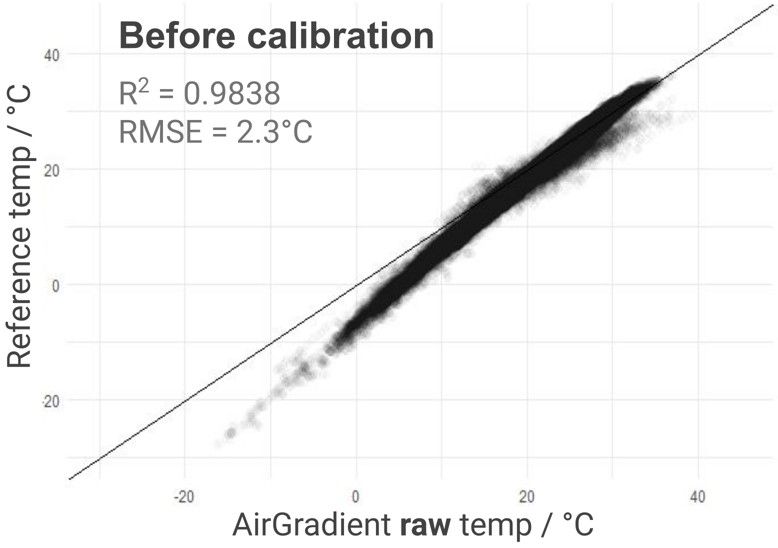


Fig. 5: Raw AirGradient vs reference.

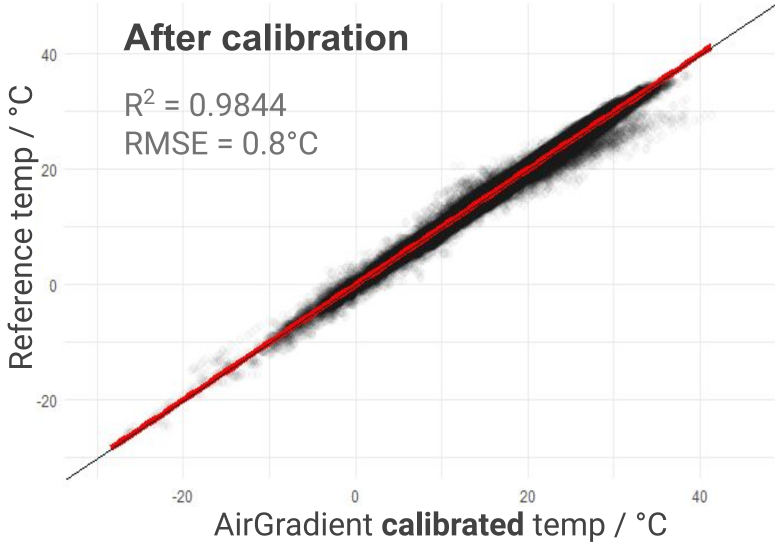


Fig. 6: Calibrated AirGradient vs reference.

Correction code (R script):

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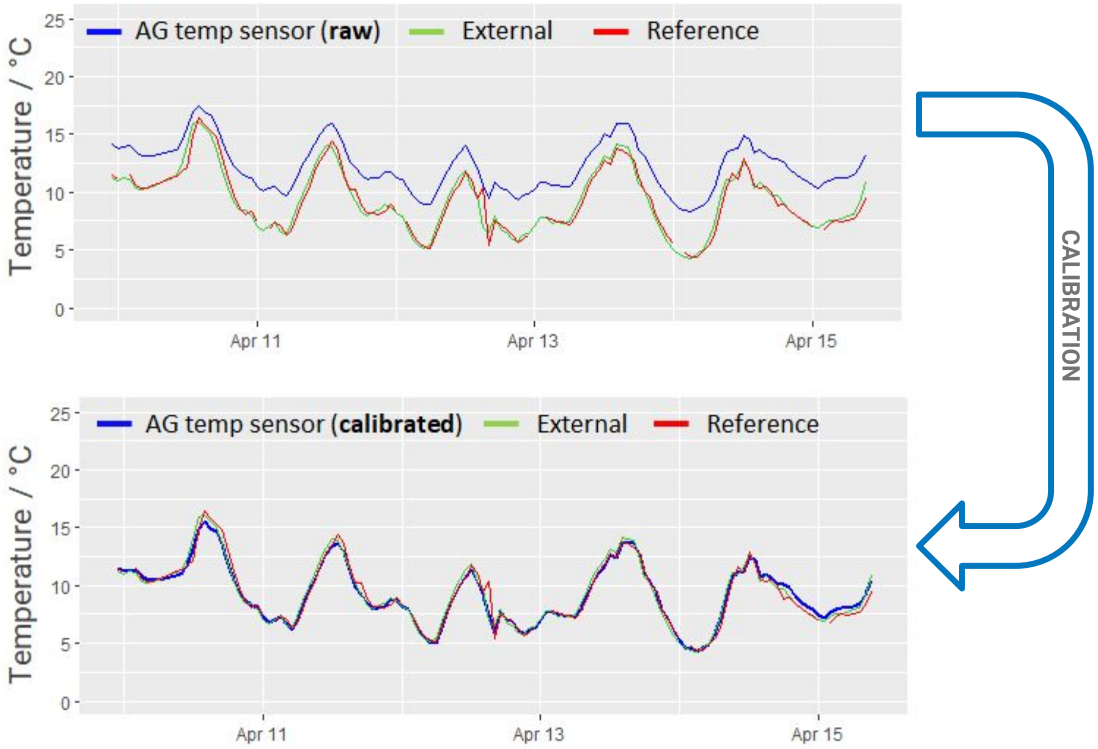
```

Raw vs. calibrated



Back to the start experiment

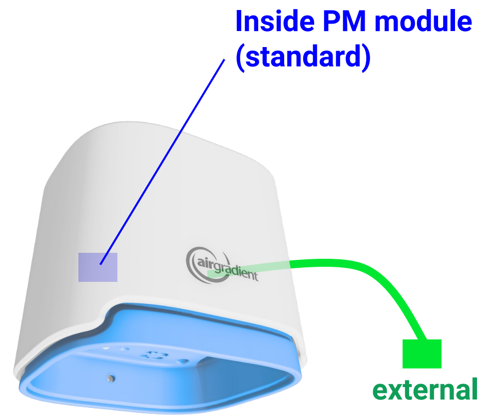
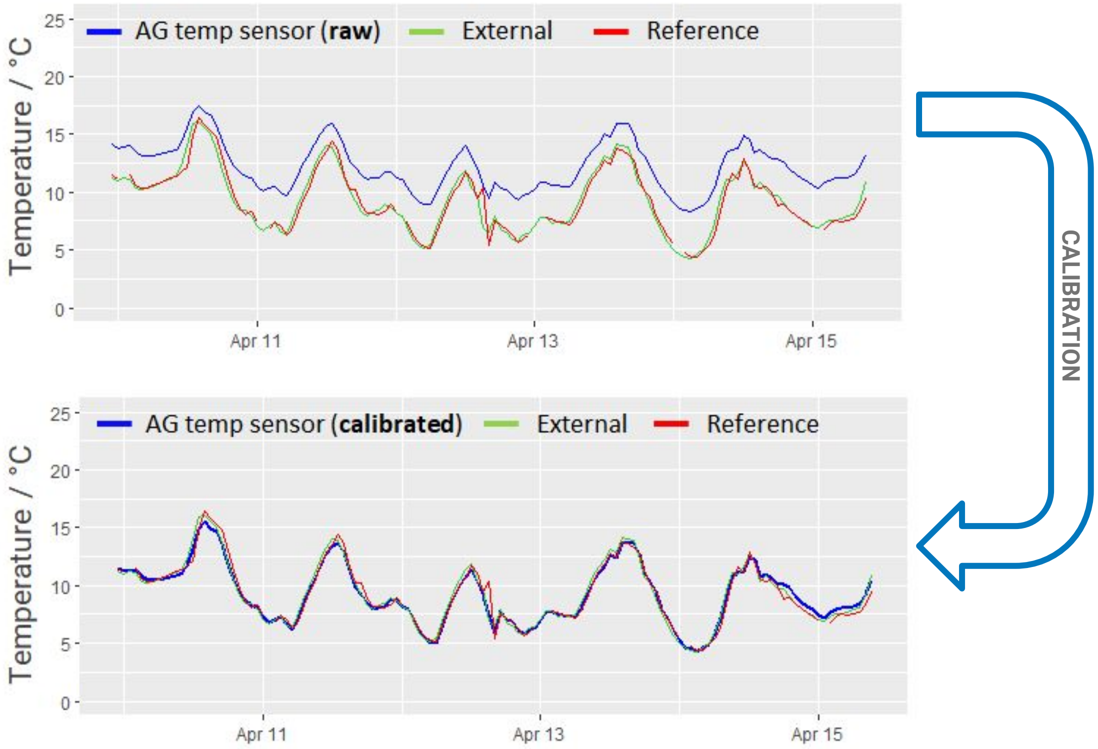


Fig. 2 and 2a: *Temp sensor integrated in PM module (blue) and outside of the monitor box (green) compared to reference measurements (red).*
Top: Raw AirGradient data. Bottom: Calibrated AirGradient data.

Raw vs. calibrated



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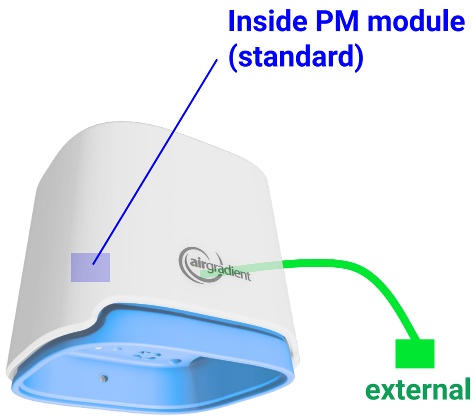

Calibration compensates for the sensor placement inside the monitor box.

Raw vs. calibrated

	RMSE raw	RMSE calibrated	# datapoints
Cold temp < 10°C	± 4.6°C	± 0.9°C	19,768
Warm temp > 10°C	± 2.1°C	± 0.8°C	322,117
Full data set	± 2.3°C	± 0.8°C	341,718

Table 2: *Comparison of the average temperature error before and after the monitor calibration.*

Raw vs. calibrated

	RMSE raw	RMSE calibrated	# datapoints
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Full data set	± 2.3°C	± 0.8°C	341,718

Table 2: *Comparison of the average temperature error before and after the monitor calibration.*

Temperature error has been successfully corrected!

Correction is implemented in latest AirGradient firmware.

Raw vs. calibrated

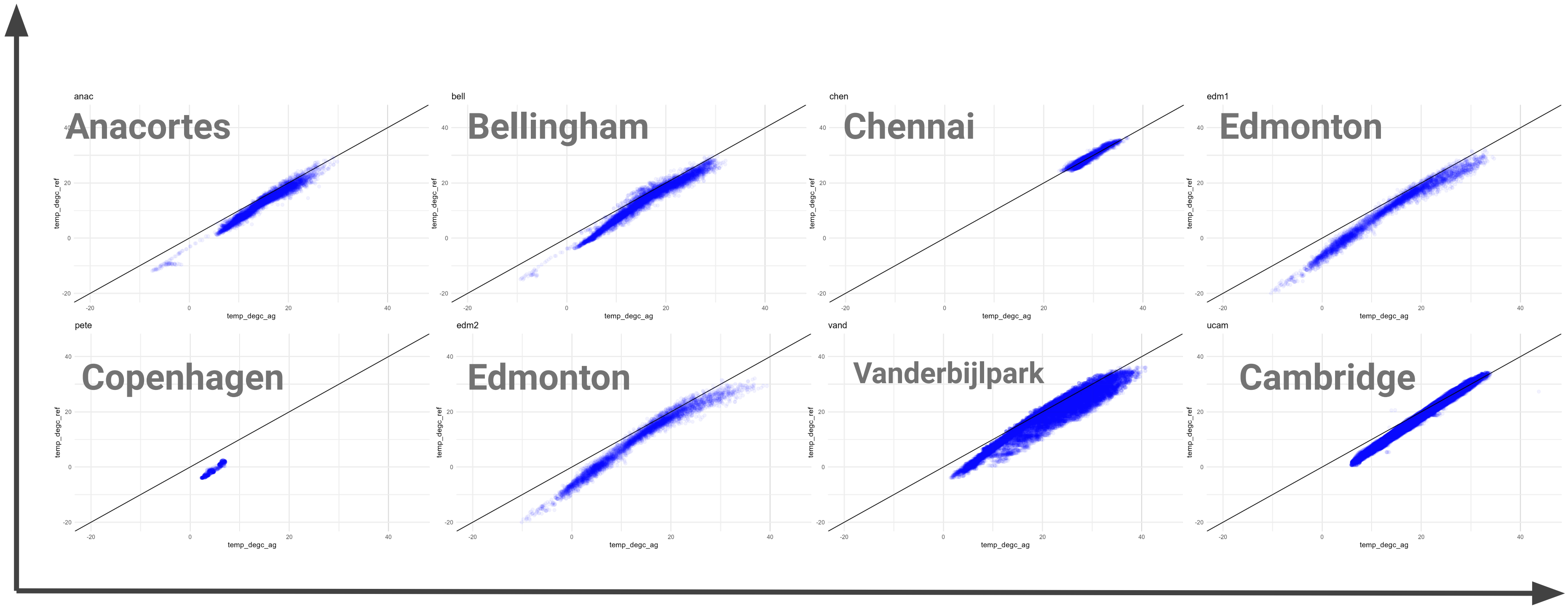


Fig. 7: *Raw AirGradient (AG) temperature data vs. reference measurements by location.*

Raw vs. **calibrated**

Reference

Correction works for all locations!

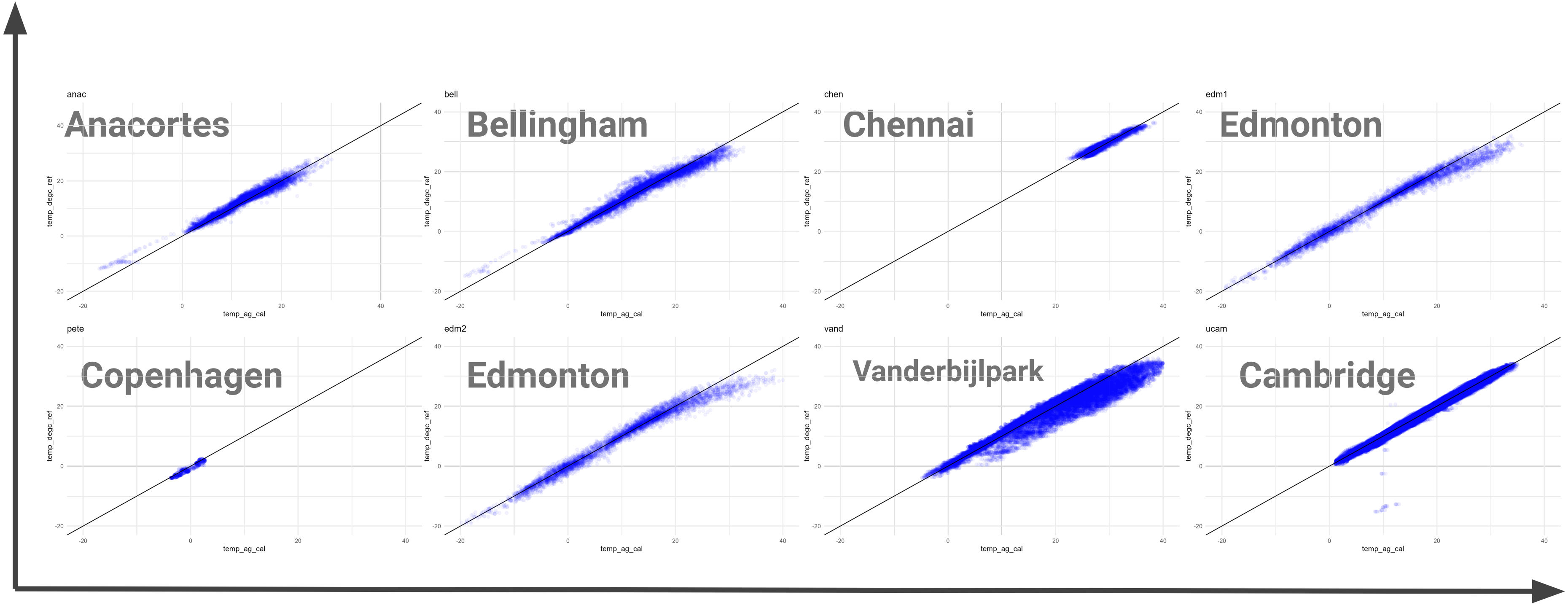


Fig. 8: Calibrated AirGradient (AG) temperature data vs. reference measurements by location.

Calibrated AG

Raw vs. **calibrated**

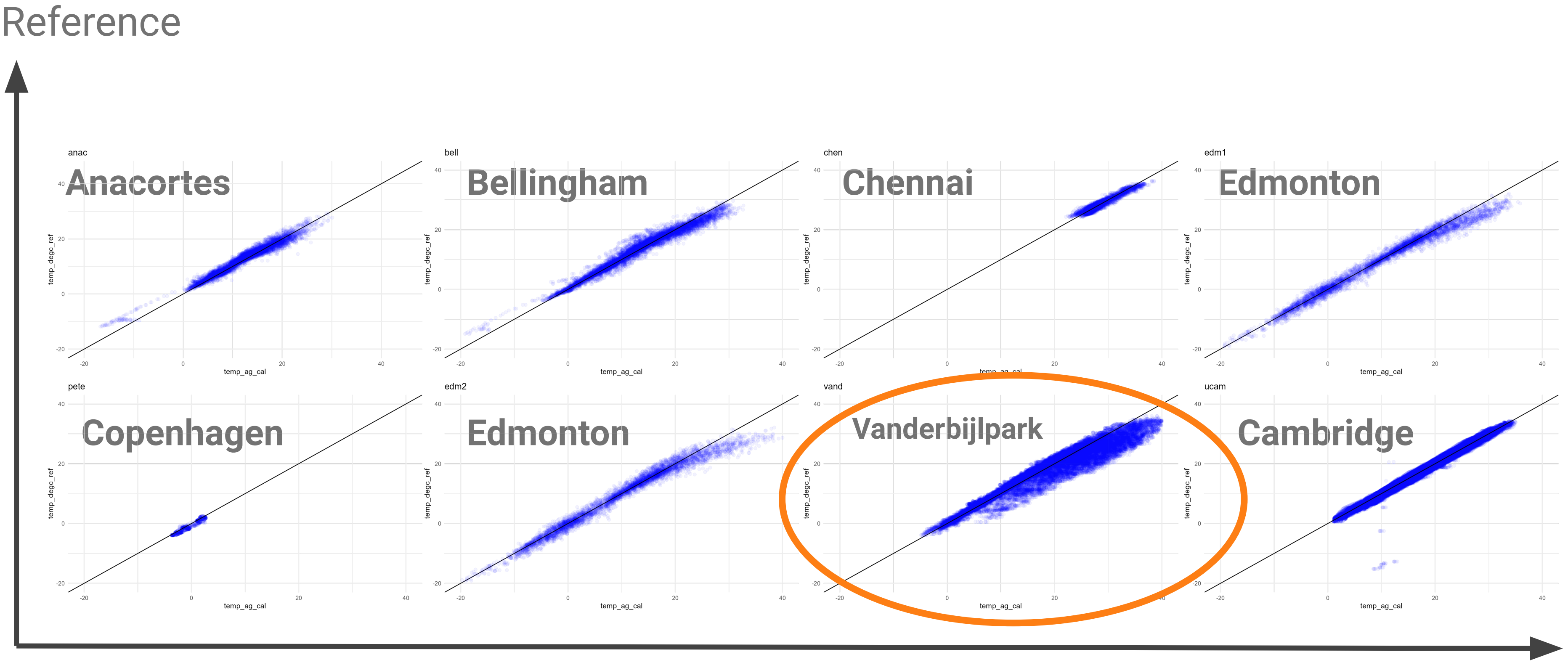


***Fig. 8:** Calibrated AirGradient (AG) temperature data vs. reference measurements by location.*

Effect of direct sunlight: Vanderbijlpark, South Africa

Night data

- All data between 20:00 and 06:00

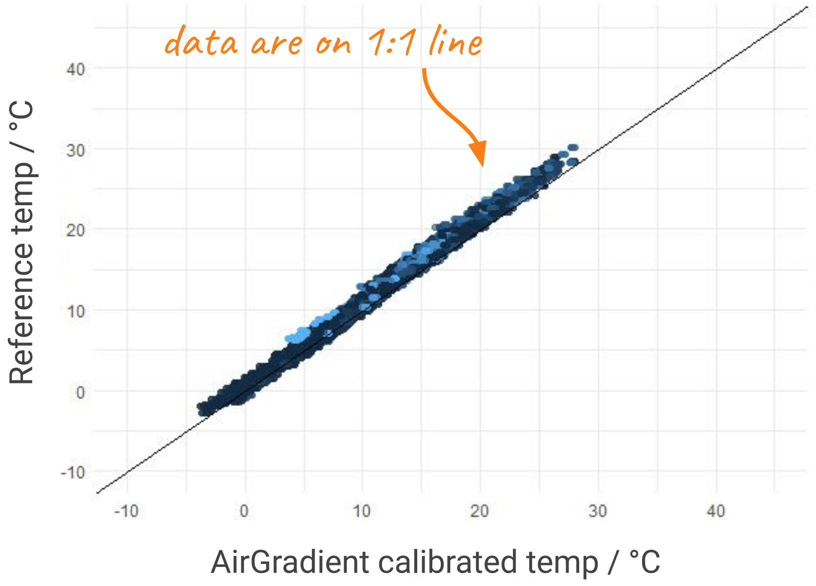


__Fig. 9:__ Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage (in %). __Nighttime__ data only.

Day data

- All data between 06:00 and 20:00

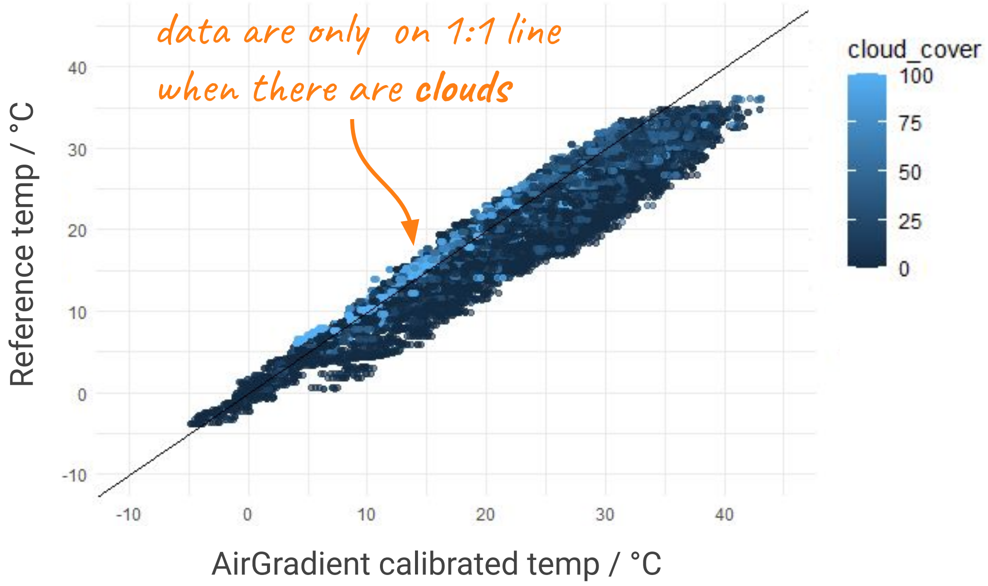


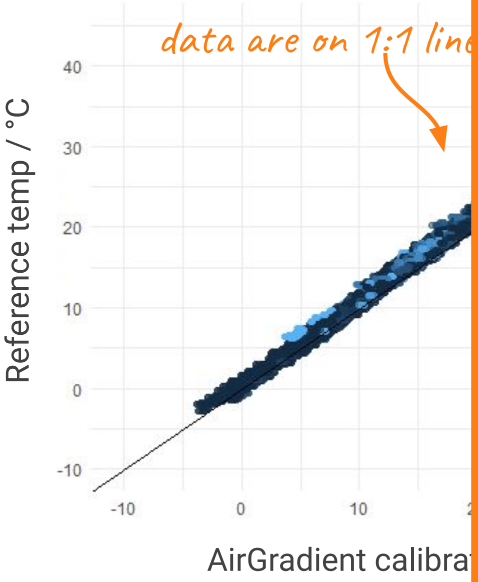
__Fig. 10:__ Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage. __Daytime__ data only.

Effect of direct sunlight: Vanderbijlpark, South Africa

Night data

- All data between

Day data



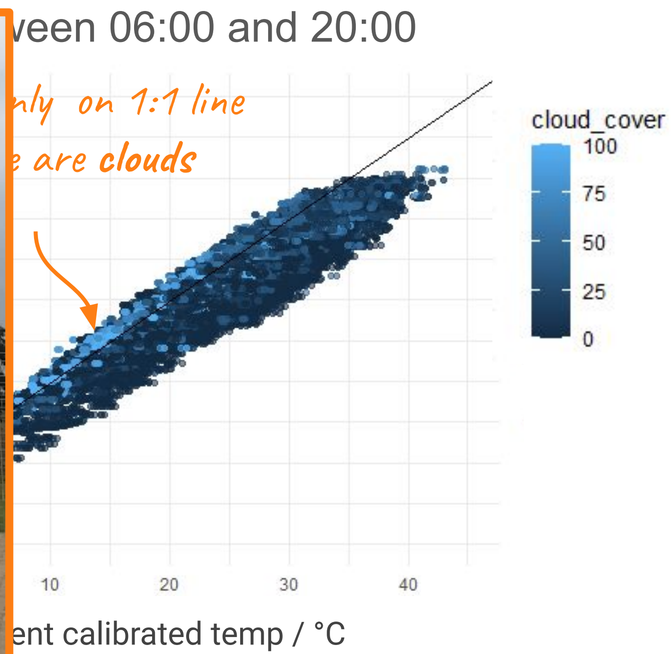


***Fig. 9:** Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage (in %). **Nighttime** data only.*

***Fig. 10:** Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage. **Daytime** data only.*

Effect of direct sunlight: Vanderbijlpark, South Africa

Night data
- All data between 20:00 and 06:00

Day data
- All data between 06:00 and 20:00

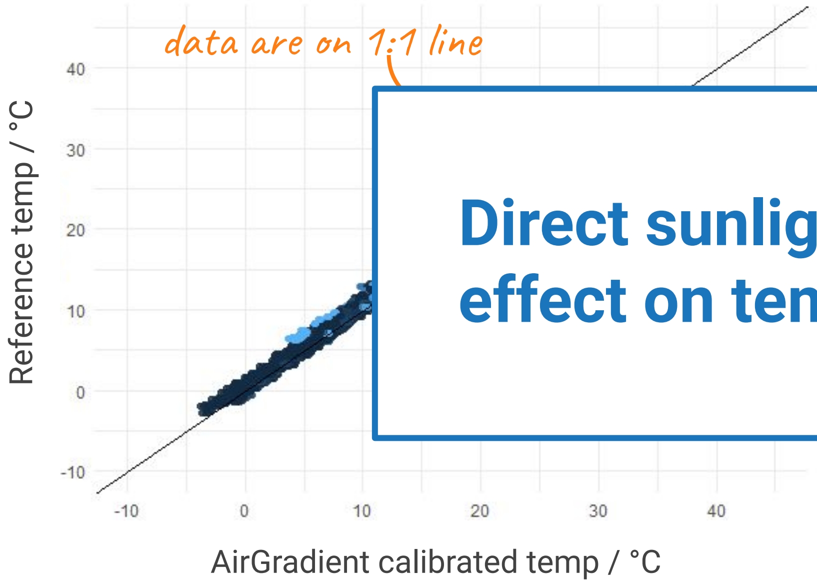


Fig. 9: *Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage (in %).* ***Nighttime*** *data only.*

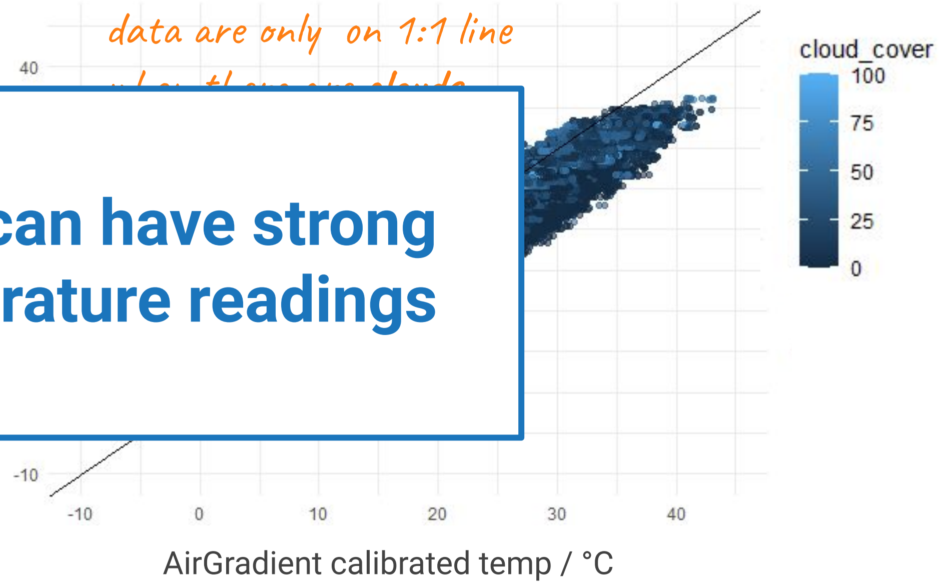


Fig. 10: *Calibrated AG vs. reference in Vanderbijlpark coloured by cloud coverage.* ***Daytime*** *data only.*

Direct sunlight can have strong effect on temperature readings

RH calibration

RH = 45%

RH = 60%

In some cases difference of 15% - 20%

Reproducibility (is the error consistent?)

City	Country	R^2	RMSE (percentage points)
Anacortes	United States	0.96	± 2.1%
Bellingham	United States	0.98	± 1.9%
Chennai	India	1	± 1.3%
Chiang Mai	Thailand	0.99	± 3.5%
Duebendorf	Switzerland	1	± 0.9%
Guatemala City	Guatemala	0.99	± 1.5%
London (Marylebone Road)	United Kingdom	0.96	± 2.5%
London (Honor Oak Park)	United Kingdom	0.99	± 1.8%
Ottawa	Canada	0.99	± 2.0%
Cambridge	United Kingdom	1	± 2.5%
Vanderbijlpark	South Africa	1	± 1.1%

Table 3: *Reproducibility of AirGradient relative humidity measurements. Performance characteristics are averaged over all sensors in each location.*

Reproducibility (is the error consistent?)

City	Country	R^2	RMSE (percentage points)
Anacortes	United States	0.96	± 2.1%
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Chennai	India	1	± 1.3%
Chia[illegible]	[illegible]	[illegible]	[illegible]%
Due[illegible]	[illegible]	[illegible]	[illegible]%
Gua[illegible]	[illegible]	[illegible]	[illegible]%
London (Marylebone Road)	United Kingdom	0.96	± 2.5%
London (Honor Oak Park)	United Kingdom	0.99	± 1.8%
Ottawa	Canada	0.99	± 2.0%
Cambridge	United Kingdom	1	± 2.5%
Vanderbijlpark	South Africa	1	± 1.1%

High reproducibility between RH sensors
→ RH error can be corrected for

Table 3: *Reproducibility of AirGradient relative humidity measurements. Performance characteristics are averaged over all sensors in each location.*

Calibration

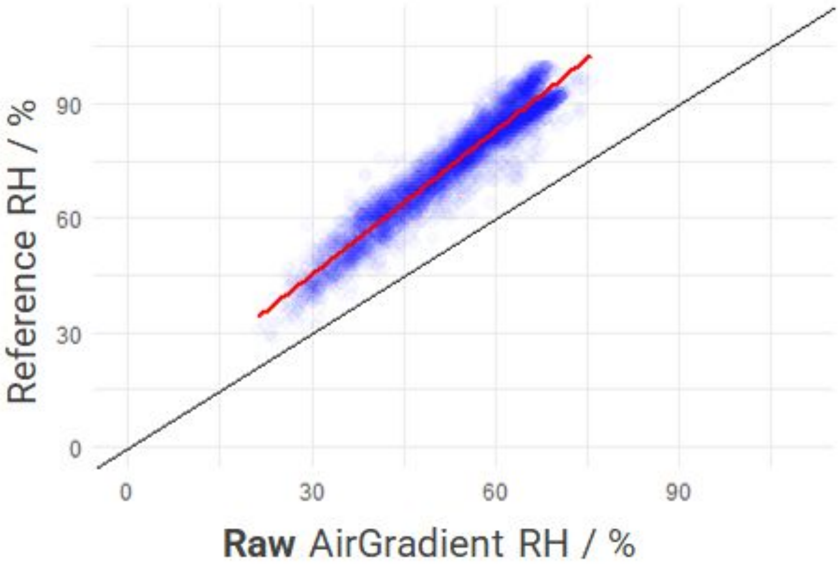


***Fig. 11: Raw** AirGradient RH measurements vs reference.*

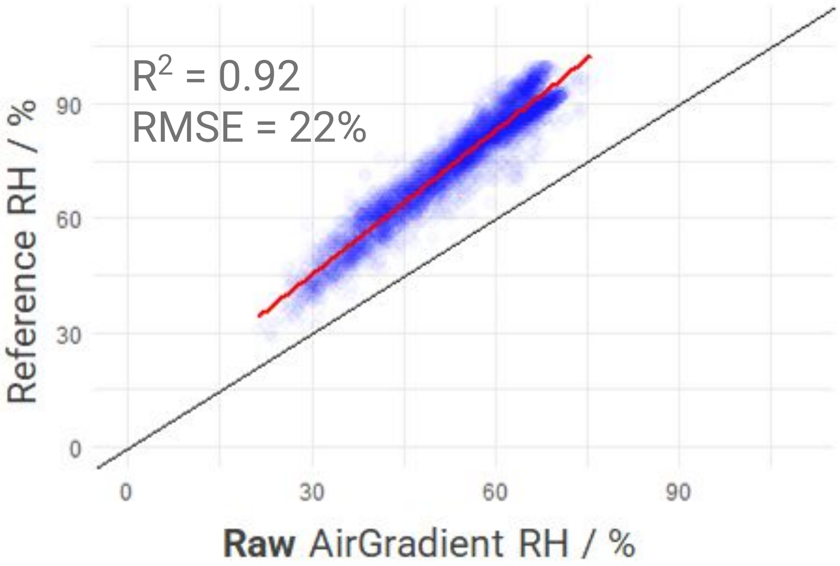


*Fig. 11: **Raw** AirGradient RH measurements vs reference.*

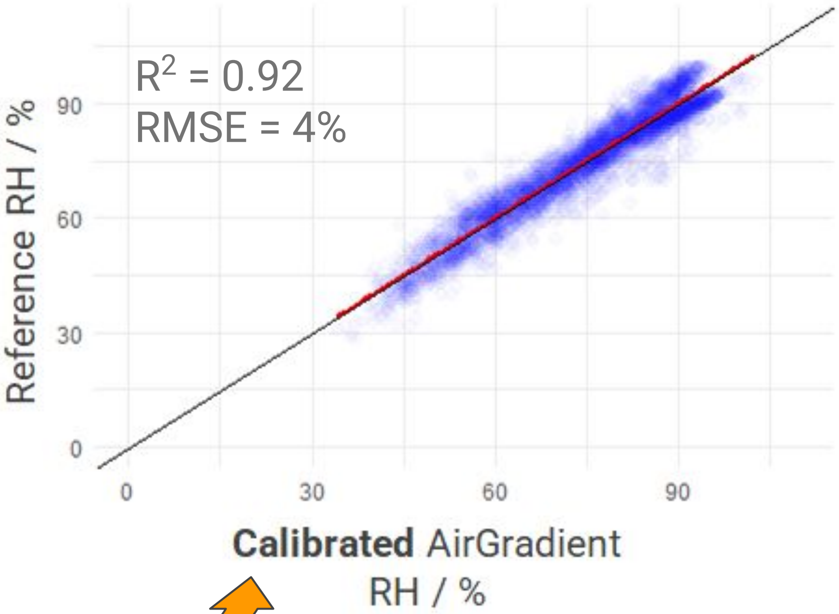
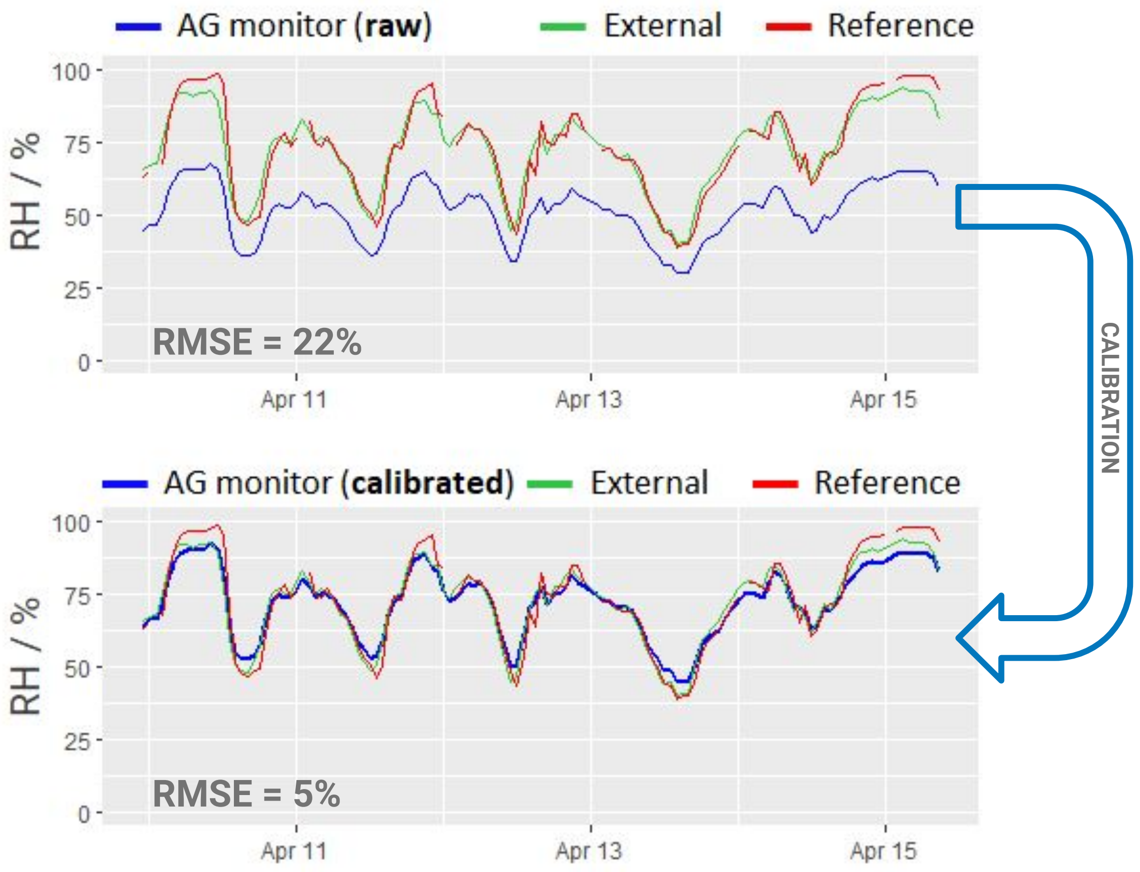
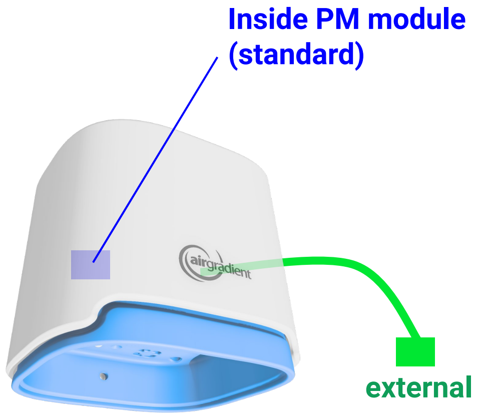


*Fig. 11: **Calibrated** AirGradient RH measurements vs ref.*

RH(calib) = RH(raw) * 1.259 + 7.34

Back to the start experiment





Solution to RH deviation

Step 1: Calibration
RH(calib) = RH(raw) * 1.259 + 7.34

Step 2: Cut data > 100%
RH(final) = if {RH(calib) > 100} then {RH(calib) = 100}

Analysis will be continued while dataset is growing
→ **Potential updates in the future**

- Temperature sensors are highly reproducible and accurate
- Impact of monitor case can be compensated for via calibration (2 temp ranges)
- Direct sunlight impacts temperature readings
- RH accuracy can be improved by simple linear calibration

And now?

Performance analysis of the…

- PM sensor: Ongoing
- CO_2 sensor: Co-locations initiated

TVOC & NOx sensors:

Define strengths & limitations
+ use cases in outdoor environments

Questions?