Supplement of

Low-complexity methods to mitigate the impact of environmental variables on low-cost UAS-based atmospheric carbon dioxide measurements

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Sensor Selection

Table S1. Examples of low-cost NDIR CO$_2$ sensors

| Manufacturer           | Vaisala | Senseair | ELT Co. | Korea Digital Co. | GE Sensing | Amphenol Adv. Sensors | Cozir | Cozir-A |
|------------------------|---------|----------|---------|-------------------|------------|-----------------------|-------|---------|
| Model                  | GMM222C | K30      | S100    | AN100             | T6615      | T6613                 |       | Cozir-A |
| Measurement range [ppm]| 0–2,000 | 0–5,000  | 0–10,000| 0–5,000          | 0–10,000  | 0–2,000               | 0–10,000 |
| Accuracy [ppm]         | ±30     | ±30      | ±50     | ±200              | ±75        | ±30                   | ±50   |
| Weight [g]             | 220     | 17       | 10      | 29                | 17         | -                     | 20    |
| Cost [USD]             | -       | 95.00    | -       | -                 | 104.81     | 99.72                 | 109.00 |

Sources: senseair.com, eltsensor.co.kr, farnell.com/datasheets/484016.pdf, amphenol-sensors.com; co2meter.com, Al-Hajjaji et al. (2017), and Yasuda et al. (2012).

Table S2. Literature search arguments and their results.

| Search string                              | Results |
|--------------------------------------------|---------|
| +CO2 +unmanned +aerial                     | 11,300  |
| +CO2 +unmanned +aerial +(K30 OR K-30 OR “K 30”) | 67 |
| +CO2 +unmanned +aerial...                  | 6       |
| +(GMM222C OR S100 OR AN100 OR T6615) -(K30 OR K-30 OR “K 30”) | |
| +Carbon +dioxide +unmanned +aerial         | 10,500  |
| +Carbon +dioxide +unmanned +aerial +(K30 OR K-30 OR “K 30”) | 62 |
| +Carbon +dioxide +unmanned +aerial...      | 3       |
| +(GMM222C OR S100 OR AN100 OR T6615) -(K30 OR K-30 OR “K 30”) | |
| +Carbon +dioxide +remotely +piloted +aircraft | 1520    |
| +Carbon +dioxide +remotely +piloted +aircraft +(K30 OR K-30 OR “K 30”) | 7 |
| +Carbon +dioxide +remotely +piloted +aircraft... | 1 |
| +(GMM222C OR S100 OR AN100 OR T6615) -(K30 OR K-30 OR “K 30”) | |
Experiments

Table S3. List all the experiments performed and their sensors. The sensor intercomparison experiments are not listed in this table.

| Type          | Name                     | Duration [min] | Reference Sensors   | Test Sensor   |
|---------------|--------------------------|----------------|--------------------|--------------|
| Chamber       | Pressure                 | 90             | LI-840A            | K30_11, K30_12 |
|               | Temperature 1            | 300            | LI-840A, LI-820    | K30_13, K30_14; K30_21, K30_22; K30_31, K30_32 |
|               | Temperature 2            | 300            | LI-840A, LI-820    | K30_21, K30_22; K30_31, K30_32 |
|               | Rel. humidity 1          | 90             | LI-840A, LI-820    | K30_13, K30_14; K30_21, K30_22; K30_31, K30_32 |
|               | Rel. humidity 2          | 90             | LI-840A, LI-820    | K30_21, K30_22; K30_31, K30_32 |
| Bench         | Pressure Correction (Learn 1) | LI-840A     | K30_21, K30_22    |
|               | Pressure Correction (Learn 2) | LI-840A     | K30_21, K30_22    |
|               | Pressure Correction (Test 1) | LI-840A     | K30_21, K30_22    |
|               | Pressure Correction (Test 1) | LI-840A     | K30_21, K30_22    |
|               | Pressure Time-response (Learn 1) | LI-840A     | K30_21, K30_22    |
|               | Pressure Time-response Learn 2 | LI-840A    | K30_21, K30_22    |
|               | Pressure Time-response Test 1 | LI-840A    | K30_21, K30_22    |
|               | Pressure Time-response Test 2 | LI-840A    | K30_21, K30_22    |
|               | Temp. and RH 1           |                |                    |
|               | Temp. and RH 2           |                |                    |
|               | Temp. and RH 3           |                |                    |
|               | Temp. and RH 4           |                |                    |
Figure S4. Time series for the sensor intercomparison. Reference and test sensors were left running inside an empty laboratory for 2 hours.
Figure S5. Environmental conditions during the 2-hour sensor intercomparison.

Table S6. Metrics for the experimental conditions for the 2-hour sensor intercomparison.

| Variable          | Sensor   | Minimum  | Maximum  | Average  | Standard deviation |
|-------------------|----------|----------|----------|----------|--------------------|
| Pressure [Pa]     | Ref_Lab  | 97231    | 97303.17 | 97261.5  | 20.98              |
|                   | Ref      | 96870    | 96952.17 | 96903.78 | 23.91              |
|                   | TS_2     | 97397.18 | 97468.89 | 97427.32 | 20.84              |
|                   | TS_3     | 97394.98 | 97481.88 | 97430.21 | 25.17              |
| Temperature [°C]  | Ref_Lab  | 50.91    | 50.91    | 50.91    | 0                  |
|                   | Ref      | 51.2     | 51.28    | 51.23    | 0.01               |
|                   | TS_2     | 26.09    | 26.39    | 26.28    | 0.08               |
|                   | TS_3     | 26.27    | 26.47    | 26.41    | 0.05               |
| H2O [ppt]         | Ref      | 13.57    | 13.75    | 13.65    | 0.03               |
| Relative Humidity [%] | TS_2   | 34.05    | 35.07    | 34.35    | 0.26               |
|                   | TS_3     | 39.27    | 40       | 39.45    | 0.16               |
Figure S7. Time series for sensor intercomparison. Reference and test sensors were left running inside an empty laboratory for 30 minutes after the second run of the chambered relative humidity experiments.
Figure S8. Environmental conditions during the 30-minute sensor intercomparison.

Table S9. Metrics for the experimental conditions for the 30-minute sensor intercomparison.

| Variable        | Sensor     | Minimum  | Maximum  | Average  | Standard deviation |
|-----------------|------------|----------|----------|----------|--------------------|
| Pressure [Pa]   | Ref_Lab    | 96928.33 | 97019.33 | 96970.4  | 32.21              |
|                 | Ref        | 96545.5  | 96637.83 | 96588.75 | 32.51              |
|                 | TS_1       | 97059.56 | 97151.18 | 97102.62 | 32.37              |
|                 | TS_3       | 97061.45 | 97157.06 | 97107.03 | 33.65              |
| Temperature [°C]| Ref_Lab    | 50.91    | 50.91    | 50.91    | 0                  |
|                 | Ref        | 51.23    | 51.23    | 51.23    | 0                  |
|                 | TS_3       | 30.86    | 32.31    | 32       | 0.34               |
| H₂O [ppt]      | Ref        | 12.22    | 13.81    | 13.34    | 0.42               |
| Relative Humidity [%] | TS_3 | 25.27    | 30.09    | 27.5     | 1.06               |
**Chamber: Pressure**

Table S10. Metrics for the experimental conditions for the chambered pressure experiment, where Ref stands for Reference sensor and TS_1 for Test System 1 (one HYT-271 and two K-30 sensors).

| Variable  | Sensor | Minimum   | Maximum   | Average | Standard deviation |
|-----------|--------|-----------|-----------|---------|--------------------|
| Pressure [Pa] | Chamber | 60,165.59 | 105,001.76 | -       | -                  |
|           | Ref    | 98,512.17 | 98,561.50 | 98,539.36 | 12.78              |
| Temperature [°C] | Chamber | 25.17 | 25.41 | 25.36 | 0.08 |
|           | TS_1   | 26.78 | 26.95 | 26.87 | 0.03               |
| H₂O [ppt]  | Ref    | 2.81 | 3.13 | 2.96 | 0.06               |
| Relative Humidity [%] | TS_1 | 43.00 | 47.09 | 45.64 | 0.98          |
| CO₂ [ppm]  | Ref    | 453.04 | 468.00 | 461.68 | 2.55               |

**Chamber: Temperature**

Table S11. Metrics for the experimental conditions during the chambered temperature experiment.

| Variable  | Sensor | Minimum   | Maximum   | Average | Standard deviation |
|-----------|--------|-----------|-----------|---------|--------------------|
| Pressure [Pa] | Ref_Lab | 96,749.67 | 97,170 | 96,886.62 | 133.11          |
|           | Ref    | 96,373.33 | 96,800 | 96,517.16 | 131               |
|           | TS_1   | 96,896.69 | 97,323.5 | 97,033.84 | 136               |
|           | TS_2   | 96,911.51 | 97,341.7 | 97,050.26 | 135.05            |
|           | TS_3   | 96,988.3 | 97,324.74 | 97,033.77 | 134.65             |
| Temperature [°C] | Chamber | 10.47 | 40.98 | - | - |
|           | TS_2   | 12.1 | 44.21 | - | - |
|           | TS_3   | 13.07 | 45.19 | - | - |
| Relative Humidity [%] | Chamber | 43.78 | 49.27 | 45.56 | 1.05 |
|           | TS_2   | 31.38 | 37.21 | 33.76 | 1.3               |
|           | TS_3   | 34.4 | 41.01 | 36.91 | 1.51               |
| CO₂ [ppm]  | Ref_Lab | 454.17 | 483.68 | 467.22 | 8.39               |
|           | Ref    | 469.12 | 485.66 | 474.65 | 4.02               |
|           | K30_13 | 471.93 | 503.9 | - | - |
|           | K30_14 | 470.69 | 502.78 | - | - |
|           | K30_21 | 471.01 | 517.61 | - | - |
|           | K30_22 | 464.32 | 510.3 | - | - |
|           | K30_31 | 464.91 | 487.22 | - | - |
|           | K30_32 | 471.12 | 510.14 | - | - |
Figure S12. Original data for the test run of the temperature correction coefficients. CO$_2$ values after corrections with coefficients from the “Learn” run.

Table S13. Metrics for the experimental conditions during the test run of the temperature correction coefficients.

| Variable          | Sensor     | Minimum  | Maximum  | Average  | Standard deviation |
|-------------------|------------|----------|----------|----------|--------------------|
| Pressure [Pa]      | Ref_Lab    | 97223.67 | 97393.17 | 97304.15 | 46.87              |
|                   | Ref        | 96862    | 97029    | 96944.27 | 43.98              |
|                   | TS_2       | 97386.73 | 97563.75 | 97470.78 | 48.25              |
|                   | TS_3       | 97386.54 | 97562.07 | 97468.35 | 47.65              |
| Temperature [°C]   | Chamber    | 10.28    | 40.25    | -        | -                  |
|                   | TS_2       | 15.26    | 41.88    | -        | -                  |
|                   | TS_3       | 15.74    | 42.54    | -        | -                  |
| Relative Humidity [%] | Chamber    | 43.48    | 47.81    | 45.17    | 1.23               |
|                   | TS_2       | 25.87    | 38.39    | 34.16    | 4.01               |
|                   | TS_3       | 30.68    | 42.32    | 38.3     | 3.65               |
| CO$_2$ [ppm]      | Ref_Lab    | 448.14   | 462.11   | 452.29   | 3.69               |
|                   | Ref        | 451.82   | 464.22   | 455.54   | 2.46               |
|                   | K30_21     | 451.87   | 494.38   | -        | -                  |
|                   | K30_22     | 454.2    | 494.87   | -        | -                  |
|                   | K30_31     | 444.91   | 465.14   | -        | -                  |
|                   | K30_32     | 453.06   | 488.83   | -        | -                  |
Figure S14. Results for the test run of the temperature correction coefficients. CO$_2$ values after corrections with coefficients from “Learn” run.
Chamber: Relative Humidity

Table S15. Metrics for the experimental conditions during the chambered relative humidity experiment.

| Variable       | Sensor  | Minimum   | Maximum   | Average  | Standard deviation |
|----------------|---------|-----------|-----------|----------|--------------------|
| Pressure [Pa]  | Ref_Lab | 96,665.17 | 97,010    | 96,782.7 | 97.64              |
|                | Ref     | 96,288.08 | 96,640    | 96,408.73| 98.57              |
|                | TS_1    | 96,810.75 | 97,145.8  | 96,919.33| 93.65              |
|                | TS_2    | 96,828.37 | 96,949.96 | 96,901.46| 40.26              |
|                | TS_3    | 96,809.64 | 97,152.3  | 96,927.45| 96.1               |
| Temperature [°C]| Chamber | 25.88     | 27.45     | 27.07    | 0.33               |
|                | TS_2    | 28.66     | 30.29     | 29.97    | 0.43               |
|                | TS_3    | 29.78     | 31.18     | 30.94    | 0.33               |
| Relative Humidity [%]| Chamber | 15.1      | 85.4      | -        | -                  |
|                | TS_2    | 11.67     | 61.75     | -        | -                  |
|                | TS_3    | 12.15     | 68.8      | -        | -                  |
| CO₂ [ppm]      | Ref_Lab | 444.38    | 449.42    | 446.5    | 1.43               |
|                | Ref     | 443.8     | 452.83    | 447.85   | 2.33               |
|                | K30_13  | 449       | 461.25    | -        | -                  |
|                | K30_14  | 448.3     | 466.06    | -        | -                  |
|                | K30_21  | 449.03    | 460.13    | -        | -                  |
|                | K30_22  | 448.9     | 462.86    | -        | -                  |
|                | K30_31  | 448.2     | 461.68    | -        | -                  |
|                | K30_32  | 448.94    | 459.06    | -        | -                  |
Figure S16. Time-series data for the experimental conditions during the test run of the relative humidity correction coefficients. The solid black curve represents the relative humidity inside the chamber. The yellow, green, and red curves represent the variables for test systems 1, 2, and 3. The dashed blue curve represents the variables for the reference sensor.
Figure S17. Results for the test run of the relative humidity correction coefficients. CO₂ values after corrections with coefficients from the “Learn” run.

Chamber: Joint Correction

Table S18. Coefficients from the joint correction method for temperature and relative humidity.

| Sensor   | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | $k_6$ | $k_7$ | $k_8$ | $k_9$ | $k_{10}$ | $R^2$ |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|-------|
| K30_21   | -0.0008 | -0.0026 | 0.0381 | -0.0050 | 0.0027 | 0.8186 | -0.0035 | -0.0585 | -0.3789 | -44.635 | 0.9869 |
| K30_22   | -0.0012 | -0.0107 | 0.0027 | -0.0067 | 0.1319 | 1.8161 | -0.0062 | -0.0901 | 0.2411 | 4.6896 | 0.9855 |
Benchtop: Pressure Time Response

Pressure Time Response Correction Test Case 2

Figure S19. Second test case for the pressure time response correction.
Figure S20. Results for the first Benchtop experimental setup (a.k.a. large plastic container). In this case, the water spray was used to increase the humidity of the container.
Figure S21. Results for the second Benchtop experimental setup (a.k.a. directly exposed to electric heater).