

This document contains item-by-item responses to the reviewer's comments. The reviewer's comments are in black, non-italicized, regular fonts. Author responses are in *blue, italicized* fonts. Changes to the manuscript will be provided during revised submission, per instructions of the Copernicus editorial team (i.e., revised manuscript and diff file). Nonetheless, examples of the corrections and a detailed view of each experiment are provided in the attached discussion supplement.

#### General comments:

We thank Reviewer #1 for his very thorough analysis of the manuscript. His commentary was encouraging and helpful in improving the final results. Following his (and reviewer's #2) suggestions, we repeated the Mesonet temperature and relative humidity experiments under more controlled conditions, added more test sensors, and adjusted the result presentation. Therefore, the final comment below is written in light of the following changes:

- The Li-820 sensor originally named CO<sub>2</sub> Independent Sensor Outside is renamed Reference Sensor Out (Ref\_OUT).
- The Li-840A sensor originally named CO<sub>2</sub> Independent Sensor Inside is renamed Reference Sensor In (Ref\_IN).
- The Senseair K30 sensors originally named CO<sub>2</sub> Test Sensors 1 and 2 are renamed K30\_##, where the first digit refers to its attached system (i.e. logger, temperature, and relative humidity sensors) and the second digit is its identification. This way the first Senseair K30 sensor of test system 2 is named K30\_21.
- The Mesonet temperature and relative humidity experiments now have a "run" identification (i.e., "Mesonet Run 1 - Temperature", "Mesonet Run 2 - Temperature", "Mesonet Run 1 - Relative humidity", etc), where Run 1 is the data originally presented in the manuscript and Runs 2 and 3 are the repetition runs.

A "Discussion Supplement" (appended to the end of this reply) shows a summary of experiments and sensors used following the model in Arzoumanian (2019; doi:10.5194/amt-12-2665-2019), supporting material to explain the low CO<sub>2</sub> values seen in the Mesonet Experiment (Run 1). The results of the correction application on the Mesonet T/RH Experiment (Run 1) dataset, followed by the results for the Mesonet T/RH Experiment (Run 2 and 3), and the adjusted Bench temperature and relative humidity Experiments. The document ends with the supporting plot for the Pressure time-response correction ("ideal signal") and a brief discussion about the reported temperature from the Li-820 reference sensor.

Please note that even though the results for the correction application on the Mesonet T/RH Experiment (Run 1) dataset are presented in the attached "Discussion Supplement", they serve only as a comparison of the correction method. Following the reviewer's suggestion, the Mesonet T/RH Experiment (Run 1) dataset will be discarded. Only Mesonet T/RH Experiment (Run 2 and 3) will be analyzed in the revised manuscript.

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*Reply for* Anonymous Referee #1

General comments:

- It is difficult to review the scientific validity of the author's comments regarding the different sensors' dependences on environmental parameters, as the analyses are mostly of a qualitative nature. Increasing the level of quantification would also enable a comparison of their results with other analyses and would be of chief interest for readers of this paper, as they will potentially be looking to apply these corrections to their sensors.
  - Some examples (not complete):
    - L 148 "This hypothesis is supported by a stronger correlation between the test and independent sensors."
    - L 156/157 "In this experiment, the absence of humidity dependence is evident." L 174/175 "This experiment showed an extreme dependence between the CO<sub>2</sub> concentration values [...] and pressure."
  - For reference on possible metrics and desired level of quantification and rigor, please consult publications in this journal like Arzoumanian (2019; doi:10.5194/amt-12-2665-2019)
- For all fits in this study, only r-values are provided and slope as well as intercept including respective errors are missing. Additionally, the factors found for the corrections (incl. time response correction) are not presented for any of the analyses, so neither the absolute dependence on environmental variables (or time response) nor the difference in dependence between the two sensors can be evaluated or compared to the scientific literature.

*We agree with the reviewer and have added plots and tables detailing each experiment's environmental conditions (pressure, temperature, relative humidity) to the revised manuscript's supplement. In addition, we have also added plots and tables with the slope, Y-intercept,  $R^2$ , and RMSE (to the linear fit) for each test sensor relative to each environmental variable and reference CO<sub>2</sub> sensor, for all experiments. The discussion supplement (attached) shows examples of these plots and tables.*

- Since not all environmental parameters are controlled in Benchtop experiments, showing the other environmental factors in the time-series and analysing them is important to ensure the isolation of relevant parameters which is a central goal of this paper.

*We agree with the reviewer. However, showing all conditions and results in one plot can obfuscate the results and make the plot harder to interpret. To address this need we have standardized the presentation of the experiments, showing all 3 environmental variables for all experiments in separate plots and tables in the revised manuscript's supplement. The discussion supplement (attached) shows examples of these plots and tables.*

*Note: Even though the environmental parameters could not be controlled for the bench experiments, their short duration limits impactful changes in pressure and temperature. Nonetheless, changes in relative humidity are seen during the bench temperature experiment due to the nature of capacitive hygrometers and their dependence on temperature to calculate RH. To help readers evaluate the impact of humidity, the H<sub>2</sub>O (ppt or mmol/mol) of the Licor 840a is also shown in the revised manuscript's supplement.*

- Some of the experiments were conducted months apart. Since NDIR sensors' optical properties (and thus dependences on environmental parameters) are known to change with time, I recommend against putting these experiments simply next to each other without some further justification or analysis.

*We agree with the reviewer. To facilitate the reader's understanding of the results we have added a table, similar to E. Arzoumanian et al (2019), summarizing all experiments and their respective sensors. We have also changed the nomenclature of our test sensors to make this more evident in plot labels and result tables.*

#### Scientific comments

- L 60 "We also isolated the effects of pressure, temperature, and relative humidity on an NDIR sensor and analyzed their impact separately."
  - Did you consider also performing a linearity analysis?

*Upon suggestion from the reviewer, we have added the slope, Y-intercept, and R<sup>2</sup> of the first order least square fit for each test sensor against each test variable and the reference sensor. In addition, we have added the RMSE for each test sensor to their fit lines. Considering the importance of isolating the other variables, for each experiment, these same parameters were also calculated for the other environment variables that are not being tested. This way we can evaluate the quality of the experiment.*

- L 79 "[...] creating appropriate conditions to simulate UAS flights."
  - Is this the case for a pressure range from 1050 to 600 hPa (~4km height) as used in the Mesonet Pressure Dependence Experiment?

*Yes. There are many research teams that perform UAS-based CO<sub>2</sub> measurements up to 2 km above ground level (AGL). In our particular case, we perform these 2 km AGL profiles in Norman, OK (~400 m above sea level) and near Boulder, CO (~1,655 m ASL). The higher take-off altitude near Boulder makes our sensors experience pressures equivalent to ~3,700 m ASL. Amongst teams with similar flight conditions, we can highlight the researchers at the National Center for Atmospheric Research (U.S.), Finnish Meteorological Institute, Meteo France, and Cyprus Institute.*

- L 87 "[...] this article considered only the CO<sub>2</sub> concentration values reported by each sensor unit."

- How were the Senseair K30-FR units configured? Which kind of onboard compensations do they already have and which ones were active?

*Different from other more robust sensors from Senseair, the K30 does not offer configuration options to the average user. According to the manufacturers, the sensors are factory calibrated and "ready-to-use" out of the box. The product documentation does not offer any information on any onboard compensation of pressure, temperature, and humidity. The only compensation mentioned is their ABC algorithm that compensates drift:*

*"The default sensor OEM unit is maintenance-free in normal environments thanks to the built-in self-correcting ABC algorithm (automatic baseline correction). This algorithm constantly keeps track of the lowest reading of the sensor over an interval of 7.5 days, and slowly corrects for any long term drift detected as compared to the expected fresh air value of 400 ppm CO<sub>2</sub>."*

*Through their development kit (or custom solution) users can change the factory calibration for "ZERO" (at 0 ppm) and "BACKGROUND" (at 400 ppm), per documentation. This allows users to do zero and span calibrations.*

*The K30 sensor does not offer any onboard pressure, temperature, or humidity compensation based on an auxiliary measurement, at least not one that can be turned ON or OFF. However, through personal correspondence and conference calls with Bakhram Gaynullin (SenseAir Engineer and co-author of Arzoumanian et. al 2019) and Carl Bengtsson (CTO of Senseair USA and Engineer on the K30 prototype), it was found that the sensor uses a proprietary algorithm leveraging the longer light path and factory calibration to reduce errors associated with the proximity of Water Vapor and Carbon Dioxide in wave-length. Additionally, it was found that the temperature of the sensor's light source is monitored during measurements. Corrections based on this measurement are unknown to the public.*

*None of the above-mentioned characteristics are available as configuration options for the average user. Therefore, the sensors were treated as a "black box" under factory settings and calibrations.*

- Li-840A temperature independence
  - Please check your assumptions here, as the manual provides a total drift of the Licor of 0.4 ppm/°C. For the temperature range of 10 to 40°C, this would equate to a drift of 12ppm, for 20 to 40°C, a drift of 8ppm.

*The Li-840A and Li-820 have internal heaters that elevate their sampling chambers to a temperature of ~51 °C (reported in the discussion supplement submitted with this response), which is above the temperatures tested in our experiments (max: ~40 °C). This characteristic eliminates their dependence within the range tested. These assumptions are validated by the new plots and tables for experimental conditions (e.g., discussion supplement figure 14 and table 13) and the results from the mesonet runs 2 and 3 (e.g. discussion supplement tables 14 and 20, and figures 14, 15, 20, and 21). In addition, the discussion supplement tables 15 and 21 show the slope, y-intercept, R<sup>2</sup>, and RMSE for the Li-840A against pressure, temperature, relative humidity, and Ref\_OUT measurements*



during mesonet temperature experiments 2 and 3. Comparing the  $R^2$  estimates for temperature and Ref\_OUT (a.k.a. the Li-820), we can conclude that temperature measurements are approximately equal or worse at predicting the behavior of the Li-840A.

Besides our analysis, we also forwarded this question to Li-cor's technical support team. The answer received was the following:

"Thank you for your email. If the heater is turned on, you should not see any significant drift in the response over the entire specified range of the LI-840A."

- Reference sensor deployment
  - Why did you choose to setup the 840A inside the chamber and the 820 outside? Was this an arbitrary choice?

The Li-840A is a CO<sub>2</sub> and H<sub>2</sub>O gas analyzer and it is considered to be independent of temperature and humidity changes in the time-scale of hours, within the temperature and RH ranges tested. The Li-820 is only a CO<sub>2</sub> analyzer and does not have any humidity measurement for active compensation. Both the Li-840A and the Li-820 have active pressure compensation. The Mesonet Calibration Laboratory is an air-conditioned room that does not experience high levels of humidity. For this reason, the Li-840a was used as a reference sensor inside the test chamber where humidity was expected to vary and the Li-820 was used as a reference outside the test chamber to characterize CO<sub>2</sub> changes in the laboratory. This reasoning was added to the experiment's description in the revised manuscript.

- Mesonet Temperature Dependence Experiment
  - Why is the data range for CO<sub>2</sub> 160 to 320 ppm? These measurements don't seem to be realistic.

This considerable reduction in CO<sub>2</sub> concentration is caused by the Thunder Scientific 2500 chamber, used in the experiments. Figure 1 in the discussion supplement shows the raw ppm values for the Li-840A (Ref\_IN), the Li-820 (Ref\_OUT), and four K30 sensors, before, during, and after the second run of the mesonet temp/RH experiments. In this figure, it is possible to see the Ref\_IN and all four K30 sensors drop their reported values from ~500 ppm to ~250 ppm after the start of the experiment, and return to ~450 ppm after the experiment ends. In the same figure, we can see the outside reference is not affected. The data in figure 2 and table 1, show that none of the pressure sensors varied greatly (all sensors show a standard deviation of approximately 106 Pa). The data also shows this effect happens before large temperature and humidity changes and is also seen on the Ref\_IN control sensor (which is independent of temperature and humidity changes in the test ranges).

Looking at the documentation of the Thunder Scientific 2500 chamber, there is mention of the use of Nitrogen to control pressure, temperature, and humidity. However, the chamber at the Mesonet Calibration Laboratory does not use this feature. In their configuration, the chamber uses water, a series of compressors, and pre-chambers to generate standard test conditions. More information about the inner workings of this chamber can be found at

[https://www.thunderscientific.com/humidity\\_equipment/model\\_2500.html](https://www.thunderscientific.com/humidity_equipment/model_2500.html). After our thorough review of the documentation, it was not clear the exact source of this effect. Nevertheless, it is apparent when analyzing the data that this effect has a near-constant behavior throughout the experiments. Therefore, an offset correction can be applied without loss of generality.

- If you consider the independent sensors to be actually independent from environmental factors, why don't you use those to correct for external disturbances? Analyzing the difference between the test sensors and the independent sensor for temperature dependencies would, then, yield more robust results.

*We agree with the reviewer. We can use the reference sensors to correct the data. In fact, that is what we did in the submitted manuscript. However, we did not do a good job explaining our choice to bring all data to the level of the Ref\_IN sensor (Li-840A). This decision was based on the robustness of the Li-840A when compared to the Li-820 (Ref\_OUT), and our wish to analyze the data at the relative reference point of the chamber environment. In hindsight, we understand how the unrealistic data presented with a lack of an explanation would confuse readers.*

*Figure 3 of the discussion supplement illustrates the impact of these two different correction strategies. In the left panel, the result of correcting the data to the Ref\_IN sensor, and in the right panel the result of correcting the data to the Ref\_OUT sensor.*

*To address this issue we used the 60 minutes prior to the experiment (e.g., from 02:00 to 03:00 in figures 1 and 2) where the conditions are stable, to find an average offset for each sensor to the Ref\_OUT sensor. This offset was then applied to the entire time series. An explanation of this strategy was also added in the revised manuscript.*

*We have added plots and tables in the discussion supplement showing intercomparisons between the reference and test sensors, before and after each mesonet experiment. These comparisons support our strategy to use the Ref\_OUT sensor to correct the data from the mesonet experiments. In these plots, the CO<sub>2</sub> concentration measured by the Atmospheric Radiation Measurement - Southern Great Plains (ARM SGP) reference tower was added to show these are reasonable atmospheric values for Oklahoma. **We understand the distance between Norman and the ARM-SGP tower does not allow for a direct comparison of the data.** Nevertheless, it is presented here to demonstrate to the reviewers that the two reference sensors were measuring values within reasonable expectations. A version of these additional plots and tables with basic statistical metrics (without the ARM-SGP data), was added to the revised manuscript supplement.*

- As you performed the pressure experiment already 9 days before the temperature experiments, the high pressure dependence was already known. Did you perform any pressure measurements during the temperature experiment to disentangle the influence of the ambient pressure changes

from the temperature changes? Or did you assess the possible effect the pressure dependence might have on the measurements?

*We did measure pressure during the temperature and humidity experiments. However, we did not deem the data from the mesonet pressure experiment good enough to determine correction coefficients. The main reason for this decision is the large CO<sub>2</sub> fluctuation in the room during the pressure experiment. Therefore, the coefficients were only determined much later during the bench experiments. Nonetheless, within our decision to repeat the mesonet temperature and humidity experiments we were able to achieve conditions where the pressure measurements showed less than 140 Pa in standard deviation (across all pressure sensors, across all temp and RH experiments). Considering the small pressure deviation, we chose not to apply a pressure correction as it could introduce uncertainty in our analysis of the impact of temperature and humidity. To mitigate our choice to not correct, we added the slope, Y-intercept, R<sup>2</sup>, and RMSE to pressure for all sensors, for all experiments on the revised manuscript.*

- Did you measure the temperature at the external independent sensor? Did you preclude any temperature interference here?

*The only temperature measured outside the test chamber was the temperature of the external reference's optical chamber, which stayed around 50 °C. As shown in the experimental conditions plot and table for each experiment. At this point, we believe the external interference was an actual increase of CO<sub>2</sub> in the lab due to the presence of mesonet technicians and building security personnel. The repeated experiments were performed overnight to eliminate this interference. The results of this strategy can be noticed in the experimental conditions table for each run (e.g., table 11 of the discussion supplement shows the second temperature experiment had standard deviations of < 30 Pa, across all sensors, 1.23 %RH inside the chamber, and 3.69 CO<sub>2</sub> ppm outside the chamber).*

- Quantification:
  - As one of the major sources of temperature dependence in NDIR spectrometers is a change in optics properties, did you consider time-lags in increasing sensor reading?

*The effects of variation in CO<sub>2</sub> in the laboratory during the first mesonet experiments were so large (e.g., std 45.14 ppm during the first temperature experiment) that it became too hard to separate the impact of the environmental variables on the test sensors. Based on the reviewer's comments the mesonet experiments were repeated. However, the Thunder Scientific chamber is limited to producing temperature and relative humidity changes in the order of tens of minutes. Since we reduce the dwell period of each step (following recommendations from reviewer #2), we believe that our data set does not support this type of study.*

*Nonetheless, our data can support the importance of a future study to evaluate the potential impact of this NDIR temperature time-lag effect in UAS-based measurements. Our results show that we were not able to produce a distinguishable temperature response within 3 minutes (during the bench temperature experiments). However, the mesonet experiments*

*did show a temperature-induced reported concentration increase within 15 minutes or less. Considering a typical UAS vertical atmospheric profile with a 3 m/s ascent rate, a continuous ascent to 1500 m takes about 8 minutes. In gas sampling flights due to slower sensor responses and pressure issues, the same type of vertical atmospheric profile includes horizontal transects at predetermined altitudes and can take about 27 minutes. Therefore, such a study would certainly be of interest to the community.*

- For which time periods did you calculate the correlation coefficients between sensor reading and temperature? If these were the actual transitions, this might be problematic because of time-lag, non-linearities or material effects.

*The correlation coefficients were calculated for the entire experiment and later only for the actual transition intervals (both shown in the original manuscript). The transition interval in those experiments was approximately 25 minutes. Therefore, using this transition interval would only be a problem if the potential time-lag issues occurred on a longer time scale. If this was the case, these effects might not even manifest in the time scales of typical UAS flights (see flight duration explanation above). Thus, we believe using this relatively slow 25-minute transition interval was not a problem. In fact, we adopted it to reduce the impact of the external changes in CO<sub>2</sub> concentration and to investigate the impact of temperature. Nonetheless, this problem was mitigated by repeating the mesonet experiments under more controlled conditions. All R<sup>2</sup> values shown in the discussion supplement are calculated for the entire time series.*

- After identifying an external interference in your measurements, it seems to me like you should not be able to draw conclusions about a sensor temperature dependence without EITHER: discarding the data and repeating the experiment without this source of interference (even Gaynullin, 2016 says that an “[a]bsolute elimination of contaminating leakages from ambient air” must be provided “to provide a reliable test environment”) OR: treating the interference by e.g. analysing the difference in readings between the Licor and K30 sensors (under the assumption that the Licor readings are independent of temperature, which has to be proven given its design specifications – cf. above)

*As mentioned above, the experiments were repeated two more times and the new results are presented in the discussion supplement attached.*

- Benchtop Temperature Dependence Experiment
  - CO<sub>2</sub> readings seem to decrease at the beginning of the experiment. Did you ensure the experiment was in a steady state with respect to CO<sub>2</sub>?

*We agree. The CO<sub>2</sub> reported by all three sensors presents a decreasing trend before the temperature change occurs. However, in a more quantitative analysis, we can show the reference sensor and the test sensor 1 present a change smaller than 3 ppm during the 90*

*seconds before the temperature change. Although 90 seconds can be considered a small stabilization period for a CO<sub>2</sub> sensor, it represents 50% of the total duration of the temperature change. Again, we agree it is not an ideal testing condition, but unfortunately, it is the limitation of this low-cost testbench setup. Nonetheless, we have revised the manuscript to highlight this experimental limitation and have limited the interpretation of the results. We also added to the discussion supplement a repetition of this experiment in slightly more stable conditions (figure 35).*

- L130/131 “Even though there is a slight 10 ppm increase [...], it occurs a full minute after the temperature is brought back near its original state.”
  - Again, might this be due to the temperature response time of optics/electronics, a large mixing volume or even some drift in timestamps of the recording PC (especially since this experiment was conducted 18 months after the other ones)? If this were the case, the increase in signal would fit very well with the expected one of the Licor due to temperature drift, which is 8ppm (cf. above).
  - Where was the temperature measured? Was the possibility of a time-lag between temperature measurement and sensor measurement of an air parcel excluded?

*As demonstrated previously the reference sensor (Li-840A) can be considered independent of temperature within the tested ranges. Therefore, we assume the reported 10 ppm increase to be an actual increase in CO<sub>2</sub> during the experiment.*

*Regarding the temperature measurements, the diaphragm pump intakes for the CO<sub>2</sub> sensors (one for the reference sensor and one for the two test sensors) were placed immediately after three PT-100 bead thermistors (10 Hz sampling, 1 Hz time response, sold and calibrated by InterMet Systems), and three IST HYT-271 capacitive hygrometers (10 Hz sampling, 4-second RH time response, and 5-second Temperature time response). The temperature shown in the original manuscript is an average of the temperature of the 3 thermistors.*

*Regarding any time shifts associated with the data loggers, we can offer the following information:*

- Both K30 sensors, the three thermistors, and the three hygrometers share the same logging system.
- The reference CO<sub>2</sub> sensor was logged separately.

*Therefore, if any logging-related issue manifested itself in the data, such an issue could only occur between the test sensors and the reference sensors, and not between the test sensors and the temperature sensors. Although a time lag issue on the data seems an unlikely explanation for the result, an actual temperature time-response behavior on the K30 cannot be ruled out with the available data set. In light of the results from the repeated mesonet experiments and upon further analysis of the bench data, it seems more likely that any temperature impacts on the*

*K30s were obfuscated by the increase in CO<sub>2</sub> during the experiment. Therefore, we revised the manuscript and limited the interpretation of the bench experiments to indicate a potential time-scale temperature-impact limitation.*

- Since this experiment does not control RH, it is difficult to use this for a impact analysis isolating the environmental parameters, which is the stated aim of the paper. This would need some further justification leveraging measured RH values during the experiment.

*We agree with the reviewer. We have limited the previous interpretation of this result as a rapid change experiment (emulating more realistic conditions encountered during UAS measurements, as pointed out by reviewer #2) with limited conclusions regarding the time scales of a temperature-induced response.*

*As mentioned previously, we have added the plots and basic statistics (min, max, avg, and std) for all three environmental variables during all experiments, as well as a comparison of the slope,  $R^2$ , and RMSE between the test sensors and the non-test variables. In this experiment, RH varied between 19 and 42 %RH (see discussion supplement figure 28 and table 27).*

*We are currently working on an analysis with the RH measurements and a comparison to the mesonet data set (a particular section of the time series, between the temperature and relative humidity experiments, where both variables change together). If successful this result may serve as a comparison to other non-isolated studies with the distinction of the more UAS-appropriate time scales.*

- Mesonet Relative Humidity Dependence Experiment
  - The same comment regarding the external interference applies here (cf. Mesonet Temperature Dependence Experiment).
  - The same comment regarding the CO<sub>2</sub> data range (120-300 ppm) applies here (cf. Mesonet Temperature Dependence Experiment).

*Answered at the "cf. Mesonet Temperature Dependence Experiment".*

- Benchtop Relative Humidity Dependence Experiment
  - Details of the humid air source are missing – is it guaranteed that temperature stays constant and only RH increases?

*The humidity source was a manual water spray. During this experiment, the minimum temperature was 22.30 and the maximum was 25.33 °C. The average was 23.75 with a 1.02 °C standard deviation.*

- L 188/189 “the correction needs to be based on the variation magnitude from the initial state”



- Can you provide some physical justification for this assertion? This is not discussed for temperature or humidity and to my knowledge, it is not common practice.

*The highlighted assertion refers to the pressure correction method NOT a temperature of relative humidity correction. The assertion serves only to warn the reader about our assumption of the linearity of pressure's impact on the K30 between sea level and the test ranges. We stated it because we used ambient pressure as initial pressure ( $P_0$ ) in the equation provided in Gaynullin et al. (2016) instead of sea-level pressure. As stated, we believe the assumption is supported by the results of the mesonet pressure experiment (correlation coefficient of 0.98 for both sensors in the range from 60000 to 105000 Pa).*

- L 202 "The results demonstrate four instances [...]"
  - Where there further instances where this method was applied unsuccessfully?

*There were only these four tests, with two sensors each for a total of 8 successful applications of the method. The manuscript was adjusted to make the text clearer.*

- Is this a robust method with respect to e.g. time and temperature?

*The method was not tested for either time or temperature corrections.*

- Fig 12: This dependence seems very linear, almost as if it were following the ideal gas law.
  - Again, please add some comments regarding pressure correction being enabled or disabled in the Senseair K30 units.

*As mentioned previously, the K30 does not have an onboard pressure sensor or a configuration for onboard pressure corrections. The linearity found seems to be in accordance with the results presented by Martin et al. (2017) and the results for the HPP3.1 sensors in Arzoumanian et. al. (2019). The contribution of this paper regarding the pressure correction was to demonstrate that coefficients obtained with a low-cost test environment without traceable canisters (bench setup) can produce satisfactory results.*

- Fig 13: There seems to be some kind of change of pressure dependence with time (similar to hysteresis effect)
  - Was this analysed further?
  - Could this be caused by the large pressure range?

*The deviation of the sensors' behavior between the three distinct lines on the left panels of figure 13 (original manuscript) seems to be associated with the changes in  $\text{CO}_2$  in the room during the experiment. Due to this change mid experiment, the same pressure does not return the same  $\text{CO}_2$  level because the measured level changed. Due to this change in concentration, the mesonet pressure experiment was only used in the manuscript to demonstrate the magnitude of the pressure impacts on the sensors. All coefficient calculations were based on data from the bench experiments.*



- L 211 "Because the pressure chamber is completely isolated from the external environment [...]":
  - In the experiment before, this chamber was not isolated which is why you had the outside reference sensor. In L 207/208 you write "the pressure correction experiment setup [...] was used again" Is this not the same, non-isolated setup?

*The MESONET pressure chamber is NOT isolated. It uses two Thompson pumps to move air in and out of the chamber (increasing and decreasing pressure). Therefore, figures 12 and 13 (in the original manuscript) show the impact of a 50 ppm CO<sub>2</sub> variation in the laboratory on the experiment results. The BENCH pressure chamber (referred to in L211 and 207/208) is considered isolated during the experiment because once the chamber is sealed the air can only be removed from the chamber (only lowering pressure). In this case, if the room CO<sub>2</sub> changes during the experiment, the sensors inside the chamber are not affected by it. The pressure and the pressure time-response corrections were both performed with data from experiments using the BENCH pressure chamber.*

- L 222/223
  - Why did you use a different data source for estimating the exponential correction time constant and the time shift? Did you consider correcting the time shift first to then estimate the exponential correction time constant from this corrected data?

*The e-folding correction used [presented in Houston and Keeler (2018) and Miloshevich et al. (2004)] only takes into consideration the difference in CO<sub>2</sub> between the current and previous measurements, the time step between the two measurements, and a predetermined coefficient (tau). Therefore, applying the time-shift before or after the e-folding correction does not yield any difference. Cases 3 and 4 were used to determine the coefficient (tau) because they are easier to calculate the time taken to reach 1\*tau (63.2% of the final step change). Cases 1 and 2 were used to calculate the time shift because using the minimum pressure and CO<sub>2</sub> for each impulse it is easier to calculate the time shift. This case selection eliminates the need for the additional derivation (or integration) that could potentially introduce errors. Potential errors from using different datasets are mitigated by using 2 sets in each type of data set (i.e., cases 1 and 2 for impulses and cases 3 and 4 for step changes).*

- L 225 "[...] an idealized signal was created [...]"
  - How did you create this idealized signal? The experiments with this data are not shown in this paper. It would be important to at least add them to the supplement for the sake of documentation and repeatability.

*First, it is important to note that the referred idealized signal is an artificial signal with the pressure error but without the pressure time-response error. Therefore, ideal means the ideal impact of pressure (without pressure time-response error). It serves only as an evaluator of the pressure time-response algorithms. It should not be used for any pressure correction algorithms. The ideal signal was generated using the timestamps of the pressure step changes and the CO<sub>2</sub> values of the K30 after stabilization, after the step*

*change. A figure with the Pressure, ideal signal, original signal, and the corrected signal is shown in section 9, figure 43 of the attached discussion supplement.*

- Why did you opt for creating an idealized signal rather than applying the pressure correction to the exponential and time shift corrected data? Is the purpose of the exponential- and time shift correction not to improve the pressure correction?

*By using the ideal signal, we were able to evaluate the effectiveness of the pressure time-response algorithm, without other potential sources of errors. Determining the effectiveness of the pressure time-response algorithm is crucial because, in a pressure correction algorithm that does not discard samples near pressure step changes (e.g., in a UAS flight under continuous ascent), the pressure time-response algorithm needs to be applied before the pressure correction algorithm. Otherwise, the pressure correction algorithm creates overcorrections near the pressure step changes (artificially increasing the reported CO<sub>2</sub> value).*

- L 231 “Unfortunately, the attempted correction was not as effective on the gradual pressure changes”
  - Where do you see a difference in expected and real outcome? Did you quantify this?

*In our case, the expected was the idealized signal. The differences noted were the sources of the RMSE reported in the manuscript. They can be seen in the step changes for the test sensor 2, after 18:26, 18:28, and 18:30 (in figure 34 of the discussion supplement the expected is the blue line, the real outcome is the gray line, and the correction attempt is the orange line). In these examples, the corrected curve shows smaller errors against the original curve than the idealized curve.*

- L 234 “we recommend repeating these experiments on a better quality chamber”
  - Why do you think the quality of the chamber is deficient? Why would smaller pressure changes help?

*The BACO Engineering 5-Gallon Vacuum Chamber Kit was not designed for this type of application. It requires an approximate 2500 Pa change to seal its lid. This large change does not allow this system to be used to study the impact of pressure changes near the ground (a known important region for studies of the impact of rotary-wing UAS on sensors). The step changes produced in this study were already at the limit of the system's vacuum pump, where the small 0.5-second pump activation period caused the pump to leak oil and probably reduced the lifespan of the system.*

Technical comments

- L 48 None of the sensors available in the market was designed for UAS-based deployment.

- None of the sensors available **on** the market **were** designed for UAS-based deployment.

*Corrected.*

- Fig 1:
  - Naming the sensor "CO2 Independent Sensor" is misleading as one might understand the sensor to be independent of CO2 instead of temperature. I suggest amending the names.

*We agree with the reviewer, the sensors were renamed reference sensors (Ref\_IN and Ref\_OUT)*

- Fig 2:
  - Line colors:
    - Please consider choosing colors which have more contrast. Without zooming in, it is difficult to differentiate the lines.
    - Why do test sensor 1 and 2 have different levels of saturation? Visually, it seems like sensor 2 is less important.

*We agree with the reviewer, the plot colors were updated in the revised manuscript and discussion supplement using more contrasting color palettes (similar to Martin et al. 2017). The colors were tested using this tool: <https://projects.susielu.com/viz-palette>.*

- Line types:
  - It is difficult to see the dashed and dash-dotted lines and doubly so to differentiate the two. Again, maybe rethink the figure layout.

*We agree with the reviewer, the plot lines were changed to solid and colors adjusted (as shown in the discussion supplement).*

- Figure 3:
  - For scatter plots between two CO2 readings, always plot the 1:1 line, as the linear fit will be misinterpreted visually to be this 1:1 correlation. Alternatively, one can also restrict the line of the linear fit to the data and use the same x- as y-limits albeit for a larger span, ensuring the 1:1 line is at a 45 degree angle.

*We agree with the reviewer and added to the discussion supplement a revised version of the plots.*

- Fig 3, 6, 8, 10:
  - Please consider using shared x- as well as shared y-axes. This makes such plots easier to read.

*We attempted to implement a version of the reviewer's suggestion (available in the discussion supplement). Although it is worth highlighting that the scatter plots are*

*presented as a matrix where rows represent test sensors and columns represent test variables (e.g., Pressure, Temperature, RH, and Reference Sensors). Therefore, x-axes may not be shared between columns (as they may represent different units), and the y-axes may not be shared between rows (although, in practice, they are very similar). Nevertheless, we attempted to implement this suggestion on the plots between two CO2 readings.*

- Fig 16:
  - RMSEs by definition cannot be negative

*Corrected.*

- Please add Pressure readings as one aim of this figure is to show the quality of the pressure correction.

*We agree with the reviewer, the change made in the revised manuscript.*

- L 196 "All cases emulate a typical UAS-based CO2 vertical profile" Did you mean flight profile?

*Even though UAS-based atmospheric vertical profiles and horizontal transects are well-known flight patterns within the weather UAS community, we agree with the reviewer. The manuscript was adjusted to "UAS-based CO2 vertical sampling flight."*

- L 196/197 "[...] there is a dwell period (in this case, 1.5 minutes) to ensure samples from the previous altitude are discarded from the system after a change in altitude."
  - change altitude to pressure or use "simulated altitude"

*Corrected to "simulated altitude".*

- L 207 "No mention of such affect was found [...]":
  - No mention of such **an effect** was found [...]

*Corrected*

- L 233 "For those who"
  - For those, **for whom**

*Corrected*

- L 257
  - Please consider adding the statements with regards to long-term stability also to section 1.1 or 2.

*We agree with the reviewer, the change made in the revised manuscript. A commentary was added to section 2.*

# Discussion Supplement for “The Impact of Environmental Variables on UAS-based Atmospheric Carbon Dioxide Measurements”

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## 1 Summary

Following the reviewers’ suggestions, we repeated the Mesonet temperature and relative humidity experiments under more controlled conditions, added more test sensors, and adjusted the result presentation. Therefore, this document is written in light of the following changes:

- The Li-820 sensor originally named CO2 Independent Sensor Outside is renamed Reference Sensor Out (Ref\_OUT).
- The Li-840A sensor originally named CO2 Independent Sensor Inside is renamed Reference Sensor In (Ref\_IN).
- The Senseair K30 sensors originally named CO2 Test Sensors 1 and 2 are renamed K30\_##, where the first digit refers to its attached test system and the second digit is its identification. This way the first Senseair K30 sensor of test system 2 is named K30\_21.
- Test systems (labeled T\_#) has its own pressure (two MS5611), temperature (three PT-100 bead thermistors), relative humidity (three IST HYT-271 hygrometer), and Carbon Dioxide (two Senseair K30).
- Environmental conditions during the experiments are labeled by chamber, reference sensor, and the test system they are associated with.
- The Mesonet temperature and relative humidity experiments now have a "run" identification (i.e., "Mesonet Run 1 Temperature", "Mesonet Run 2 Temperature", "Mesonet Run 1 Relative humidity", etc), where Run 1 is the data originally presented in the manuscript and Runs 2 and 3 are the repetition runs.

The following sections provide supporting material to explain the low CO<sub>2</sub> values seen in the Mesonet Experiment (Run 1). The results of the correction application on the Mesonet T/RH Experiment (Run 1) dataset, followed by the results for the Mesonet T/RH Experiment (Run 2 and 3), and the adjusted Bench temperature and relative humidity Experiments. The document ends with the supporting plot for the Pressure time-response correction ("ideal signal").

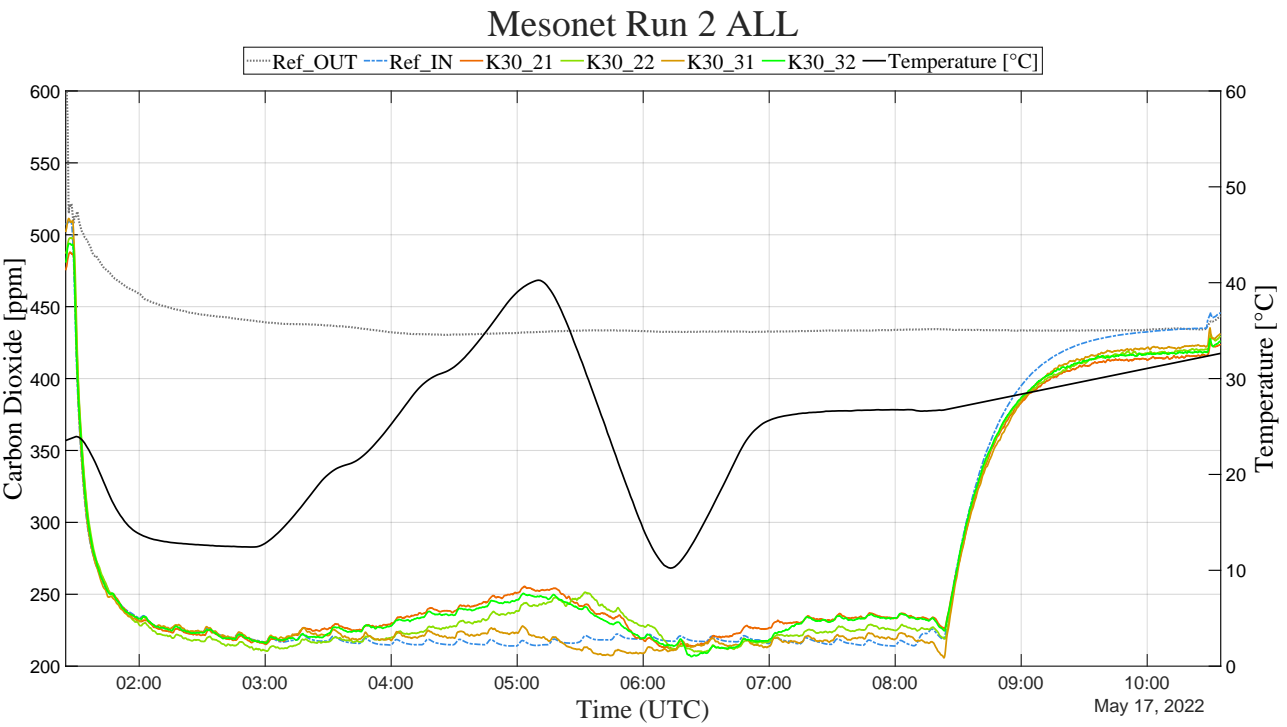
Please note that even though the results for the correction application on the Mesonet T/RH Experiment (Run 1) dataset are presented in the attached "Discussion Supplement", they serve only as a comparison of the correction method. Following the reviewer's suggestion, the Mesonet T/RH Experiment (Run 1) dataset will be discarded. Only Mesonet T/RH Experiment (Run 2 and 3) will be analyzed in the revised manuscript.

## **1.1 Experiments summary**

The following tables cross lists all the experiments performed and their sensors. The sensor intercomparison experiments are not listed on the table. They were performed before the first run of the Mesonet experiments, before the second run of the Mesonet experiments, in between the second and third runs, and after the third run of the Mesonet experiments.

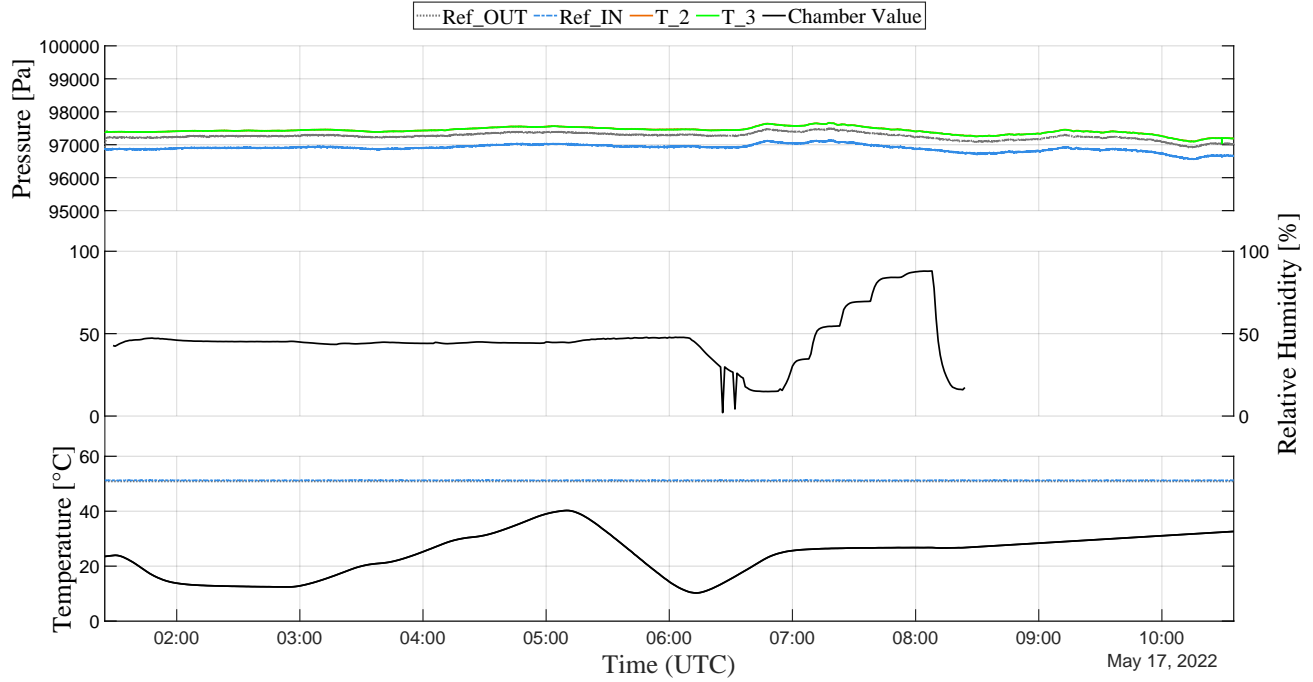
Location	Name	Reference Sensors	Test Sensor
Mesonet	Run 1 Pressure	Ref_IN	K30_11, K30_12
	Run 1 Temperature	Ref_IN, Ref_OUT	K30_11, K30_12
	Run 1 Relative Humidity	Ref_IN, Ref_OUT	K30_11, K30_12
	Run 2 Temperature	Ref_IN, Ref_OUT	K30_21, K30_22, K30_31, K30_32
	Run 2 Relative Humidity	Ref_IN, Ref_OUT	K30_21, K30_22, K30_31, K30_32
	Run 3 Temperature	Ref_IN, Ref_OUT	K30_21, K30_22, K30_31, K30_32, K30_13, K30_14
	Run 3 Relative Humidity	Ref_IN, Ref_OUT	K30_21, K30_22, K30_31, K30_32, K30_13, K30_14
Bench	Run 1 Pressure Correction	Ref_IN	K30_21, K30_22
	Run 2 Pressure Correction	Ref_IN	K30_21, K30_22
	Run 3 Pressure Correction	Ref_IN	K30_21, K30_22
	Run 4 Pressure Correction	Ref_IN	K30_21, K30_22
	Pressure Time-response Learn 1	Ref_IN	K30_21, K30_22, K30_31, K30_32
	Pressure Time-response Learn 2	Ref_IN	K30_21, K30_22, K30_31, K30_32
	Pressure Time-response Test 1	Ref_IN	K30_21, K30_22, K30_31, K30_32
	Pressure Time-response Test 2	Ref_IN	K30_21, K30_22, K30_31, K30_32
	Run 1 Temperature	Ref_IN	K30_21, K30_22
	Run 1 Relative Humidity	Ref_IN	K30_21, K30_22
	Run 2 Temperature	Ref_IN	K30_21, K30_22
	Run 2 Relative Humidity	Ref_IN	K30_21, K30_22
	Run 3 Relative Humidity	Ref_IN	K30_21, K30_22





**Figure 1.** Data showing the impact of the Thunder Scientific 2500 chamber on the reported CO<sub>2</sub> values. The chamber was turned on at 01:29:37 and turned off at 08:24:43.

## Experimental Conditions for Mesonet Run 2 ALL

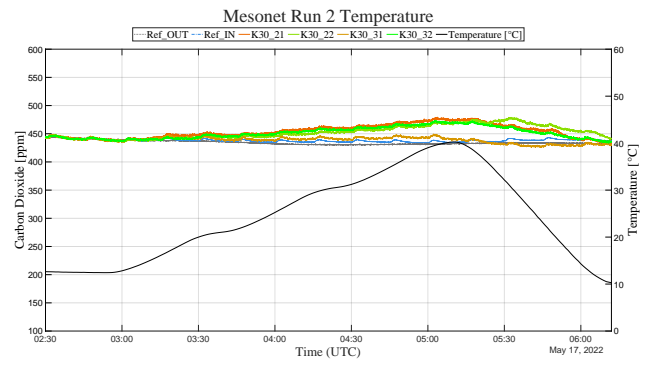
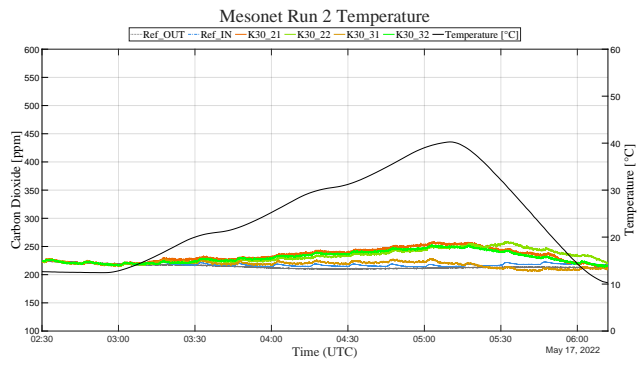


**Figure 2.** Environmental conditions during the second run of the Mesonet Temperature and Relative Humidity experiments. The chamber was turned on at 01:29:37 and turned off at 08:24:43. During this period the pressure (all sensors) and internal temperature (reference sensors) does not vary greatly.

**Table 1.** Metrics for the experimental conditions for the complete second run of the Mesonet Experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	96910	97500	97262.68	105.94
	Ref_IN	96540	97160	96902.5	107.37
	T_2	97066.57	97669.28	97430.29	106.42
	T_3	97039.22	97665.22	97427.47	106.54
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0*
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	10.23	40.26	-	-
Relative Humidity [%]	Chamber	2.06	88.03	-	-

\*Please see section 10 of this document for explanation about this zero deviation.



**Figure 3.** Comparison of the reference offset strategies. On the left the all sensors are brought to the level of the Ref\_IN sensor, on the right, to the Ref\_OUT sensor.

3 Mesonet Experiment 1

3.1 Reference Intercomparison

Experimental Conditions for Reference Intercomparison Before Mesonet Run 1

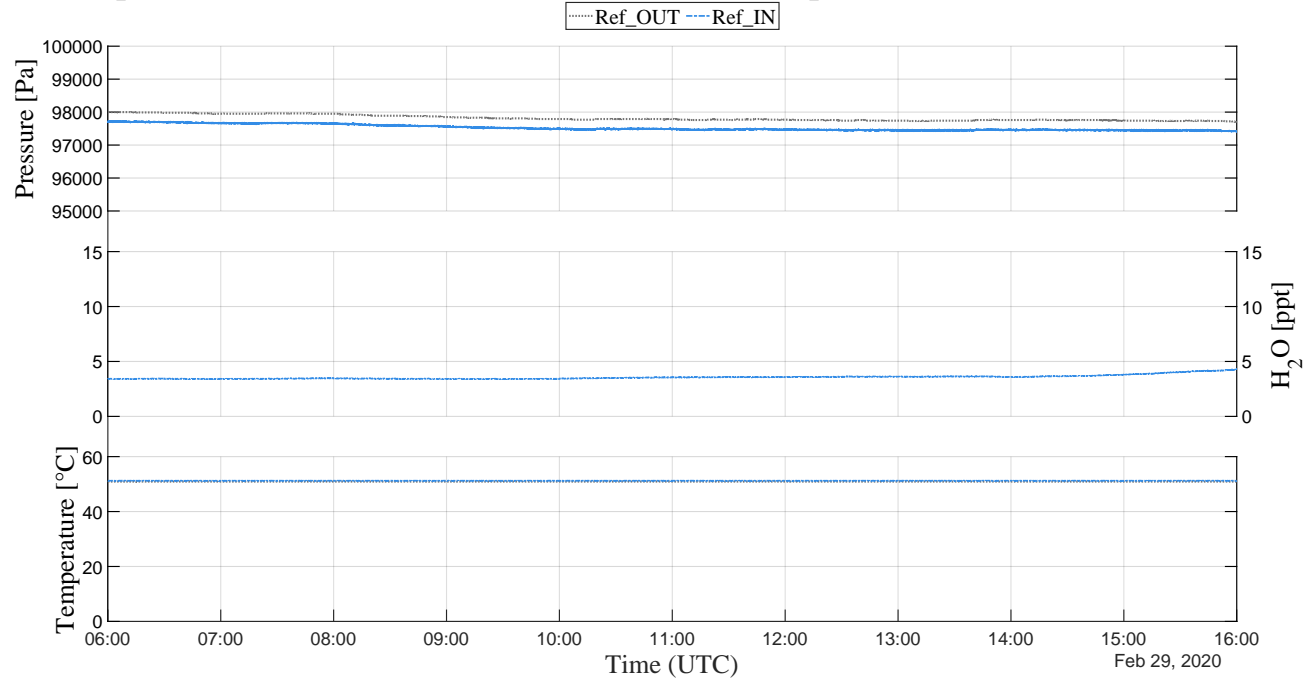


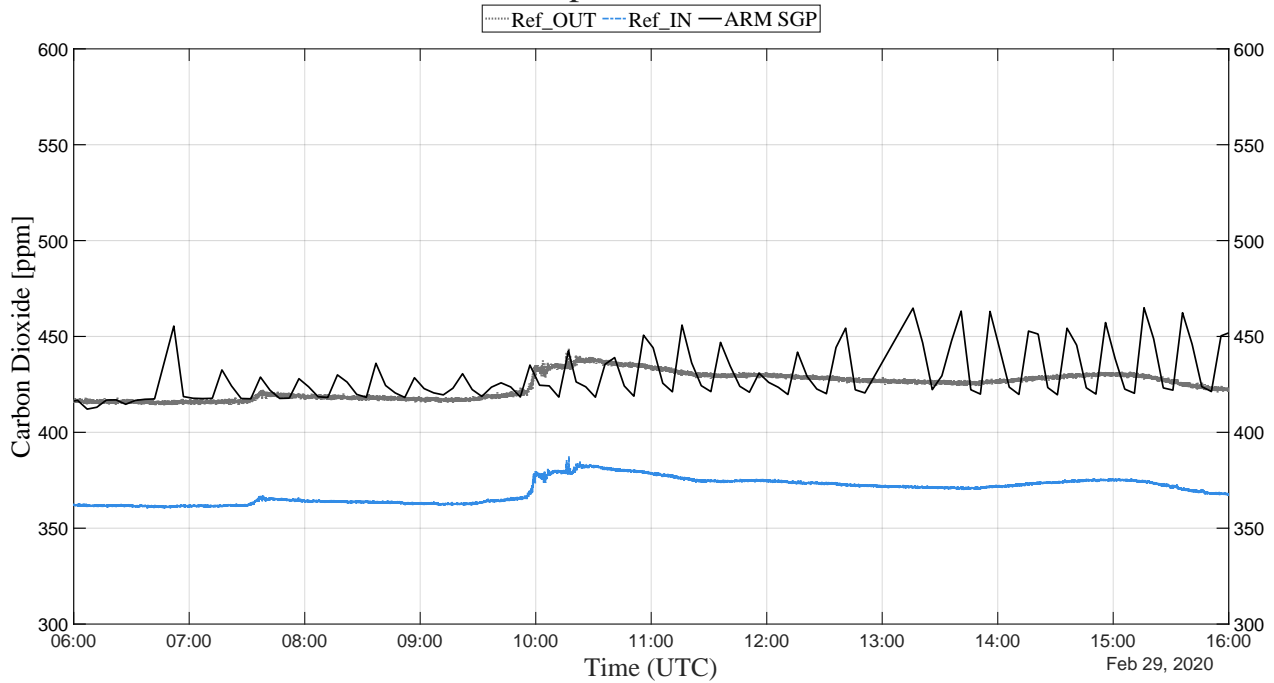
Figure 4. Environmental conditions during the intercomparison before the first Mesonet experiments.

Table 2. Metrics for the experimental conditions for the intercomparison before first Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	97700	98000	97819.24	87.62
	Ref_IN	97380	97740	97526.47	88.92
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0*
	Ref_IN	51.17	51.25	51.22	0.02
H <sub>2</sub> O [ppt]	Ref_IN	3.38	4.3	3.57	0.18

\*Please see section 10 of this document for explanation about this zero deviation.

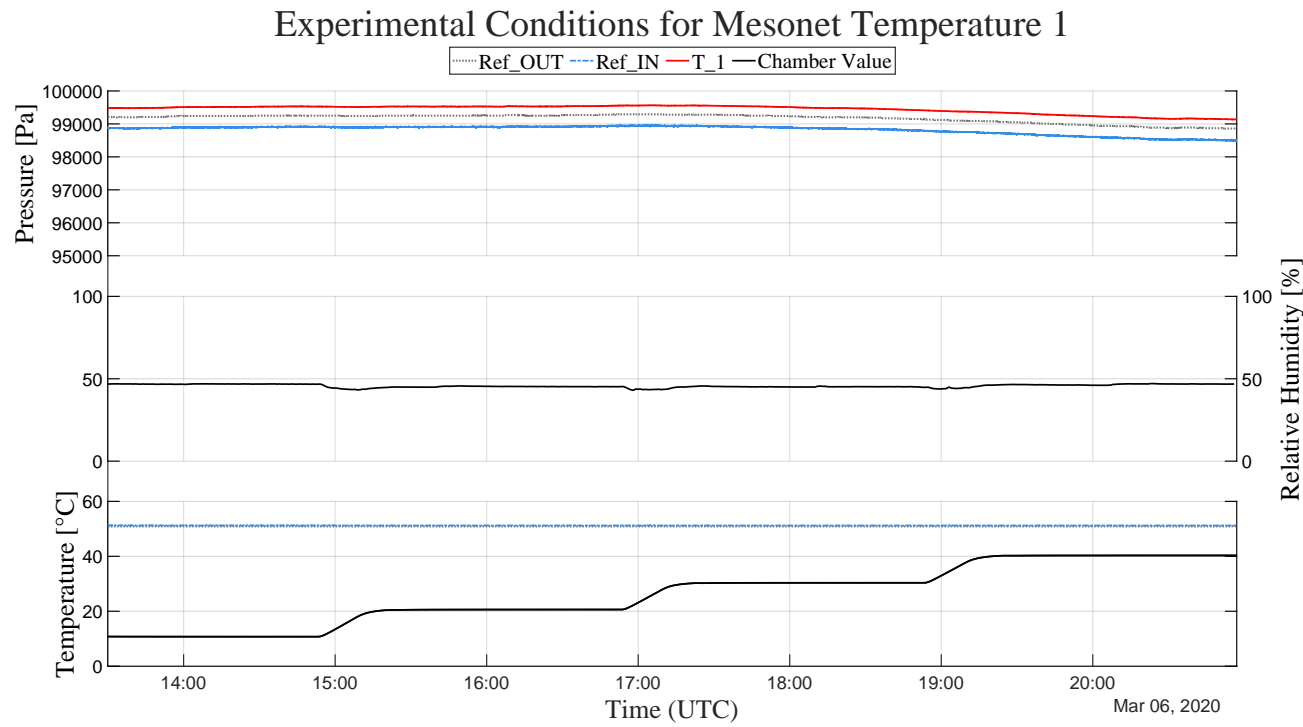
## Reference Intercomparison Before Mesonet Run 1



**Figure 5.** Results for the intercomparison before the first Mesonet experiment. At this date, the two reference presented a constant 54.75 ppm offset. After correcting this offset, the RMSE was  $1.63 * 10^{-14}$  ppm.

**Table 3.** Metrics for the intercomparison before the first Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	413.91	443.85	424.57	6.51
	Ref_IN	360.24	387.49	369.82	6.14
	ARM SGP	412.1	464.98	429.74	11.85

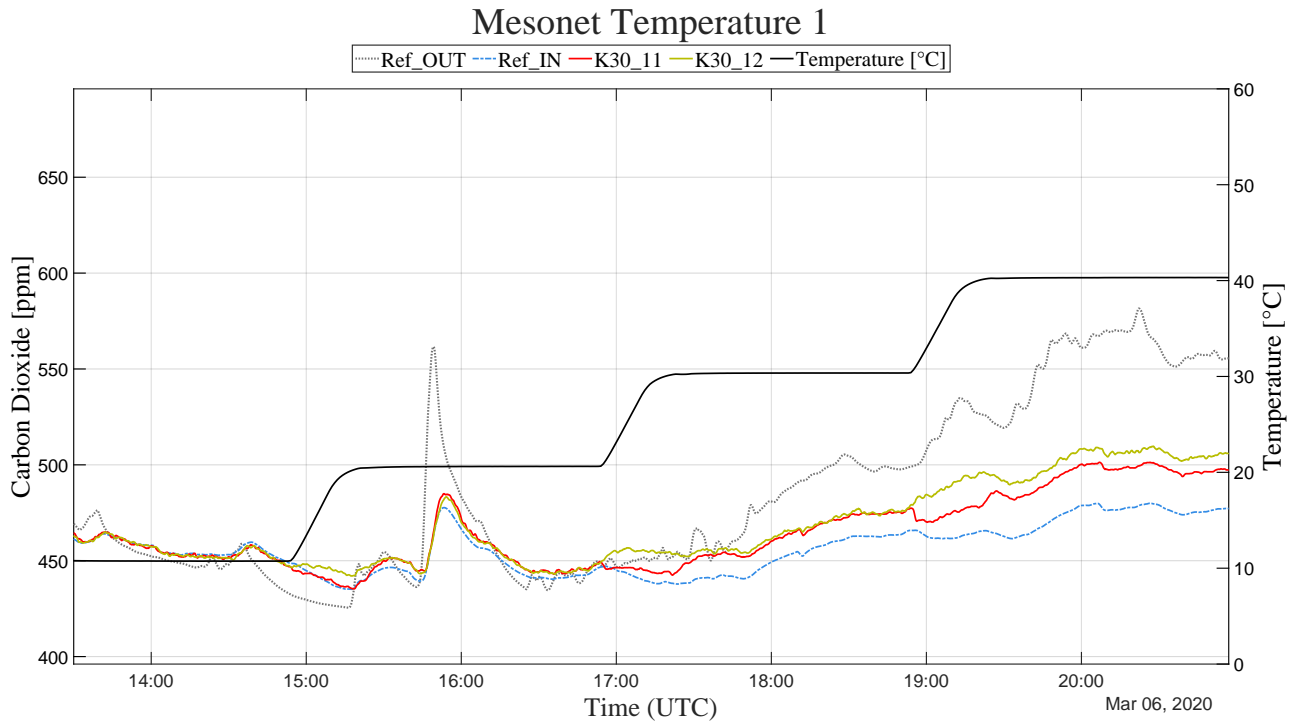


**Figure 6.** Experimental conditions during the first Mesonet Temperature run.

**Table 4.** Metrics for the experimental conditions during the first Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	98860	99290	99170.04	128.85
	Ref_IN	98460	98970	98825.68	134.19
	T_1	99133.8	99565.99	99445.19	127.6
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0*
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	10.74	40.32	-	-
Relative Humidity [%]	Chamber	43	47.09	45.64	0.98

\* Please see section 10 of this document for explanation about this zero deviation.



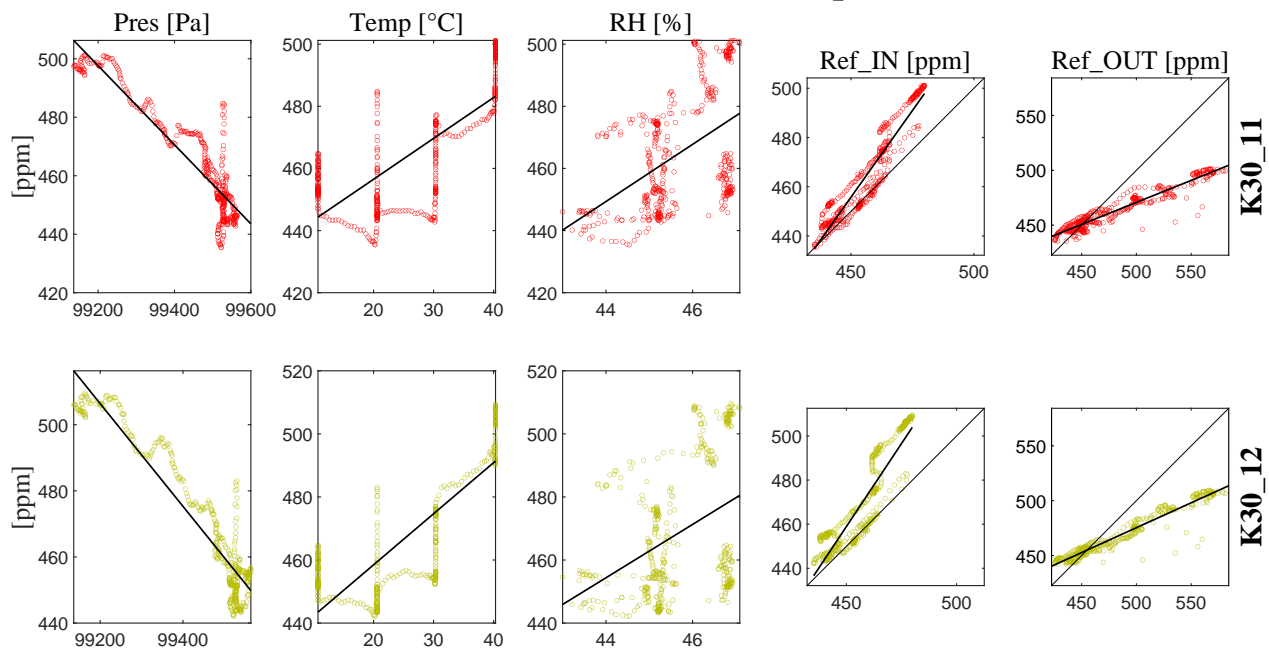
**Figure 7.** Results for the first Mesonet Temperature run.

**Table 5.** Carbon Dioxide metrics for the first Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	425.48	581.55	484.34	45.08
	Ref_IN	435.11	479.91	456.2	12.7
	K30_11	435.35	501.35	464.47	18.86
	K30_12	442.05	509.72	468.27	21.15



## Correlation for the Mesonet Temperature 1

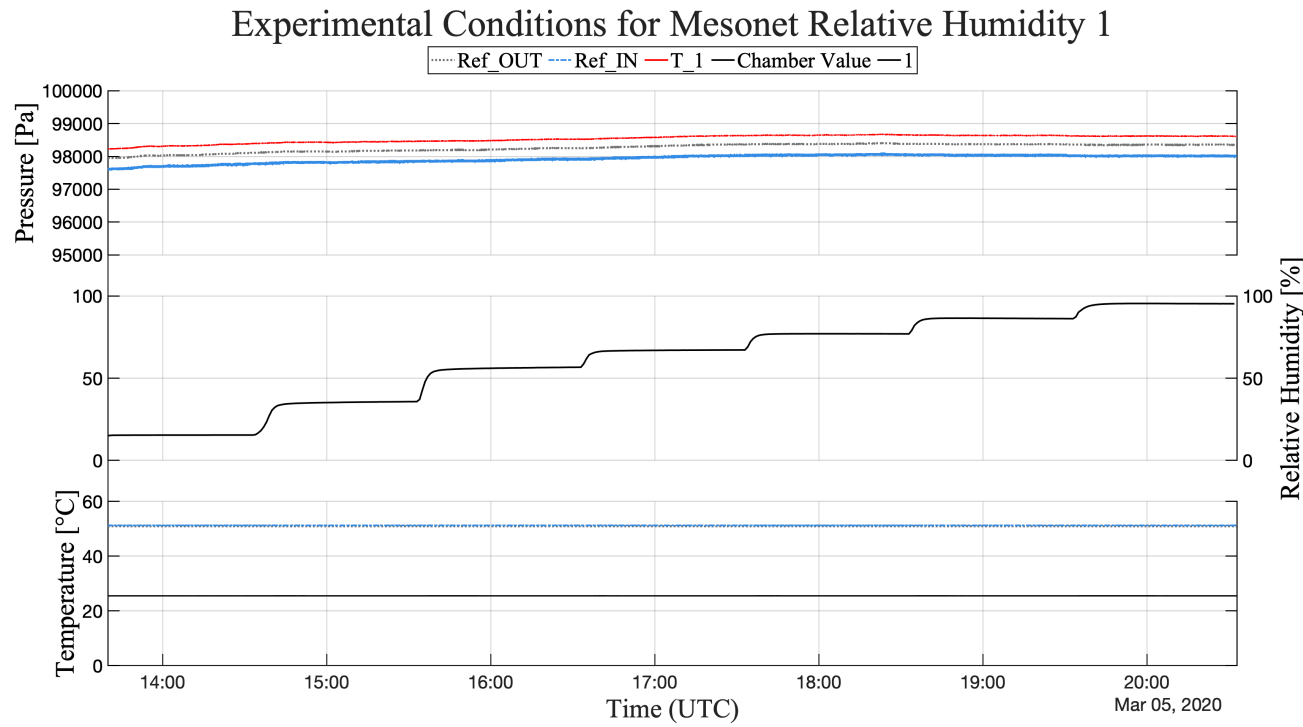


**Figure 8.** Scatter plots for the first Mesonet Temperature run.

**Table 6.** Linear fit metrics for the first Mesonet Temperature run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
Ref_IN	Pressure	-0.08	8212.38	0.68	7.19
	Temperature	0.6	440.47	0.25	11
	Relative Humidity	7.42	117.68	0.33	10.43
	Ref_OUT	0.25	337.26	0.76	6.22
K30_11	Pressure	-0.14	13911.4	0.84	7.61
	Temperature	1.32	430.2	0.54	12.79
	Relative Humidity	9.19	44.89	0.23	16.57
	Ref_IN	1.41	-178.06	0.9	5.98
	Ref_OUT	0.4	270.02	0.92	5.31
K30_12	Pressure	-0.16	15918.25	0.88	7.38
	Temperature	1.62	426.07	0.65	12.5
	Relative Humidity	8.46	82.31	0.15	19.46
	Ref_IN	1.5	-218.19	0.82	9.08
	Ref_OUT	0.45	248.4	0.94	5.37

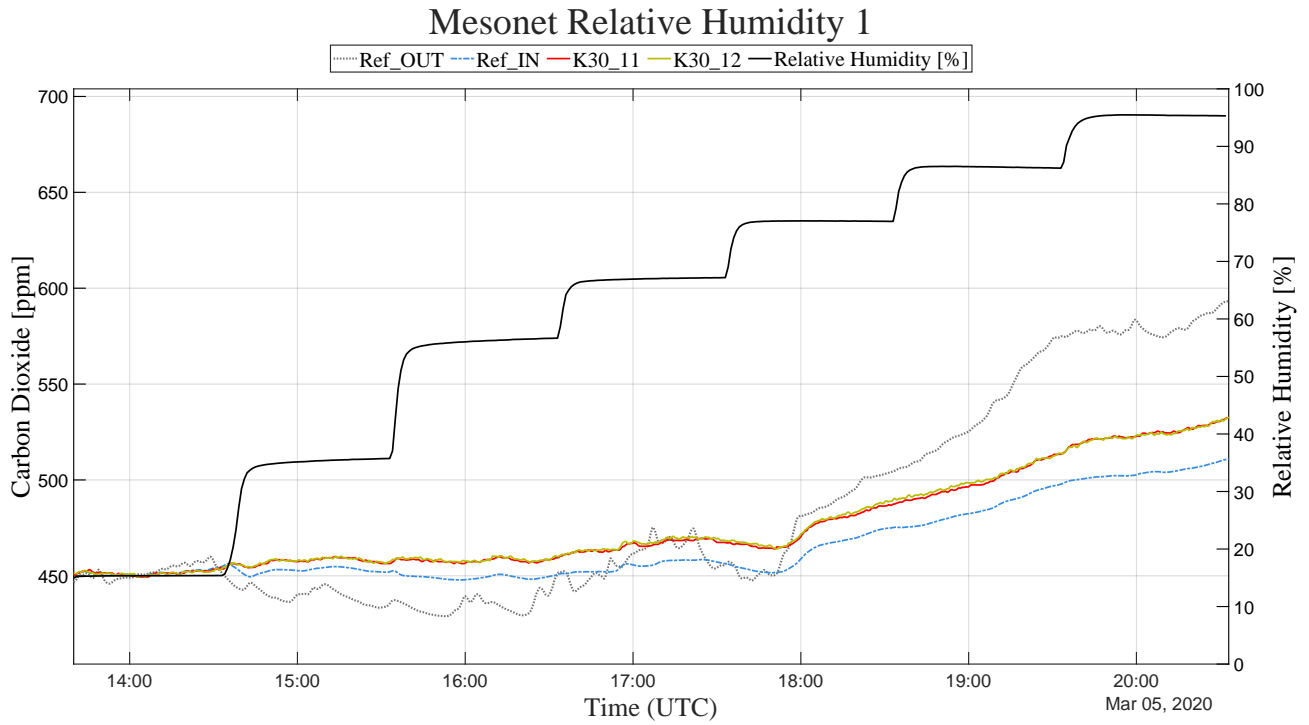
3.3 Relative Humidity



**Figure 9.** Experimental conditions during the first Mesonet Relative Humidity run.

**Table 7.** Metrics for the experimental conditions during the first Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	97950	98410	98264.73	121.25
	Ref_IN	97590	98100	97930.66	121.5
	T_1	98225.48	98674.64	98537.13	115.1
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	25.47	25.5	25.48	0.01
Relative Humidity [%]	Chamber	14.97	95.48	-	-

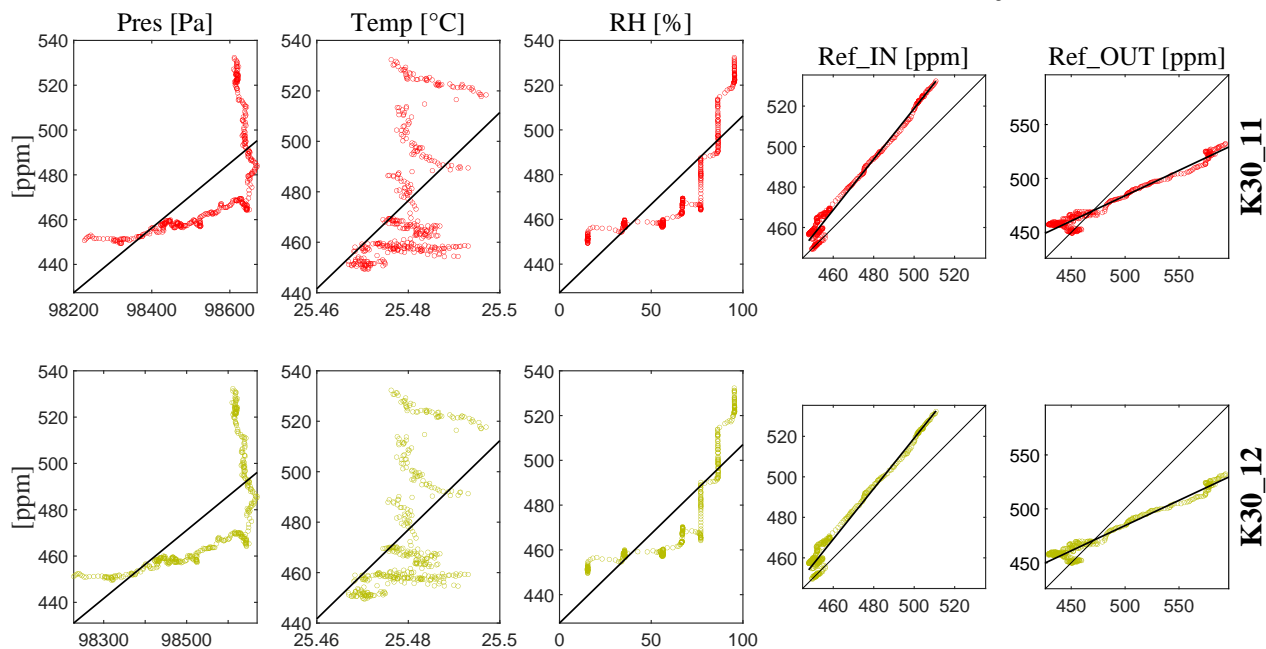


**Figure 10.** Results for the first Mesonet Relative Humidity run.

**Table 8.** Carbon Dioxide metrics for the first Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	428.93	593.21	483	52.16
	Ref_IN	447.85	510.86	465.9	19.74
	K30_11	449.41	532.41	476.07	24.97
	K30_12	449.43	532.8	476.58	24.91

# Correlation for the Mesonet Relative Humidity 1



**Figure 11.** Scatter plots for the first Mesonet Relative Humidity run.

**Table 9.** Linear fit metrics for the first Mesonet Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_11	Pressure	0.14	-13756.32	0.44	18.64
	Temperature	1747.35	-44046.02	0.19	22.52
	Relative Humidity	0.79	427.22	0.69	13.91
	Ref_IN	1.25	-107.72	0.98	3.48
	Ref_OUT	0.47	249.43	0.96	4.96
K30_12	Pressure	0.15	-14021.01	0.46	18.27
	Temperature	1765.67	-44512.15	0.19	22.4
	Relative Humidity	0.8	427.3	0.71	13.52
	Ref_IN	1.25	-104.56	0.98	3.81
	Ref_OUT	0.47	250.86	0.96	5.13

4 Mesonet Experiment 2

4.1 Reference Sensors

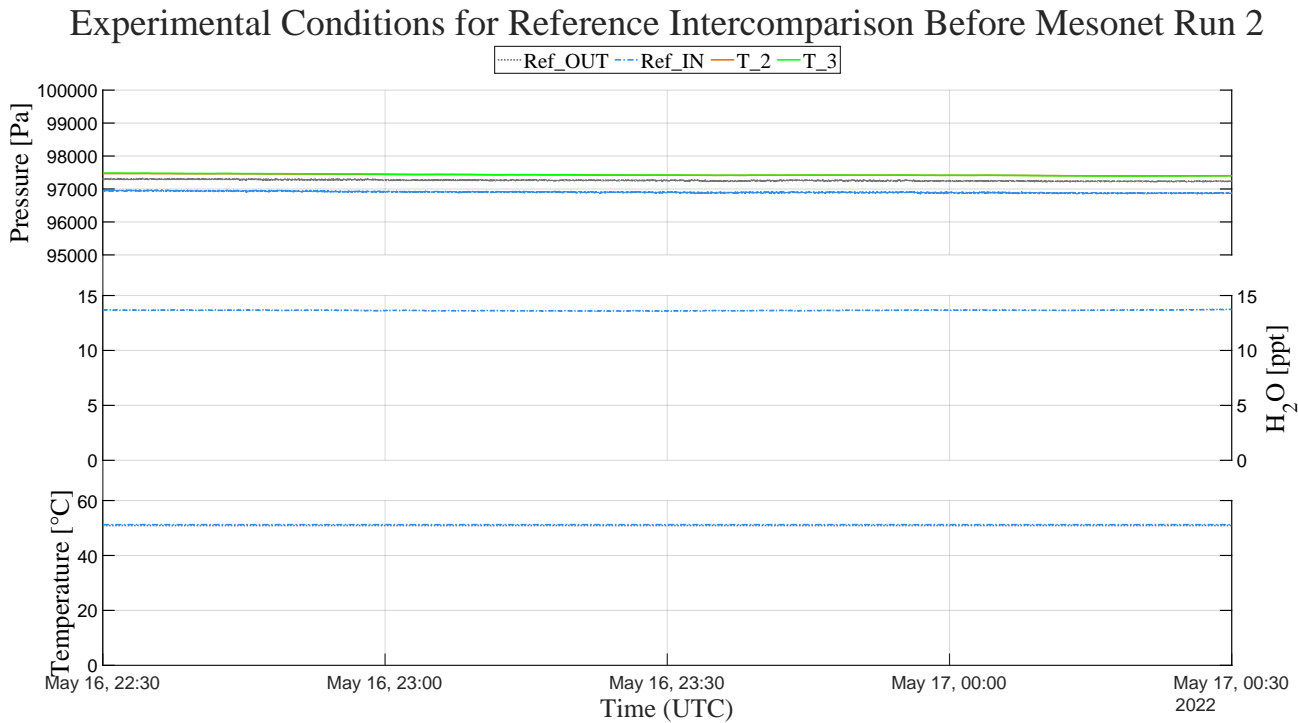
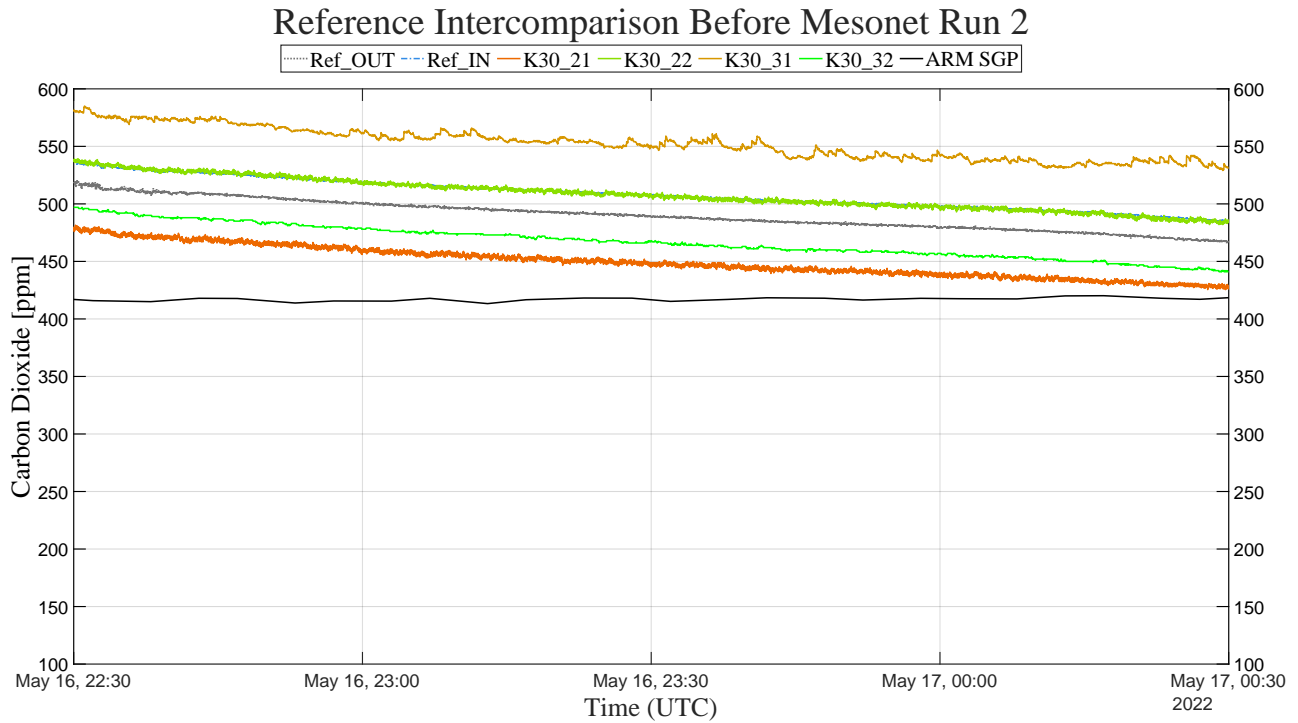


Figure 12. Experimental conditions for the intercomparison before second Mesonet experiments.

Table 10. Metrics for the experimental conditions for the intercomparison before second Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	97220	97320	97261.68	23.66
	Ref_IN	96830	96980	96904.07	26.97
	T_1	97395.68	97470.13	97427.53	20.73
	T_2	97393.41	97483.26	97430.47	25.02
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.2	51.28	51.23	0.01
H <sub>2</sub> O [ppt]	Ref_IN	13.57	13.75	13.65	0.03

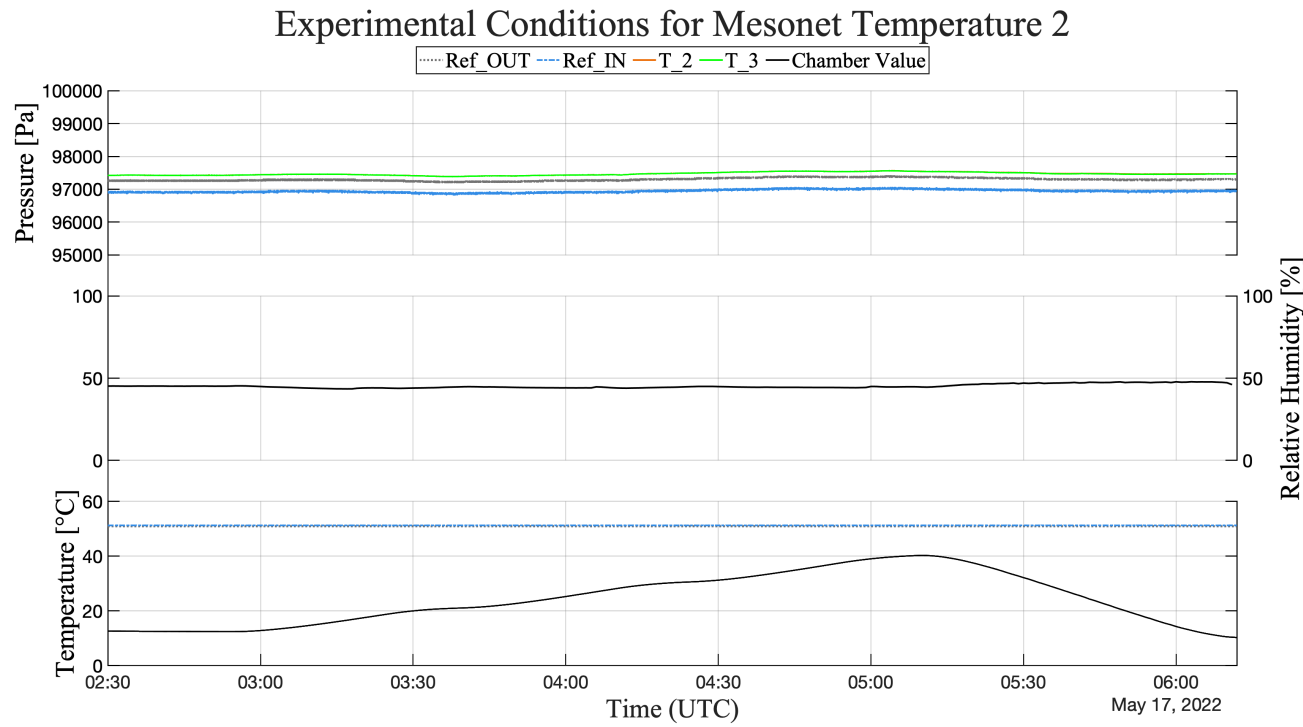


**Figure 13.** Results for the intercomparison before the second Mesonet experiment. At this date, the two reference presented a constant 18.23 ppm offset. After correcting this offset, the RMSE was  $1.53 \times 10^{-14}$  ppm.

**Table 11.** Metrics for the intercomparison before the second Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	465.75	520.45	490.28	13.02
	Ref_IN	484.46	538.11	508.51	13.17
	ARM SGP	413.32	420.2	417.05	1.42
	K30_21	425.5	481.5	449.68	13.55
	K30_22	482	539	508.29	13.93
	K30_31	529	585	552.27	13.48
	K30_32	441	497	467.25	14.28

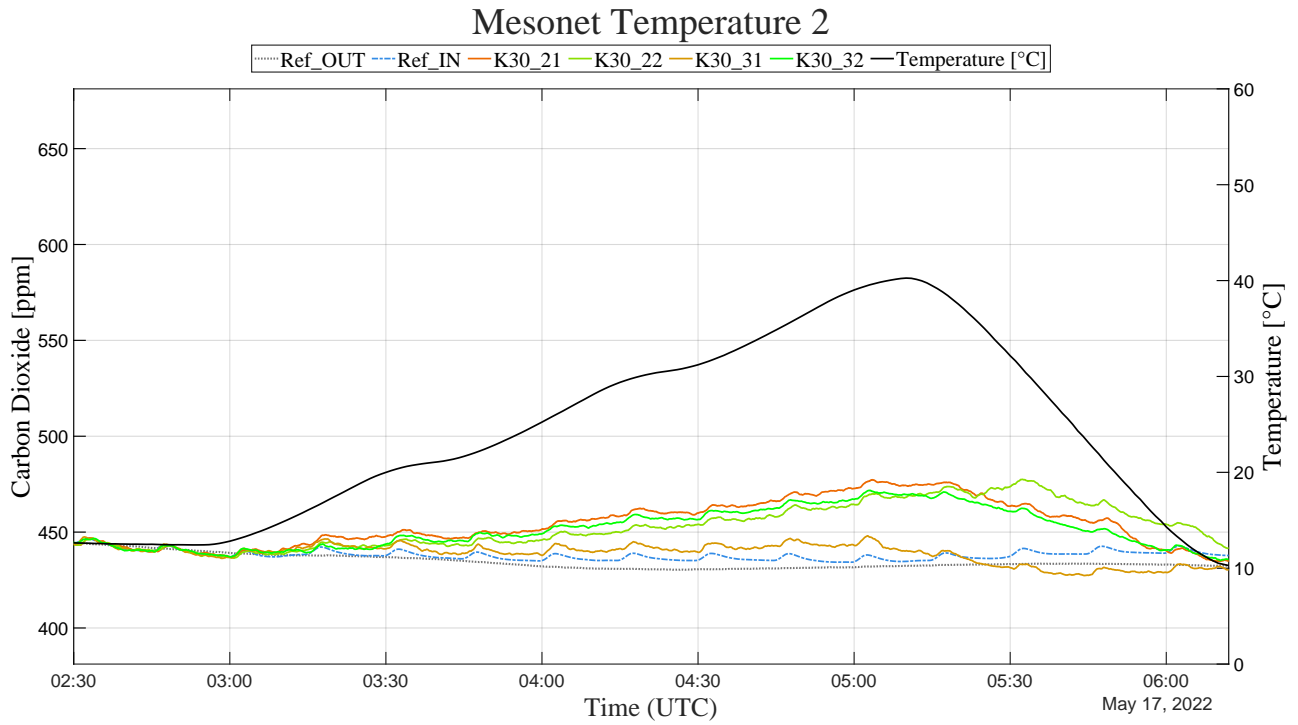




**Figure 14.** Experimental conditions during the second Mesonet Temperature run.

**Table 12.** Metrics for the experimental conditions during the second Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	97210	97400	97304.12	47.69
	Ref_IN	96830	97050	96944.33	45.83
	T_2	97385.18	97565.27	97470.79	48.26
	T_3	97385.21	97563.27	97468.38	47.66
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	10.28	40.26	-	-
Relative Humidity [%]	Chamber	43.48	47.81	45.17	1.23

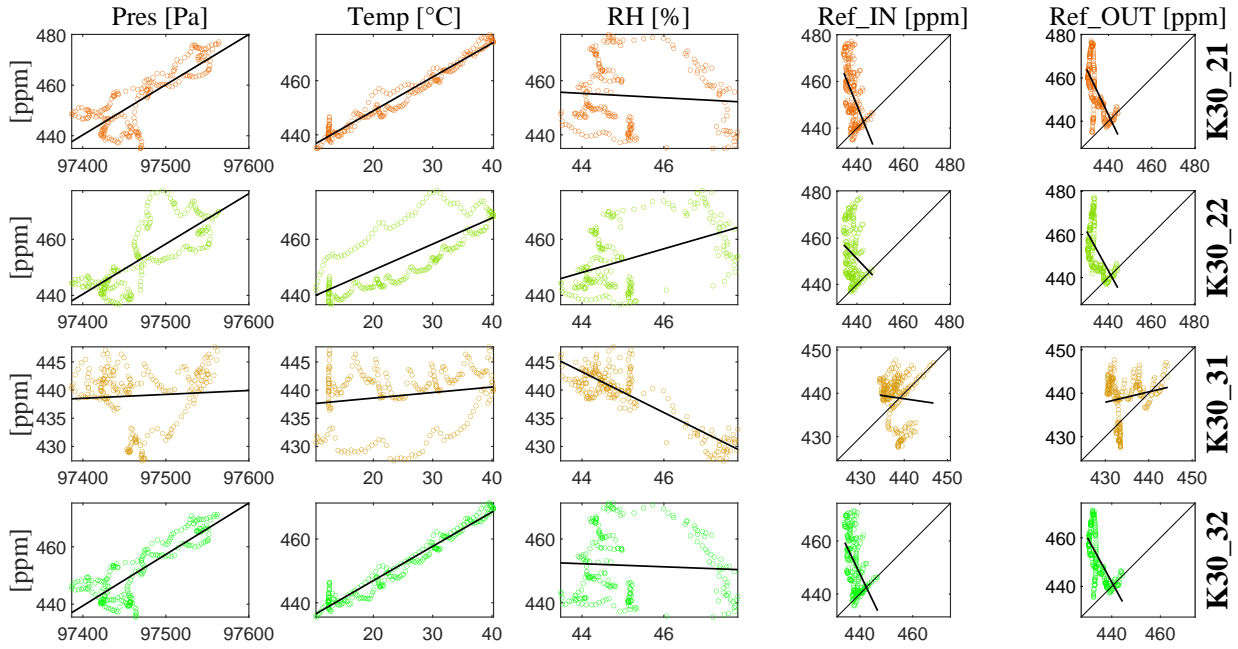


**Figure 15.** Results for the second Mesonet Temperature run.

**Table 13.** Carbon Dioxide metrics for the second Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	430.39	444.43	434.57	3.68
	Ref_IN	434.32	446.82	438.07	2.47
	K30_21	434.62	477.32	454.36	11.88
	K30_22	436.42	477.51	453.11	11.29
	K30_31	427.33	448.05	439.02	5.08
	K30_32	435.23	471.76	451.68	10.29

## Correlation for the Mesonet Temperature 2

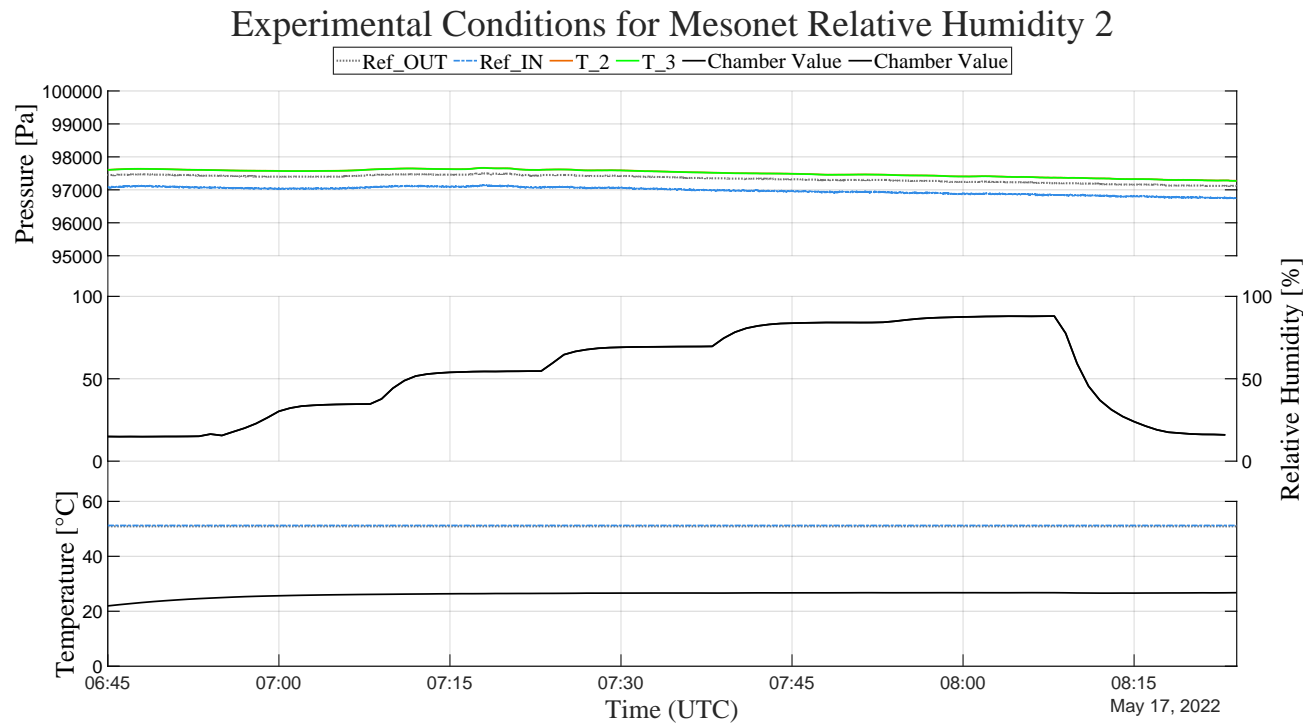


**Figure 16.** Scatter plots for the second Mesonet Temperature run.

**Table 14.** Linear fit metrics for the second Mesonet Temperature run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
Ref_IN	Pressure	-0.02	2538.79	0.15	2.26
	Temperature	-0.17	442.25	0.42	1.87
	Relative Humidity	0.68	407.18	0.12	2.31
	Ref_OUT	0.44	245.07	0.44	1.83
K30_21	Pressure	0.2	-18931.25	0.65	6.99
	Temperature	1.25	423.91	0.96	2.35
	Relative Humidity	-0.81	490.97	0.01	11.83
	Ref_IN	-2.47	1536.34	0.26	10.21
	Ref_OUT	-2.09	1363.93	0.42	9.03
K30_22	Pressure	0.18	-17025.1	0.59	7.24
	Temperature	0.93	430.45	0.59	7.23
	Relative Humidity	4.22	262.52	0.21	10.03
	Ref_IN	-1.05	912.85	0.05	10.98
	Ref_OUT	-1.82	1242.14	0.35	9.08
K30_31	Pressure	0.01	-235.81	0	5.05
	Temperature	0.1	436.62	0.03	4.98
	Relative Humidity	-3.61	602.12	0.76	2.47
	Ref_IN	-0.15	503.29	0.01	5.05
	Ref_OUT	0.24	335.75	0.03	4.99
K30_32	Pressure	0.18	-16989.37	0.69	5.75
	Temperature	1.08	425.42	0.95	2.24
	Relative Humidity	-0.48	473.53	0	10.27
	Ref_IN	-2.08	1361.23	0.25	8.93
	Ref_OUT	-1.82	1243.47	0.43	7.79

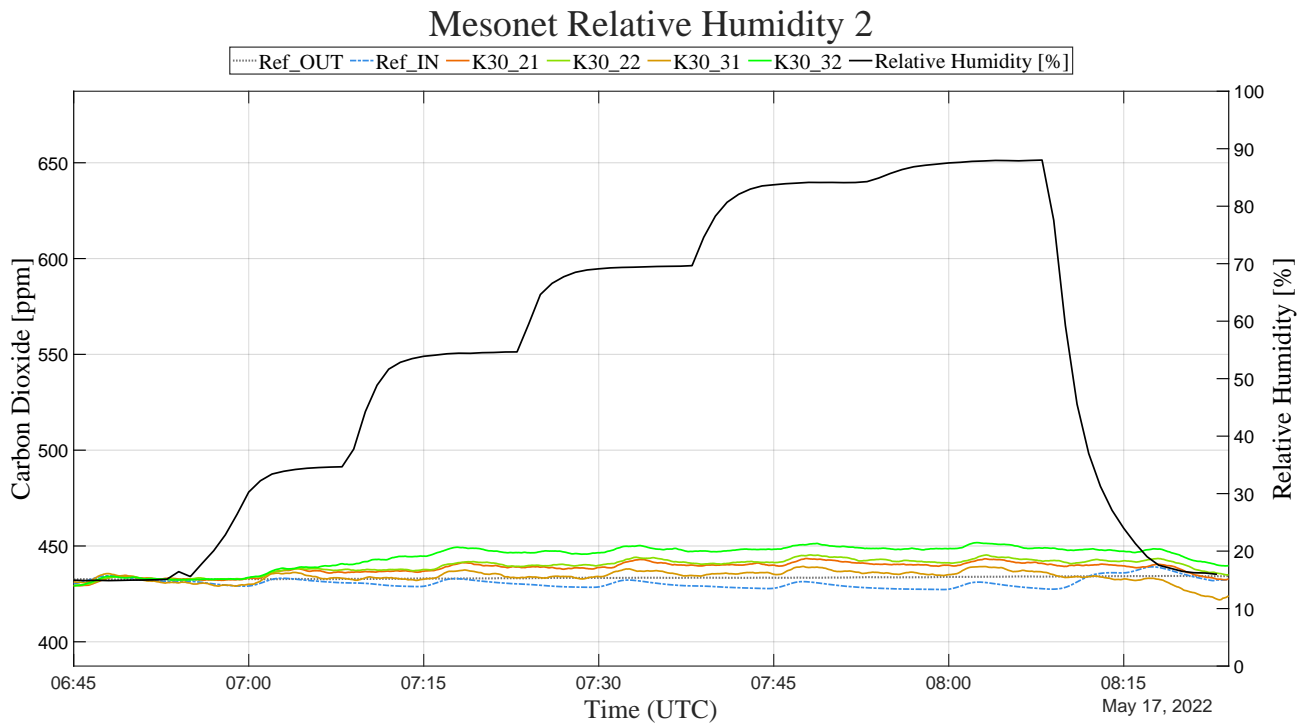
4.3 Relative Humidity



**Figure 17.** Experimental conditions during the second Mesonet Relative Humidity run.

**Table 15.** Metrics for the experimental conditions during the second Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	97100	97500	97342.03	111.34
	Ref_IN	96720	97160	96980.96	111
	T_2	97274.8	97669.28	97511.81	112.58
	T_3	97270.3	97665.22	97508.13	112.64
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.2	51.28	51.23	0.01
	Chamber	21.95	26.76	26.2	0.95
Relative Humidity [%]	Chamber	14.87	88.03	-	-

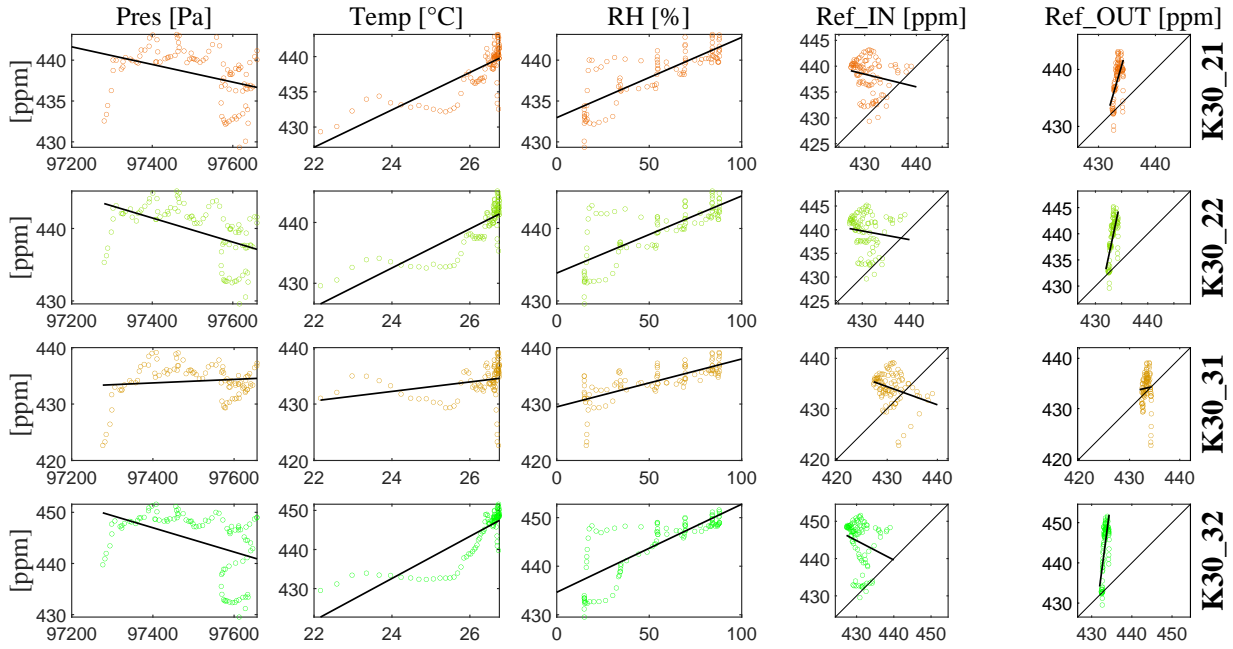


**Figure 18.** Results for the second Mesonet Relative Humidity run.

**Table 16.** Carbon Dioxide metrics for the second Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	432.36	434.37	433.36	0.57
	Ref_IN	427.27	439.11	430.78	2.54
	K30_21	429.1	443.48	438.27	3.27
	K30_22	429.23	445.32	439.59	3.75
	K30_31	421.89	439.33	434.08	3.09
	K30_32	429.27	451.75	444.42	6.1

## Correlation for the Mesonet Relative Humidity 2



**Figure 19.** Scatter plots for the second Mesonet Relative Humidity run.

**Table 17.** Linear fit metrics for the second Mesonet Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_21	Pressure	-0.01	1489.63	0.14	3.02
	Temperature	2.65	368.72	0.6	2.06
	Relative Humidity	0.1	432.97	0.65	1.92
	Ref_IN	-0.25	544.31	0.04	3.19
	Ref_OUT	3.42	-1043.98	0.35	2.62
K30_22	Pressure	-0.02	2062.65	0.25	3.24
	Temperature	3.22	355.25	0.67	2.16
	Relative Humidity	0.11	433.84	0.58	2.43
	Ref_IN	-0.18	519.04	0.02	3.71
	Ref_OUT	4.7	-1597.44	0.5	2.64
K30_31	Pressure	0	128.65	0.01	3.05
	Temperature	0.84	412.08	0.07	2.96
	Relative Humidity	0.08	429.5	0.55	2.07
	Ref_IN	-0.36	589.56	0.09	2.93
	Ref_OUT	0.23	335.68	0	3.07
K30_32	Pressure	-0.02	2753.61	0.19	5.48
	Temperature	5.39	303.33	0.7	3.32
	Relative Humidity	0.18	434.63	0.63	3.69
	Ref_IN	-0.52	668.32	0.05	5.95
	Ref_OUT	7.6	-2850.09	0.5	4.32



5 Mesonet Experiment 3

5.1 Temperature

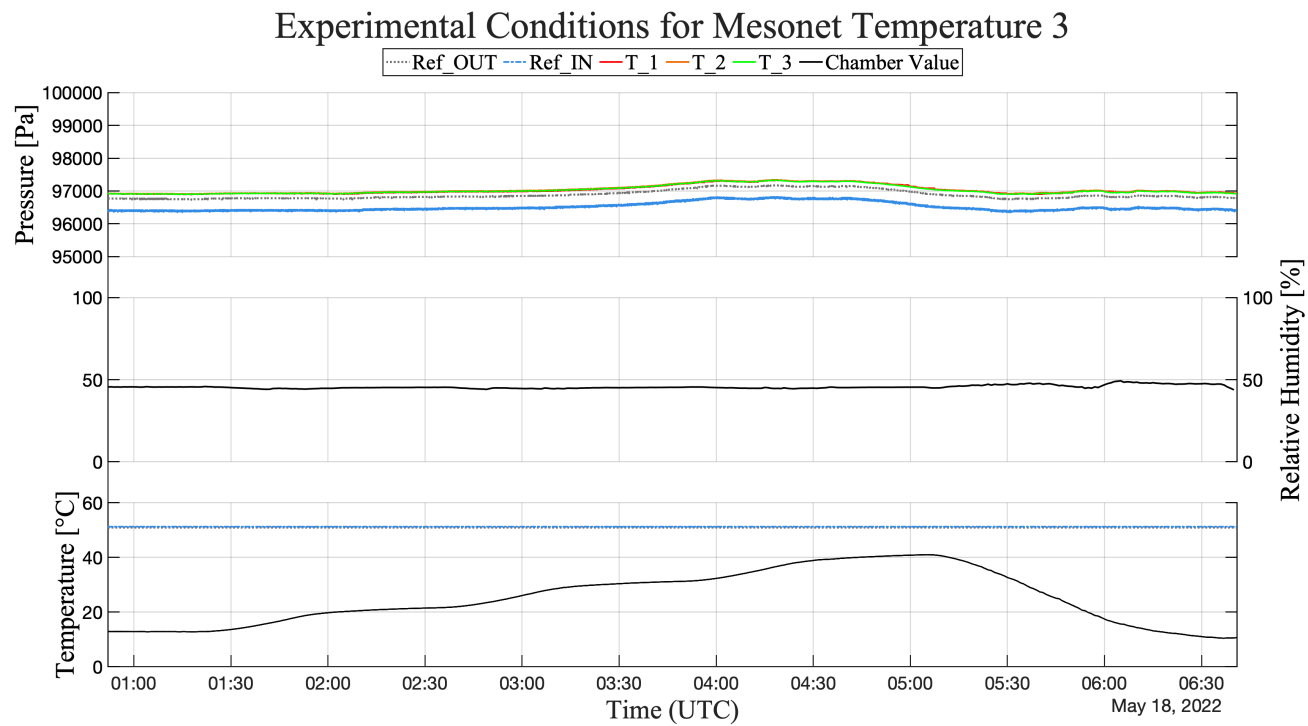
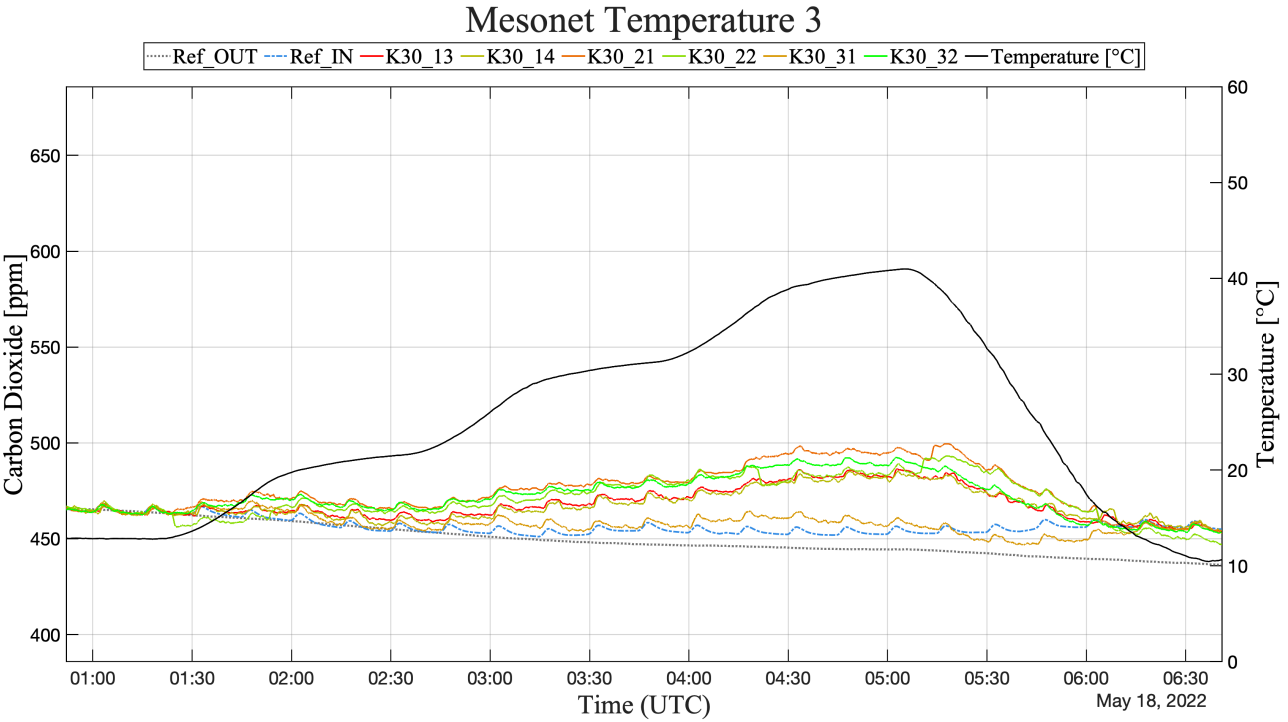


Figure 20. Experimental conditions during the third Mesonet Temperature run.

**Table 18.** Metrics for the experimental conditions during the third Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	96730	97170	96886.92	133.07
	Ref_IN	96350	96820	96517.46	131.51
	T_1	96893.91	97325.16	97034.12	135.93
	T_2	96909.97	97343.58	97050.6	134.92
	T_3	96895.46	97326.49	97034.11	134.52
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	10.44	40.98	-	-
Relative Humidity [%]	Chamber	43.78	49.27	45.56	1.05

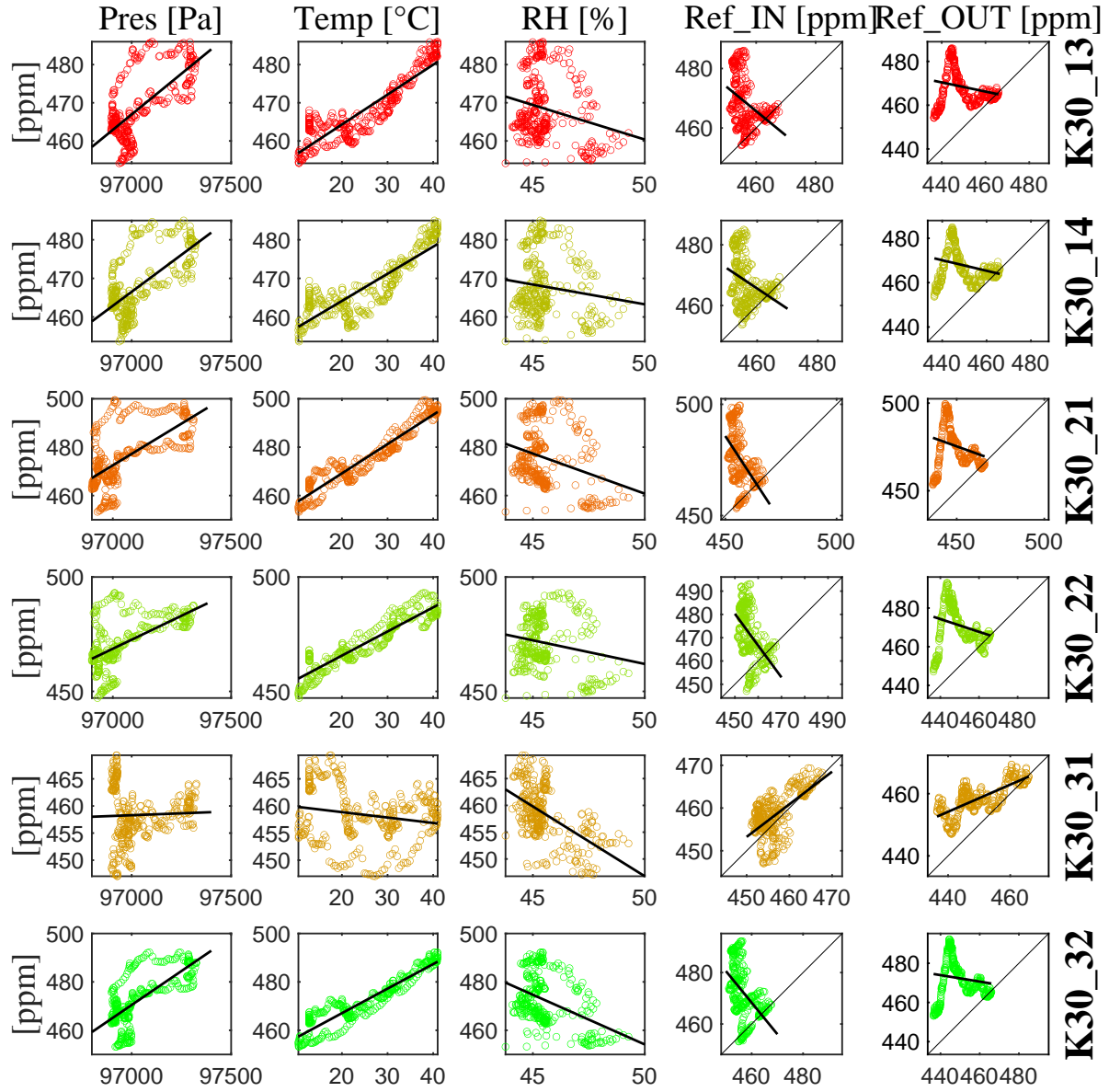


**Figure 21.** Results for the third Mesonet Temperature run.

**Table 19.** Carbon Dioxide metrics for the third Mesonet Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	436.43	465.98	449.53	8.36
	Ref_IN	451.11	467.77	456.67	4.03
	K30_13	454.01	486.43	468.41	8.42
	K30_14	452.86	485.25	467.83	7.9
	K30_21	452.92	499.52	475.51	12.3
	K30_22	446.99	493.18	471.16	11.07
	K30_31	446.81	469.85	458.34	4.97
	K30_32	452.9	492.42	472.37	10.47

## Correlation for the Mesonet Temperature 3

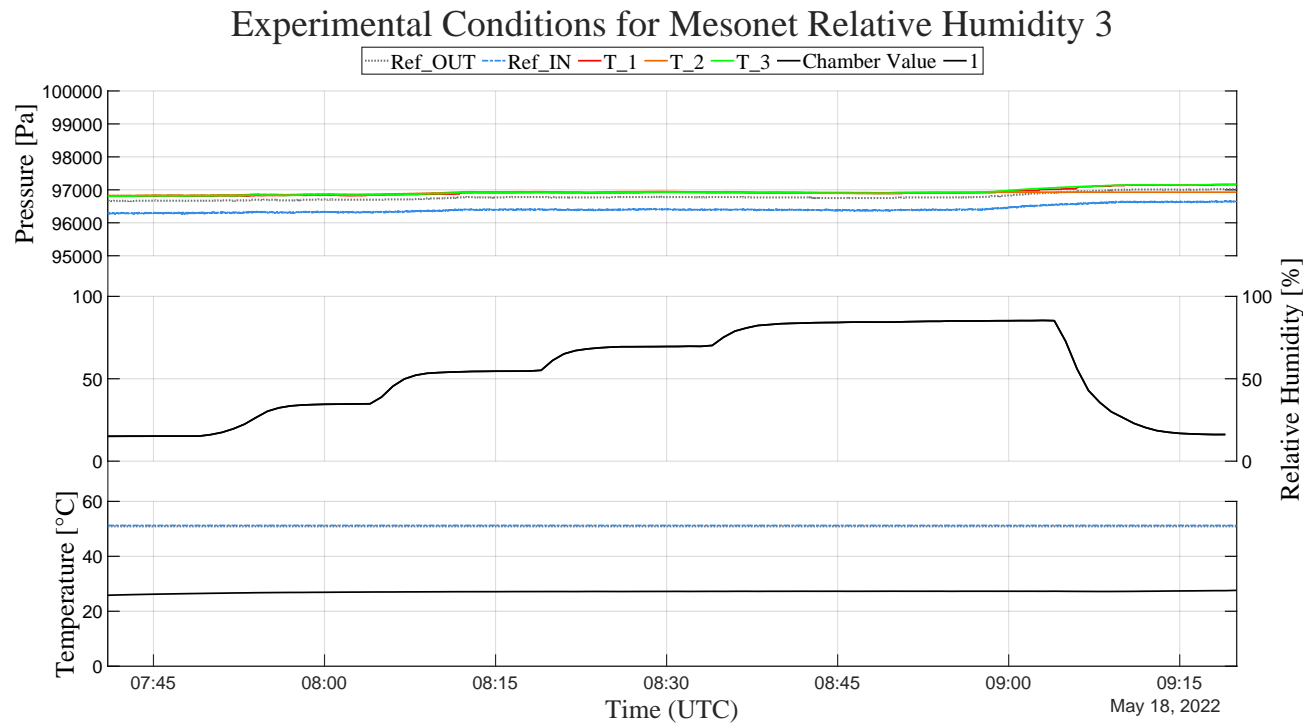


**Figure 22.** Scatter plots for the third Mesonet Temperature run.

**Table 20.** Linear fit metrics for the third Mesonet Temperature run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
Ref_IN	Pressure	-0.02	2078.44	0.3	3.37
	Temperature	-0.3	464.16	0.51	2.81
	Relative Humidity	0.09	452.78	0	4.02
	Ref_OUT	0.32	313.36	0.44	3.01
K30_13	Pressure	0.04	-3669.06	0.47	6.1
	Temperature	0.78	448.64	0.81	3.64
	Relative Humidity	-1.81	550.89	0.05	8.2
	Ref_IN	-0.82	842.92	0.15	7.74
	Ref_OUT	-0.21	562.65	0.04	8.23
K30_14	Pressure	0.04	-3251.44	0.44	5.93
	Temperature	0.7	450.08	0.75	3.98
	Relative Humidity	-1.03	514.56	0.02	7.82
	Ref_IN	-0.67	772.65	0.12	7.42
	Ref_OUT	-0.24	574.91	0.06	7.64
K30_21	Pressure	0.06	-5286.77	0.42	9.33
	Temperature	1.21	444.97	0.91	3.71
	Relative Humidity	-3.32	626.54	0.08	11.8
	Ref_IN	-1.53	1175.94	0.25	10.64
	Ref_OUT	-0.36	637.62	0.06	11.92
K30_22	Pressure	0.05	-4347.35	0.37	8.81
	Temperature	1.05	444.56	0.85	4.25
	Relative Humidity	-2.07	565.27	0.04	10.85
	Ref_IN	-1.37	1094.61	0.25	9.6
	Ref_OUT	-0.33	619.19	0.06	10.72
K30_31	Pressure	0	321.94	0	4.96
	Temperature	-0.1	460.86	0.04	4.87
	Relative Humidity	-2.6	576.97	0.3	4.15
	Ref_IN	0.76	109.91	0.38	3.9
	Ref_OUT	0.44	262.08	0.54	3.36
K30_32	Pressure	0.06	-4964.63	0.52	7.27
	Temperature	1.01	446.77	0.88	3.59
	Relative Humidity	-4.11	659.47	0.17	9.55
	Ref_IN	-1.23	1032.26	0.22	9.24
	Ref_OUT	-0.16	546.35	0.02	10.38

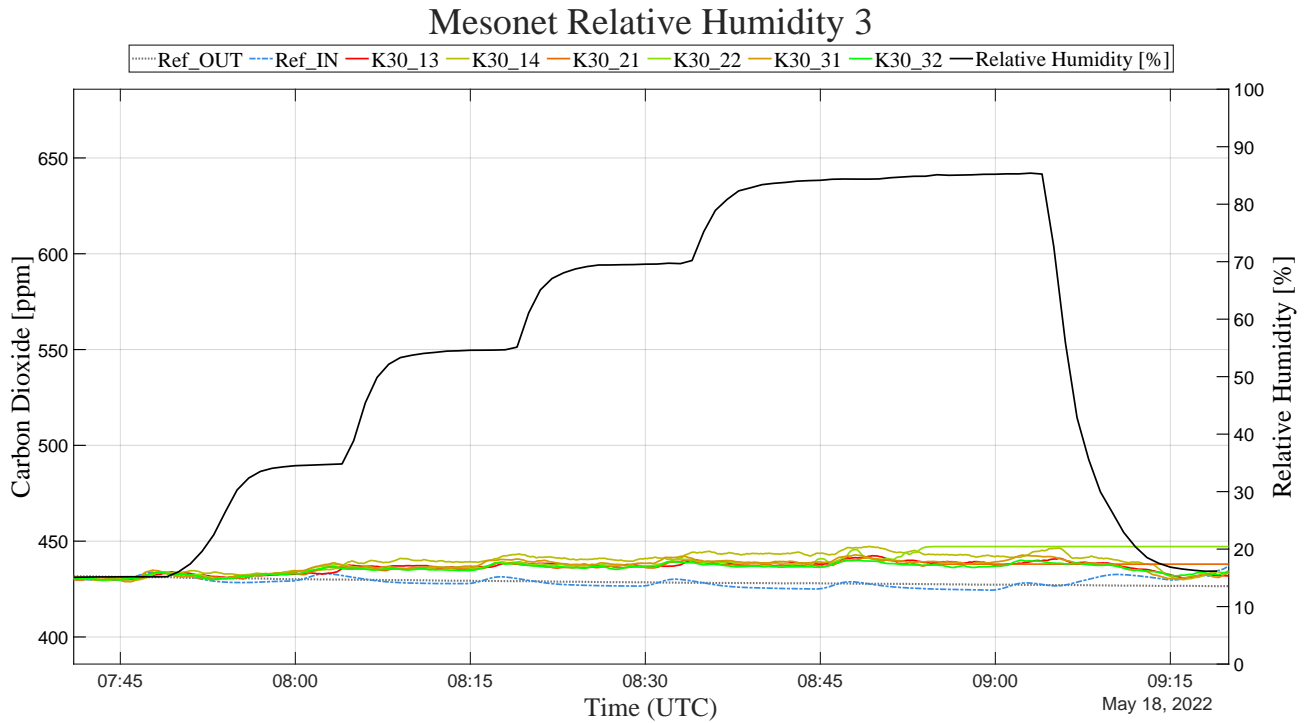
5.2 Relative Humidity



**Figure 23.** Experimental conditions during the third Mesonet Relative Humidity run.

**Table 21.** Metrics for the experimental conditions during the third Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	96660	97020	96787.52	101.93
	Ref_IN	96250	96680	96413.49	103.39
	T_1	96805.94	97161.59	96924.18	98.27
	T_2	96821.58	96951.79	96908.85	36.22
	T_3	96803.85	97169.14	96932.27	100.46
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.17	51.28	51.23	0.01
	Chamber	25.83	27.61	27.08	0.33
Relative Humidity [%]	Chamber	15.1	85.4	-	-

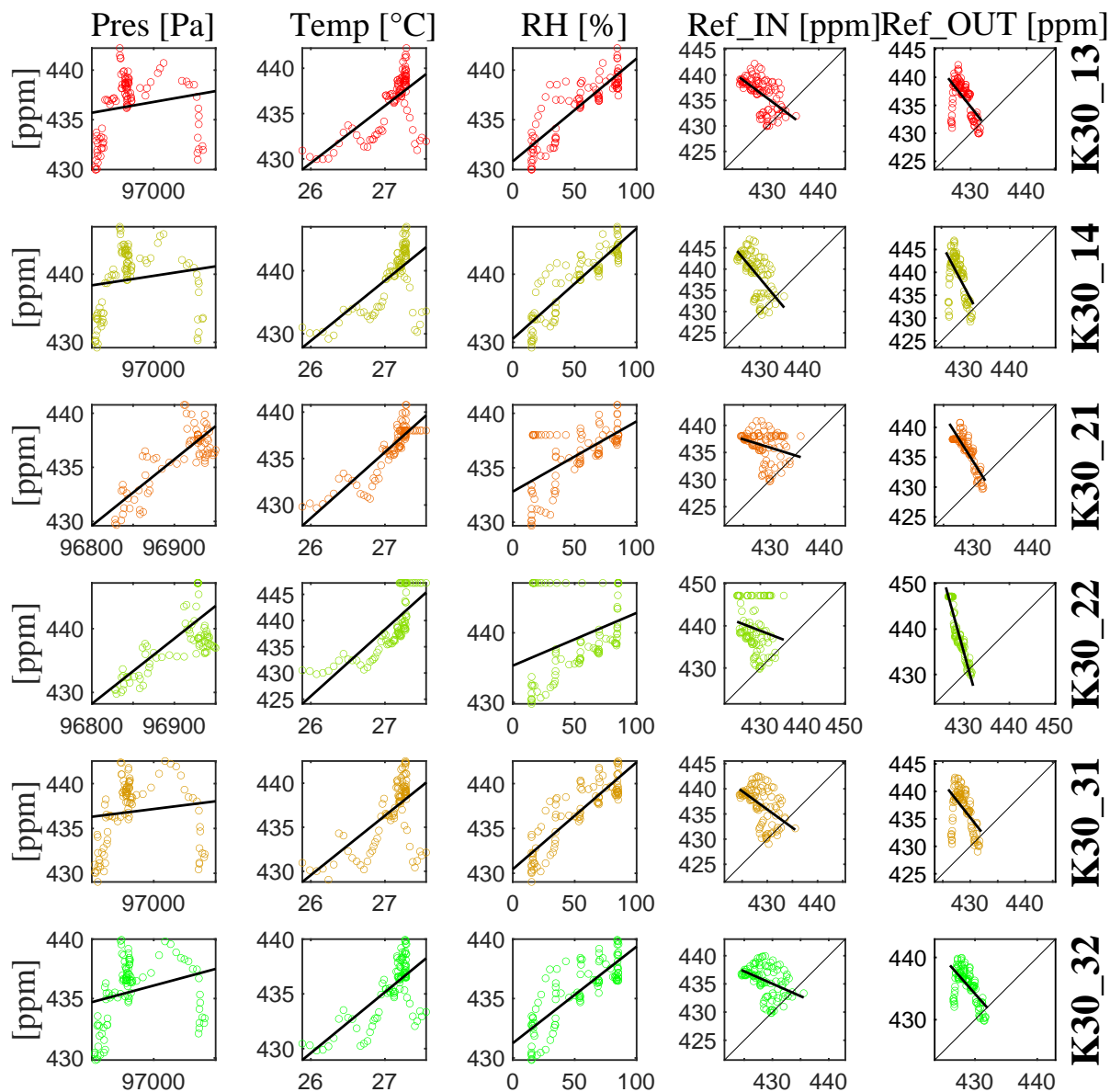


**Figure 24.** Results for the third Mesonet Relative Humidity run.

**Table 22.** Carbon Dioxide metrics for the third Mesonet Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	426.49	431.72	428.72	1.45
	Ref_IN	424.45	437.28	428.66	2.46
	K30_13	429.9	442.38	436.38	3.13
	K30_14	429.07	447.24	439.24	4.75
	K30_21	429.52	441.41	436.28	2.66
	K30_22	429.48	447.17	439.36	5.56
	K30_31	428.83	442.83	436.88	3.59
	K30_32	429.72	440.2	435.62	2.63

## Correlation for the Mesonet Relative Humidity 3

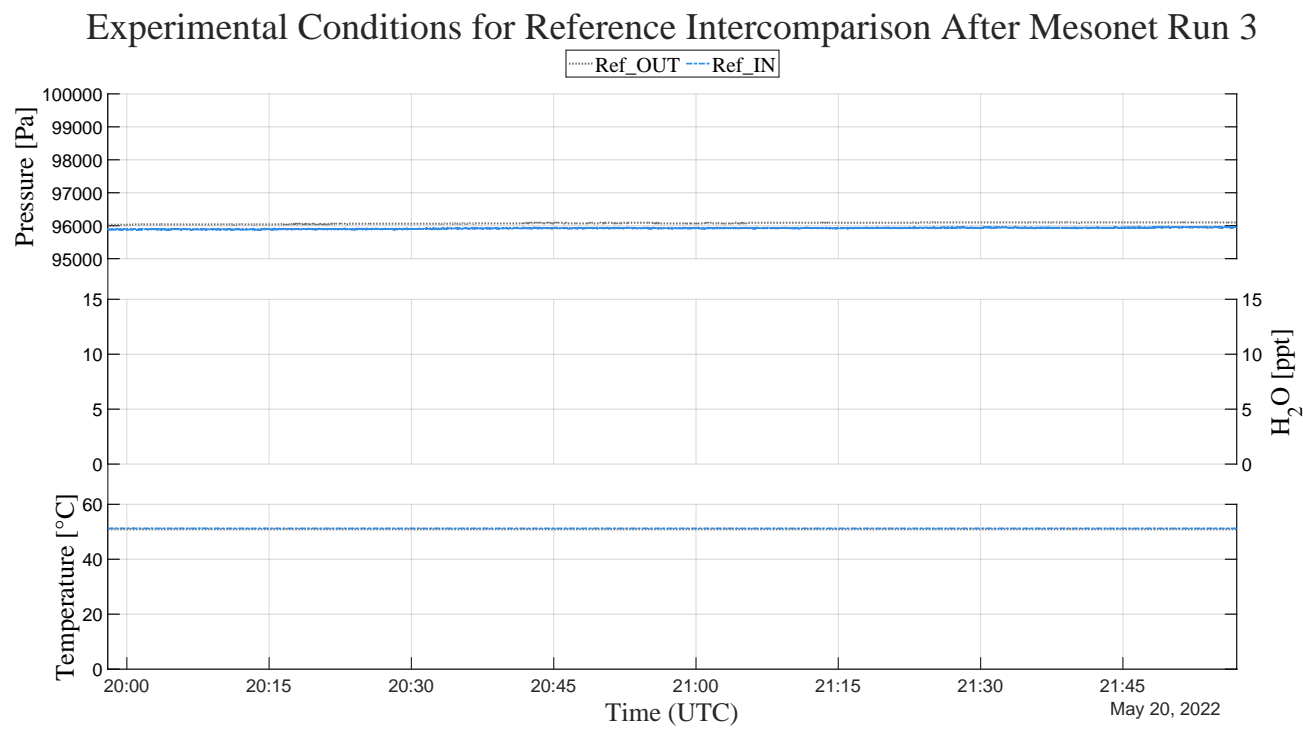


**Figure 25.** Scatter plots for the third Mesonet Relative Humidity run.



**Table 23.** Linear fit metrics for the third Mesonet Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_13	Pressure	0.01	-92.64	0.03	3.08
	Temperature	6.31	265.53	0.45	2.33
	Relative Humidity	0.1	430.8	0.75	1.55
	Ref_IN	-0.75	756.54	0.34	2.53
	Ref_OUT	-1.27	981.63	0.35	2.52
K30_14	Pressure	0.01	-236.3	0.02	4.68
	Temperature	9.54	180.9	0.44	3.53
	Relative Humidity	0.16	430.51	0.8	2.1
	Ref_IN	-1.2	955.06	0.39	3.71
	Ref_OUT	-1.89	1249.99	0.33	3.86
K30_21	Pressure	0.06	-5512.96	0.7	1.45
	Temperature	7.11	243.81	0.79	1.23
	Relative Humidity	0.06	432.81	0.41	2.04
	Ref_IN	-0.31	569.21	0.08	2.54
	Ref_OUT	-1.59	1117.18	0.75	1.32
K30_22	Pressure	0.1	-9486.42	0.45	4.13
	Temperature	12.72	94.92	0.57	3.62
	Relative Humidity	0.08	435.27	0.13	5.18
	Ref_IN	-0.39	604.51	0.03	5.46
	Ref_OUT	-3.61	1988.63	0.89	1.84
K30_31	Pressure	0	18.48	0.01	3.55
	Temperature	6.75	254.08	0.39	2.8
	Relative Humidity	0.12	430.45	0.76	1.75
	Ref_IN	-0.73	748.53	0.25	3.11
	Ref_OUT	-1.28	983.93	0.27	3.06
K30_32	Pressure	0.01	-242.33	0.07	2.52
	Temperature	5.56	285.04	0.49	1.86
	Relative Humidity	0.08	431.25	0.66	1.52
	Ref_IN	-0.44	624.66	0.17	2.38
	Ref_OUT	-1.14	923.1	0.4	2.03

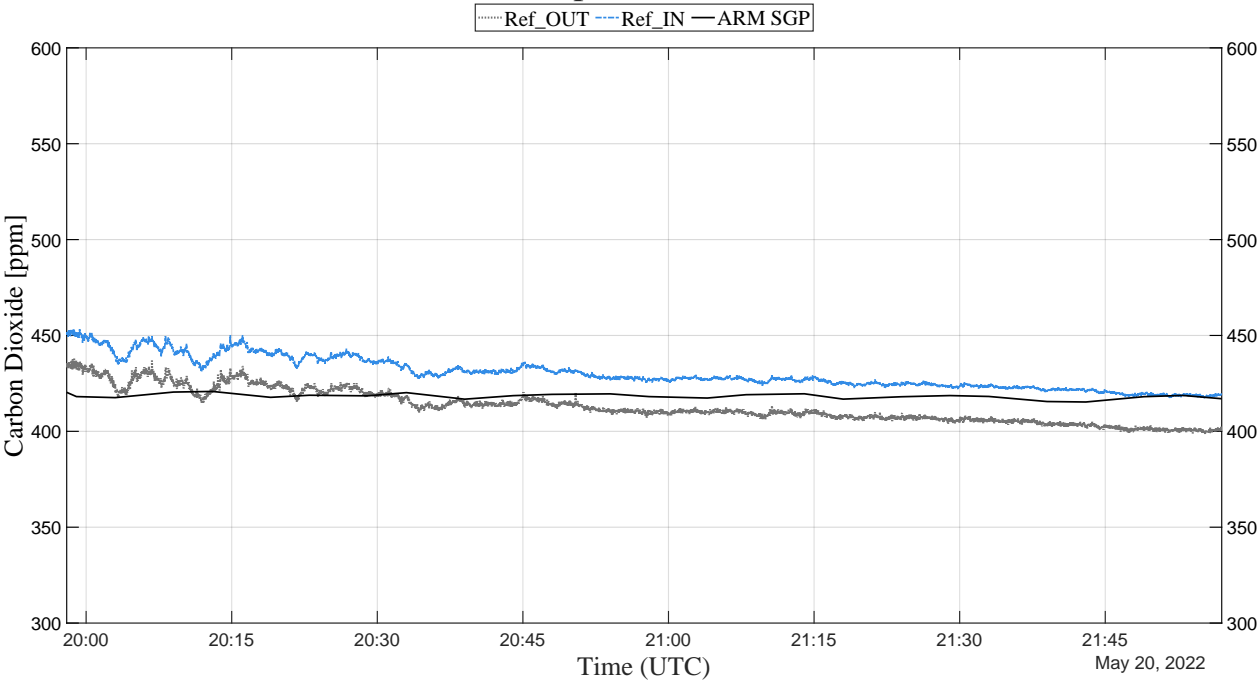


**Figure 26.** Experimental conditions for the intercomparison after third Mesonet experiments.

**Table 24.** Metrics for the experimental conditions for the intercomparison after third Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_OUT	96030	96120	96075.97	22.5
	Ref_IN	95850	95980	95921.67	24.51
Temperature [°C]	Ref_OUT	50.91	50.91	50.91	0
	Ref_IN	51.17	51.25	51.23	0.01
H <sub>2</sub> O [ppt]	Ref_IN	18.03	20.88	18.87	0.61

### Reference Intercomparison After Mesonet Run 3



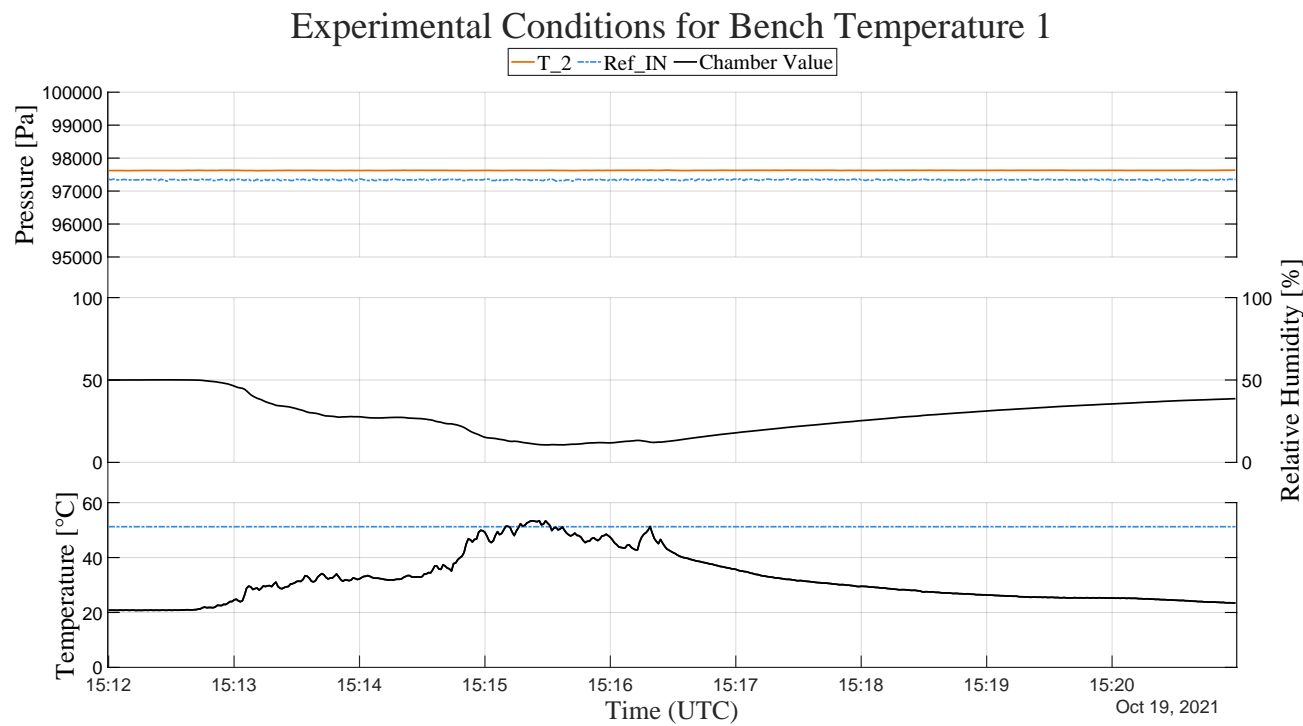
**Figure 27.** Results for the intercomparison after the third Mesonet experiment. At this date, the two reference presented a constant 17.24 ppm offset. After correcting this offset, the RMSE was  $1.12 \times 10^{-14}$  ppm.

**Table 25.** Metrics for the intercomparison after the third Mesonet experiments.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_OUT	398.62	437.86	413.05	8.74
	Ref_IN	417.4	453.29	430.29	8.27
	ARM SGP	415.3	420.81	418.31	1.15

6    Benchtop Experiments 1

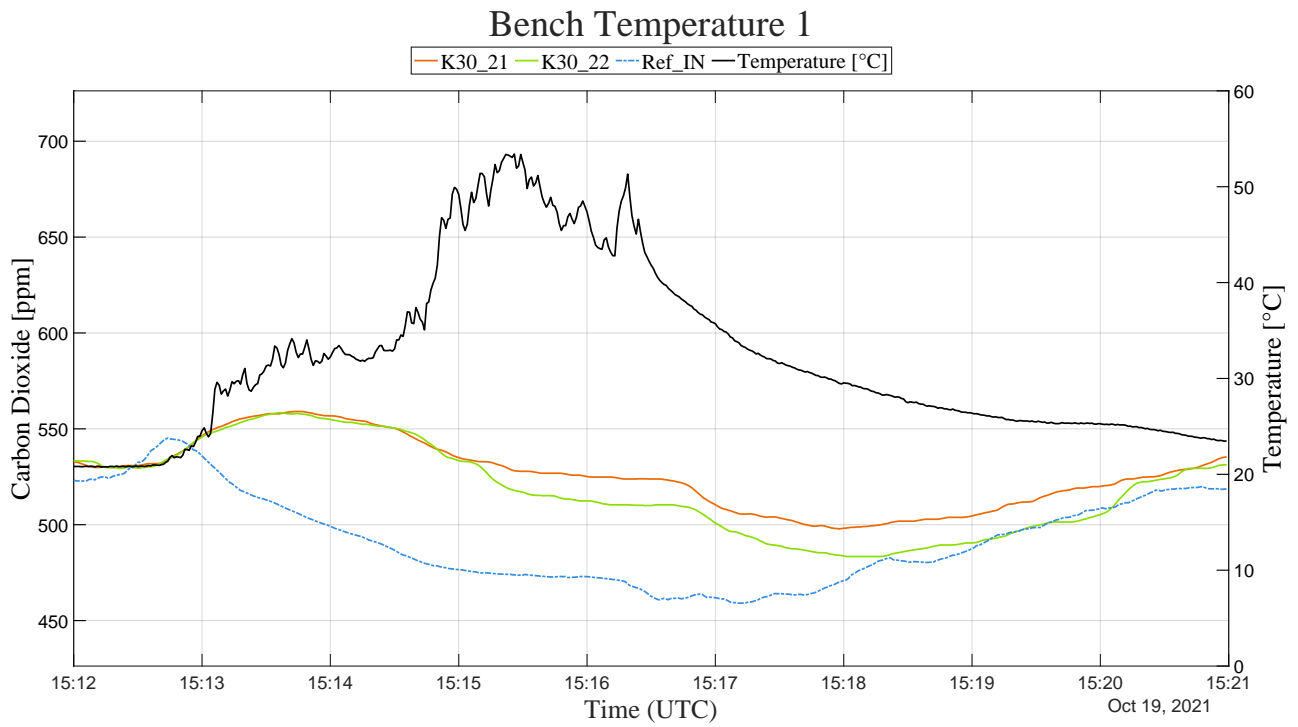
6.1    Temperature



**Figure 28.** Experimental conditions during the first Bench Temperature run.

**Table 26.** Metrics for the experimental conditions during the first Bench Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_IN	97300	97370	97342.1	13.57
	T_2	97617.75	97634.8	97626.68	2.82
Temperature [°C]	Ref_IN	51.17	51.25	51.23	0.01
	T_2	20.75	53.41	-	-
Relative Humidity [%]	T_2	10.62	50.09	28.31	11.43

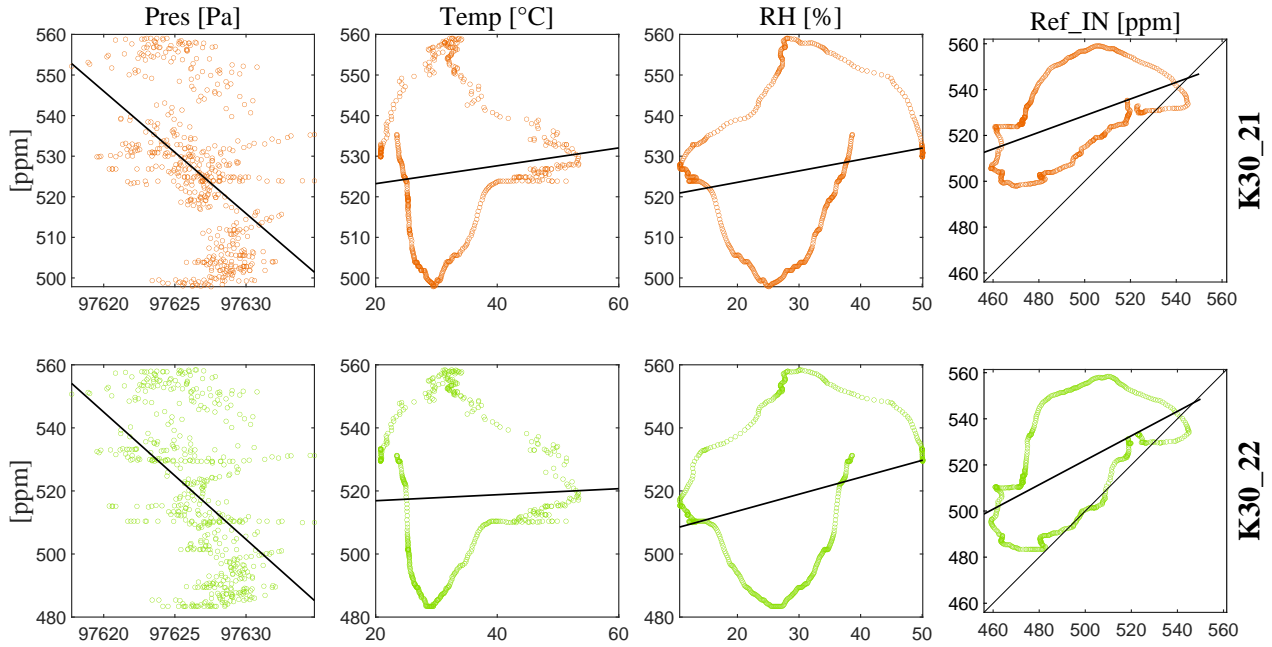


**Figure 29.** Results for the first Bench Temperature run.

**Table 27.** Carbon Dioxide metrics for the first Bench Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_IN	459.04	545.15	492.49	23.76
	K30_21	497.84	559.03	525.9	17.94
	K30_22	483.39	558.39	518.05	23.47

## Correlation for the Bench Temperature 1



**Figure 30.** Scatter plots for the first Bench Temperature run.

**Table 28.** Linear fit metrics for the first Bench Temperature run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_21	Pressure	-3.01	294698.42	0.22	15.79
	Temperature	0.22	518.82	0.01	17.82
	Relative Humidity	0.28	517.94	0.03	17.63
	Ref_IN	0.36	346.62	0.23	15.7
K30_22	Pressure	-4.04	394541.7	0.23	20.51
	Temperature	0.1	514.98	0	23.43
	Relative Humidity	0.54	502.84	0.07	22.63
	Ref_IN	0.53	256.9	0.29	19.78

6.2 Relative Humidity

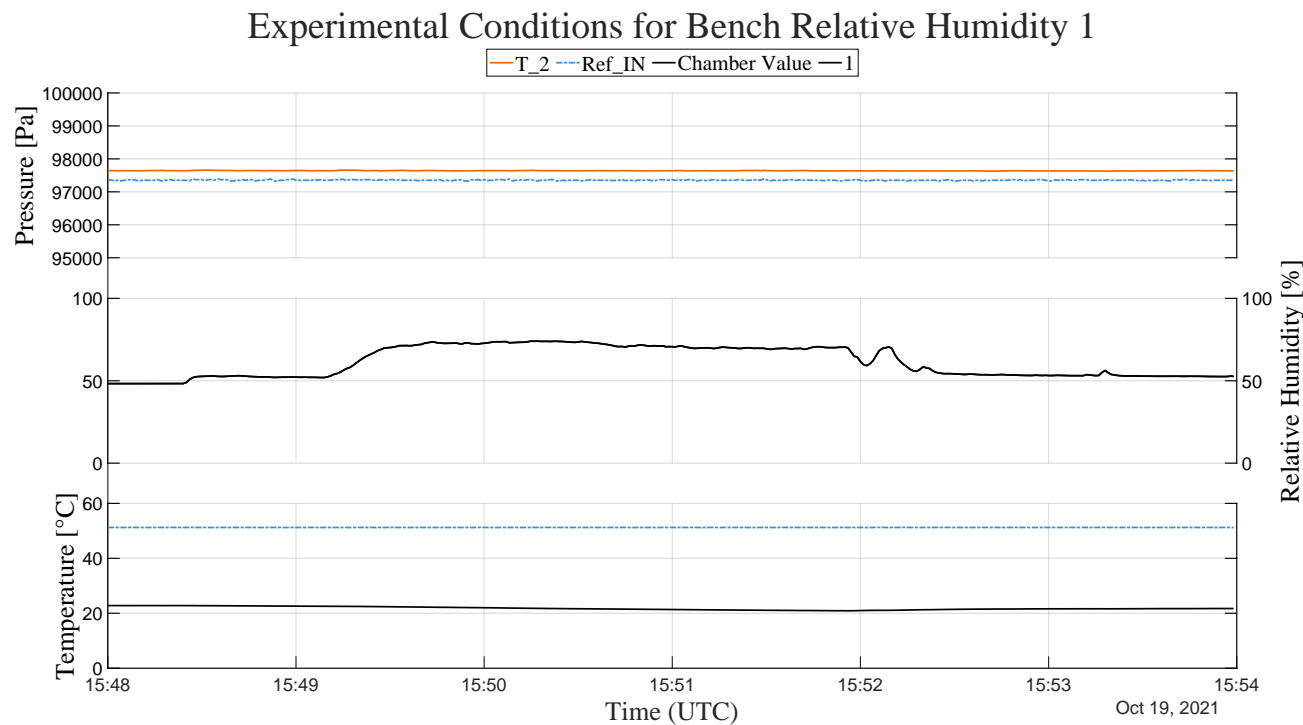
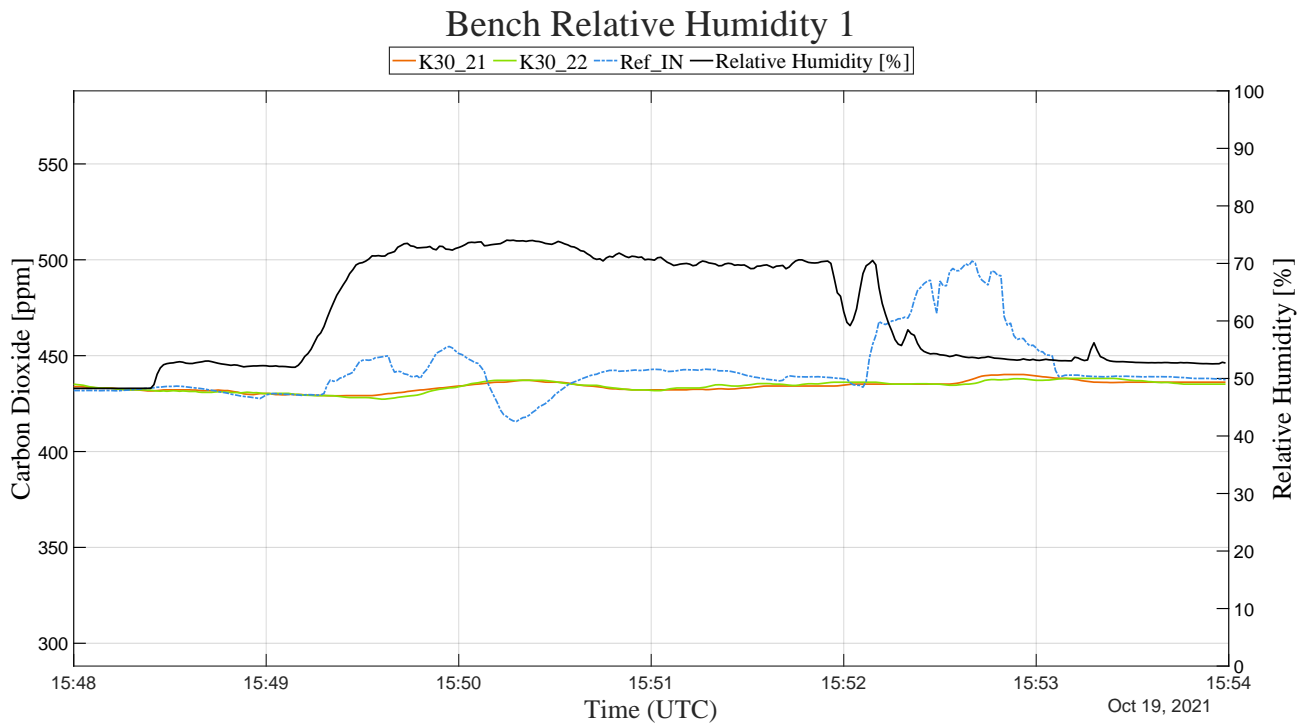


Figure 31. Experimental conditions during the first Bench Relative Humidity run.

Table 29. Metrics for the experimental conditions during the first Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_IN	97320	97390	97353	13.16
	T_2	97627.66	97659.9	97640.33	5.71
Temperature [°C]	Ref_IN	51.17	51.25	51.23	0.01
	T_2	20.9	22.79	21.81	0.58
Relative Humidity [%]	T_2	48.27	74.04	-	-



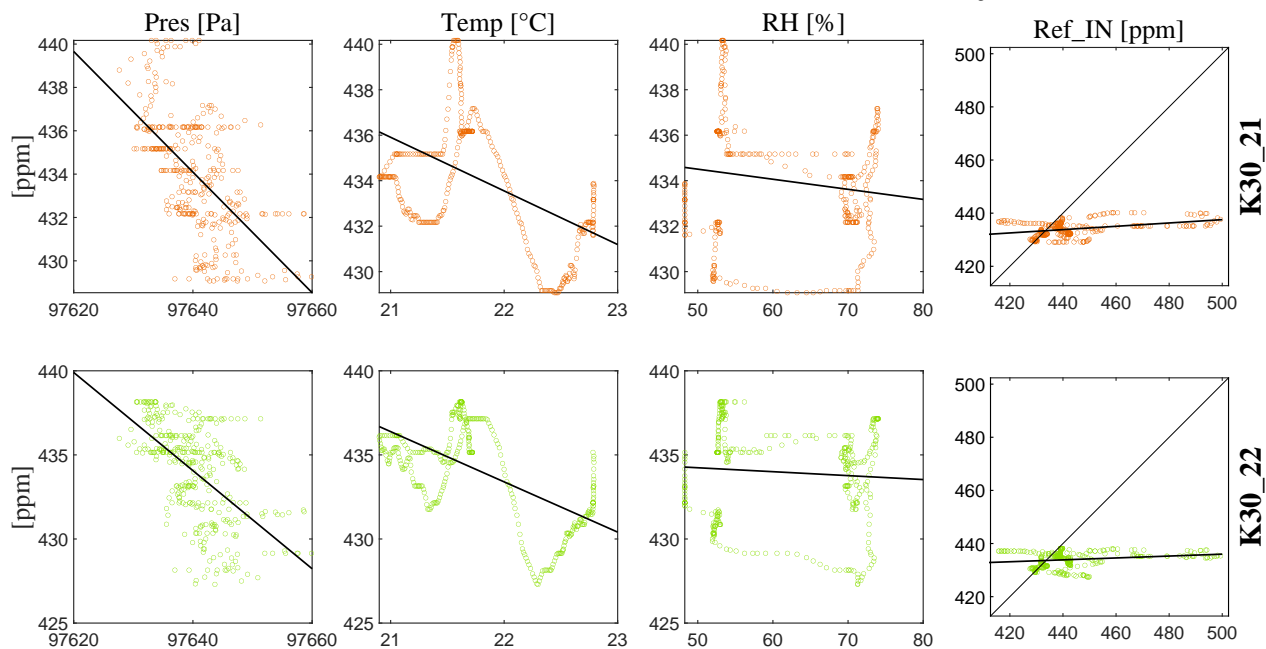
**Figure 32.** Results for the first Bench Relative Humidity run.

**Table 30.** Carbon Dioxide metrics for the first Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_IN	415.71	499.36	443.18	16.68
	K30_21	429.07	440.17	434	2.74
	K30_22	427.3	438.15	433.97	2.85



# Correlation for the Bench Relative Humidity 1

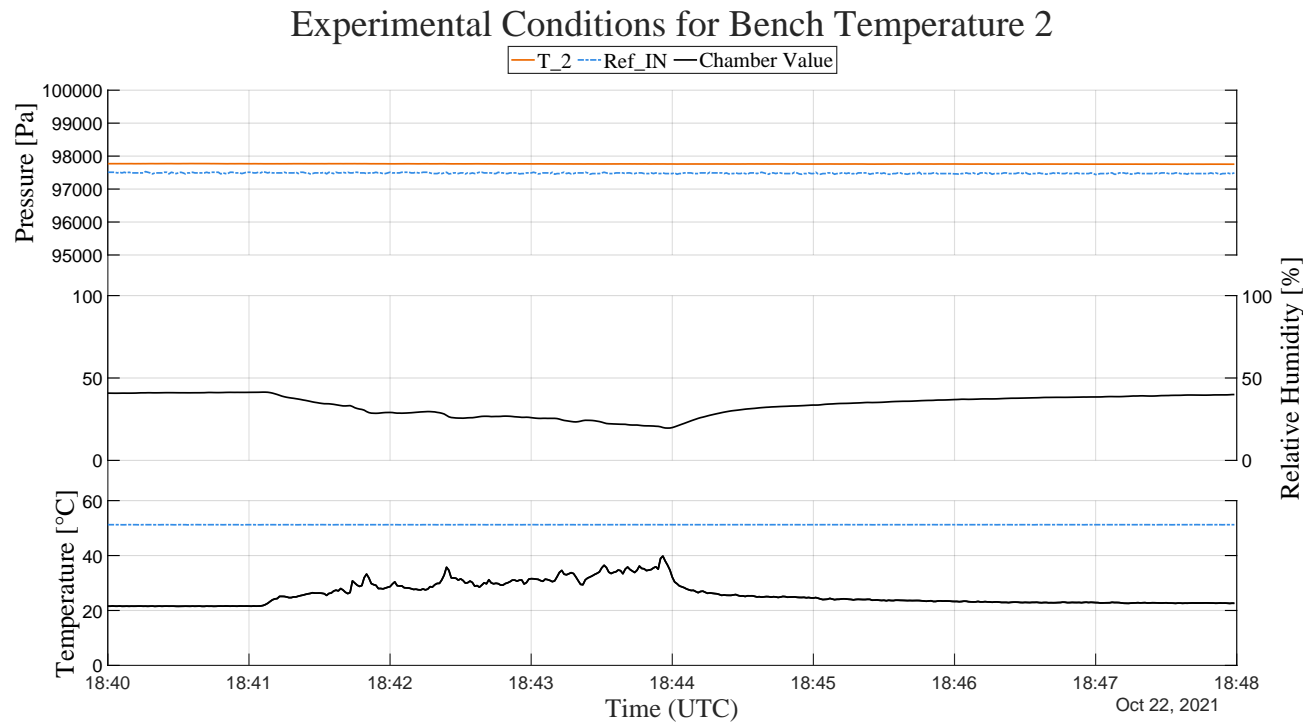


**Figure 33.** Scatter plots for the first Bench Relative Humidity run.

**Table 31.** Linear fit metrics for the first Bench Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	$R^2$	RMSE
K30_21	Pressure	-0.28	27598.92	0.34	2.23
	Temperature	-2.36	485.44	0.25	2.37
	Relative Humidity	-0.04	436.72	0.02	2.71
	Ref_IN	0.06	406.28	0.14	2.54
K30_22	Pressure	-0.29	28917.54	0.34	2.31
	Temperature	-2.99	499.14	0.37	2.26
	Relative Humidity	-0.02	435.4	0.01	2.84
	Ref_IN	0.04	418.13	0.04	2.79

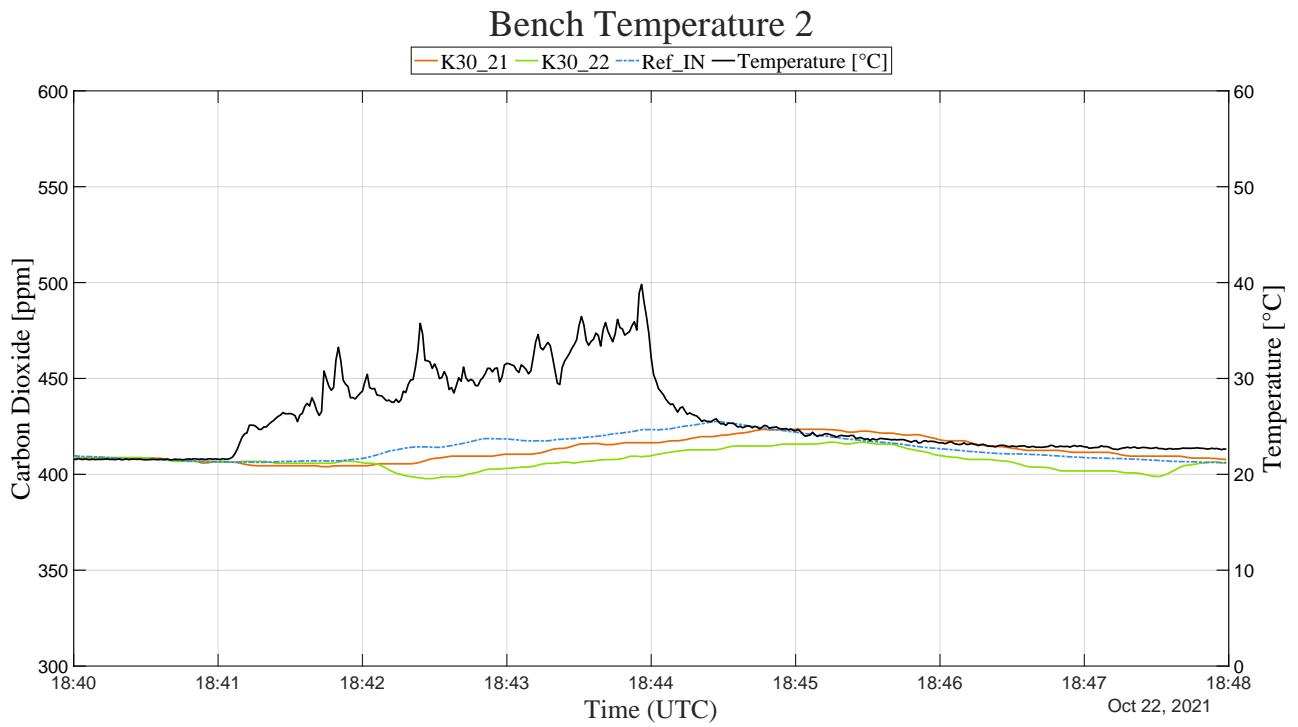
50   7.1   Temperature



**Figure 34.** Experimental conditions during the second Bench Temperature run.

**Table 32.** Metrics for the experimental conditions during the second Bench Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_IN	97440	97530	97482.13	16.39
	T_2	97754.06	97773.67	97762.57	5.1
Temperature [°C]	Ref_IN	51.17	51.25	51.23	0.01
	T_2	21.51	39.81	-	-
Relative Humidity [%]	T_2	19.61	41.42	33.56	6.33

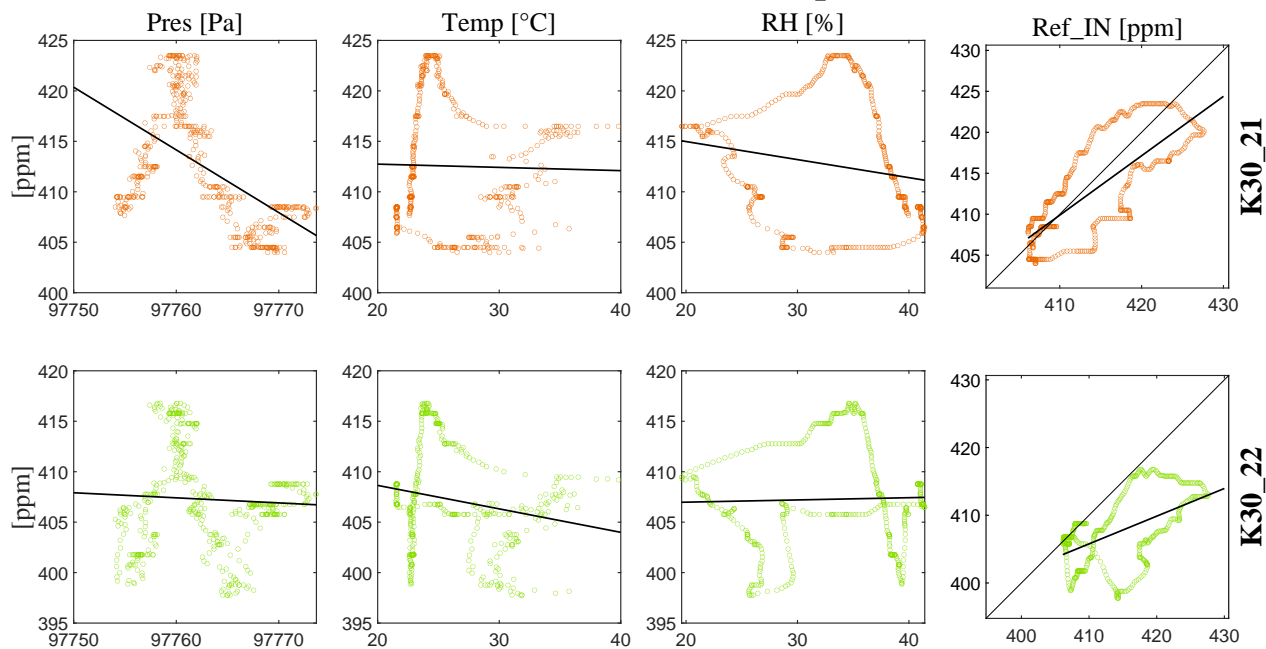


**Figure 35.** Results for the second Bench Temperature run.

**Table 33.** Carbon Dioxide metrics for the second Bench Temperature run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_IN	406.13	427.64	413.68	6.41
	K30_21	403.99	423.49	412.55	6.05
	K30_22	397.77	416.77	407.28	4.96

# Correlation for the Bench Temperature 2

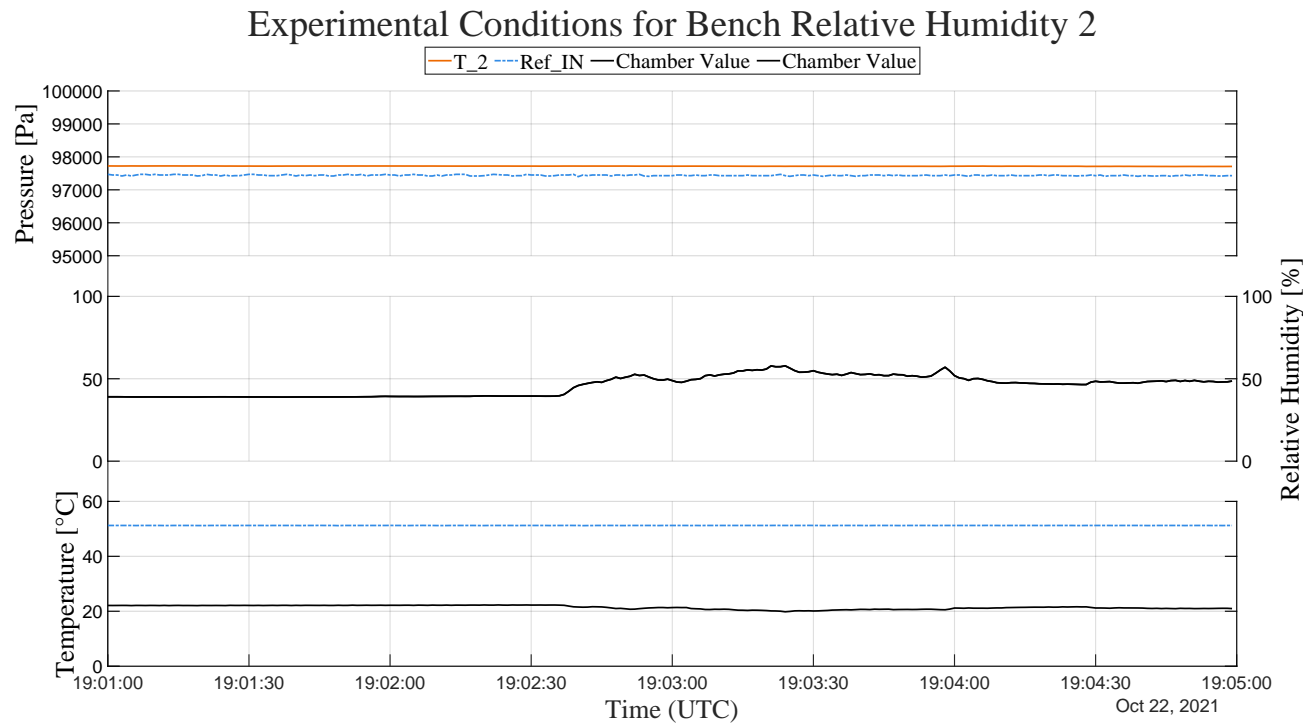


**Figure 36.** Scatter plots for the second Bench Temperature run.

**Table 34.** Linear fit metrics for the second Bench Temperature run.

Sensor	Predictor	Slope	Y-Intercept	$R^2$	RMSE
K30_21	Pressure	-0.62	61137.65	0.27	5.15
	Temperature	-0.03	413.39	0	6.04
	Relative Humidity	-0.18	418.56	0.04	5.94
	Ref_IN	0.73	112.51	0.59	3.87
K30_22	Pressure	-0.05	5327.96	0	4.95
	Temperature	-0.23	413.29	0.04	4.86
	Relative Humidity	0.02	406.54	0	4.96
	Ref_IN	0.41	238.09	0.28	4.21

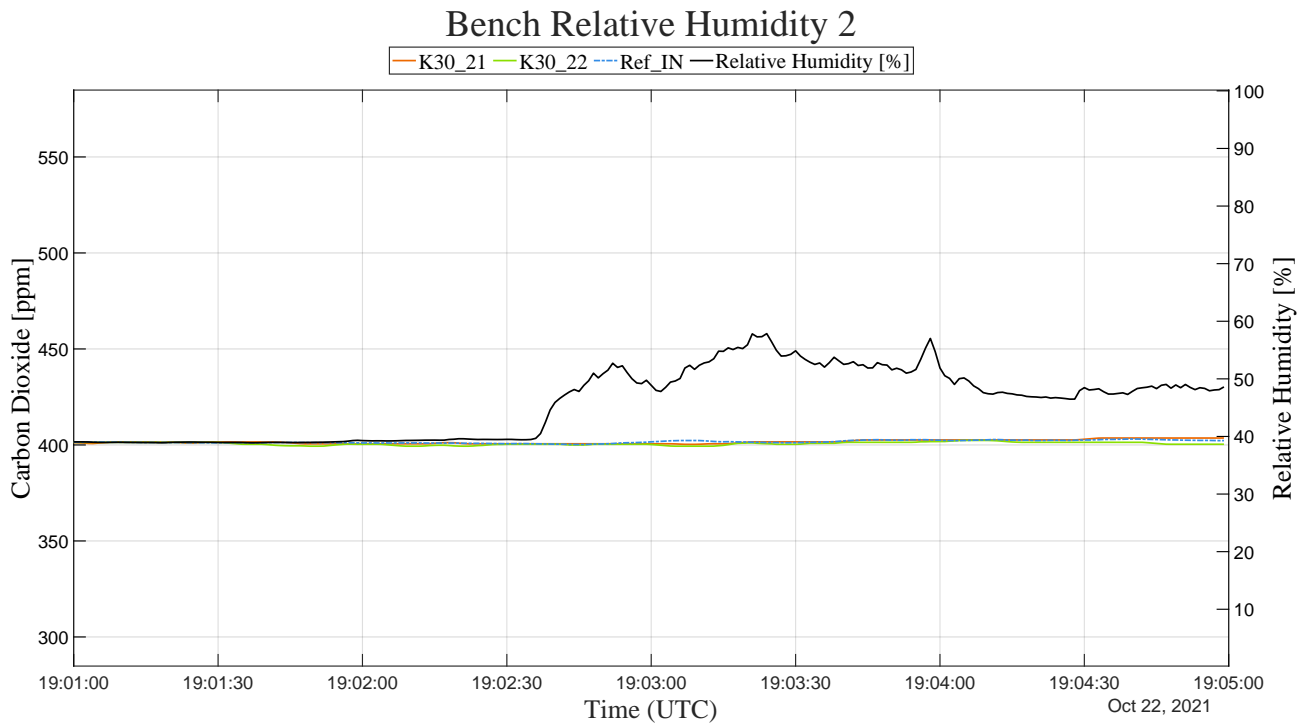
7.2 Relative Humidity



**Figure 37.** Experimental conditions during the second Bench Relative Humidity run.

**Table 35.** Metrics for the experimental conditions during the second Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_IN	97400	97470	97439.71	15.51
	T_2	97707.94	97724.89	97717.96	4.32
Temperature [°C]	Ref_IN	51.17	51.25	51.22	0.01
	T_2	19.8	22.3	21.44	0.69
Relative Humidity [%]	T_2	38.9	57.85	45.78	5.99

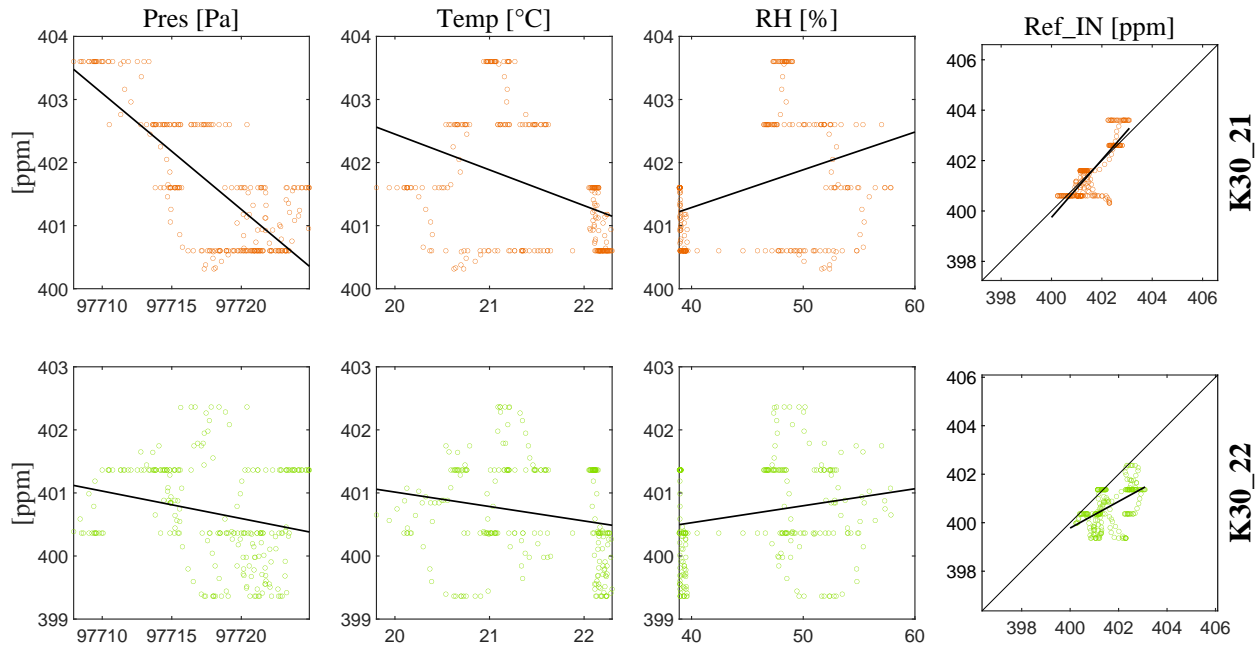


**Figure 38.** Results for the second Bench Relative Humidity run.

**Table 36.** Carbon Dioxide metrics for the second Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_IN	400.31	403.6	401.63	1.04
	K30_21	399.36	402.36	400.68	0.79
	K30_22	400.24	403.09	401.65	0.75

## Correlation for the Bench Relative Humidity 2



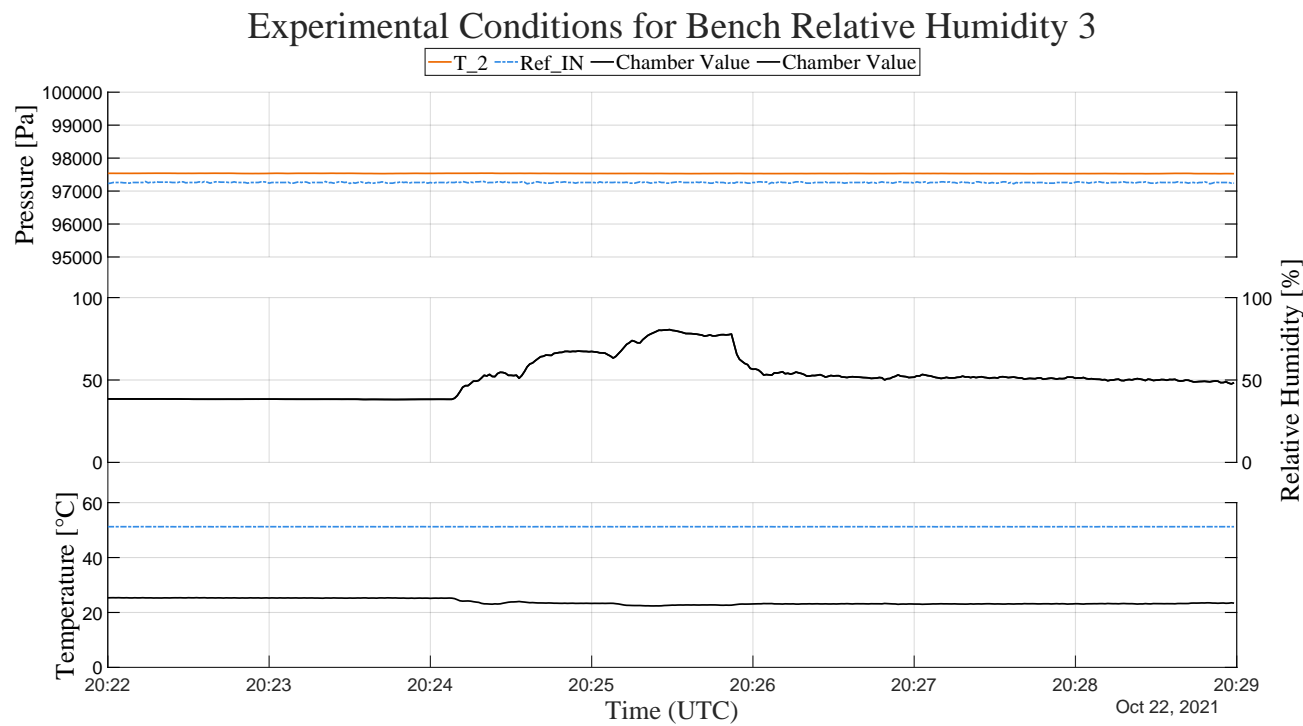
**Figure 39.** Scatter plots for the second Bench Relative Humidity run.

**Table 37.** Linear fit metrics for the second Bench Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_21	Pressure	-0.18	18403.68	0.59	0.67
	Temperature	-0.57	413.78	0.14	0.96
	Relative Humidity	0.06	398.89	0.12	0.97
	Ref_IN	1.14	-57.65	0.68	0.59
K30_22	Pressure	-0.04	4655.61	0.06	0.76
	Temperature	-0.23	405.59	0.04	0.77
	Relative Humidity	0.03	399.45	0.04	0.77
	Ref_IN	0.55	180.63	0.27	0.67

8    Benchtop Experiments 3

8.1    Relative Humidity

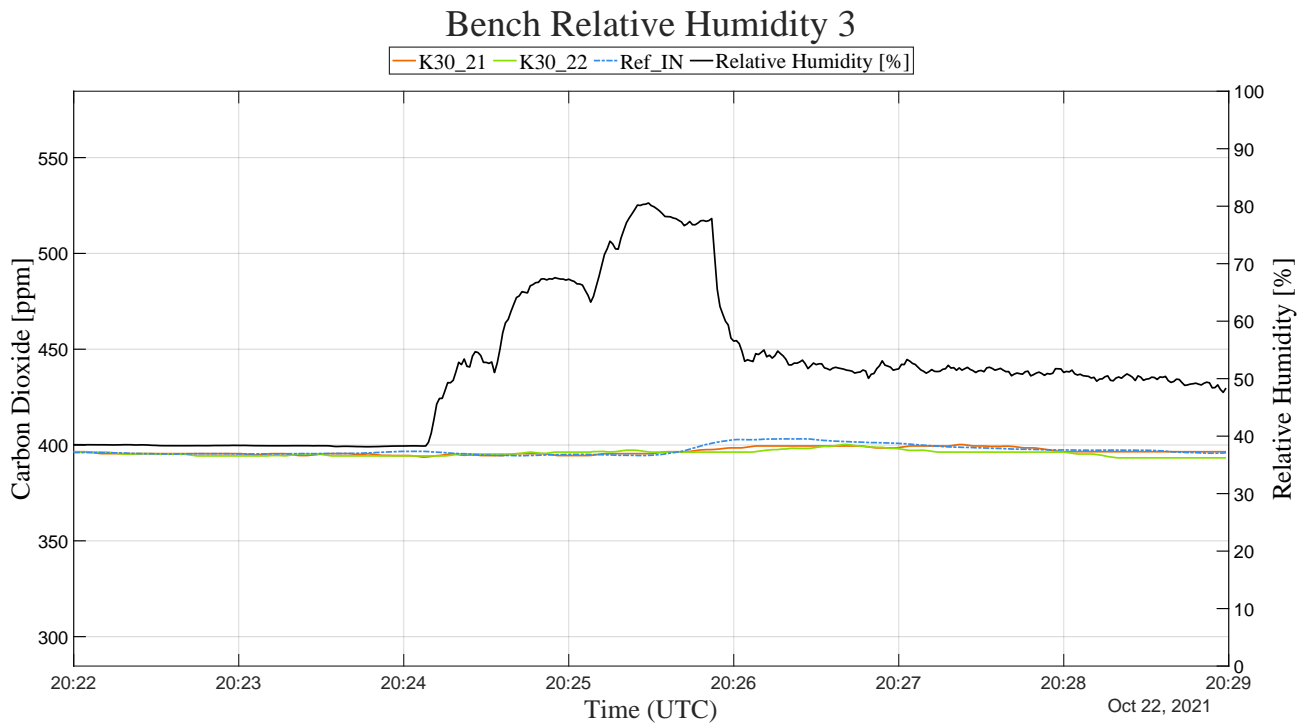


**Figure 40.** Experimental conditions during the third Bench Relative Humidity run.

**Table 38.** Metrics for the experimental conditions during the third Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
Pressure [Pa]	Ref_IN	97220	97290	97259.79	13.42
	T_2	97526.79	97542.3	97533.86	3.63
Temperature [°C]	Ref_IN	51.17	51.25	51.23	0.01
	T_2	22.38	25.39	23.82	1.02
Relative Humidity [%]	T_2	38.16	80.56	-	-



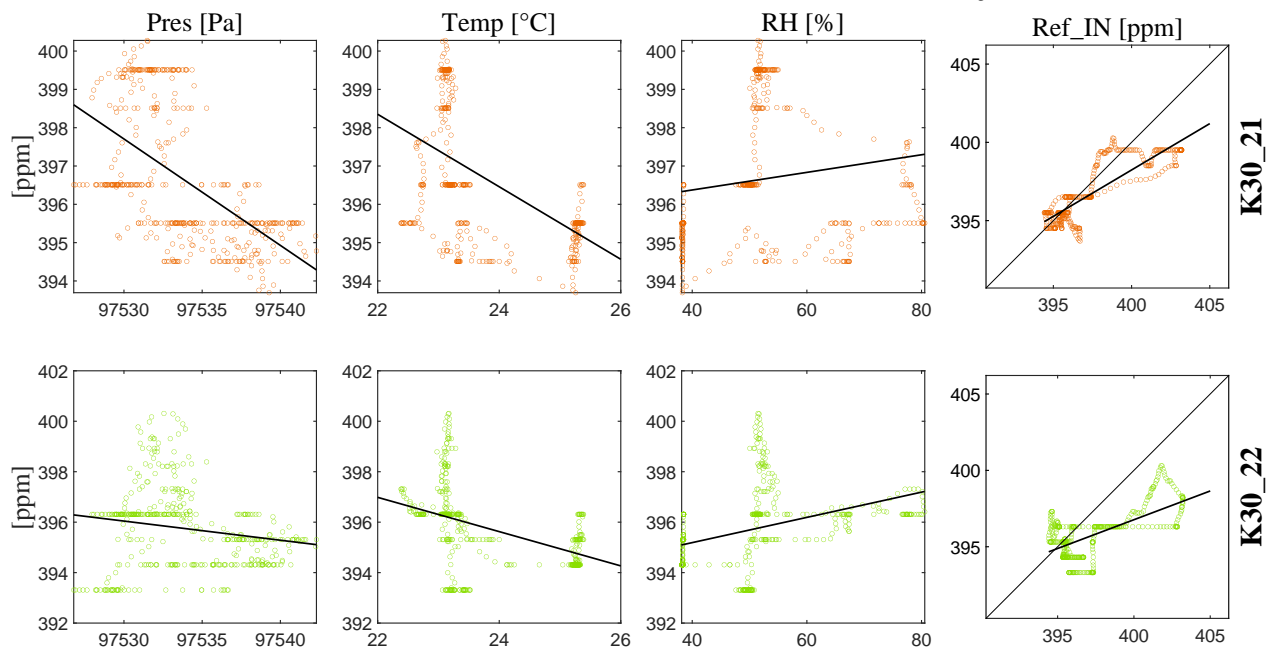


**Figure 41.** Results for the third Bench Relative Humidity run.

**Table 39.** Carbon Dioxide metrics for the third Bench Relative Humidity run.

Variable	Sensor	Minimum	Maximum	Average	Standard deviation
CO <sub>2</sub> [ppm]	Ref_IN	394.42	403.21	397.29	2.59
	K30_21	393.69	400.28	396.63	1.79
	K30_22	393.31	400.31	395.75	1.55

# Correlation for the Bench Relative Humidity 3

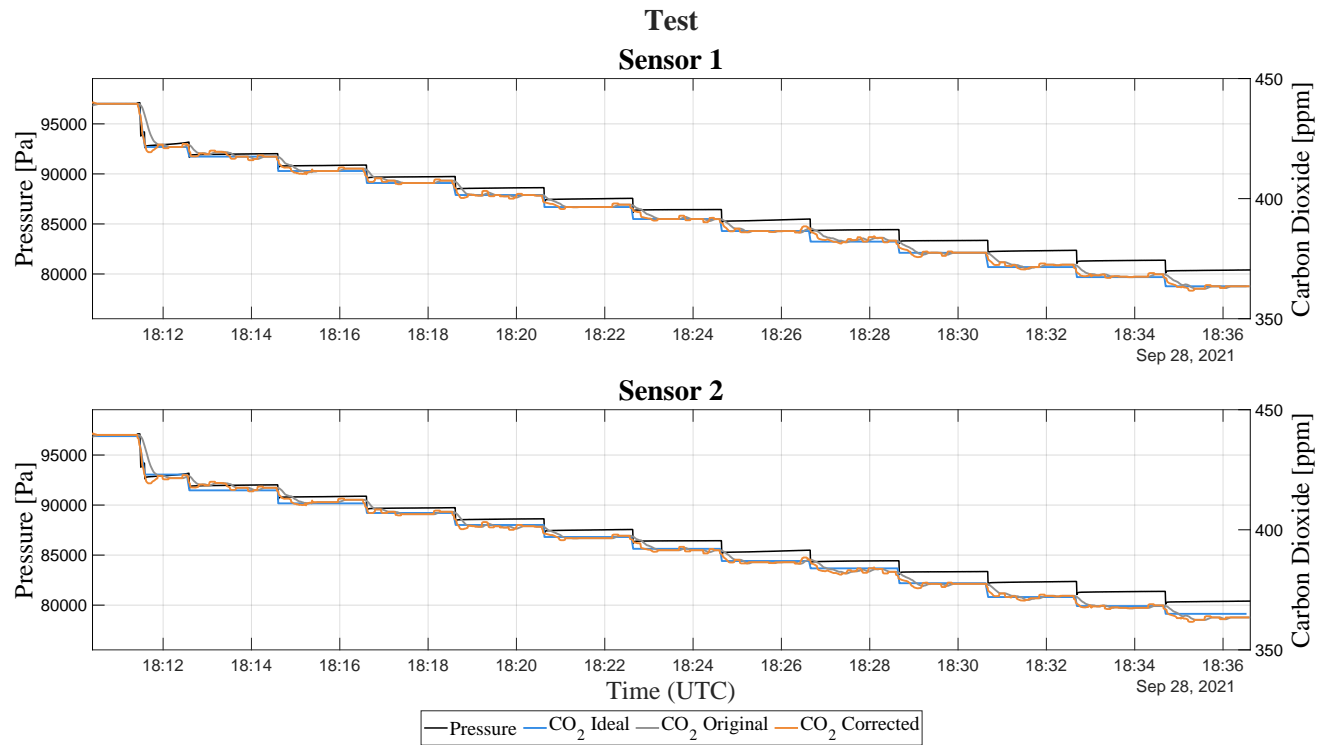


**Figure 42.** Scatter plots for the third Bench Relative Humidity run.

**Table 40.** Linear fit metrics for the third Bench Relative Humidity run.

Sensor	Predictor	Slope	Y-Intercept	R <sup>2</sup>	RMSE
K30_21	Pressure	-0.28	27483.54	0.32	1.48
	Temperature	-0.95	419.17	0.29	1.51
	Relative Humidity	0.02	395.46	0.02	1.77
	Ref_IN	0.59	161.25	0.73	0.92
K30_22	Pressure	-0.08	7801.26	0.03	1.52
	Temperature	-0.68	411.93	0.2	1.39
	Relative Humidity	0.05	393.19	0.15	1.43
	Ref_IN	0.38	246.1	0.4	1.2

9 Ideal Pressure Time Response

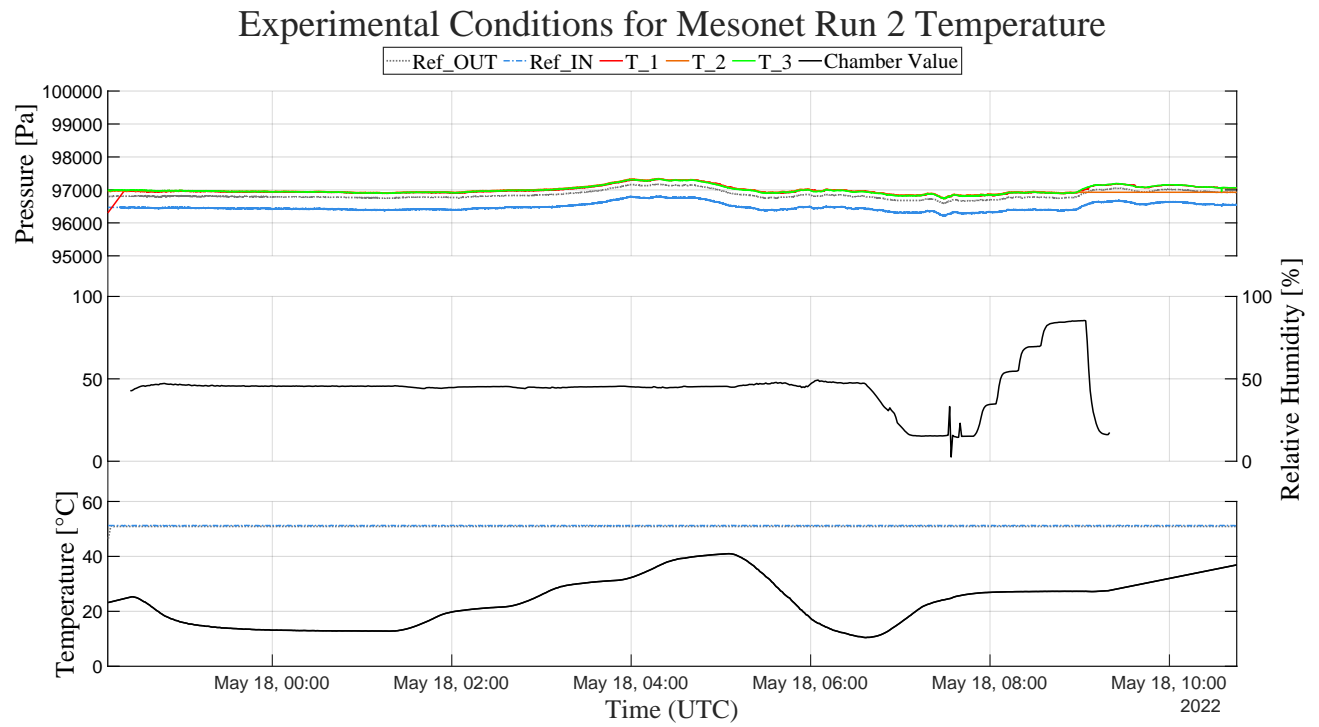


**Figure 43.** Example of idealized signal for pressure time-response correction. It is important to note that the referred idealized signal is an artificial signal with the pressure error but without the pressure time-response error. Therefore, ideal means the ideal impact of pressure (without pressure time-response error). It serves only as an evaluator of the pressure time-response algorithms. It should not be used for any pressure correction algorithms. The ideal signal was generated using the timestamps of the pressure step changes and the CO<sub>2</sub> values of the K30 after stabilization, after the step change.

55 10 Temperature Li-820 (Ref\_OUT)

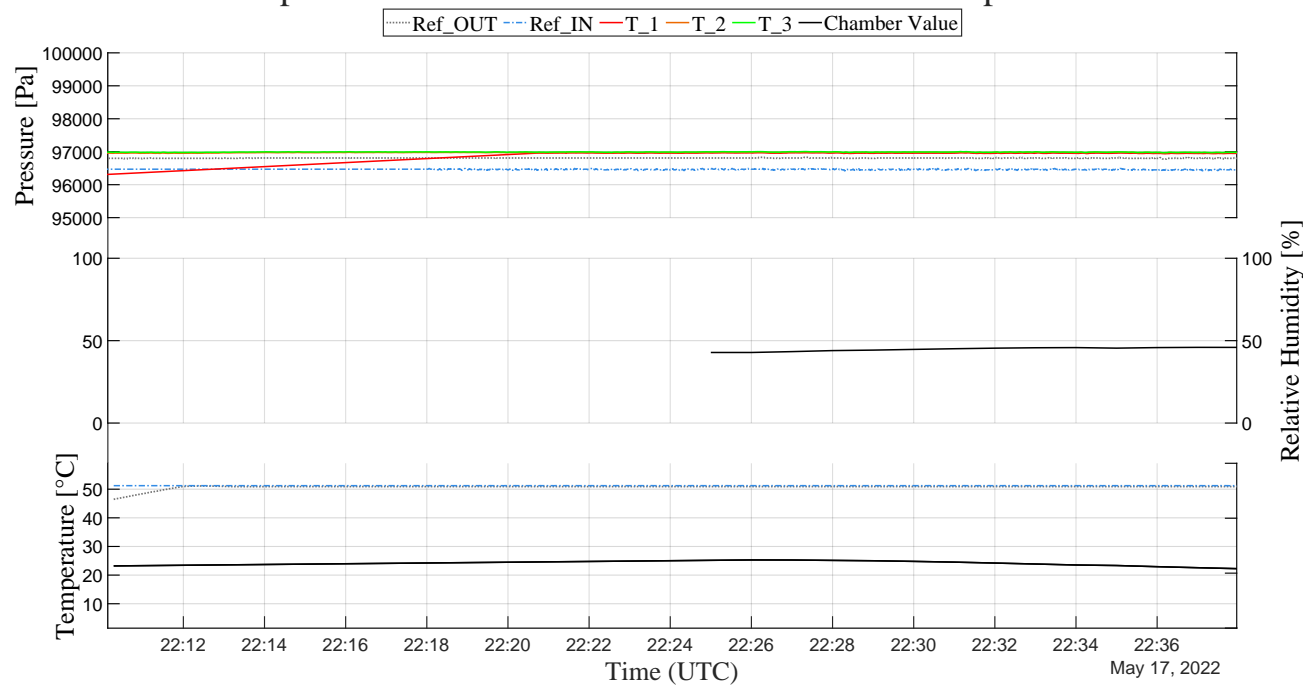
In all experimental condition tables in this document, the reported temperature for the optical chamber of the Li-820 (a.k.a. Ref\_OUT) is 50.91 degrees Celsius with its standard deviation equal to zero. This may appear to be a manuscript preparation error (e.g., a copy and paste error), but it is not. To investigate the matter we first evaluated if our dataset ever showed any temperature different than 50.91 for this sensor. At beginning of all experiments our loggers recorded the warm-up ramp of this sensor with temperatures below 50.91 (as can be seen in figures 44 and 45). However, after this warm-up period the sensor does not report a value different than 50.91. Analyzing the temperatures reported by the Li-840A (a.k.a. Ref\_IN), the largest deviation reported by this sensor for all experiments was 0.02 degrees Celsius. Therefore it is possible that the analog to digital converter (ADC) in the Li-820 is not capable of detecting these small fluctuations. Another contributing factor to the standard

deviation equal to zero, is our data trimming strategy. We only calculates the deviation for the test periods. At the beginning of each test period, the Li-820's heater has had at least one hour to stabilize temperature of the sensor's optical chamber. At this point we do not have any reason to believe any malfunction on the sensor.



**Figure 44.** Complete data series for the experimental conditions of the second run of the Mesonet Temperature and Relative humidity experiments showing temperatures lower than 50.91 for a minutes.

# Experimental Conditions for Mesonet Run 2 Temperature



**Figure 45.** Zoomed view of figure 44 showing a temperature variation of the Li-820 (a.k.a. Ref\_OUT) optical chamber.