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Accuracy and Air Temperature Dependency of Commercial Low-cost NDIR CO_2 Sensors: An Experimental Investigation

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SUMMARY
An experimental campaign investigated the dependency of air temperature on the CO_2 concentration accuracy for commercial low-cost NDIR CO_2 sensors from the manufacturers Netatmo and IC-Meter. The test was conducted under different temperatures and CO_2 concentrations based on steady state conditions. Highly accurate instruments were employed to obtain reference temperatures and CO_2 concentrations. The IC-Meter modules were vaguely influenced by temperature, resulting in no significant difference compared to the reference concentration values. However, the Netatmo station modules were found to be positively temperature dependent.

INTRODUCTION
Recently, low-cost, wireless sensors dedicated to monitoring of indoor air quality (i.e. CO_2 concentration) have become commercially available. Most systems use either ceramic thick film gas sensors or Non-Dispersive Infrared sensors (NDIR) to measure the CO_2 concentration (Miyachi et al. 2003). Even though the thick film type is more affordable than the NDIR gas sensor, the latter type has more technological advantages such as long term stability and high accuracy (Park et al. 2010). On the other hand, some concerns regarding the NDIR overall precision, and whether these instruments can keep accuracy over time are risen, especially as its detector is very sensitive to the variation of ambient temperature (Giberti et al. 2009). Hurst et al. (2011) and Yasuda et al. (2012) compared different NDIR CO_2 devices and concluded that a calibration is needed to provide reasonably accurate CO_2 concentration measurements. C. R. Martin et al. (2017) mentioned that if these types of sensors are individually calibrated, selected for stability and corrected for sensitivity to temperature, pressure and RH, the practical error of these sensors is <5 ppm, or approximately 1% of the observed value. Cory (2016) investigated the accuracy of different CO_2 sensors using WiFi communication to a cloud based user interface. Each of the sensors tested fell within the manufacturer's stated accuracy range of ±30 ppm ±3% of the reading when compared to a high-accuracy Los Gatos Research analyzer. Low-cost NDIR sensors are widely used in commercial products and these have been used, although with caution, for scientific research (MacNaughton et al. 2016). MacNaughton el al. (2016) investigated indoor environmental quality (IEQ) in green buildings through two phase studies. Initiated by monitoring participants for two weeks at their workplace prior to relocation to Syracuse Center of Excellence. The CO_2 sensors in the Netatmo's were tested with calibration gas after each phase of the study. An offset equal to the difference between 400 ppm and what the instrument read as 400 ppm using the calibration gas was calculated for all devices during each phase. The CO_2 data was adjusted first by this offset and second by a scaling factor to match the 1000 ppm reading to 1000 ppm. This process corrected both the intercept and slope of the collected data to match experimentally derived values.
In this paper, an experimental campaign was carried out to describe the behaviour of two wireless commercial systems from the manufacturers "Netatmo" and "IC-Meter" capable of measuring CO_2 concentration implementing NDIR technique under different ranges of indoor temperature and CO_2 concentrations. The aim was to investigate how air temperature variations affected the accuracy of the CO_2 sensors.

METHODS

EXPERIMENTAL SETUP
The performance of the two CO_2 sensors was investigated in a climate chamber with a volume of 30 m^3 at the Technical University of Denmark. The chamber was well insulated preventing outside factors to inflict the temperature inside the chamber. A Dostmann Electronic "P750" was used to measure the reference temperature (Dostmann Electronic). It is a highly accurate thermometer with a maximum uncertainty of ± 0.03°C which was calibrated yearly by an external instance. To control whether the CO_2 concentrations measured by the investigated instruments deviated from the actual CO_2 concentration, a precise reference instrument was employed. Such an instrument was a Photoacoustic Gas Monitor "INNOVA 1412i" developed by LumaSense Technologies Inc. and it has a detection limit of ± 1.5 ppm for CO_2 (Lumasense Technologies) which was also calibrated regularly by an external instance.
Concerning the sensors calibration, instructions described by each manufacturer through their websites were implemented (Netatmo Calibration; IC-Meter Calibration). The Netatmo modules were manually calibrated inside the climate chamber at 16°C with a fresh air exchange rate of more than 16 h^{-1} and no occupants inside the chamber ensuring an outdoor CO_2 concentration throughout the calibration period. The IC-Meter modules were manually calibrated in outdoor conditions where the sensors assumed an outdoor CO_2 concentration of 400 ppm.
Although, both modules did have an automatic calibration function, all modules were manually calibrated prior to the experiment and therefore the auto calibration was switched off.
The experiment was conducted for five steady state (SS) air temperatures controlled by chamber's ventilation system. The selected range of air temperature values was 16°C, 20°C, 23°C, 27°C and 30°C. For each air temperature five different SS CO_2 concentrations were reached (600ppm, 900ppm, 1300ppm, 1700ppm and 2100ppm). The CO_2

concentrations were achieved by dosing a constant amount from a CO_2 tank while supplying with a constant fresh air exchange rate to the chamber fulfilling SS CO_2 concentration with the mass balance equation. The SS CO_2 concentration were kept for an hour to collect several measurements from the instruments under investigation, instruments that measured once every five minutes. Figure 1 illustrates the experimental process step by step.

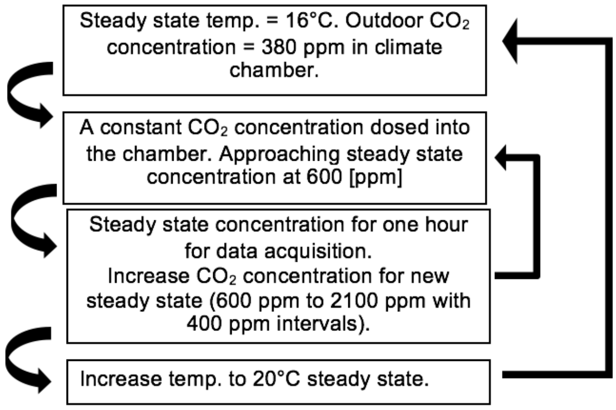

Figure 1. Step by step description of the experimental process.

The SS CO_2 concentrations and the SS temperatures reached throughout the experiment are listed in Table 1.

Table 1. Steady state temperatures and steady state CO_2 concentrations obtained throughout the experiment period.

Temperature	16°C	20°C	23°C	27°C	30°C
Steady state CO_2 concentration one	600 ppm	600 ppm	600 ppm	600 ppm	600 ppm
Steady state CO_2 concentration two	900 ppm	900 ppm	900 ppm	900 ppm	900 ppm
Steady state CO_2 concentration three	1300 ppm	1300 ppm	1300 ppm	1300 ppm	1300 ppm
Steady state CO_2 concentration four	1700 ppm	1700 ppm	1700 ppm	1700 ppm	1700 ppm
Steady state CO_2 concentration five	2100 ppm	2100 ppm	2100 ppm	2100 ppm	2100 ppm

INSTRUMENTS UNDER INVESTIGATION

Netatmo

The set-up of Netatmo products consisted of a main station, as shown in Figure 2, capable of measuring indoor climate parameters such as air temperature, relative humidity and CO_2 concentration. The measurements had time steps of five minutes and these were uploaded to the cloud instantly. The systems had been implemented in several studies before (Douzis et al. 2016; Log 2017; Meier et al. 2017; Pocero et al. 2017; MacNaughton et al. 2016). Another aspect of this study taken into consideration was to check whether the accuracy of the sensor was affected by time. Accordingly, new modules and modules that had been in use 24 months in other projects prior to the experiment were tested. The specified accuracy of the CO_2 sensor in the Netatmo modules is ± 50 ppm or ± 5% of the measured value within a concentration range of 0 ppm to 5000 ppm (Netatmo).

IC-Meter

Two generations of IC-meter modules was investigated, one was the IC-Meter Basic (version 3.0) and the second was IC-Meter Mobile (version 4.3). The difference lies in connection type, the Basic is Wi-Fi/Ethernet communication and the latter communicates through a GSM based module. The IC-Meter module measures temperature, CO_2 and RH, and cloud data storage system is implemented with a capability to analyse the heat, water and energy consumption in relation to climate and weather outside. The CO_2 sensor in the IC-Meter announces an accuracy of ± 30 ppm or ± 3% of the measured value in the concentration range 400 ppm to 2000 ppm (Senseair).

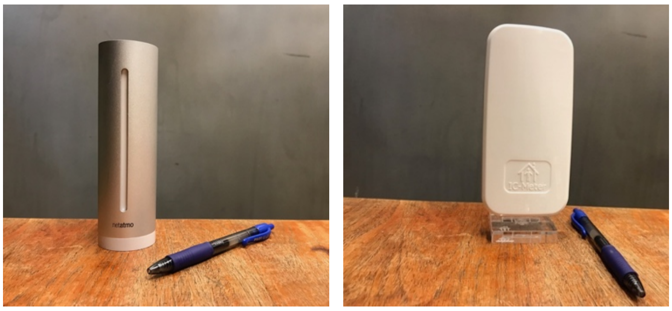

Figure 2. Left: Netatmo station module. Right: IC-Meter.

RESULTS

Figure 3 and Figure 4 show the CO_2 concentration profiles of 600 ppm for the two Netatmo modules. The actual CO_2 concentration was measured with the reference instrument to be 600 ppm ± 30 ppm for each of the analysed temperatures. The Netatmo modules measurements of CO_2 concentration was positively correlated with temperature. At 30°C, both the used and the new Netatmo modules measured 800 ppm higher CO_2 concentrations than the reference measurement throughout the steady state concentration.

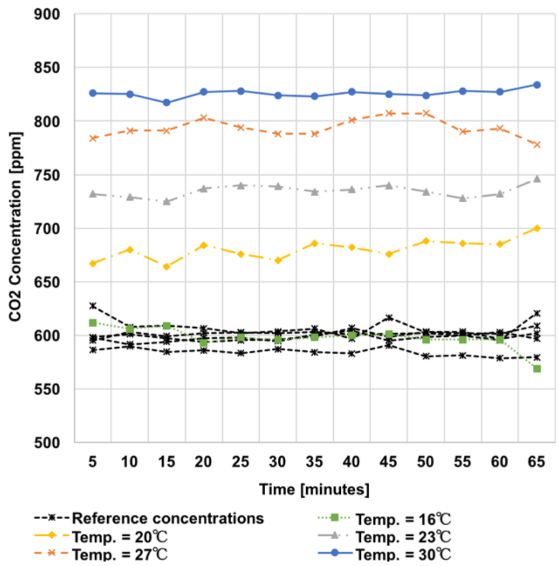

Figure 3. Measurements of CO_2 concentration at different temperatures by the used Netatmo station module. Reference concentrations were 600 ppm ± 30 ppm.

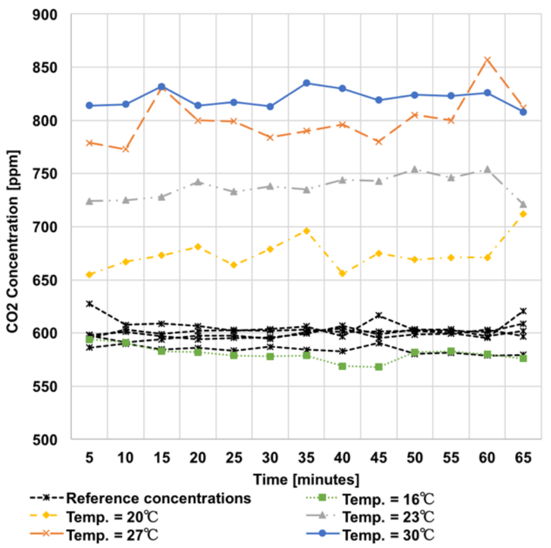

Figure 4. Measurements of CO_2 concentration at different temperatures by the new Netatmo station module. Reference concentrations were 600 ppm ± 30 ppm.

Likewise Figure 5 and Figure 6 show the CO_2 concentration profiles at 600 ppm for the two IC-Meter modules. The measured CO_2 concentrations of the IC-Meter modules were not dependent on the temperature. At 30°C, IC-Meter Basic module was less than 50 ppm from the reference value. At the same temperature, the IC-Meter Mobile module was less than 100 ppm from the reference CO_2 concentration.

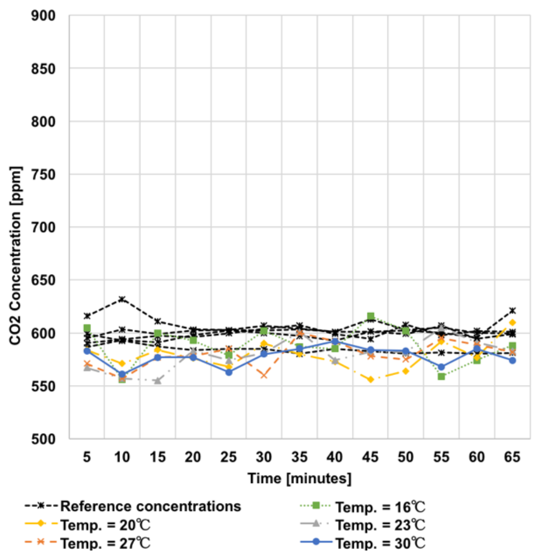

Figure 5. Measurements of CO_2 concentration at different temperatures by the IC-Meter Basic module. Reference concentrations were 600 ppm ± 30 ppm.

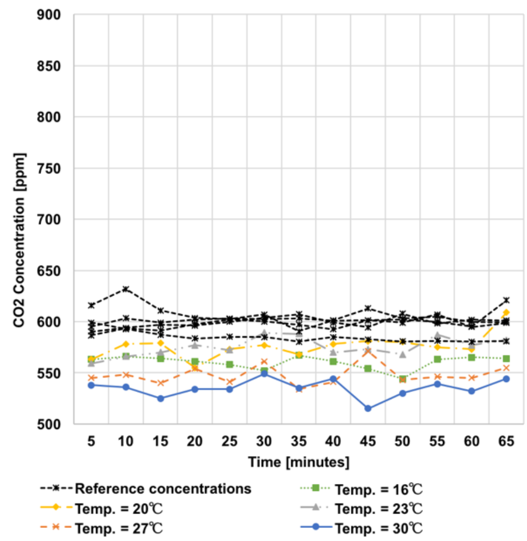

Figure 6. Measurements of CO_2 concentration at different temperatures by the IC-Meter Mobile module. Reference concentrations were 600 ppm ± 30 ppm.

The "Root Mean Squared error" (RMSE) (Equation 1) have been calculated for the four modules to determine the deviation between measured and reference data.

$$RMSE = \sqrt{n^{-1} \cdot \sum_{j=1}^{n} (s_j - e_j)^2} \qquad (1)$$

Where s_j and e_j are the reference measurements (INNOVA) and the instrument measurements (Netatmo/IC-Meter) respectively, and n is the number of measurements under the steady state concentration. In Table 2 the RMSE values are listed for the 600 ppm SS concentrations achieved for each temperature. The IC-Meter modules are within a RMSE of 50 ppm. Further it shows that there is no noticeable difference between the Basic version and Mobile version of the IC-Meter modules.
The Netatmo modules had an increasing RMSE towards higher temperatures as shown at Figure 4 and Figure 5 and it showed that both CO_2 sensors were temperature dependent. It is also highlighted in Table 2 that there was no difference between the used and the new Netatmo modules.

Table 2. RMSE for the SS concentration at 600 ppm for each of the investigated SS temperatures.

Temperature at 600 ppm	Netatmo Module new	Netatmo Module used	IC-Meter Basic	IC-Meter Mobile
16 °C	13.94 ppm	24.60 ppm	27.91 ppm	47.59 ppm
20 °C	78.45 ppm	68.90 ppm	26.00 ppm	27.39 ppm
23 °C	135.53 ppm	137.04 ppm	23.19 ppm	25.08 ppm
27 °C	195.86 ppm	205.15 ppm	20.81 ppm	49.89 ppm
30 °C	241.57 ppm	237.10 ppm	13.14 ppm	50.73 ppm

Figure 7 is a boxplot of the error in measured CO_2 concentration compared to the reference instrument during the five SS test temperatures and the five SS CO_2 concentrations for the used and the new Netatmo module,

the IC-meter Basic and the IC-meter Mobile module. The SS temperature and the SS CO_2 concentrations were treated as categorical variables in Figure 7. Hence, these values do not reflect the actual measured reference values, but should be understood as the conditions aimed for during the experiment, as small variations in temperature and CO_2 concentration would always be present. Each boxplot contains the median measured error, inter quartile range, upper and lower quartiles.
The results from the two Netatmo modules showed that the error in the CO_2 concentration increased with increasing temperature. This temperature dependency was observed for all steady state conditions.
The temperature dependency of the Netatmo modules resulted in high measurement uncertainties, above 750 ppm for the used Netatmo sensor and up to 600 ppm for the new Netatmo sensor, as shown at Figure 7.
The results for the IC-meters appeared to have no temperature dependency as the measurement uncertainty remained at the same level during all test temperatures. The uncertainty of the measurement did increase slightly with the CO_2-concentration.

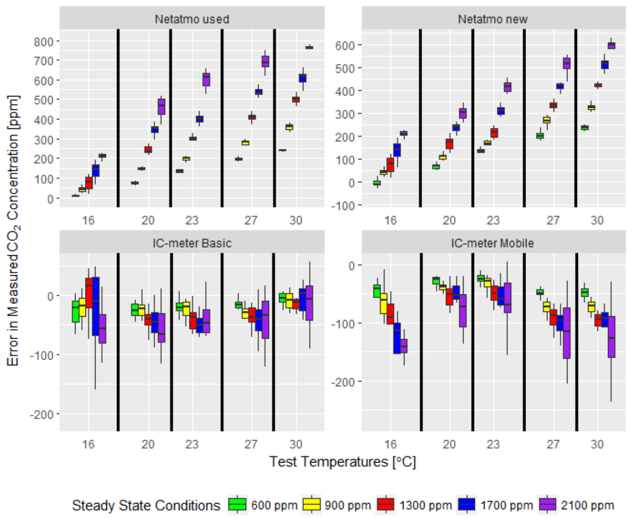

Figure 7. Boxplots showing the IC-Meter modules and Netatmo modules measurements for five SS CO_2 concentrations and five SS temperatures.

Linear regression analysis of the correlation between the errors in measured CO_2 concentration at 600 ppm as a function of room temperature revealed that both the used and new Netatmo modules were temperature dependent and that linear models would explain more than 96 % of the variance in the CO_2 concentration measurement error for both modules as shown in Table 3. The IC-meter modules were tested under the same conditions, but only the IC-Meter Basic module showed a slight temperature dependency. The variance in the CO_2 concentration measurement error explained by temperature was below 9% for both IC-meter modules.

Table 3 shows the probability of the data being randomly obtained, the adjusted R^2 and the linear model coefficients in the form of slope (a) and intercept (b). The slope determines the change in measurement error per degree temperature change, while the intercept determines the measurement error at 0 °C.

Table 3. Linear models showing how well the measurements are fitted for a steady state CO_2 concentration of 600 ppm.

Model	**p-value**	**Adjusted R^2**	**Linear Model coef.**
Netatmo module used 600 ppm	$p < 2.2 \cdot 10^{-16}$	0.9913	a = 16.41 b = -250.5
Netatmo module new 600 ppm	$p < 2.2 \cdot 10^{-16}$	0.9686	a = 17.18 b = -269.8
IC-meter Basic 600 ppm	p = 0.0115	0.08961	a = 0.985 b = -39.9
IC-meter Mobile 600 ppm	p = 0.1138	0.02518	a = -0.571 b = -25.4

Further statistical significance testing was performed for all modules during all steady state conditions. All tests revealed a temperature dependency of the Netatmo modules while it did not reveal a temperature dependency of the IC-meter modules.

DISCUSSION

Calibration of cloud-based sensors is essential to obtain credible results. The CO_2 sensors in the Netatmo modules were highly dependent on the air temperature. In the Netatmo modules it was found that accuracy of CO_2 concentration measurements was high if the value of air temperature under investigation was close to the air temperature in which the manual calibration occurred. The overall accuracy of the CO_2 sensors in the IC-Meter modules did not exceed ± 50 ppm and it was not related to temperature variations.
The temperature dependency of the Netatmo NDIR sensor could be a result of changing light output from the inferred source as a function of temperature.
To compensate, the change in inferred light output from the NDIR sensor should be known per degree of temperature change. Then by measuring the change in temperature from the calibration state to the measurement state a correcting factor due to temperature could be calculated and added to the measured value.
The IC-meter modules did not in general experience a temperature dependency.

CONCLUSIONS

In this study, it was concluded that one of the two investigated types of NDIR sensors had a clear positive temperature dependency while the other was only vaguely correlated to temperature. The accuracy of new and 2 year old sensors was comparable indicating that the accuracy of the sensors was not affected by time.
Generally, detailed information concerning type of sensors used in cloud based WIFI modules, accuracy, automatic calibration, etc. should be provided thoroughly on the websites to enforce successful interaction with end users and support credibility.

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