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Non-uniformity in outdoor CO_2 concentration in city of Copenhagen

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Abstract. The accurate data of outdoor CO_2 concentration are important for the proper design of ventilation and thus for indoor air quality and energy use in buildings. Typical design practice is to assume outdoor CO_2 concentration to be 400 ppm. However, the outdoor CO_2 concentration may be different in different areas of cities. This paper presents preliminary results of long-term (one year) outdoor CO_2 concentration changes in four districts of Copenhagen (Denmark). The districts included downtown area and suburbs with different surroundings. Four buildings were selected for the measurements, one building in each district. Outdoor CO_2 concentration measurements were performed at two levels – ground level and top of the buildings. Special attention was paid to use accurate measuring instruments. The instruments were carefully calibrated before the measurements. The calibration of the instruments was checked periodically. In this paper, preliminary results from summer and autumn measurements are presented. The outdoor CO_2 concentration varied over the day and from day to day in the range between 340 and 450 ppm. The CO_2 concentration at the ground of the buildings was usually 10 to 40 ppm higher than that at the top level in autumn. At the buildings in the suburbs, during the working hours, the outdoor CO_2 concentration measured on the top level close to the intake duct was on average 408 ppm. At the building in the downtown area, that was on average 414 ppm. However, the outdoor CO_2 concentration varied depending on the building, level and time. During the working hours, the 75 percentiles of outdoor CO_2 concentration varied between 384 ppm and 442 ppm, which indicates that the required ventilation rate could be different over 10% depending on the building location site, measurement height and time. In order to ensure the required indoor limits of CO_2 concentration, CO_2 measurements must be performed close to the location of the outdoor air intake.

1 Introduction

The ventilation of spaces is intended primarily to provide occupants with clean air for breathing. The generated pollution (including CO_2) is diluted by supplying clean ventilation air, which in most of the cases is outdoor air surrounding the ventilated building. At present, indoor CO_2 concentration is used as a simple parameter to limit the level of pollution in rooms in the Danish Building Regulations 2018 (BR18) [1].

For designing the ventilation system, the outdoor CO_2 concentration is important. At constant number of occupants in a room, the ventilation rate of outdoor air required to reduce the indoor CO_2 level below the recommended maximum of 1000 ppm will depend on the CO_2 concentration in the outdoor air (Equation 1).

$$q = G_{CO2} / (C_{h,i} – C_{h,o}) \times 10^6 \qquad (1)$$

Where, q is the required ventilation rate (m^3/h); G_{CO2} is the CO_2 generation rate in the room at room conditions (m^3/h); $C_{h,i}$ is the maximum allowed volume fraction of CO_2 in the indoor air (ppm); $C_{h,o}$ is the CO_2 volume fraction in the outdoor air (ppm).

BR18 suggests that the typical outdoor CO_2 concentrations are approximately 400-ppm in urban areas. However, George et al. [2], Idso et al. [3], Vogt et al. [4] and Kilkki et al. [5] have reported CO_2 levels higher than 500 ppm. Furthermore, the National Oceanic and Atmospheric Administration/ Earth System Research Laboratory (NOOA/ESRL) estimates that the recent average global CO_2 concentration is higher than 400 ppm [6]. Moreover, the outdoor CO_2 concentration is not constant; it is varying over the day and over the year [2-5]. In some cases, the variation reported over the same day was up to 60 ppm [4, 7]. This variation is not considered in the present ventilation design practice, i.e. it is assumed constant outdoor CO_2 concentration of 400 ppm.

At present, there is no data on the outdoor CO_2 concentration in Copenhagen and its districts, as well as how it changes during the year seasons. The outdoor CO_2 concentration may be different in different areas of cities. Only in the most advanced demand control

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ventilation systems the outdoor CO_2 concentration is measured and used as one of the control parameters. This study aims to obtain reliable and accurate information on outdoor CO_2 concentration in Greater Copenhagen by conducting field measurements. This paper presents preliminary results of long-term (one year) outdoor CO_2 concentration changes in four districts of Copenhagen (Denmark).

2 Methods

2.1. Measuring sites

Four districts of Greater Copenhagen in Denmark, which included downtown area and suburbs with different surroundings, were selected to find the non-uniformity in outdoor CO_2 concentration. Four buildings were selected for the measurements, i.e. one building in each district. The location of the buildings is shown in Figure 1 and specified in Table 1.

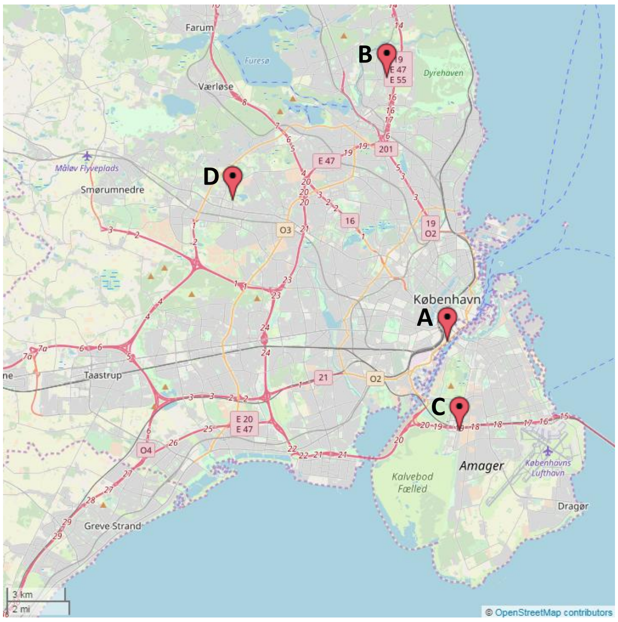

Fig. 1. Location of the buildings in Greater Copenhagen.

Table 1. Buildings for the measurements.

Building	Area	Lat/long	Elevation at the top	Measurement periods
Bldg. A	Downtown	55.67 N 12.57 W	20 m	19/7/2018~ 1/10/2018, 16/10/2018~ 7/11/2018
Bldg. B	Suburb	55.79 N 12.52 W	20 m	
Bldg. C	Suburb*	55.63 N 12.58 W	30 m	5/10/2018~ 16/10/2018
Bldg. D	Suburb	55.73 N 12.40 W	10 m	

*The building is located in an urban area with high traffic.

2.2 Instruments

Four instruments from two manufactures were used; two identical instruments from each manufacturer. In Table 2 the instruments are identified as “Inst. T” and “Inst. G”. The instruments used a nondispersive infrared method for the CO_2 measurements. The accuracy shown in Table 2 was calculated by considering the accuracy of the reference gas mixture as well as the effects of temperature, humidity, pressure and noises of output and logging on the long-stability of the measurements. The accuracy was calculated by assuming a reading value of 500 ppm CO_2 concentration. Both instruments compensate the measured data for temperature changes, and this compensation is based on built-in temperature sensors. During the measurements the relative humidity and the pressure changed in the ranges, respectively 24.4 – 94.4% and 984.6 – 1029 hPa according to the climate data covered in Section 2.4. The effect of humidity on accuracy of the Inst. T with humidity compensation is small, ± 0.006% of reading / g/m^3 H_2O, for CO_2 below 1000 ppm. The humidity does not influence the accuracy due to the operational principle of Inst. G. The effect of pressure on accuracy of Inst. T with pressure compensation is 0.5 % of reading, for CO2 below 1000 ppm and pressure within 900 hPa to 1050 hPa. The effect of pressure on accuracy of Inst. G can be considered by adding 0.1 % of reading. Inst. G compensates the measured outputs for absolute pressure changes.

Table 2. Instruments for measuring outdoor CO_2 concentration.

Instru-ment	Meter	Logger	Resolu-tion	Accuracy around 500 ppm
Inst. T	GMP343 (Vaisala)	UX120-006M (Onset)	0.1 ppm	± 33 ppm
Inst. G	FCM41 (Sensotron)		1 ppm	± 35.5 ppm

Special attention was paid to use accurate measuring instruments. The instruments were carefully calibrated in the laboratory at Technical University of Denmark at three reference CO_2 concentrations levels of 0 ppm, 500 ppm and 1001 ppm using Nitrogen mixed with CO_2. Calibration equations were developed. The accuracy level of the gas mixture used was ± 0.5 %. During the calibration, Teflon tubes with the same length as during in the actual field measurements were used for air sampling. The calibration was conducted just before each measurement period.

2.3 Measurements

Outdoor CO_2 concentration measurements were performed at two levels – ground level and top of the buildings. Since, the target was to investigate the concentration of CO_2 in the outdoor air used for ventilation, the air sampling tube of one of the two instruments was placed very close to the intake duct of the ventilation system. The instruments T sampled air at the top level of the buildings, and the instruments G at the ground level. The sampling time was 1 minute.

2.4 Climate data

Data measured by a climate station located near the Building B (Table 1) was used as the representative data of the climate in Greater Copenhagen. The climate data were used to find the relation between the measured outdoor CO_2 concentration and outdoor temperature, wind direction and strength, etc. The climate station is located at the Department of Civil Engineering, Technical University of Denmark, at the roof of building 119 (55.79 N 12.53 W, elevation 8 m). The data can be downloaded from a website [8]. One-minute time step data was used in this study.

Specific humidity was calculated by Equations 2, 3 and 4 using the raw data of air pressure, relative humidity and air temperature. Equation 4 is known as the Tetens equation.

$$\varphi_s = \varepsilon f / [P - f (1 - \varepsilon)] \times 10^3 \quad (2)$$

$$f = f_s \varphi_r \times 100 \quad (3)$$

$$f_s = 6.1078 \exp [17.27 T / (T + 237.3)] \quad (4)$$

Where, φ_s is the specific humidity (g/kg); ε is the molecular weight ratio of vapour to dry air (0.622); P is the air pressure (hPa); f is the vapour pressure (hPa); f_s is the saturated vapour pressure (hPa); φ_r is the relative humidity (%); T is the air temperature (°C).

2.5 Data processing

The calibration equations were used to obtain accurate outdoor CO_2 concentration based on the measurements. For the purpose of reducing random noise, the collected outdoor CO_2 concentration data (sampled each minute) and the data for the different meteorological parameters were used to calculate one hour averages. The average of wind speed was calculated by using scalar average method.

3 Results and discussion

3.1 Outdoor CO_2 concentration

Figure 2 shows one hour average of outdoor CO_2 concentration measured at Building A and B from 0:00 to 24:00 for one week (October 24 – October 31). Figure 3 shows the average CO_2 levels measured at Building C and D from 0:00 to 24:00 for one week (October 8 – October 15).

The outdoor CO_2 concentration measured at the top and ground level of each building, made a similar change with time, although no typical diurnal change can be seen. During these periods, the outdoor CO_2 concentration at the top tended to be around 10 to 40 ppm lower than that at the ground. The outdoor CO_2 concentration at the top varied in the range between 390 and 440 ppm and at the ground level it varied in the range between 400 and 450 ppm.

Figure 4 shows one hour average of outdoor CO_2 concentration measured at the four buildings from 6:00 to 7:00 every day. Similarly, Figures 5, 6, 7 and 8 show the one hour average CO_2 concentrations for the periods

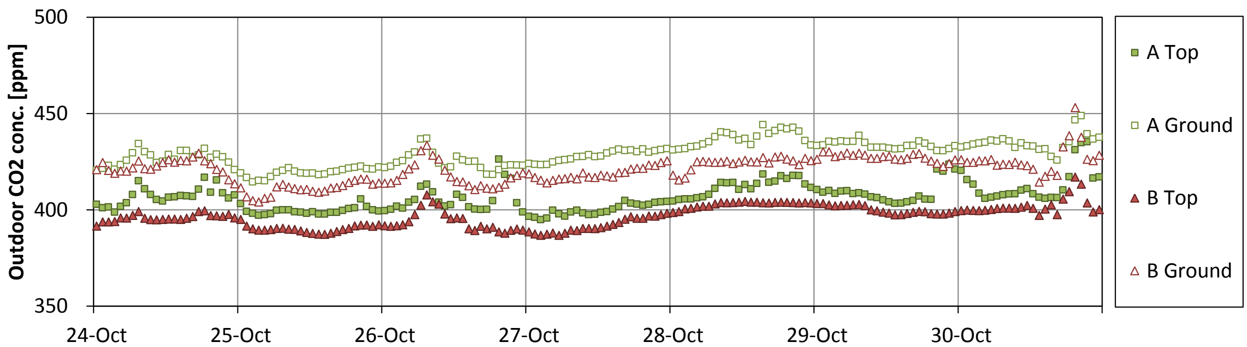

Fig. 2. One hour average of outdoor CO_2 concentration measured at Building A and B.

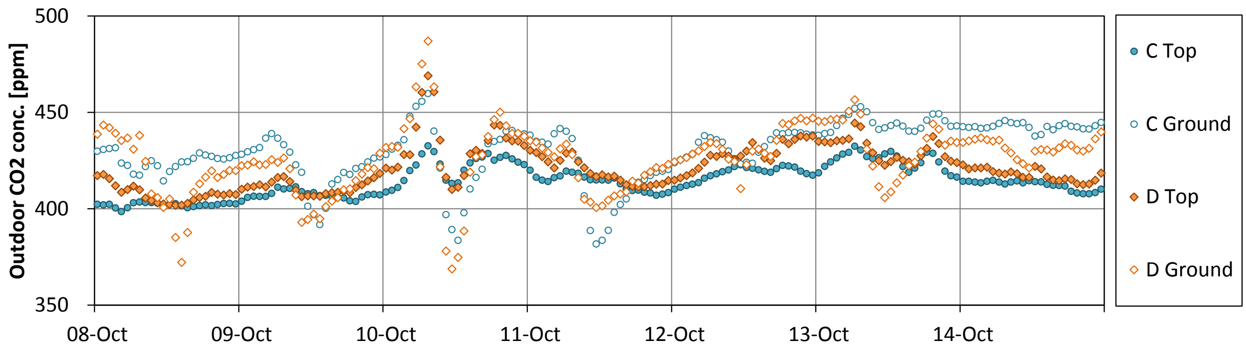

Fig. 3. One hour average of outdoor CO_2 concentration measured at Building C and D.

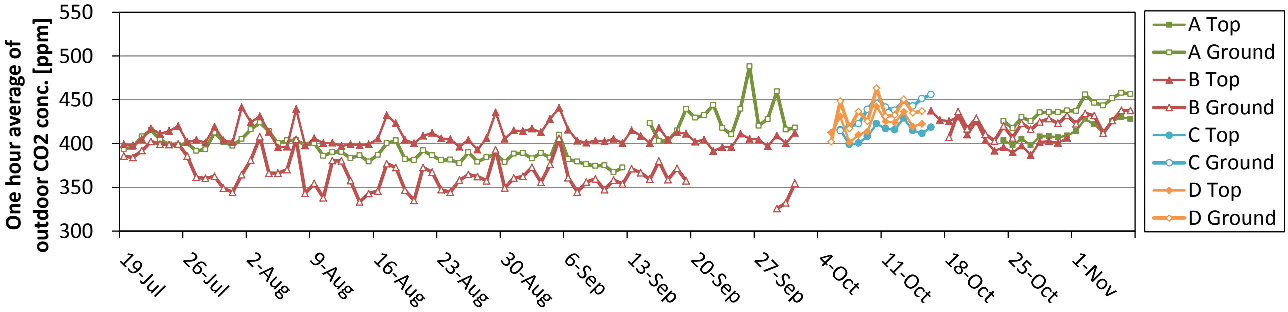

Fig. 4. One hour average of outdoor CO_2 concentration from 6:00 till 7:00 am every day.

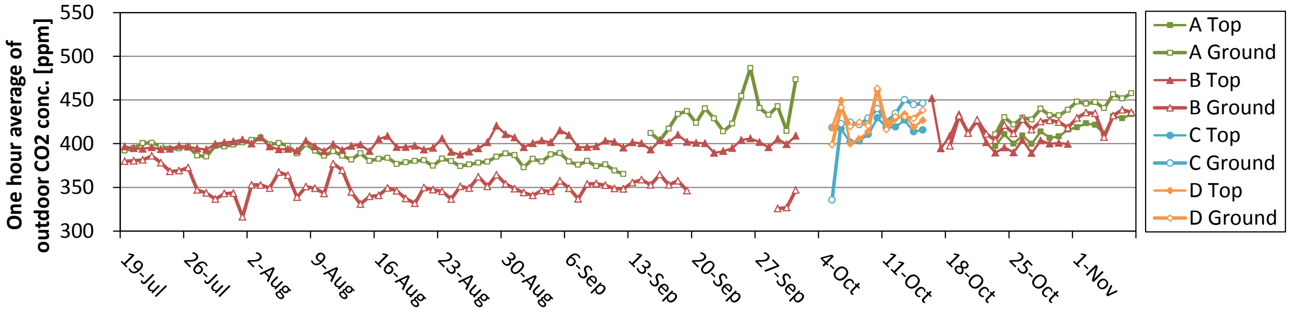

Fig. 5. One hour average of outdoor CO_2 concentration from 9:00 till 10:00 am every day.

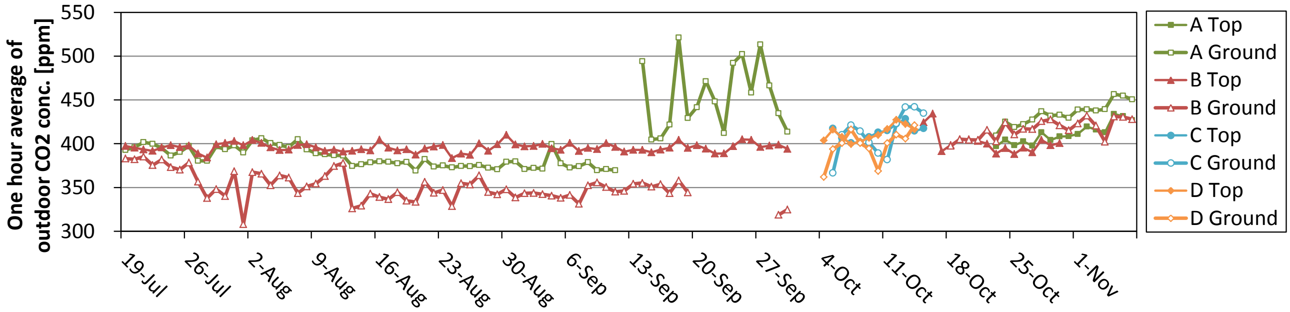

Fig. 6. One hour average of outdoor CO_2 concentration from 12:00 till 13:00 pm every day.

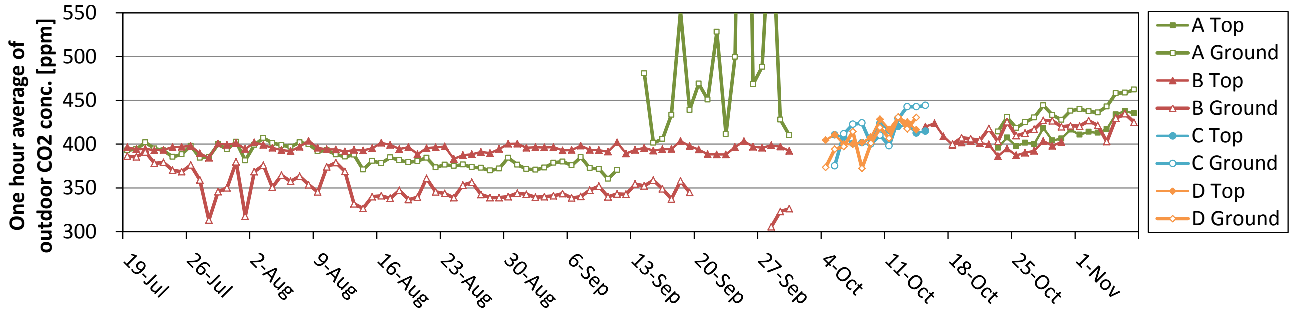

Fig. 7. One hour average of outdoor CO_2 concentration from 15:00 till 16:00 pm every day.

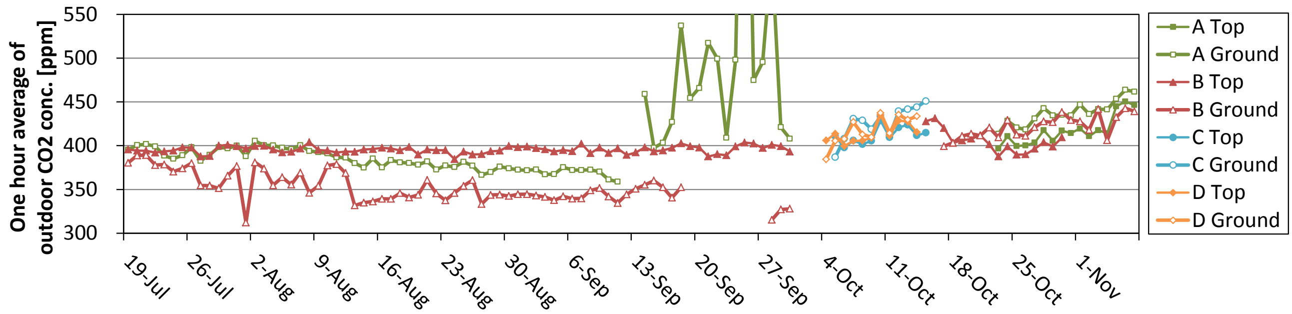

Fig. 8. One hour average of outdoor CO_2 concentration from 18:00 till 19:00 pm every day.

Table 2. Statistics of one hour average of outdoor CO_2 concentration (ppm) measured at the top of the buildings.

Bldg./Level	A Top					B Top					C Top					D Top				
Hour	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00
Average	413	414	412	413	417	408	400	397	396	397	414	416	413	412	412	422	425	412	413	414
Maximum	430	434	434	438	450	441	452	434	424	431	429	430	428	424	429	442	461	427	431	435
75 percentile	424	422	417	418	418	414	404	399	399	399	418	419	417	418	418	428	431	416	421	421
Median	409	413	410	412	414	405	399	396	396	396	416	417	414	413	411	422	424	410	411	412
25 percentile	406	408	404	403	405	400	395	393	393	393	410	412	407	407	406	413	416	405	403	406
Minimum	398	397	397	396	397	387	387	384	383	385	399	402	401	401	398	401	400	400	400	400

Table 3. Statistics of one hour average of outdoor CO_2 concentration (ppm) measured at the ground of the buildings.

Bldg./Level	A Ground					B Ground					C Ground					D Ground				
Hour	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00	6:00	9:00	12:00	15:00	18:00
Average	407	405	407	418	416	379	369	367	366	370	439	425	411	418	427	434	428	398	405	418
Maximum	488	487	521	1121	992	438	439	432	435	443	456	450	442	444	451	463	463	421	431	437
75 percentile	424	429	429	431	432	405	384	385	389	394	450	442	429	436	440	443	435	408	418	432
Median	402	397	396	396	397	371	353	355	354	355	441	429	414	423	431	435	429	401	407	414
25 percentile	387	383	379	381	378	357	346	343	341	343	430	424	395	405	415	428	420	394	396	409
Minimum	367	365	369	360	359	325	316	308	305	312	415	335	366	375	387	402	399	362	372	384

Table 4. Required ventilation rate per person to keep indoor CO_2 level of 1000 ppm

Outdoor CO_2 concentration [ppm]	Indoor CO_2 concentration [ppm]	Indoor CO_2 generation rate [m^3/h/person]	Required ventilation rate [m^3/h/person]
350	1000	0.019	29.2
400	1000	0.019	31.7
450	1000	0.019	34.5
500	1000	0.019	38.0
550	1000	0.019	42.2

from 9:00 – 10:00, 12:00 – 13:00, 15:00 – 16:00 and 18:00 – 19:00 respectively. Note that Central European Summer Time (CEST) was used for the clock time until 3:00 on October 28. Afterwards, the clocks in Denmark were turned 1 hour backward following the Central European Time (CET). As a result, the data-loggers of the instruments were also set to the CET. The data measured at the top of Building A from July till September was missed. Several periods of the data measured at the ground of Building A and B in September and at the top of Building B in November were also missed.

The results in Figures 4, 5, 6, 7 and 8 indicate that the outdoor CO_2 concentration was different during each day even during the same time period of the days at the same measured location. During the period from July till September, the outdoor CO_2 concentration at the top of Building B tended to be around 50 ppm higher than that at the ground. On the other hand, in October and November, the outdoor CO_2 concentration at the top tended to be around 10 to 40 ppm lower than that at the ground. In the latter half of September, the outdoor CO_2 concentration at the ground of Building A was relatively high compared to concentration measured at Building B, at both levels. The concentration measurements at the ground of Building A might have been affected by human activities near the building. The average of the outdoor CO_2 concentration in October and November seems to be higher than that in the period from July till September.

Table 2 shows the statistics of one hour average of outdoor CO_2 concentration measured at the top of the buildings. Similarly, Table 3 shows the statistics of the average CO_2 levels measured at the ground of the buildings.

Differences in the CO_2 levels were observed between the top and ground levels of each building. Thus, in order to perform proper calculation of the amount of supplied outdoor ventilation air that will ensure the required indoor limits of CO_2 concentration, CO_2 measurements must be performed close to the outdoor air intake.

The average CO_2 concentration at noon tended to be lower than that in the morning and evening. This might be caused by photosynthesis of plants. The possibility will be analysed in our future study with the data in winter.

The maximum CO_2 concentration at the top tended to be lower than that at the ground. The difference between 75 percentile and 25 percentile at the top varied at the range only between 6 ppm to 18 ppm which was within the accuracy of the instruments. On the other hand, the corresponding difference at the ground varied between 14 ppm to 54 ppm. These results indicate that the outdoor CO_2 concentration at the ground might have larger change and could be higher than that at the top. We can conclude that it is better to place the intake of supply air duct for the ventilation as close as possible to the building top.

Table 5. Correlation coefficient between different climate parameters and outdoor CO_2 concentration.

Level		Top				Ground			
Climate parameters	Building	**A**	B	**C**	**D**	A	**B**	C	D
Global irradiance, shortwave [W/m²]		-0.11	-0.33	0.12	-0.10	-0.10	-0.29	-0.22	-0.38
Diffuse horizontal irradiance, shortwave [W/m²]		-0.19	-0.36	-0.03	-0.26	-0.13	-0.35	-0.31	-0.52
Direct normal irradiance, shortwave [W/m²]		0.01	-0.22	0.23	0.08	-0.02	-0.17	-0.06	-0.11
Downwelling horizontal irradiance, longwave [W/m²]		0.05	-0.22	0.42	0.10	-0.31	-0.56	-0.16	-0.33
Wind speed [m/s]		**-0.69**	-0.39	-0.61	**-0.63**	0.17	-0.04	-0.43	-0.53
Air temperature [°C]		0.10	-0.15	0.51	0.19	-0.34	-0.59	-0.09	-0.22
Specific humidity [g/kg]		0.37	0.11	**0.59**	0.34	-0.41	**-0.59**	-0.16	-0.12
Air pressure [hPa]		0.31	0.39	0.48	0.39	0.11	-0.05	0.13	0.08
Precipitation [mm/h]		N.A.	-0.05	N.A.	N.A.	-0.07	-0.12	N.A.	N.A.

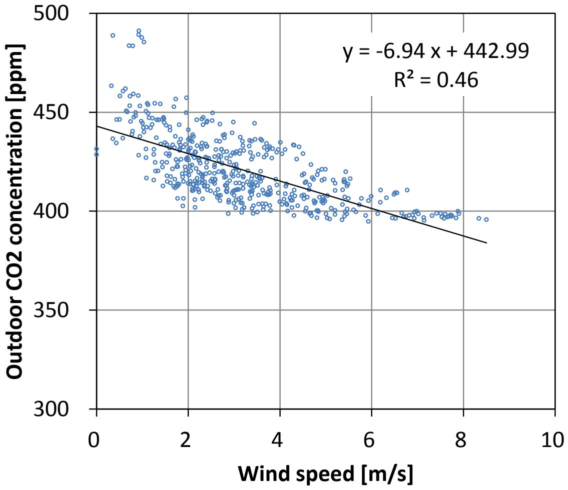

Fig. 9. Wind speed vs outdoor CO_2 concentration at the top of Building A.

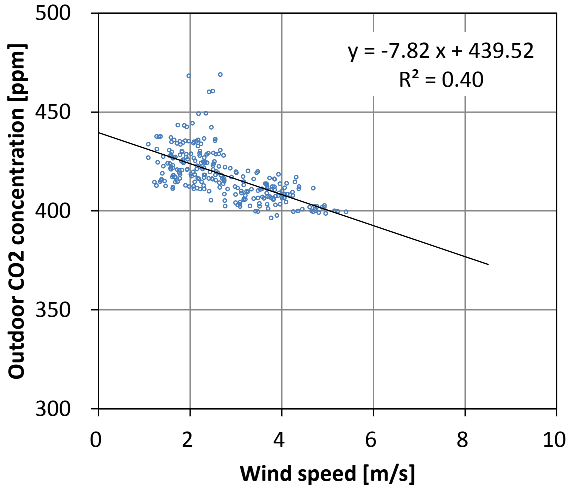

Fig. 10. Wind speed vs outdoor CO_2 concentration at the top of Building D.

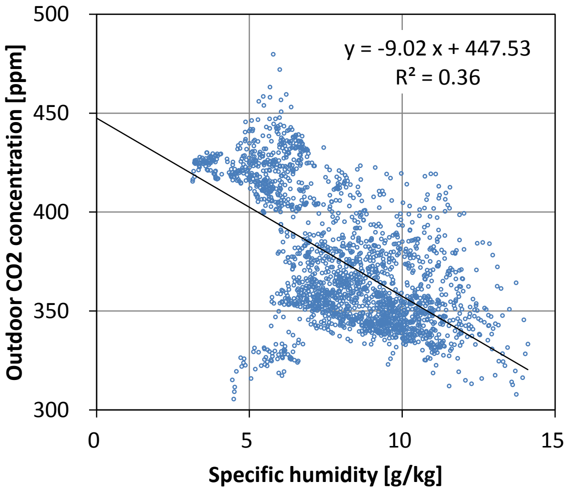

Fig. 11. Specific humidity vs outdoor CO_2 concentration at the ground of Building B.

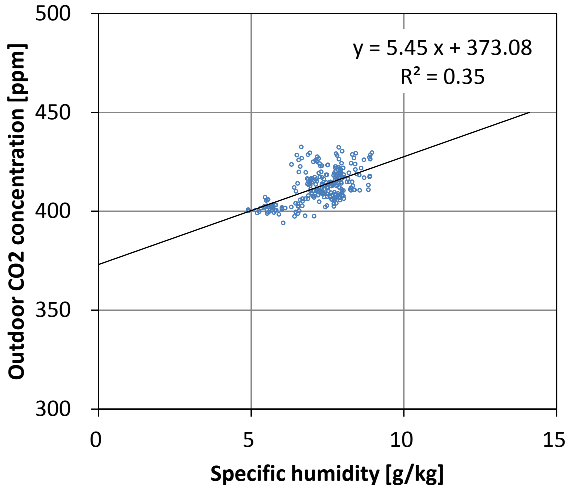

Fig. 12. Specific humidity vs outdoor CO2 concentration at the top of Building C.

Table 4 shows the required ventilation rate per person to keep indoor CO_2 level to be 1000 ppm calculated by using Equation 1. The CO_2 generation rate of an adult occupant performing sedentary activity (1.2 met) is assumed 19 L per hour [9]. The results in Table 4 show that a change by 50 ppm in the outdoor CO_2 concentration causes a change by approximately 10% in the required ventilation rate.

During the design of building ventilation, it is not efficient to adopt the maximum value of the outdoor CO_2 concentration because the high required ventilation rate will lead to high energy consumption of the fan, heating and cooling. But, to reduce the time that the indoor CO2 concentration exceeds the maximum allowed level, in calculations it might be better to consider not the average of outdoor CO2 concentration but the 75percentile of that as the assumed outdoor CO_2 concentration.

During the working hours from 8:00 to 18:00, the value of 75 percentiles in Tables 2 and 3 varied between 384 ppm (at 9:00 at the ground of Building B) and 442 ppm (at 9:00 at the ground of Building C), which indicates that the required ventilation rate could be different over 10% depending on the site, height and time.

3.2 Correlation with climate parameters

Table 5 shows the correlation coefficient between different climate parameters and outdoor CO_2 concentration.

The wind speed was correlated negatively with the outdoor CO_2 concentration, especially at the top of the buildings as shown in Figure 9 and 10. The wind might mix the atmosphere and balance its CO_2 concentration. This tendency will be stronger in the area of higher elevation than that of lower.

The specific humidity was correlated negatively with the outdoor CO_2 concentration measured at the ground of Building B as shown in Figure 11. This supports the result reported by Marrero at al [10]. They analysed the data obtained at a building surrounded by residential houses with gardens and parks and concluded that the outdoor CO_2 concentration in dry days becomes higher compared to wet days. The high humidity during wet days boosts the photosynthesis of plants thus absorbing more CO_2. On the other hand, as shown in Table 5, the specific humidity seemed to be correlated positively with the outdoor CO_2 concentration measured at the top of Building C, but as shown in Figure 12, the specific humidity in this building varied in small range, between 5 g/kg and 9 g/kg. This means the correlation coefficient in this case is not that indicative.

4 Conclusions

Long-term (one year) measurements of outdoor CO_2 concentration at the ground and the top level of four buildings in Greater Copenhagen (Denmark) have been planned to find the CO_2 variation in different areas of the city. In this paper, preliminary results from summer and autumn measurements were presented.

At buildings in suburbs, over the working hours from 8:00 to 18:00, the outdoor CO_2 concentration measured on the top level close to the intake duct was on average 408 ppm. At the building in downtown area, the corresponding concentration was on average 414 ppm. The CO2 concentration measured at the ground of the buildings was usually 10 ppm to 40 ppm higher than that at the top level in autumn. The differences were within the uncertainty of the measurements. However, the outdoor CO2 concentration variations over the day and from day to day were greater than the uncertainty of the measurements: in the range between 341 ppm at the lowest of 25 percentiles and 450 ppm at the highest of 75 percentiles. During the working hours, the value of 75 percentiles of outdoor CO_2 concentration varied between 384 ppm and 442 ppm, which indicates that the required ventilation rate could be different over 10% depending on the building location site, measurement height and time. The outdoor CO_2 concentration could be affected by the climate parameters of wind speed and humidity. Therefore, in order to perform proper calculation of the supplied ventilation rate that will ensure the required indoor limits of CO2 concentration, CO2 measurements must be performed close to the outdoor air intake.

The measurements of outdoor CO_2 concentration and analyses of results will be continued in 2019.

Acknowledgements

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