Effects of Meteorological Factors on CO_2 concentrations

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ABSTRACT

Amid the contaminant issues, air pollution has awakened more interest due to its potential health risk and its direct effect on human productivity. The overall indoor environment quality depends on the contribution of both the indoor and the outdoor air quality. The outdoor air pollutants penetrate indoor environments through mechanical and natural ventilation as well as by infiltrations through cracks and leaks in building's envelope. The interaction between the indoor and outdoor air may be studied by the air exchange rate. One of the most useful techniques to measure the air exchange rate is the tracer gas technique namely the metabolic CO_2 decay tracer gas technique. In this technique, the outdoor CO_2 concentration is usually considered constant, while in reality it follows a daily cycle. The possibility of modelling this daily cycle is fundamental to reduce the uncertainty in the calculation of air exchange rate and for a better understanding of the indoor/outdoor relationships. A better model of the outdoor air pollution, its sources and diffusion will have positive repercussion on indoor air quality modelling.

This study aims to determine the changes in ambient CO_2 concentration throughout the day depending on the weather conditions in a building situated in Horst, The Netherlands. In line with this purpose, the CO_2 concentration was measured inside and outside an office building in an urban location during a 2-year period. Meteorological observations and outdoor CO_2 concentration were obtained from a weather station set in the building roof and atmospheric stability parameters were consulted in NOAA database. The variations and correlations of the outdoor CO_2 concentration against various outdoor meteorological factors, namely temperature, dew point, relative humidity, barometric pressure, wind speed and direction, precipitation and solar irradiation were studied. It is found through statistical regression techniques that ambient CO_2 concentration is negatively correlated with temperature, wind speed, wind speed gust and radiation. The correlation of the relative humidity, dew point and precipitation with the ambient CO_2 concentration is not so clear because the moisture content in the air is related to the air temperature and has different effects in the vegetation. It was confirmed a relationship where ambient CO_2 concentration decreases with the planetary boundary depth, the vertical mixing coefficient, downward shortwave radiation and Pasquill stability index. All these parameters increase the turbulence augmenting the diffusion of CO_2 in the atmosphere. On the other hand, the pressure has local and regional effects on the winds regime. It can change local winds and therefore the local shear stress and the turbulence. On the other hand, it can also modify regional winds that can advect air masses with different properties that change the ambient CO_2 concentration.

KEYWORDS

tracer gas method, air infiltration, atmospheric CO_2, Meteorological conditions

1 INTRODUCTION

Nowadays, most of the people spend almost the 90% of their time indoors. This fact increases the interest in indoor air quality. According to *Carmichael* (Carmichael,2004), air quality can be defined as follows: "chemical state of the indoor and ambient atmosphere including constituents that pose a risk to health, those which may alter visibility and any other aspects of the chemical state of the atmosphere that have a high impact on human activities or the environment." Almost all studies found that poor indoor air quality can easily affect the productivity in a workplace. The poor indoor air quality has a strong and direct correlation with increased sick leave, increased number of mistakes, of complaints and of accidents at the workplace. (Mahbob N. S. et al., 2011). Also, decision-making and work performance decrease when the pollutants and CO_2 concentrations increase (Satish U. et al., 2012).

The indoor environmental quality is the outcome of the indoor pollutant sources and the infiltration and input by ventilation of outdoor air pollution (Chun Chen, 2011; Leung, 2015). Some indoor sources are occupants, cleaning and cooking. The existence of these sources makes the indoor air more polluted than the outdoor air. This justifies the need for ventilation. It can take place through three different mechanisms: mechanical ventilation, natural ventilation, and infiltration. The tracer gas method is a commonly used process to monitor the rate of air exchange. This method involves injecting a trace of gas into an area and, as, its evolution shows the air flow, therefore it gives the rate of ventilation. A tracer gas habitually used is the metabolic CO_2 generated by the occupants, as it is safe (non-flammable, non-toxic, non-allergic ...), non-reactive, measurable, well mixed in the air and evenly distributed in the space as people are distributed all over the study space (Hänninnen, 2012). The CO_2 in the ambient is assumed to be in a background concentration which is stable and steady so the injection of the CO_2 in high concentration is easily measured (Sherman, 1990). But the ambient CO_2 concentration levels vary during the day, present usually a minimum level in the early afternoon and a maximum level in the early morning. The peak-to-peak amplitude fluctuates from 50 ppm to 200 ppm. This fluctuation is according to the behaviour of sources, mainly vegetation and traffic. The climate factors, as could be geography, air composition, air evolution and the interaction between them can modify the diurnal cycle. Previous research has addressed several aspects of the effects of meteorology conditions on ambient CO_2 concentration:

- the sources, vegetation and traffic, are the first elements in shaping the concentration of ambient CO_2 depending on the climate conditions (Sreenivas, 2016; Xueref-Remy, 2016);
- the evolution and intensity of the atmospheric boundary layer are also aspects widely discussed, for example by *de Wekker* (de Wekker, 2009) or *Huang* (Huang, 2015);
- and wind patterns are studied by *Jiang* (Jiang, 2016) and *Strong* (Strong, 2011).

This paper describes the research into the relationship of outdoor CO_2 concentration under different meteorological conditions. The following meteorological parameters were monitored in an attempt to study their effects on the outdoor CO_2 concentration: air temperature, dew point, barometric pressure, relative humidity, precipitation, wind speed, wind direction and solar irradiation. Atmospheric stability and diffusion parameters were collected from the NOAA database.

2 MATERIALS AND METHODS

2.1 Theoretical formulation

The tracer gas techniques are based on the fundamental mass balance equation for the fully mixed gas in the investigated volume.

$$\frac{dC}{dt} = E + \lambda C_{ext} - \lambda C \quad (1)$$

Where C is CO_2 concentration in the room ($mg \cdot m^{-3}$); E is CO_2 emission rate of indoor sources ($mg \cdot h^{-1} m^{-3}$); λ is the air exchange rate (h^{-1}); C_{ext} is the outdoor CO_2 concentration ($mg\ m^{-3}$). Experimentally this technique consists in release uniformly metabolic CO_2 in a close space until the maximum level is reached. Once there is no emission, unoccupied space, the CO_2 will be diluted by outdoor air with lower concentration values. In this case, the evolution of the indoor CO_2 concentration has an exponential behaviour described by the Eq. 2. The evolution of the indoor CO_2 concentration during the whole experiment is illustrated in figure 1.

$$C(t) - C_{equi} = (C_0 - C_{equi})e^{-\lambda t} \quad (2)$$

Where C(t) is the instant concentration in the room ($mg \cdot m^{-3}$); C_{equi} is the equilibrium concentration that in the CO_2 decay tracer method equals to the outdoor concentration ($mg \cdot m^{-3}$); C_0 is the initial concentration ($mg \cdot m^{-3}$); λ is the air change rate (h^{-1}); t is the time (h).

This method assumes that the equilibrium concentration, in this case, the outdoor CO_2 concentration is constant. However, the outdoor CO_2 concentration follows a diurnal cycle as it is studied in the consecutive sections.

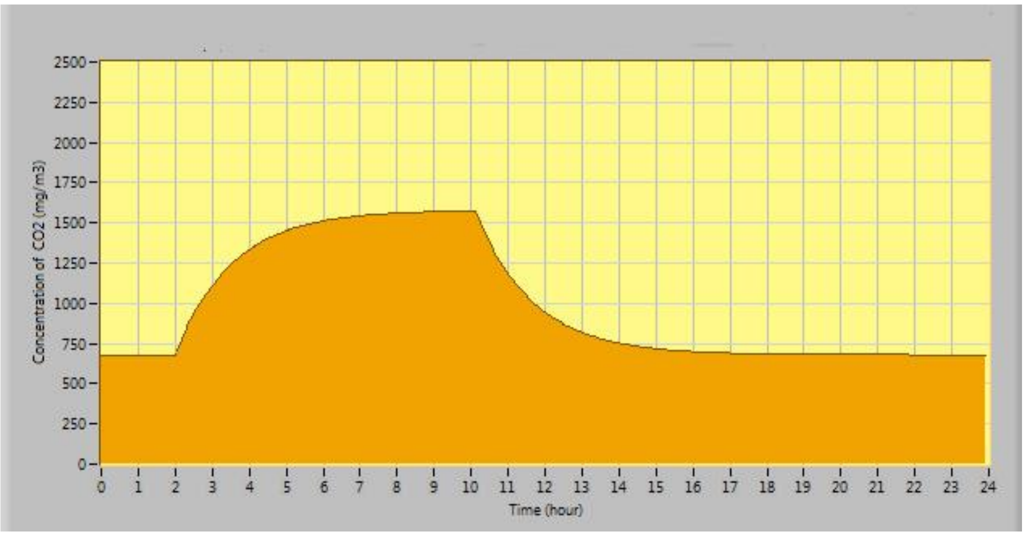

Figure 1: Indoor CO_2 concentration during a day in an occupied space.

2.2 Experimental site description

The study site is the Horst aan de Maas Town Hall building in the province of Limburg, south-eastern of Netherlands, (51.45N 6.05E, elevation 26m) located in the centre of the city. It is an administrative building surrounded by residential houses with gardens and parks (Fig. 2). The climate is a mild temperate fully humid climate with warm summers. The average annual temperature is 10.5ºC. Over the course of the year, the temperature typically varies from 3ºC to 19ºC and is rarely below -5ºC or above 30ºC. Average monthly temperatures vary by 10ºC. Horst has mostly partly-cloudy days in summer, and overcast skies during winters. Average annual rainfall amounts to 559 mm and raining approximately the same, 37 mm per month, throughout the year. The relative humidity is high, with an average annual of 81%. The average wind speed is 13 Km/h, with prevailing string winds from southwest in autumn and winter, and calm winds during spring and summer.

2.3 Measurements and Data Processing

The outdoor station measures the following parameters: air temperature, relative humidity, barometric pressure, wind speed and direction, solar irradiance, CO_2 concentration, particle matter PM10, PM2.5 and PM1.0. The anemometer and the pyrometer are mounted on poles at 5m over roof level. The sensors produce raw data each 0.1s, of which a 5 min average is calculated. For the purpose of reducing random noise, the signal of the different meteorological parameters and the atmospheric CO_2 concentration was filtered using a 1-D median filtering and a Savitzky-Golay FIR filter with frame length of 6 hours.

Figure 2: Map of Horst, town hall highlighted in yellow.

The stability parameters were downloaded from the dataset GDAS (Global Data Assimilation System) from NOAA (National Oceanic & Atmospheric Administration) database which has an output time step of 3 hours and a resolution of 0.5º.

The data used are almost two years, from April 19, 2016 to February 18, 2018. In order to estimate relationships between the outdoor CO_2 concentration and the different meteorological conditions, linear regression was performed, calculating the R-square coefficient. In the section that follows, the results obtained will be discussed.

3 RESULTS AND DISCUSSION

The time evolution of the atmospheric CO_2 concentration during August 2017 is presented in Fig. 2. It is shown only a month in order to appreciate the diurnal cycle. Atmospheric CO_2 concentration varies most days, as a result of photosynthesis- respiration cycle of vegetation and traffic emissions. The diurnal peak-to-peak amplitude can vary from 50 ppm to 200 ppm.

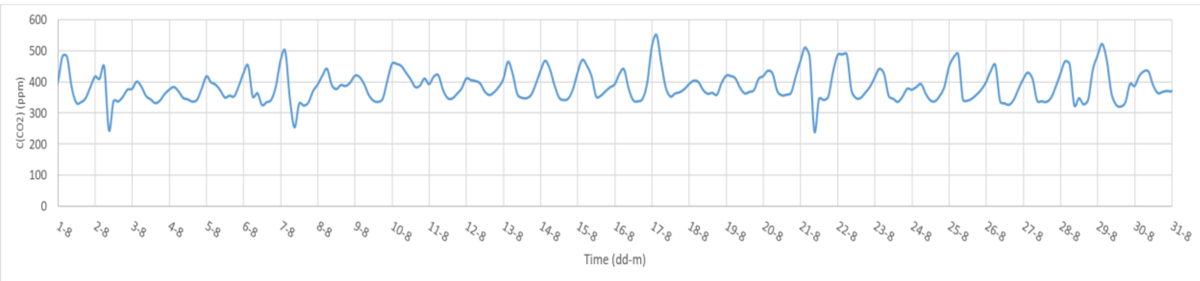

Figure 3: Outdoor CO_2 concentration during August 2017.

To understand this behaviour, the correlation between the concentration of atmospheric CO_2 and the different meteorological parameters is studied. These correlations are analysed by calculating the Pearson coefficient and R-squared percentage. The results of the correlational analysis are summarised in Table 1. According to the R-square percent, the variation of the atmospheric CO_2 concentration is due mainly to the variations in temperature, wind speed, the friction velocity and the specific humidity. The R-square percent shown in the table do not add up to 100% since the variables studied are not independent of each other. For example, high insolation leads to an increase in the temperature of the air that increases the thermal turbulence and with it the atmospheric instability.

High temperatures increase the convection of the air next to the soil improving the dilution of CO_2 in the air and thus reducing its concentration. This is reflected in the negative correlation coefficient.

Strong winds and high wind shear, measured by the friction velocity, develop mechanical turbulence. More mechanical turbulence mixes better the CO_2 in the air and reduces its levels. During storms, stronger winds blow and there are stronger shears developing mechanical turbulence that boosts the dispersion of CO_2. While sunny windless days bring less shear and higher CO_2 concentrations.

In summary, most of the variations of the diurnal cycle of the atmospheric CO_2 concentration can be explained by the intensity of the mechanical or thermal turbulence, that is, the atmospheric stability.

Table 1: Pearson Coefficient and R-square percentage between different meteorological parameters and atmospheric CO_2 concentration.

Parameters	Pearson Coef.	R-square %	Parameters	Pearson Coef.	R-square %
Temperature	**-0.886**	**78**	Friction velocity	**-0.604**	**37**
Pressure	0.165	3	Roughness height	-0.352	12
Spec. Humidity	-0.588	35	Solar Radiation	-0.506	26
Precipitation	-0.108	1	Atm. Boundary layer height	-0.341	12
Wind Speed	**-0.672**	**45**	Cloud cover	-0.277	8
Wind direction	-0.437	19	Vertical diffusive coef.	-0.212	5
Latent heat	-0.547	30	Horizontal diff. coef.	-0.183	3
Sensible heat	-0.417	17	Pasquill Stability index	-0.246	6

Other variables that influence the concentration of atmospheric CO_2 to a lesser extent are those related to water in the atmosphere. Its relationship with the concentration of CO_2 is more complex. Humidity boosts photosynthesis absorbing more CO_2. In dry days the atmospheric CO_2 levels are higher (Fig. 4). The latent heat represents the loss of energy from the surface due to evaporation. High latent heat flow means more heat into the atmosphere increasing the thermal mixing. In general, the overcast sky paralyzes the photosynthesis-respiration cycle of the vegetation and stops the release of CO_2 (Fig. 5). As shown in figure 4 the CO_2 cycle is better defined during clear sky days.

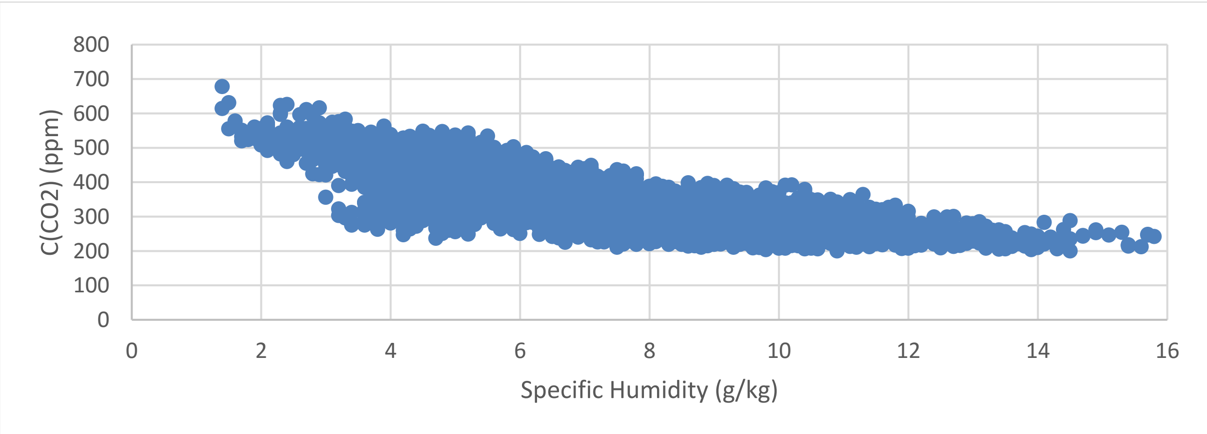

Figure 4: Specific humidity vs atmospheric CO_2 concentration.

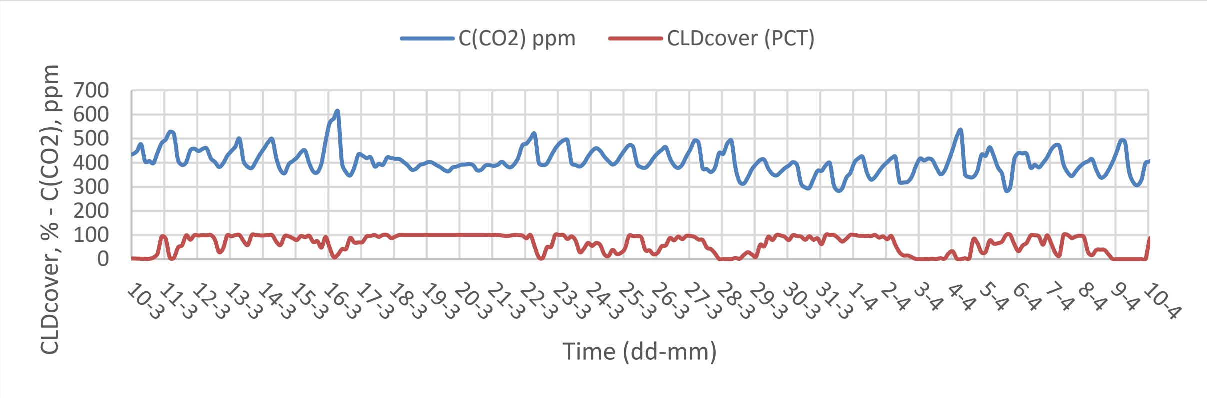

Figure 5: Time evolution of atmospheric CO_2 concentration and cloud cover percentage between March 10, 2017 and April 9, 2017.

The maxima and minima can be more marked thanks to the effect of regional winds. These winds can bring to the town masses of polluted air that raise the maximum. Or on the contrary, they can bring clean air that prevents the rise of CO_2 levels and cause a more pronounced minimum. The trajectories of the masses arriving at the lowest minimum episode can be seen in Fig.6. Strong winds of 32 km/h blow the polluted air to the North. This effect explains the lower minima during these overcast days. These graphs were developed using the HYSPLIT model (Hybrid Single Particle Lagrangian Integrated Trajectory) from NOAA's webpage based on GDAS dataset (Stein, 2015) and by *Cameron Beccario* based on GEOS-5 (Goddard Earth Observing System) and CAMS (Copernicus Atmosphere Monitoring System) dataset.

Figure 6: Models based in GDAS dataset, day March 31, 2017: (left) CO_2 concentration and wind, high concentrations are blown to the North by strong winds, (right) trajectories of air masses arriving to Horst, altitude: red: 100m, blue: 500m, green: 1000m

4 CONCLUSIONS

It is found that the atmospheric CO_2 concentration has a diurnal cycle due to the behaviour of its sources. In our study the traffic emissions are neglected as the maxima are just before sunrise indicating that no more Co2 is released once the photosynthesis begins. The diurnal cycle is amplified by some meteorological conditions, especially those related to mechanical and thermal turbulence and wind regimes. Other meteorological parameters like pressure or precipitation and cloud cover seem either to have little effect or that their effects are subdued by the dominant ones. Their effects are assuming to be important only in singular occasions.

This study is based on the assumption that the atmospheric CO_2 concentration is linearly correlated with these meteorological parameters. This assumption is based on mathematical simplicity and previous literatures and experience (Garcia-Talavera et al., 2001). Obviously, further measurements for longer periods and work on rigorous modelling of the outdoor CO_2 concentration relationship with any parameters must be carried out in future.

This work merely represents the first attempt to accomplish a more profound knowledge of indoor air quality and its relationship with weather conditions.

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