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Analysis of different ventilation strategies and CO_2 distribution in a naturally ventilated classroom

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HIGHLIGHTS

- Natural ventilation strategies were tested in a classroom by CO_2 monitoring.
- Continuous and distributed cross-ventilation achieved adequate CO_2 levels.
- 17 sensors provided detailed data on the CO_2 spatial distribution inside the room.
- The sampling height was found to play a relevant role in CO_2 readings.
- Sensors installed on the walls yielded lower CO_2 levels than the average.

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ABSTRACT

CO_2 monitoring has proven to be an effective and affordable way of controlling air ventilation rates, a paramount task for minimizing airborne contagions in indoor shared spaces. In this work, the CO_2 distribution in a naturally-ventilated classroom has been thoroughly characterized, gaining information not only on the effectiveness of diverse ventilation strategies but also on the expected differences between CO_2 values when varying the sampling location within the room. The results confirm that an adequate renewal of the air in the room requires the use of cross-ventilation, with openings in different walls. Furthermore, it was found that ventilation is optimized, for a given total opening area, when the openings are distributed as much as possible among different windows. For most of the studied conditions, a global windows opening area of 1.24 m^2 with an open door was typically enough to yield CO_2 concentrations below 700 ppm. The CO_2 readings displayed a noticeable and consistent dependency on the sampling height, with below-average values at 0.75 m, the highest concentrations at 1.5 m, and levels close to the average when sampling at a height of 2.2 m. For a given height, the influence of the sampling location within the room was weaker, and more dependent on the specific ventilation strategy applied. However, the tests consistently showed CO_2 records significantly lower for sensors installed on the walls. Besides a detailed spatial and temporal characterization of the ventilation process under different ventilation strategies, these results are thought to provide useful and novel information for a judicious placement of CO_2 monitoring systems.

1. Introduction

The importance of a sufficient ventilation rate within any indoor space has been well known for many years. Since carbon dioxide (CO_2) is produced by human metabolism, the concentration of this gas can provide useful insight into ventilation rates in occupied indoor spaces (Olesen, 2004). Namely, the excess of CO_2 concentration (as compared to outdoor levels) is related to the amount of indoor air which has been already breathed by occupants, and therefore to the ventilation quality (e.g., see (Fan et al., 2021; Kabirikopaei and Lau, 2020; Asif and Zeeshan, 2020)). However, as discussed in (ASHRAE, 2022), using CO_2 as indicator of outdoor air ventilation should carefully consider that ventilation requirements depend on the space type, the occupancy and on the occupant characteristics. Taking into account the aforementioned

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limitations, some regulations provide guidelines to verify that indoor spaces are sufficiently ventilated by using CO_2 measurements. Even though air quality depends on many more variables than ventilation (ASHRAE, 2022), the so-called 'basic classifications of indoor air quality' (IDA 1, 2, 3 and 4) introduced in (European Committee for Standardization, 2006; Gobierno de España, 2007) are solely related to a required level of ventilation, being the CO_2 concentration measured inside buildings one of the proposed methods to estimate ventilation quality level.

The importance of ventilation in highly occupied spaces such as schools has been highlighted in many studies, such as in (Myhrvold et al., 1996), where a 3 year-long investigation revealed a correlation between the student's performance, health issues and the CO_2 level measured in the classroom. Subsequent works (e.g., (Mendell et al., 2013; Toftum et al., 2015; Johnson et al., 2018)) have endorsed the importance of keeping an adequate ventilation rate in any shared indoor space.

The recent outbreak of the COVID-19 pandemic (declared by the World Health Organization on March 11, 2020) has prompted a renewed interest in indoor air quality and ventilation. This is due to the fact that, after intense scientific debate, the airborne mechanism has been proven to be, at least, an important route for COVID-19 transmission (Tang et al., 2021; Noorimotlagh et al., 2020; Greenhalgh et al., 2021). Through talking, coughing or even breathing, people emit small respiratory droplets that show a continuum size distribution, with a large fraction being able to remain suspended in air for minutes or even hours. If an individual is infected, the virus-laden aerosols (droplets $<$100 μm (Prather et al., 2020)) can remain suspended for long times and infect other people through inhalation, especially in poorly ventilated indoor environments. Under such conditions, airborne virus levels can build up, leading even to superspreading events (e.g., (Miller et al., 2021)) only explainable through the airborne mechanism.

In view of this, promoting a proper ventilation rate in any indoor space, and particularly in places where many occupants share the same air for an extended period of time such as in schools, has become paramount for limiting the spread of COVID-19 (Villers et al., 2021). Even though mechanical ventilation systems typically allow for a good control of the ventilation rate, many schools are not equipped with such systems, relying only on natural ventilation. This is the case for most Spanish schools, where the manual opening of windows is the only way to ventilate classrooms (Alonso et al., 2021). Since natural ventilation strongly depends on non-controllable and varying factors (i.e., internal and external temperature, wind direction and speed, etc.), the control of the ventilation rate becomes a challenging task for such settings.

The problem of estimating the ventilation rate required to minimize contagion risks is not trivial. To measure the concentration of aerosols exhaled by humans has been proven to be challenging, expensive, slow and not scalable (Villers et al., 2021; Peng and Jimenez, 2021). By contrast, CO_2 has been proposed in various studies (e.g., (Peng and Jimenez, 2021; Rudnick and Milton, 2003)) as a useful proxy for the concentration of aerosols exhaled by humans. Even though particle and gas dynamics certainly differ due to the effects of gravity, inertia and surface deposition, tracer gases were found in (Ai et al., 2020) to be suitable surrogates of exhaled fine droplet nuclei when it comes to study airborne transmission. As a result, carbon dioxide monitoring becomes a useful and inexpensive tool to assess airborne contagion risk in shared spaces. Furthermore, the immediacy of this measurement allows for its use to prompt quick decisions to minimize risks, such as to increase ventilation, to limit the room capacity or even to evacuate all the occupants.

The measurement of CO_2 levels in indoor spaces to minimize airborne infection is closely related to the aforementioned pre-pandemic regulations and guidelines related to ventilation. Namely, some of them (e.g., (European Committee for Standardization, 2006; Gobierno de España, 2007)) were also devised using CO_2 as a proxy for other co-exhaled bio-effluents. In fact, the Spanish regulation (Gobierno de España, 2007) states that indoor air CO_2 concentrations inside classrooms should remain below 500 ppm above the background outdoor level. This corresponds to an IDA 2 category in the aforementioned 'basic classification of indoor air quality' in (European Committee for Standardization, 2006; Gobierno de España, 2007). Even if an air exchange corresponding to IDA 2 might be appropriate for a classroom under normal circumstances, it might be still insufficient to effectively reduce the virus airborne transmission during this pandemic situation. Moreover, this compulsory ventilation requirement applies only to new buildings after the standard was approved in 2008, so that most existing schools are not even covered by this regulation.

Defining CO_2 thresholds to ensure safe indoor spaces is a complex task, since airborne contagion risk not only depends on the air renewal rate with outdoor air, but also on other variables such as occupancy, duration of the event, incidence rate, use of masks, etc. Thus, for a given infection risk, it is not possible to provide a single recommendation of indoor CO_2 threshold (Peng and Jimenez, 2021), as this threshold depends on the specific circumstances. The correlation between infection risk and CO_2 excess level has been modeled in a number of recent works (e.g., (Peng and Jimenez, 2021; Bazant et al., 2021; Vouriot et al., 2021; Stabile et al., 2021; Park et al., 2021)), most of them based on the Wells–Riley model of aerosol infection in a well-mixed room (Riley et al., 1978). However, given the emergency context of the current pandemic situation, many guidelines have proposed fixed CO_2 thresholds for assessing in an easy and straightforward way the minimum ventilation level required in common everyday activities.

Alternatively, some guidelines are expressed in terms of the recommended number of air changes per hour (ACH). For instance, a minimum of 5 ACH is proposed in the guide published by the Harvard T.H. Chan School of Public Health (Joseph Allen et al., 2021) to reduce COVID infection risks in classrooms, resulting in approximately 700 ppm CO_2 for a typical US school classroom of 5000 ft^3 occupied by 15 teenagers. However, it should be noted that, for this fixed ACH, the CO_2 concentration (and, hence, the fraction of re-breathed air in the room) would be higher in classrooms with more students per unit of volume, relatively common in Spain and in many other countries.

Several works have studied ventilation and CO_2 levels in schools, both for cases with mechanical and natural ventilation. A thorough literature review reveals that students often have to spend long periods of time in poorly ventilated spaces. For instance, Zemitis et al. (2021) recorded CO_2 concentrations in a naturally ventilated school in Latvia. Under normal operation, CO_2 levels averaged around 2400 ppm, with a maximum of more than 4400 ppm. These values clearly point to an insufficient ventilation and, consequently, an increased risk of airborne transmission. Similar results have been reported in other works, such as (Toftum et al., 2015), where an analysis of 820 Danish classrooms revealed that, for most of the school time, CO_2 levels exceeded 1000 ppm. Classrooms depending on the manual opening of windows showed higher CO_2 concentrations than those equipped with mechanical ventilation systems. Almeida et al. (2017) studied this same issue in a milder climate (Portugal). This study shows that in two schools (out of the eight studied), the average CO_2 measured exceeded 2000 ppm, being greater than 1500 ppm in other four buildings. Other studies focused on studying the indoor air quality of naturally ventilated classrooms in Southern Europe (e.g., (Fernández-Agüera et al., 2019) in Spain, or (Turanjanin et al., 2014) in Serbia) also showing average CO_2 levels significantly above 1000 ppm. In view of this situation, many recent guidelines and protocols recommended that, in order to reduce as much as possible COVID-19 airborne transmission in schools, ventilation should be prioritized over thermal comfort, establishing the introduction of outdoor air as mandatory regardless of the ambience and room conditions. A recent study by Alonso et al. (2021) analyzed the effects of the pandemic on thermal comfort and indoor air quality in two classrooms of southern Spain during the winter season. The study highlighted a clear lowering of CO_2 levels after these emergency protocols were implemented, with weekly averages below 700 ppm (in contrast with pre-pandemic values of more than 1000 ppm). However, this was achieved through a clear deterioration in thermal comfort conditions.

The challenge of achieving a safe indoor environment with acceptable comfort remains a substantial issue to be addressed, especially for spaces relying entirely on natural ventilation. Currently, the only viable and cost-effective way of attaining this is through manual airing strategies combined with continuous monitoring of CO_2 indoor levels to provide fast feedback, prompting for required actions such a change in the openings or in the occupancy level. As discussed above, a series of works in the literature have addressed both natural ventilation strategies and CO_2 measurements in schools. The most common approach consists in monitoring CO_2 levels through one analyzer per classroom (e.g., (Toftum et al., 2015; Alonso et al., 2021; Vouriot et al., 2021; Zemitis et al., 2021; Turanjanin et al., 2014)) or by averaging the results provided by a few of them (e.g., (Park et al., 2021; Almeida et al., 2017)). However, as stated in (Vouriot et al., 2021), when multiple sensors are placed in a space, the differing CO_2 levels recorded can indicate the variation of risk within that space. Furthermore, as also highlighted in (Vouriot et al., 2021), there is a clear lack of detailed information regarding how CO_2 levels might vary within an indoor space such as a classroom, as well as on the most judicious placement of monitoring systems. The ISO 16000–26 provides some well-known recommendations for CO_2 sampling in indoor spaces (AENOR, 2012), such as to place the sampling point at 1.5 m from the floor, or to keep a distance of at least 1–2 m between sensor and windows. Furthermore, a distance of 1.5–2 m should be kept between sensors and people in the room. Unfortunately, these guidelines cannot be always followed in classrooms under normal teaching activities. Probably because of this, there is some heterogeneity in the placement of CO_2 sensors in the aforementioned works. Besides, many schools consider placing CO_2 sensors on walls or even hang them from the ceiling so that they remain unobtrusive and out of the reach of students. In the authors' opinion, there is a clear lack of information regarding if such measurements would be representative for a proper assessment of CO_2 levels and contagion risk within the room.

The authors carried out an extensive test campaign during the winter 2020/21, as an attempt to promote ventilation assisted by CO_2 monitoring as a key measure for prevention of COVID-19 in schools and to develop some guidelines that could be helpful for teachers. The experience accumulated in many primary and secondary schools (about 300 CO_2 records collected throughout different school days in more than 130 different spaces, including classrooms, corridors, etc.) demonstrated that manually-operated windows can provide enough ventilation to keep CO_2 levels below 700–800 ppm in most cases (about 80–90%). However, there was a clear need for more detailed knowledge on the effectiveness of different ventilation strategies or practical details like the location of CO_2 sensors. With that purpose, detailed tests were conducted in a few selected cases.

This work summarizes the main results and conclusions obtained from a detailed characterization of the CO_2 levels recorded in a naturally ventilated classroom, representative of commonly used classrooms in Spanish Primary Schools. Differences among zones and heights were explored and quantified by the continuous monitoring of CO_2 concentration through 17 sensors under normal operation of teaching activities. The analysis of these data under different and well-controlled conditions has provided detailed information that might be useful for sensor placement as well as for validating modeling tools addressing naturally-ventilated indoor spaces. Furthermore, different ventilation strategies have been tested, varying key conditions such as the windows and door openings, the location and distribution of these openings (e.g., cross ventilation vs. single-sided ventilation), the occupancy and the activity of the occupants. The intermittent opening of windows has been also compared with the continuous ventilation mode. After analyzing and discussing the obtained results, a series of conclusions and recommendations are presented in the final section of the current work, regarding the differences found between room zones and heights in terms of measured CO_2, potentially suitable locations for CO_2 sampling and the most effective ventilation strategies.

2. Experimental method

The field measurements were performed in an urban Primary School located in the city of Zaragoza (northeast of Spain), in December 2020. As it is common in most Spanish schools built before 2008 (when regulations on this issue appeared, see (Gobierno de España, 2007)), there are no mechanical ventilation systems, and therefore the only way to ventilate the building is through the manual opening of windows. A medium-sized (63 m^2 in surface, 3 m in height) and representative classroom of this school was selected for a detailed characterization of different ventilation strategies and spatial variations of CO_2 levels. As it can be observed in Fig. 1, this classroom has a rectangular plan, and it is located on the ground floor of the building. The door leads to a corridor shared with other classrooms, and two of its walls (facing west and north) are covered with sliding windows of 1.55 m in height. The classroom is normally attended by 20 students (6^{th} graders, 11–12 years old) and one teacher.

The campaign described in this work consisted in 4 complete school days (10^{th}, 11^{th}, 15^{th} and December 18, 2020). After the last day, the acquired data was thought to be sufficient for the aforementioned objectives, and thus the campaign was finished. Ambient conditions during the first 3 days were typical of Continental-Mediterranean climate winters (Zaragoza has a Köppen-Geiger climate classification of BSk). Temperature records at the starting of these school days ranged between 6 and 8 °C, steadily increasing until reaching 10–15 °C at the end. By contrast, the fourth day (18^{th} December) was foggy, with considerably lower and more stable temperatures (4–6 °C throughout all the school day). Wind velocities were typically below 10 km/h for all the cases, about half of the historic average in Zaragoza for December (Hernández, 1990). Therefore, velocities were sufficiently low and similar throughout the test period to discard any significant influence of wind on the differences found among the various strategies explored.

A total of 17 CO_2 sensors were used in this study. This number of sensors provided a much higher spatial resolution when compared to previous works, allowing to characterize in a detailed manner the whole ventilation process within the room. A matrix of measurement positions was defined and maintained throughout the study. A sketch showing the position of each sensor is displayed in Fig. 2, both from a top view (left) and as observed from a cross section across A-A′ points (right). As it can be seen in Fig. 2 (left), two sensors (P1 and P2) were installed on the walls, at heights of 1.5 and 2.2 m respectively. Eight more sensors (T1 to T8) were distributed on tripods at a height of 1.5 m (considered optimal to avoid direct exposure to the seated students' breath; this is the height recommended in the ISO 16000-26 standard). Sensor T9 was placed on the teacher's table, at a height of 1 m. The central row, defined by T4-T5-T6, actually consisted of 9 sensors distributed into three heights: the upper one (2.2 m), with H1, H2 and H3 (see Fig. 2, right). The lower one (0.75 m) had sensors H7, H8 and H9. As for the sensors installed at the intermediate level (1.5 m), they can be either referred as T4, T5 and T6 (when discussing on differences among room zones for an approximately constant height, Fig. 2 left) or H4, H5, H6 (when discussing on differences between heights, Fig. 2 right).

In order to quantify differences among heights or room zones, the average of all sensors installed in a given plane can be calculated. For any given condition (kept stable between times t_1 and t_2), the deviation between CO_2 concentration for sensor i (C_i) and the average value in the studied plane (C_{avg}) is defined as:

$$D_i = \int_{t_1}^{t_2} \frac{C_i(t) - C_{avg}(t)}{t_2 - t_1} dt \qquad (1)$$

As for the conditions explored, each campaign day was divided into several periods. For any given period, the main variables (i.e.,

Fig. 1. Pictures of the analyzed classroom. Views from opposite points within the room: from the entrance (left) and from the background (right).

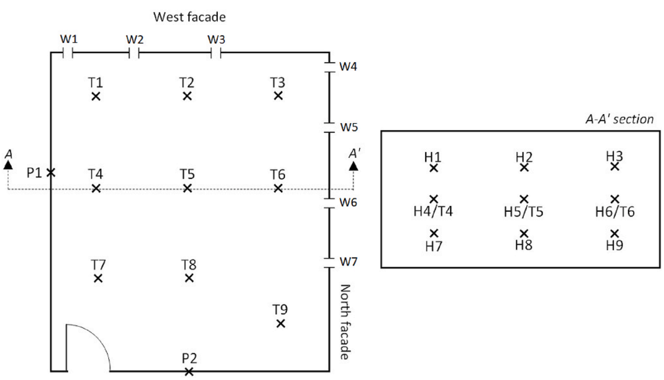

Fig. 2. Sketch showing the sensors location. Note that the plan view only displays the windows openings that were used over the course of the study (W1 to W7).

ventilation mode, open area exposed to outdoor air, opening of the door and occupancy) were kept constant. Table 1 summarizes the test matrix, detailing the value of these main variables during each of the periods.

Table 1
Test matrix summarizing the values of the main variables throughout the studied periods in the campaign.

Day	Period	Ventilation mode	Windows openings	Door	Occupancy
1	1.1	Continuous	1.24 m^2, distributed	Open	20
	1.2	Continuous	1.24 m^2, distributed	Closed	20
2	2.1	Continuous	1.24 m^2, distributed	Open	19
	2.2	Continuous	0.70 m^2, one-sided (W)	Open	19
	2.3	Continuous	0.70 m^2, one-sided (W)	Closed	19
	2.4	Continuous	0.54 m^2, one-sided (N)	Open	19
	2.5	Continuous	0.93 m^2, distributed	Open	19
	2.6	Continuous	1.39 m^2, distributed	Open	19
3	3.1	Continuous	1.24 m^2, distributed	Open	18
	3.2	Continuous	1.24 m^2 in one window	Open	18
	3.3	Intermittent (5–15)	4.96 m^2–0 m^2	Open	18
	3.4	Mixed (5–15)	4.96 m^2–0.62 m^2	Open	18
4	4.1	Intermittent (5–15)	4.96 m^2–0 m^2	Open	21
	4.2	Mixed (5–15)	4.96 m^2–0.62 m^2	Open	21
	4.3	Continuous	1.24 m^2, distributed	Open	21

The first day of measurements was devoted to study continuous and distributed ventilation, being the door opening the only key variable modified. Besides ascertaining the relevance of the door opening, the second day also explored a modification in the windows opening area and location (one-sided vs. distributed). The first two periods in the third day (3.1 and 3.2) also addressed distributed and one-sided ventilation, in this case for a fixed open area of 1.24 m^2. Periods 3.2, 3.3 and the whole fourth day intended to characterize three different ventilation modes: continuous, intermittent and mixed. Intermittent ventilation was included to the study because this was the common recommendation in many regional educational protocols to minimize COVID-19 infection risk. For instance, the instructions given by the Aragonese Department of Education for the course 2020–2021 (Gobierno de Aragón, 2020) only imposed that windows should be opened before the arrival of students, during breaks and after the students leave the classroom. Due to the long time interval between breaks (50 min) and, in order to avoid exposing the students to poorly ventilated conditions, an alternative strategy for intermittent ventilation was tested here, based on a 5–15 routine. That is, 5 min with fully opened windows followed by 15 min without any opening to outdoor air.

The sensors used in this work to quantify CO_2 concentration were Aranet4, which use NDIR (Non Dispersive Infra-Red) technology, with an accuracy of ±50 ppm for the range 0–2000 ppm. The devices were adjusted at a sampling rate of one measurement per minute and the data were stored in the devices' internal memory, and collected afterwards through Bluetooth connection. All sensors were regularly calibrated following the manufacturer's instructions. That is, they were exposed to outdoor air in the city's outskirts, far away from any potential CO_2 emission source. Upon completion of the calibration sequence, a CO_2 concentration of 400 ppm was assigned to these ambient conditions. Measurements outside the school (which is located in an urban area) provided CO_2 values in the order of 450 ppm, so that CO_2 levels above that threshold can be considered to stem from the occupants' exhalation. It is worth to note that NDIR Aranet4 sensors were thoroughly compared with a reference CO_2 detector in (Villanueva et al., 2021), where average deviations of approximately 2% over the 400–900 ppm range were reported with remarkably narrow variability among different Aranet4 units, pointing therefore to an accuracy similar to that of the reference measuring device and above the one specified in their data sheet.

3. Results and discussion

3.1. Analysis of different ventilation strategies

This section aims to analyze the ventilation strategies described in Table 1, as well as the effect of different key variables on the problem of a naturally ventilated classroom under normal teaching conditions. In order to clearly ascertain the effect of each variable on the resulting CO_2 levels, the average of all the 17 sensor readings is provided here (differences among them will be explored in the next section).

As detailed in the Introduction, a given excess of CO_2 concentration cannot directly provide a risk assessment for COVID transmission, which also depends on other variables affecting airborne contagion (use of masks, masks efficiency, potential treatments of air, kind of activity performed, probability of infective population, etc.). However, since CO_2 is generally accepted as a good indicator of ventilation rate, some guidelines have proposed CO_2 thresholds as reference for achieving safe indoor conditions under typical school settings. Good examples are the 700 ppm suggested in (Joseph Allen et al., 2021), or the CO_2 concentration levels proposed in (Di Gilio et al., 2021) for different risk classes (i.e., <700 ppm for low, 700–800 ppm for moderate, 800–1000 ppm for high, and >1000 ppm for very high COVID transmission risk).

The results provided in this paper will be always presented in terms of CO_2 concentration, so that they can either be compared with this kind of reference thresholds or used as input data to risk-assessment models for airborne transmission.

3.1.1. First day: continuous ventilation with fixed openings

As summarized in Table 1, the first day of tests aimed to characterize the classroom ventilation under a fixed total open area to outdoor air (1.24 m^2). This corresponds to an opening length of 80 cm, with the following distribution (see Fig. 2): 15 cm in W1, W2, W4 and W5, 10 cm in W6 and W7. The only controllable variables that were modified in this first day of the experimental campaign were the following: door opening, number of occupants and activity. It is worth to note that, for cases with an open door, the location of the openings produced cross ventilation conditions, recommended in several works (e.g., see (Park et al., 2021; Zhou et al., 2021)) to enhance outdoor airflow rates. The temporal evolution of average CO_2 levels measured in the classroom, as well as the changes in key variables are summarized in Fig. 3. Complementarily, and in order to better visualize this information, a video displaying the temporal and spatial evolution of CO_2 within the room for these conditions has been included as Appendix A of the Supplementary material (*'20201210_CO2evolution_H=150 cm.avi'*).

One of the main results in Fig. 3 is that the studied classroom, under normal operation and with the door open, remains adequately ventilated with the proposed windows openings. Average CO_2 levels under these conditions peak at 754 ppm (around 10:00), being most of the time lower than 700 ppm. By contrast, if the door is closed (as it happens at 10:43–11:00 and 11:35–12:40) CO_2 levels sharply grow, quickly exceeding 700 ppm due to a reduction in natural ventilation. The sudden drop in CO_2 concentration just after opening the door at 12:40 is a further proof of the substantial role of the door opening.

The effect of the occupants number and activity can be also extracted from Fig. 3. At the start of the school day, occupancy quickly grows in the interval 8:55–9:00. During these 5 min, pupils remain in class without the teacher, and therefore the level of activity is high, with students moving around the room and talking out loud. This is clearly reflected in a sudden increase in the CO_2 level, which is subsequently reduced after 9:00, when the teacher enters the room and the level of activity decreases. The class is interrupted at 9:45, when students rearrange their tables, increasing again the room activity and CO_2 levels. Afterwards, pupils take an exam, remaining therefore the class completely calm. Under such conditions, the average CO_2 concentration decreases until reaching a quite constant value ~570 ppm. This quasi-steady value is only altered by the already mentioned closure of the door at 10:43. After the break, the level of activity remains roughly constant until 13:00, when the school day is finished. After the teacher leaves the room, students stand and talk loudly, causing a distinct peak in CO_2 levels, as it can be verified in Fig. 3.

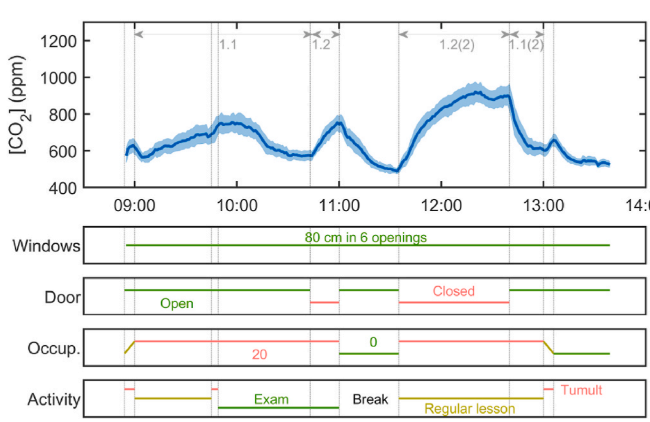

Fig. 3. Temporal evolution of average CO_2 levels and key variables in the first day of field measurements for the periods defined in Table 1. The shaded area represents ± one standard deviation of all sensors in the room.

3.1.2. Second day: continuous ventilation modifying openings width and distribution

During the second day of measurements, the ventilation strategies presented in Table 1 were tested, with the windows opening lengths for each period summarized in Table 2. Contrary to the rest of the campaign, only 11 sensors were used during this day, namely those presented in Fig. 2 (left). The temporal evolution of the average CO_2 concentration measured in the classroom is presented in Fig. 4, along with the changes in key variables explored during this second day. Appendix A of the Supplementary material includes a video showing the temporal and spatial evolution of CO_2 within the classroom (file *'20201211_CO2evolution_H=150 cm.avi'*).

In this case, the door was left open throughout all the school day but for a 45-min interval (10:30–11:15), where it was closed remaining all the other variables constant. The quick increase in CO_2 levels registered during that short interval of time (from 650 to 1200 ppm) confirms again the effectiveness of cross-ventilation. Regarding occupancy and level of activity, Fig. 4 further supports the conclusions extracted from Fig. 3. Namely, the higher level of activity displayed by pupils at the beginning and end of the school day leads to distinct increases in CO_2 concentration, with occupancy showing a clear (and practically immediate) correlation with CO_2 levels in the classroom. As for the different openings listed in Table 2, the first window setting was analogous to that used in the first day (i.e., 80 cm total opening distributed between both facades). Again, this configuration is found in Fig. 4 to provide low CO_2 levels, stabilizing at around 580 ppm for a low level of activity (regular lesson).

The closing of all the windows in the north facade (at 9:50) leads to an increase to ~660 ppm. This change from ventilation through two facades to only one also worsens the distribution of outdoor air across the room and triggers a greater difference between sensor readings (as observed in the video in the Supplementary materials as well as from the wider standard deviation band plotted in Fig. 4). The sharp variations caused by two essentially transient events (the aforementioned door closure and the mid-day break), affect the CO_2 recorded for the third strategy (35 cm openings in the north facade), hindering direct comparison with the previous conditions. It is clear from Fig. 4 that, with a total opening of only 45 cm, the break is insufficient for removing the CO_2 accumulated through the previous poor ventilation conditions. Even if a slight improvement is noted when changing again to 60 cm

Table 2
Windows openings (in cm) for each ventilation strategy tested in the second day of field measurements.

	W1	W2	W3	W4	W5	W6	W7
Distrib. 80 cm	15	15	15	0	15	10	10
Side W 45 cm	15	15	15	0	0	0	0
Side N 35 cm	0	0	0	0	15	10	10
Distrib. 60 cm	10	10	10	0	10	10	10
Distrib. 90 cm	15	15	15	0	15	15	15

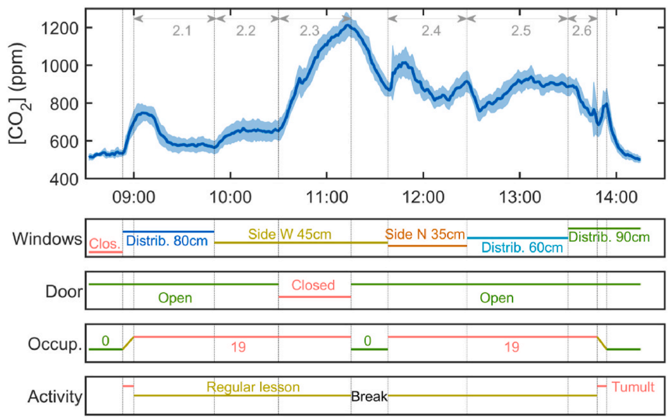

Fig. 4. Temporal evolution of CO_2 levels and key variables in the second day of field measurements for the periods defined in Table 1. The shaded area represents ± one standard deviation of all sensors in the room.

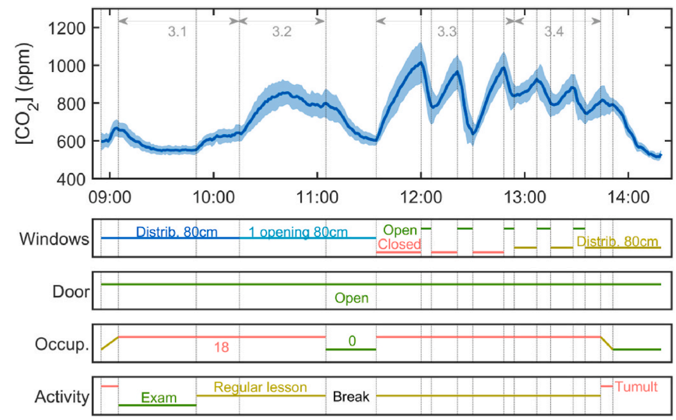

Fig. 5. Temporal evolution of CO_2 levels and key variables in the third day of field measurements for the periods defined in Table 1. The shaded area represents ± one standard deviation of all sensors in the room.

distributed, it is only when the total opening is increased to 90 cm that the CO_2 levels are clearly reduced.

3.1.3. Third day: continuous vs. intermittent ventilation

As summarized in Table 1, the first half of this day was focused on comparing two different strategies for a fixed total opening of 80 cm: only one window vs. *distributed* among the 6 windows. After the mid-day break, the aim was to explore intermittent and mixed ventilation through the aforementioned 5–15 min routines. The objective here is to investigate the dynamics of natural ventilation in this particular setting, in order to verify if the intermittent ventilation protocols recommended by some authorities (e.g., (Gobierno de Aragón, 2020)) can provide adequate ventilation under the explored conditions. The windows openings used for each strategy are given in Table 3. The temporal evolution of CO_2 concentration measured in the classroom is displayed in Fig. 5, along with the changes in key variables.

As it can be observed in Fig. 5, the door was left open throughout all the school day, so that this variable does not affect the comparison among strategies, satisfying always cross-ventilation conditions. The entrance of students a few minutes before 9:00 is marked again by a distinct rise in CO_2 levels, followed by a progressive decrease as pupils begin an exam at 9:05. Quite stable conditions are achieved, with CO_2 concentration around 550 ppm. The end of the exam at 9:50 causes an increase in the recorded levels, which stabilize at ~630 ppm. Note that these values are consistent with those reported in previous sections for the same conditions (80 cm distributed openings). By contrast, the change from *distributed* to single-opening ventilation at 10:15 causes a clear rise in the measured CO_2, which appears to stabilize around 800 ppm. As it was previously discussed, this change also induces a greater dispersion between sensor readings. Namely, the average standard deviation calculated from the 17 sensors rises from 25.5 ppm (period with 80 cm distributed) to 61.0 ppm (period with 80 cm in one window). In the next section, the portions of the room with poorer and better ventilation conditions will be analyzed.

After the mid-day break, the ventilation mode changes from continuous to intermittent. The closure of all the classroom windows upon the pupil's entrance immediately causes a sharp boost in the recorded CO_2, reaching 1015 ppm at 12:00. Then, a 6-min-long full opening of four windows (see Table 3) reduces this level to around 780 ppm, being afterwards increased to 970 ppm due to the following 15-min closure. The 9 min elapsed between 12:21 to 12:30 with the four open windows reduces again this level to around 640 ppm. In general, it can be observed that both the accumulation and dilution of CO_2 within the classroom show quick dynamics. From the presented data it is clear that CO_2 accumulation transients show a timescale of the same order as that of the dilution process with four fully opened windows (4.96 m^2 opening to outdoor air). Thus, it can be said that in this classroom (which is thought to be representative of typical Spanish school settings), the occasional opening of windows is clearly insufficient to achieve good ventilation. Even by opening windows every 15 min (a strategy quite unlikely to be implemented in most schools due to the inconvenience of manually operate windows every few minutes), the average CO_2 levels displayed in Fig. 5 are clearly higher than those recorded for continuous ventilation with sufficient opening areas (e.g., a total aperture of 1.24 m^2). As it will be also concluded in the following section, the quick accumulation of exhaled air in the classroom makes continuous ventilation necessary to reduce airborne contagion risk. The final part of the session displayed in Fig. 5 explored a mixed strategy: full opening of four windows during 5 min followed by 15 min with 10 cm opening per window (see Table 3). This strategy improved natural ventilation conditions, as the average CO_2 level shows a clearly decreasing trend after 12:48.

Table 3
Windows openings (in cm) for each ventilation strategy tested in the third and fourth days of field measurements.

	W1	W2	W3	W4	W5	W6	W7
Distrib. 80 cm	15	15	15	0	15	10	10
One opening 80 cm	0	80	0	0	0	0	0
4 windows open	0	80	80	0	80	80	0
Distrib. 40 cm	0	10	10	0	10	10	0

3.1.4. Fourth day: continuous vs. intermittent ventilation

The objective in the fourth test day was to further study and compare intermittent, continuous and mixed ventilation modes (see Table 1). To that end, the set of windows openings were the same as those provided in Table 3. The temporal evolution of CO_2 concentration, presented in Fig. 6, confirms the already discussed behaviors when using intermittent ventilation. That is, the characteristic times for CO_2 accumulation and dispersion phenomena are both quite short, and of the same order. Upon the entrance of the first students at 8:55, the CO_2 levels inside the classroom are very low (530 ppm). However, after only 15 min with closed windows, CO_2 levels reach 1000 ppm, and would have grown even further had the windows not been opened at 9:10. The same ventilation cycle was repeated four times, with all the other variables kept unchanged, resulting in a notably repeatable behavior with CO_2 concentrations varying between 750 and 1000 ppm. Assuming (on an order-of-magnitude and simplified approach) a linear behavior in the CO_2 evolution during these very short time lapses, CO_2 decreases at a rate of 50.5 ppm/min when the four windows are fully open whereas, when the classroom is completely closed, these levels increase by a rate

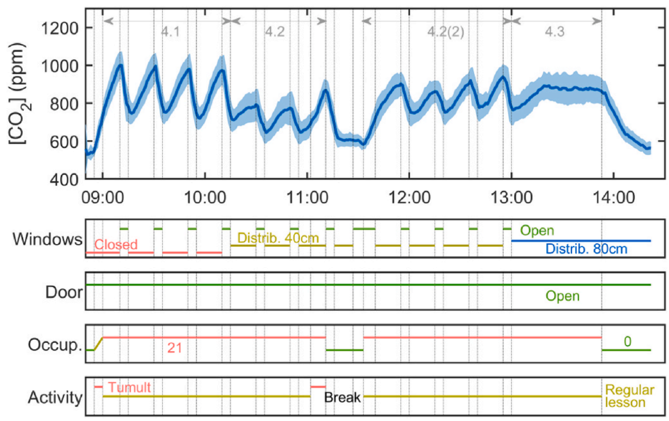

Fig. 6. Temporal evolution of CO_2 levels and key variables in the fourth day of field measurements for the periods defined in Table 1. The shaded area represents ± one standard deviation of all sensors in the room.

of 16.0 ppm/min. It is worth to note that these values are found to be quite repeatable, with standard deviations of 1.5 and 0.9 ppm/min respectively. The only exception is the first upward ramp (from 8:55 to 9:10), where a considerably greater rise in CO_2 was recorded (30.9 ppm/min). This is explained by the high level of activity displayed by students when entering the classroom without the teacher's presence. Thus, this first interval has not been included to calculate CO_2 variation rates indicative of regular lesson conditions.

At 10:15 the ventilation strategy changes to a mixed cycle. Consistently with the previous day, this change noticeably improves ventilation in the room, and the average CO_2 concentration decreases during the first 2 cycles. However, a tumult in class (i.e., students standing up, talking aloud and shouting) recorded just before the mid-day break distinctly boosts CO_2 levels, pointing again to the clear importance of occupants' level of activity. After the break, the CO_2 concentration rises again, swinging between 750 and 900 ppm, with a slightly increasing trend. These results contrast with the previously mentioned 2 first cycles, where CO_2 levels were significantly lower. The change to a continuous ventilation mode with 80 cm distributed openings at 13:00 does not achieve either to lower CO_2 concentration, reaching a quite constant value around 875 ppm. The level of activity in the class during this second part of the school day was found to be regular (yellow level in Fig. 6), and therefore the differences with previously presented results under the same conditions should be sought in complex variables such as the airflow patterns within the building, affected not only by the classroom and outdoor conditions (which were duly registered), but also by those of the neighboring rooms and corridors. Especially relevant would be to ascertain if the studied classroom acts as entrance of outdoor air to the building or as an outlet for the air coming from other spaces (which would already polluted with CO_2 and other bio-effluents). A complete and integrated study of the whole school building (or at least, of the closest classrooms and corridors) would be required to understand the airflow patterns between rooms. This is clearly out of the scope of the current work, although it is worth to stress here the complexity of naturally ventilating a building, since all spaces are interlinked, acting some rooms as entrances and others as outlets for the circulating airflows.

3.2. *Influence of the sensor placement*

This section studies the differences found among the 17 sensors installed in the classroom. As detailed in the Experimental Method, these sensors were distributed in order to characterize differences in terms of zones and heights within the room. The following two subsections address both cases.

3.2.1. *Differences in height*

To ascertain differences among heights, Fig. 7 presents the deviations (D_i, as defined in Equation (1)) calculated for all the 9 sensors distributed in the 3 × 3 matrix depicted in Fig. 2 (right). These deviations are calculated separately for all the ventilation strategies explored in the previous section, only removing the time lapses when the classroom remained empty.

As illustrated in Fig. 7, the measured CO_2 concentration exhibits consistent variations with the sampling height. On the one hand, sensors installed at 0.75 m (H7, H8 and H9) provide noticeably lower CO_2 values than the plane average, with deviations of −60.8, −42.4 and −39.5 ppm respectively. On the other hand, sensors mounted at 1.5 m (H4, H5 and H6) show the opposite behavior, with distinctly higher values compared to the average. Finally, the upper analyzers (H1, H2 and H3, mounted at 2.2 m) show deviations <10 ppm, displaying thus CO_2 concentrations much closer to the plane average. As previously discussed, the values shown in Fig. 7 correspond to global deviations calculated by considering all the explored ventilation strategies.

However, it is also clear that the different strategies explored throughout this work can induce differences in the CO_2 distribution, and thus, the deviation D_i for a given position can significantly vary between strategies. To further analyze this potential variability between conditions, Table 4 presents the deviations calculated for each sensor position for all the time periods defined in Table 1.

These data further confirm the aforementioned global tendencies, since it is clear that the sensors located at 0.75 m provide significantly below-average values for practically all the explored time periods, whereas the opposite can be said for the sensors deployed at 1.50 m. Among the latter, only the position H6 displays a more mixed behavior, with negative deviations for time periods of continuous, *distributed* ventilation (1.1, 1.1(2) and 3.1). This is consistent with the location of H6 being close to windows W5 and W6 (see Fig. 2), more easily reached by outdoor air than H4 and H5. The sensors installed at 2.2 m present a much closer behavior to the plane average, showing deviations generally small and, thus, being quite representative of the average CO_2 levels in the room. In order to complement the data presented in Table 4, the reader can also gain information on the effect of the sampling height by means of the CO_2 temporal evolution plots included in the first section of the Appendix B in the Supplementary material.

3.2.2. *Differences among zones*

Analogously to the previous analysis on heights, the 11 sensors presented in Fig. 2 (left) were employed to ascertain differences among different zones of the classroom. Fig. 8 illustrates the deviations calculated through Equation (1) for all the ventilation strategies explored.

In general, global deviations presented in Fig. 8 are considerably lower than those reported in Fig. 7. This would point to a greater importance of the sampling height compared to the sampling zone, at least for the set of conditions explored in this work. The obvious exception would be the sensors on the walls (P1 and P2 in Fig. 8). In

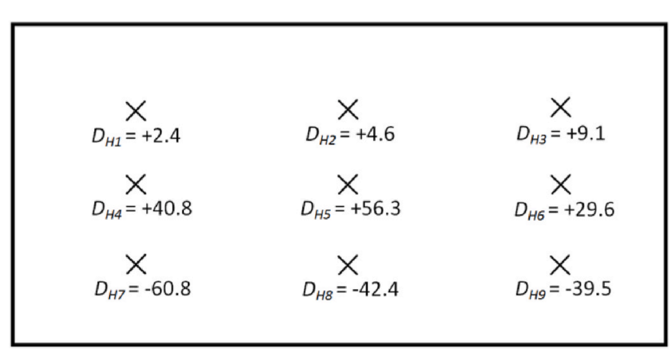

Fig. 7. Global deviations (in ppm CO_2) calculated for each sensor during the time lapses when the class was occupied.

Table 4
Deviations calculated for each sensor position (D_i) for the different periods defined in Table 1. Cells have been colored according to their numerical value in D_i: red colors highlight positive deviations and green colors negative ones.

ID Cond.	Δt (min)	D_{H1} (ppm)	D_{H2} (ppm)	D_{H3} (ppm)	D_{H4} (ppm)	D_{H5} (ppm)	D_{H6} (ppm)	D_{H7} (ppm)	D_{H8} (ppm)	D_{H9} (ppm)
1.1	103	+11	+5	+11	+42	+25	-16	-39	-23	-18
1.2	17	-20	-21	+4	+36	+42	-6	-39	+6	-1
1.2(2)	65	-20	-12	+3	+53	+73	+16	-67	-32	-14
1.1(2)	20	+61	+49	+10	+17	-10	-31	-38	-21	-37
3.1	70	+8	+15	+6	+17	+11	-15	-12	-17	-12
3.2	50	-2	-13	-7	+58	+65	+64	-51	-45	-69
3.3	80	+14	+15	+21	+72	+73	+50	-74	-75	-96
3.4	50	+2	+7	+21	+62	+63	+49	-86	-73	-44
4.1	70	+18	+23	+50	+29	+41	+49	-83	-71	-55
4.2	50	-5	+7	-6	+18	+93	+38	-93	-23	-29
4.2(2)	80	-14	-9	-4	+27	+80	+65	-70	-41	-34
4.3	50	-14	-7	-18	+40	+100	+62	-69	-51	-42
Global	**705**	**+2.4**	**+4.6**	**+9.1**	**+40.8**	**+56.3**	**+29.6**	**-60.8**	**-42.4**	**-39.5**

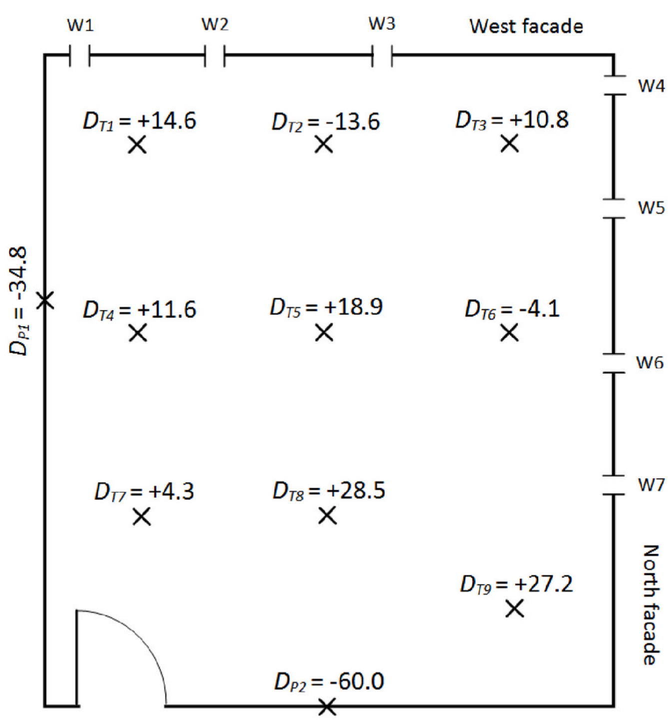

Fig. 8. Global deviations (in ppm CO_2) calculated for each sensor during the time lapses when the class was occupied.

those cases, global deviations become significant, with these sensors providing 34.8 and 60.0 ppm below the average. The location of the most commonly used openings throughout this study (W1, W2, W3, W5, W6 and W7) can explain the slightly lower CO_2 concentration recorded at positions T2 and T6, since they are installed between these openings. On the contrary, sensors T8 and T9 display the poorest ventilation conditions in Fig. 8, with positive deviations of 28.5 and 27.2 ppm respectively. Their location, far away from expected flow paths between the windows and the door, might explain these higher CO_2 values. To gain further insight into the CO_2 distribution within different zones for each ventilation strategy, Table 5 presents the deviations calculated for each sensor position for all the periods defined in Table 1.

In this case, a greater variability can be found when compared to Table 4. Some sensors, such as T2 and T3, show a large dependency on the condition, with deviations ranging from quite negative values to more than 100 ppm above the plane average. It is worth to note that periods with a *distributed* and continuous ventilation (e.g., 1.1, 2.1, 2.5, 2.6 or 3.1) tend to favor lower CO_2 levels in these positions, being intermittent strategies (e.g., 3.3, 3.4, 4.1 or 4.2) responsible for the positive deviations. Other locations provide more consistent behaviors throughout all the evaluated time lapses. The clearest examples are the sensors located on the walls (P1 and P2), which display considerably lower CO_2 measurements compared to their counterparts for most of the explored conditions. This may be due to the fact that, although the circulation of outdoor air is not very different from other zones, these sampling locations are farther away from CO_2 generators (occupants), resulting in a consistent bias toward lower values. Analyzers T8 and T9 (and, to a lesser extent, also T1, T4, T5 and T7) typically show values above the average. On the contrary, sensor T6 displays distinctly lower values compared to other analyzers in the zone, possibly due to the closeness of this sensor to windows W5 and W6. Besides the data presented in Table 5, the plots showing the evolution of CO_2, included in the second section of Appendix B in the Supplementary material, provide further information on the effect of the sampling zone.

3.3. Limitations and final remarks

- The reported results are intended as a case study in order to gain further insight on the effect of different natural ventilation strategies and their impact on indoor CO_2 spatial distribution, for which not much information was available by the time this campaign was conducted. The classroom selected for the study can be considered representative of Spanish Primary Schools, but the reported behaviors might vary for rooms with different size, occupancy, number/size of windows, etc. Therefore, the analysis of other situations of interest (e.g., a representative University classroom, office or hospital ward) may yield useful information for such settings.
- Outdoor weather (and particularly, wind) plays a relevant role in the natural ventilation of indoor spaces. Measurements in this study were performed with low and similar wind velocities, aiming to minimize the effect of this uncontrolled parameter on the results. For any given opening setting, the air change rate is expected to rise as outdoor wind velocities increase.

Table 5
Deviations calculated for each sensor position (D_i) for the different periods defined in Table 1. Cells have been colored according to their numerical value in D_i: red colors highlight positive deviations and green colors negative ones.

ID Cond.	Δt (min)	D_{T1} (ppm)	D_{T2} (ppm)	D_{T3} (ppm)	D_{T4} (ppm)	D_{T5} (ppm)	D_{T6} (ppm)	D_{T7} (ppm)	D_{T8} (ppm)	D_{T9} (ppm)	D_{P1} (ppm)	D_{P2} (ppm)
1.1	103	+3	-6	-60	+35	+18	-24	+51	+61	-11	-62	-5
1.2	17	+4	+36	-16	+27	+34	-14	+21	+38	-33	-58	-38
1.2(2)	65	+11	+60	-22	+30	+50	-7	+7	+42	-60	-60	-50
1.1(2)	20	+13	-15	-115	+7	-20	-42	+21	+76	+21	-18	+72
2.1	50	+14	-69	-43	+17	-13	-17	+19	+38	+60	+9	-15
2.2	40	+10	-110	+4	+42	+34	-3	+34	+31	-12	+25	-55
2.3	45	+24	-88	-35	+51	+32	+41	+2	+49	+37	-47	-66
2.4	49	+66	-27	+14	+4	-9	+1	+6	+32	+45	-63	-69
2.5	63	+69	-70	-16	+13	+10	-14	+12	+37	+41	-39	-44
2.6	18	+60	-70	-50	+23	+6	-61	+44	+41	+47	-36	-4
3.1	70	+13	-64	-3	+4	-2	-28	+25	+27	+35	+9	-16
3.2	50	0	+40	+69	+11	+18	+16	-16	+17	-7	-40	-107
3.3	80	+30	+27	+28	+26	+26	+3	-26	+10	+6	-21	-108
3.4	50	-21	-9	+32	+11	+13	-1	-9	+36	+33	-32	-54
4.1	70	+3	+22	+109	-15	-2	+6	-50	-3	+48	-22	-95
4.2	50	+18	+32	+76	-19	+56	+1	-57	-31	+92	-58	-111

- Due to practical limitations, sensors could only be installed about 30 min before the arrival of students, being uninstalled shortly after their departure. However, the recording of CO_2 concentration before and after school hours would provide useful data on the background indoor levels.
- Even if this study addresses a detailed characterization of a single classroom, it is worth to emphasize the complexity of natural ventilation inside buildings. A complete and integrated study of the whole building (i.e., by simultaneously monitoring different rooms and corridors) would be required to fully understand airflow patterns between spaces.
- Despite the broad variability in building characteristics, wind, etc, CO_2 monitoring appears as a most useful tool to evaluate ventilation conditions and to drive any regulation method (either manual or automatic) so as to achieve air change rates that ensure healthy conditions and, at the same time, avoid excessive ventilation rates that could lead to unnecessarily high energy consumption and/or thermal discomfort.

4. Conclusions and recommendations

This study addresses a detailed characterization of the CO_2 levels reached within a naturally-ventilated Primary Education classroom. To this end, 17 sensors have been installed at different locations in this room, monitoring CO_2 concentration under normal teaching activity in winter and by employing different ventilation strategies. This is thought to provide useful data not only on the most effective way of ventilating this typology of classroom, but also on the spatial distribution of CO_2. Furthermore, the experimental data might be used to validate modeling tools addressing natural ventilation and airborne contagion risk. These conclusions can be also considered as recommendations for similar setups, achieving an efficient indoor air renewal with outdoor air as a general and relevant objective.

The data clearly confirm that a *continuous* ventilation is absolutely necessary for achieving acceptable ventilation conditions. The accumulation of CO_2 (and thus, of other exhaled bio-effluents) has proven to be considerably fast and of the same order as the CO_2 evacuation rate with four windows fully open (4.96 m^2 opening to outdoor air). CO_2 concentration increased at a rate around 16 ppm/min just after closing all windows in the classroom. These results show that intermittent ventilation strategies where windows remain closed for an extended period of time are clearly insufficient to effectively limit COVID-19 airborne transmission.

The results also highlight the key importance of the door opening to achieve *cross-ventilation* conditions. In the author's opinion, this aspect is often overlooked in practice, despite the fact that it usually plays an essential role in the air circulation within the room. Situations with good ventilation (e.g., average CO_2 concentrations below 700 ppm) sharply deteriorate after the door closure, improving quickly as soon as the door is opened again. These results are in line with the recommendation of cross-ventilation as the optimal strategy to naturally ventilate indoor spaces.

Moreover, for a fixed total open area, *distributed* ventilation strategies, by apportioning it among the available windows, afford a more efficient use of the outdoor air admitted into the classroom. Under such conditions, 6 openings with 1.24 m^2 total exposure achieved a good ventilation level for most cases under the studied configuration. The change from this distributed setting to the same exposure area concentrated in only one window, in both cases in a cross-ventilation configuration with an open door, induced not only a distinct rise in average CO_2 levels, but it also significantly increased differences among different room zones.

Another relevant variable that was studied is the activity of the occupants. Situations when pupils remained calmed and quiet (such as during exams) provided a substantial decrease in CO_2 levels, whereas scenarios when students were more active and agitated yielded a distinct and immediate rise in CO_2. Thus, it is clear that, for cases with higher metabolic activity of the occupants, the ventilation rate should be increased to keep low CO_2 levels.

Regarding the differences found between the 17 sensors installed in the classroom, a clear and quite consistent dependency on the sampling height was found. Analyzers installed at 0.75 m above the floor provided lower CO_2 levels than the average, whereas sensors at 1.5 m yielded noticeable higher ones. The third explored sampling height (2.2 m) produced results much closer to the room average. Thus, the installation of sensors at this height would, under this configuration, provide representative results of the average level in the classroom. Mounting sensors at 2.2 m also has the advantage of being unobtrusive for students and teachers as well as less prone to be affected by breath plumes, and therefore it can be considered to be a good option for CO_2 sampling.

The sampling zone within the room was found to be less relevant than the height, with considerably lower differences between measuring positions and a higher dependency on the ventilation mode and the induced flow paths. The more marked differences were found for the two sensors installed on the walls, which consistently provided lower CO_2 levels than the average for the vast majority of the explored conditions. Thus, it is worth noting that, even if the installation of sampling devices on walls appears to be a convenient choice, it might underestimate the actual CO_2 levels inside the room.

CRediT authorship contribution statement

Álvaro Muelas: Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Pilar Remacha:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources. **Antonio Pina:** Methodology, Formal analysis, Investigation, Resources. **Eduardo Tizné:** Methodology, Software, Formal analysis, Investigation, Resources. **Said El-Kadmiri:** Investigation. **Ana Ruiz:** Investigation. **Diego Aranda:** Investigation, Resources. **Javier Ballester:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2022.119176.

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