Journal of Building Engineering 63 (2023) 105459

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Full length article

Variations in classroom ventilation during the COVID-19 pandemic: Insights from monitoring 36 naturally ventilated classrooms in the UK during 2021

Henry C. Burridge [b,*,1], Stavros Bontitsopoulos [a,b,1], Christopher Brown [c], Holly Carter [d], Katherine Roberts [b], Carolanne Vouriot [b], Dale Weston [d], Mark Mon-Williams [e], Natalie Williams [d], Catherine Noakes [a]

[a] University of Leeds, School of Civil Engineering, Woodhouse, Leeds LS2 9JT, UK
[b] Imperial College London, Department of Civil and Environmental Engineering, Exhibition Rd, South Kensington, London SW7 2BX, UK
[c] University of Leeds, Centre for Applied Education Research, Woodhouse, Leeds LS2 9JT, UK
[d] UK Health Security Agency, Behavioural Science and Insights Unit, Wellington House, 133-155 Waterloo Road, London SE1 8UG, UK
[e] University of Leeds, School of Psychology, Woodhouse, Leeds LS2 9JT, UK

ARTICLE INFO

Keywords:
Indoor air quality
UK schools
Primary & secondary education
CO_2 monitors
Natural ventilation
Airborne disease transmission
COVID-19
Infection risk

ABSTRACT

Seasonal changes in the measured CO_2 levels at four schools are herein presented through a set of indoor air quality metrics that were gathered during the height of the COVID-19 pandemic in the UK. Data from non-intrusive environmental monitoring units were remotely collected throughout 2021 from 36 naturally ventilated classrooms at two primary schools and two secondary schools in England. Measurements were analysed to assess the indoor CO_2 concentration and temperature . Relative to UK school air quality guidance, the CO_2 levels within classrooms remained relatively low during periods of warmer weather, with elevated CO_2 levels being evident during the colder seasons, indicating lower levels of per person ventilation during these colder periods. However, CO_2 data from the cold period during the latter part of 2021, imply that the per person classroom ventilation levels were significantly lower than those achieved during a similarly cold weather period during the early part of the year. Given that the classroom architecture and usage remained unchanged, this finding suggests that changes in the ventilation behaviours within the classrooms may have altered, and raises questions as to what may have given rise to such change, in a year when, messaging and public concerns regarding COVID-19 varied within the UK. Significant variations were observed when contrasting data, both between schools, and between classrooms within the same school building; suggesting that work is required to understand and catalogue the existing ventilation provisions and architecture within UK classrooms, and that more work is required to ascertain the effects of classroom ventilation behaviours.

1. Introduction

Following the Christmas holiday period of 2020, UK school attendance was severely restricted due to the national 'lockdown' imposed to curb the spread of the COVID-19 pandemic, including the cessation of in-person schooling for all but the most vulnerable

* Corresponding author.
E-mail addresses: h.burridge@imperial.ac.uk (H.C. Burridge), s.bontitsopoulos16@imperial.ac.uk (S. Bontitsopoulos).
[1] Joint lead author.

https://doi.org/10.1016/j.jobe.2022.105459
Received 29 July 2022; Received in revised form 17 October 2022; Accepted 21 October 2022
Available online 15 November 2022
2352-7102/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Table 1
Information for the schools and classrooms participating in the environmental monitoring study. School names have been anonymised to protect identifying details.

	School ID	No. sensors/ classrooms	Sensor/ classroom ID	Comments
Primary schools (children aged 4–11 years old)	PA PB	6 8	{2, 4 → 8} {1 → 8}	Sensors PA−1 and PA−3 were excluded from the analysis due to inconsistent readings and indications that they have been installed in non-classroom environments.
Secondary schools (children aged 11–18 years old)	SA SB	8 12	{1 → 6, 9 → 12} {1→12}	SA−7 and SA−8 were similarly excluded as their respective rooms saw different usage (a gym and an administrative space) according to the study metadata.

children and those of 'key workers' [1]. Restrictions such as these and the increased acceptance that COVID-19 could be spread via the airborne route [e.g. 2,3] resulted in an increased focus on the ventilation of enclosed spaces including learning environments within schools during Spring 2021 when restrictions were eased. Taking motivation from the growing awareness around indoor air quality, we report an analysis of the (per person) ventilation of four UK schools during 2021, from the post-lockdown return to full schooling in England (8th March 2021) and until the end of the calendar year (i.e. 31st December 2021) (see Table 1).

Ventilation is recognised as an important proactive measure to mitigate the spread of the SARS-CoV-2 virus which causes COVID-19 [4] and to provide a healthy and productive learning environment [5,6]. Historically, studies have sought to evidence any links between poor ventilation and sickness absence [7] and lower academic performance in schools [e.g. 8–10], but throughout the year 2021 the pandemic brought the epidemiological implications of classroom ventilation into even sharper focus. Assessment of classroom air quality in UK schools has become an increasing concern throughout the pandemic, culminating in the large-scale deployment of CO_2 monitors by the UK's Department for Education [e.g. 11] in late 2021; these monitors only display data in-room and do not record air quality parameters. Higher CO_2 levels can be an indicator of more restrained ventilation behaviours in classrooms, particularly those that are naturally ventilated. This behaviour can reduce air exchange, and may be a particular challenge during the winter months due to the need to shield the school occupants from the lower outdoor temperatures, in a way that retains thermal comfort and also preserves energy consumption. Reduced ventilation provisions may have a number of health implications including an increased risk of airborne transmission of infection. Measurement of CO_2 as a proxy for per person ventilation levels in school classrooms and other settings has gained particular attention during the pandemic [12]. These methods assess the expected exposure to rebreathed air (i.e. air that has been exhaled by other individuals) via CO_2 as a proxy for the room fresh air change rate and can express this as an estimate for the resulting airborne infection risk using Wells–Riley based models [following 13]. Links between the indoor CO_2 concentration and the likelihood of airborne infection from the SARS-CoV-2 virus in particular, have been explored by a number of studies [including 14,15] and we have previously assessed this for mechanically ventilated UK school classrooms using datasets of existing CO_2 measurements [16]. Vouriot et al. [16] present such calculations using pre-pandemic CO_2 data taken from 45 UK classrooms within 11 schools. The precise results for the risk obtained are sensitive to the parameterisation of the infection process, expressed by the 'quanta generation rate', but irrespective of this, Vouriot et al. [16] show that a reduction in per person ventilation rates systematically increases the risk in winter, roughly doubling it compared with the summer.

The current focus on the effects of indoor air quality at schools has implications that are wider than infection risk. Globally, children form a large section of the population who are most vulnerable to the impacts of air pollution and, very often, societies' aspirations postulate that children should be required to spend significant portions of their time in schools. For example, UK law requires that all children aged between four and sixteen must receive a suitable full-time education, which typically takes place in classrooms. In the present study we report the analysis of data gathered in 36 classrooms across four schools throughout the calendar year of 2021, a year which saw the UK at its height of the pandemic; to our knowledge this data set is unique in its timing and scale. The indoor air quality was monitored through non-intrusive environmental sensors, which measured the CO_2 concentration, room temperature, and relative humidity consistently. The recorded data were analysed to extract conclusions on the classroom environmental conditions throughout the calendar year, and to gain insight into the underlying causes. We highlight the seasonal variation in the 36 naturally ventilated classrooms due to factors like thermal comfort, inline with observations in previous studies [16,17]. Crucially, we also evidence significant chronological variations that match the shifting epidemiological concerns related to the pandemic, during a time when the restrictions and the national guidance imposed by the UK government along with the individual school population's exposure and familiarity with COVID-19 underwent systematic and significant change.

The study methodology and the key aspects of the data analysis are described in Section 2. The monitored indoor air quality data are examined in Section 3, with emphasis placed on the seasonal and temporal variation of CO_2, the correlation of CO_2 with temperature, and the occurrence of CO_2 'events' (i.e. instances when the indoor CO_2 concentration surpasses given thresholds), we examine variations in the data between early and late 2021, and Section 4 concludes this paper by highlighting key findings and implications of the research.

2. Study methodology

It was part of the study's aim that the monitoring be carried out in a manner which would be achievable for larger scale school air quality studies. As such, direct researcher intervention was minimised, which was also in accordance with the COVID-19 restrictions imposed on UK schools during the study period. Regular telephone and video calls were utilised to ensure that the research data gathered was of consistent quality, and where concerns arose, in-person visits to the relevant schools were arranged.

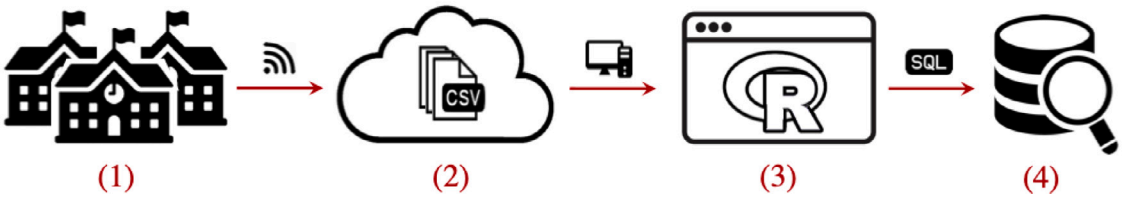


Fig. 1. Schematic of the data flow for the present research project: (1) On-site acquisition, (2) Wireless transmission to the cloud in tabulated format, (3) Remote access and processing in R, (4) Format conversion and storage in searchable SQL database.

Table 2
Definitions of the weather periods used within the analysis and the corresponding mean outdoor temperature during each weather period, $\overline{T_{out}}$. We abbreviate 'academic year' to 'AY'.

Date period	Designation	$\overline{T_{out}}$
Return to full schooling in March 2021		
08/Mar–30/April/2021	Cold period 1	7.0 °C
01/May–28/May/2021	Transitional period 1	10.0 °C
31/May–23/Jul/2021	Warm period 1	16.5 °C
Summer break between AY 2020–2021 and AY 2021–2022		
03/Sep–26/Sep/2021	Warm period 2	15.7 °C
27/Sep–31/Oct/2021	Transitional period 2	11.9 °C
01/Nov–17/Dec/2021	Cold period 2	6.8 °C

2.1. Sample size

This pilot study has been carried out by supplying environmental monitors to 36 classrooms[2] across four schools in the counties of West Yorkshire and Lancashire in Northern England. Data acquisition commenced early in 2021 and continued for the rest of the calendar year. All classrooms in the study were naturally ventilated with ventilation provided by occupants manually opening and closing windows and doors. The participating schools were categorised into two groups, according to the stage of formal education that they offered; in the UK, 'primary schools' provide education for children aged four to eleven, and 'secondary schools' educate children aged eleven to eighteen. The study included two schools in each category which are designated PA, PB and SA, SB for the primary and secondary schools respectively.

The number of schools and classrooms included in the investigation was carefully selected to ensure that the project was delivered efficiently, as well as to reflect a balanced approach with regard to the costs and resources required to facilitate the research. The selected sample size compares favourably with relevant studies reporting statistically significant results based on CO_2 monitoring in educational settings. For example, the studies of Bakó-Biró et al. [8,9],Clements-Croome et al. [10],Wargocki and Da Silva [18] and Di Gilio et al. [19] report observations based on data gathered from between 3 and 16 classrooms over relatively short time periods (typically 2–3 weeks). As such, the measurements gathered in the current investigation are robust in terms of the sample size and the study duration, as evidenced by the statistical significance of the results reported herein (see Section 3.4).

2.2. Installed monitors

For the purposes of the present investigation, the four participating schools were provided with non-intrusive monitors, i.e. those without any in-room displays (in this case *Sensair EXPLORA* CO_2 monitors), that recorded time series of the CO_2 concentration (with an accuracy equal to the maximum of ±30 ppm, or 3% of the reading, over the range 400–10 000 ppm), temperature (with an accuracy equal to ±0.2 °C over the range 0–50 °C) and relative humidity (with an accuracy equal to ±2% over the range 10%–90%) throughout the duration of the study. One monitor was installed in each of the 36 classrooms. The data collected from these monitors were used only for research purposes, and were not visible, nor communicated, to school staff during the study. In accordance with the study aim to remain scalable and inform larger studies, and to adhere to COVID-19 restrictions in UK schools, the placement of the sensors within each classroom was carried out by school site-staff. At each school, designated personnel were given training and guidance in order to select suitable locations for each monitor. This included that the monitors should always be placed within the breathing zone, taken to be between heights of 1 m and 1.5 m from the floor, and at least 2 m away from any openable windows or doors. As the study progressed, checks of the monitors placement were allowed — this ensured that project researchers were able to check that all monitors had been suitably placed and that their location had been accurately recorded on engineering plans of the school sites.

[2] 40 is the nominal number of classrooms monitored, however data from 4 monitors where excluded from the present analysis, as the rooms where the sensors were installed saw different usage.

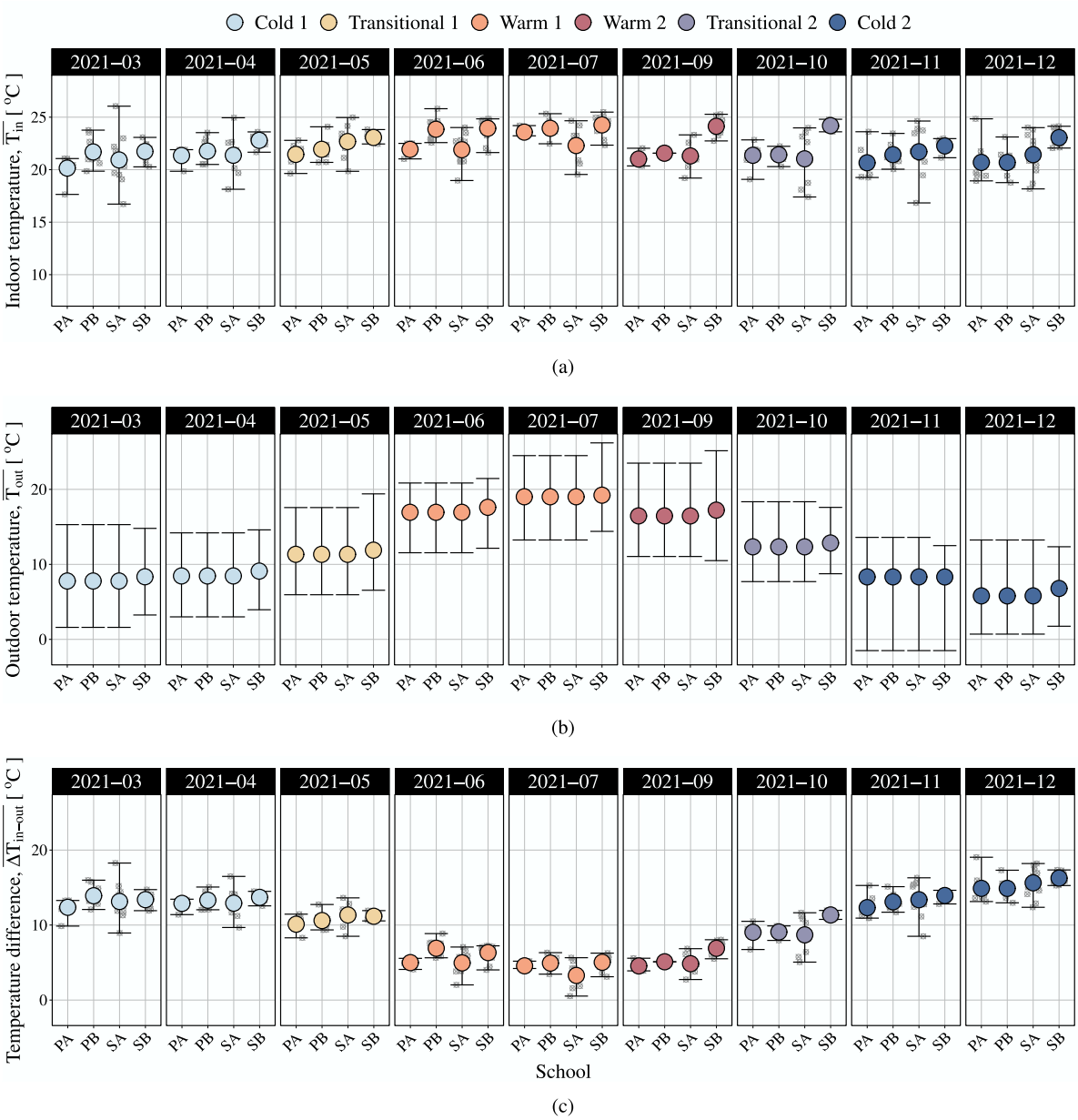


Fig. 2. The variation in monthly mean temperatures across the four schools and classrooms within. The classroom temperature during occupied hours, T_{in}, daytime mean external temperature, T_{out}, and the difference $\Delta T_{in-out} = T_{in} - T_{out}$ are marked by the large (black outlined) circles when averaged per month and per school. Where appropriate, monthly averaged classroom values are faintly marked by small circles — with the maximum and minimum classroom means highlighted by the interval ranges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Measurements were stored in 5-min averages. The analysis detailed herein concerns only data recorded during the 'occupied hours' defined to be between 9 am and 4 pm by the UK Government's Department for Education [20]; individual school calendars were used to ensure data was only included from a particular school when that site was operational. The timings of the occupied hours have been adjusted further according to school-specific religious and cultural variations that became apparent; e.g. to account for timetable changes that enable no teaching on Friday afternoon's for particular religious schools. These adjustments were informed by the official timetables gathered from the schools. In so doing, the reported analysis concerns only times when the schools were occupied and operational.

Although it was not feasible to measure occupancy of the classrooms on a daily basis during the study, information obtained from the participating schools indicated that the occupancy was typically between 27 and 33 individuals (25–30 pupils and 1–3 staff members) in both primary and secondary schools. In the two primary schools the same pupils and teachers occupied the

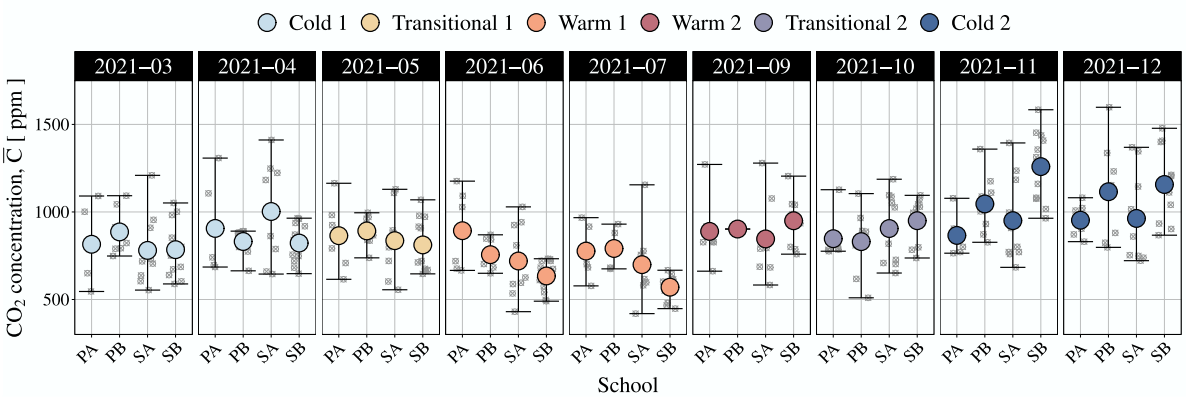


Fig. 3. Monthly mean CO_2 variation across the four schools between March and December 2021. The school averaged mean CO_2 levels during occupied hours are denoted by large coloured dots (outlined in black), while the equivalent classroom averages are marked by smaller dots, with the interval ranges highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

same classroom every day, while in the two secondary schools more variation in occupancy was expected, as teachers and pupils move between rooms for different lessons. Occupancy and type of activity were considered when determining in which classrooms to install monitors. We deliberately identified classrooms with regular usage and avoided placing monitors in spaces which were either used infrequently or which were used for specialist purposes that may have influenced the data collection (e.g. science laboratories, design technology workshops, art rooms). Moreover, we make no assertions as to the total ventilation levels being achieved in each classroom; however, monitored CO_2 levels are widely accepted as being broadly indicative of per person ventilation levels [2,12], especially in spaces with relatively long duration occupancy, like classrooms.

2.3. Data pipeline

The data gathered by the air quality monitors were uploaded to a cloud-based repository. This repository allowed near real-time access of the classroom air quality dataset from remote locations. The data were subsequently fed into a set of bespoke R programming scripts that were developed for the purpose of statistical processing and analysis. In addition to the processing, the scripts accounted for the scalability of the database arising from the ongoing weekly data collection — see Fig. 1 for an illustration of the data pipeline. The newest data were automatically appended onto a searchable SQL database which contained all historical observations and past statistical outputs. The SQL database also served the needs of compatibility, ease of sharing and quick access to the most up-to-date dataset, thus facilitating collaboration between the different individuals and institutions that form the working group of this study. The variation in air quality conditions over the study period was analysed by defining six periods of time, based on the mean external daytime temperature conditions as shown in 2 and discussed below.

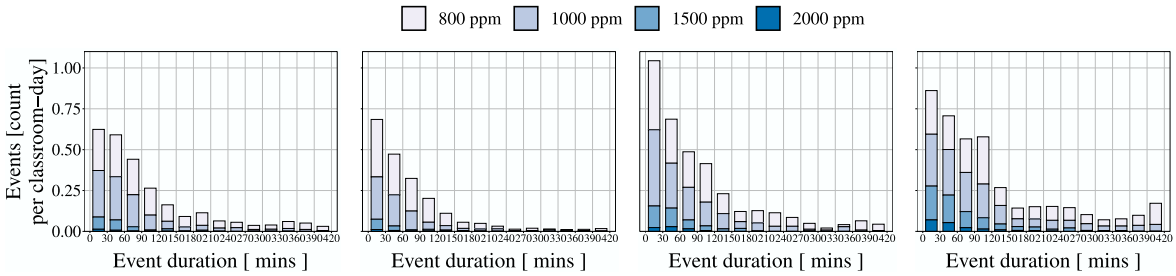
3. Results

3.1. Seasonal temperature variations within the classroom data

Fig. 2 illustrates the temperature variation for the four schools within the study from March 2021 to December 2021, i.e. the entire duration for which UK schools were open during 2021. In each pane, large coloured dots (outlined in black) mark the monthly mean values relevant to each school, where appropriate (top, (a), and bottom, (b), panes) smaller dots mark the monthly means from each classroom. The top pane (Fig. 2(a)) conveys that the mean indoor temperature, $\overline{T_{in}}$, for the majority of classrooms is retained within a relatively narrow band of approximately 20–25 °C throughout the year. Fig. 2(b) shows the corresponding mean outdoor daytime temperature,[3] $\overline{T_{out}}$, as recorded by the MET office weather station closest to each of the four schools (always within a few kilometers of each study school) [21]. The outdoor temperature records have been acquired through a public platform operated by the UK Centre for Environmental Data Analysis (CEDA), providing online access to data for use by the environmental science community. Fig. 2(c) portrays the mean monthly temperature difference, $\overline{\Delta T}_{in-out} = \overline{T_{in}} - \overline{T_{out}}$, between the indoor and the outdoor environment.

The analysis shown in Fig. 2(b) and (c), underpins our choice to highlight air quality trends by dividing the study period into intervals that correspond to the seasonal weather variations during the year. The mean external temperatures during March and

[3] Strictly the 12-h average temperature between 9 am and 9 pm based on available data, we note that it was not possible to exactly match the occupied hours defined by [20], i.e. 9 am to 4 pm, but further note that discrepancy applied throughout and so any errors introduced are likely to be broadly consistent and not affect our choice of weather period; the only metric that depends on measurements of outdoor temperature.



		Cold period 1	Warm period 1	Warm period 2	Cold period 2
Events per classroom-day	≥ 800 ppm	2.6	2	3.4	3.9
	≥ 1 000 ppm	1.3	0.8	1.7	2.3
	≥ 1 500 ppm	0.2	0.1	0.4	0.8
	≥ 2 000 ppm	0	0	0.1	0.2

Fig. 4. Histogram of CO_2 'events', i.e. instances when the measured indoor classroom concentration surpasses a given set of thresholds T_{CO_2} = {800 ppm, 1000 ppm, 1500 ppm, 2000 ppm}. The data are aggregated for all four schools and the frequency of differing duration events is presented.

April were not dissimilar to those in November and December, see Table 2. Moreover, external temperatures in June and July, were broadly similar to those in September. These facts inform our determination of 'cold', 'warm' weather periods used herein, as well as the intermediate 'transitional' periods; defined, with the start and end of each of these periods broadly coinciding with the start and end of the corresponding calendar months. The chosen designations of weather periods in this study are shown in Table 2, along with the mean outdoor temperature during each weather period.

3.1.1. Monthly CO_2 and temperature variation

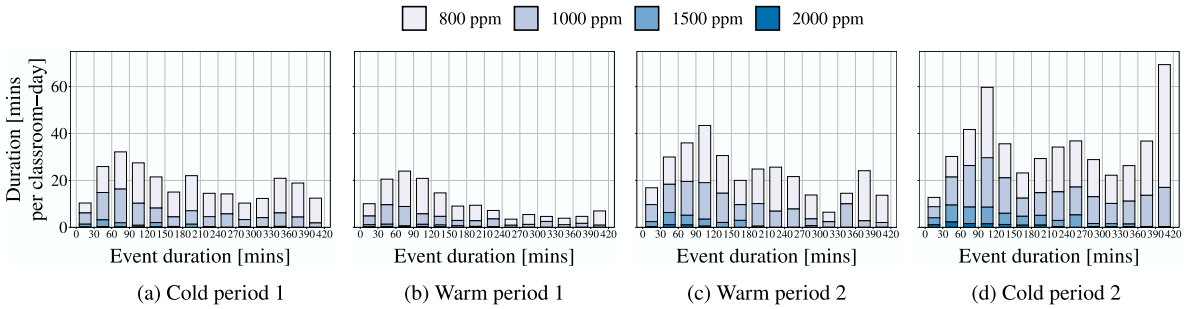
Fig. 3 illustrates the variation of the mean monthly CO_2 as measured at each school. Once again, large coloured dots (outlined in black) mark the school-level data (averaged across all the classrooms at each individual site), and smaller coloured dots, along with the interval ranges, portray the spread of the monthly mean values within the classrooms of each school.

Seasonal variations are apparent in Fig. 3, although further differences are also noticeable beyond the variation observed in the temperature data. Broadly speaking, warmer seasons correspond to lower concentrations of CO_2 (<1000 ppm). Furthermore, throughout the 'Transitional 1' period (from early May 2021) until the end of October 2021 (the start of 'Cold 2') almost all of the classrooms attained ventilation conditions that adhered to the pre-pandemic design guidance issued by the UK [20]. This guidance (Building Bulletin 101) stipulates the naturally ventilated classrooms should avoid daily average CO_2 values above 1500 ppm and further specifies that peak CO_2 concentration in classrooms should not exceed 2000 ppm (an excess of 1600 ppm above outdoor baseline) for any consecutive 20 min period per day. Notably, the data suggest that CO_2 concentrations were also relatively low during 'Cold period 1' (March and April 2021). During the subsequent, similarly cold, 'Cold period 2', there is a noticeable increase in the classroom monthly averaged CO_2 concentration levels, occasionally above ≥1500 ppm in breach of the guidelines issued by the Department for Education [20]. We investigate the statistical significance of these observations in Section 3.4.

The data presented in Fig. 2(c) indicates the scale of the driving potential for buoyancy-driven ventilation to occur, resulting from the variation, with temperature, of the densities of the indoor and the outdoor air. Therefore, the component of the forcing due to the temperature difference that contributes to driving the natural ventilation is increased during periods when the temperature difference is largest, hence all else being like-for-like, opening of the classroom windows would be expected to result in greater classroom ventilation rates during colder periods. Fig. 3, particularly during the period 'Warm 1', shows that, even when the indoor–outdoor temperature difference is smallest, these facts do not preclude adequate ventilation of these classrooms. Crucially though, the observation of increased CO_2 and the inference of lessened per person ventilation levels during colder periods (see Fig. 3) suggests that the increased potential for natural ventilation of classrooms during colder weather is negated. During these periods occupants of UK classrooms face thermal comfort challenges from the cold outdoor air.

3.1.2. Examining the implication of different CO_2 thresholds through the resulting CO_2 'events'

The following assessment considers the CO_2 conditions in the context of guidelines published by the UK Scientific Advisory Group for Emergencies (SAGE) during the COVID-19 pandemic [22], as well as the Department for Education's 'Building Bulletin 101: Guidelines on ventilation, thermal comfort and indoor air quality in schools' [20]. The SAGE guidance suggests that indoor CO_2 values below 800 ppm can be considered an indication of a 'well ventilated space', whilst consistent monitor readings that surpass 1500 ppm 'are likely to indicate overcrowding or poor ventilation'. These two thresholds represent an excess CO_2 of 400 ppm and 1100 ppm, respectively (taking a baseline outdoor environmental CO_2 concentration of 400 ppm). As highlighted above, the values stated in Building Bulletin 101 (1500 ppm and 2000 ppm) are higher than values recommended to manage infection risk in a pandemic context.



		Cold period 1	Warm period 1	Warm period 2	Cold period 2
Minutes per classroom-day	< 800 ppm	348	368	372	378
	≥ 800 ppm	161	93	189	255
	≥ 1 000 ppm	85	45	113	172
	≥ 1 500 ppm	11	6	21	49
	≥ 2 000 ppm	1	1	3	11

Fig. 5. The duration of 'events', in minutes per classroom-day, for the thresholds T_{CO_2} = {800 ppm, 1000 ppm, 1500 ppm, 2000 ppm}, as well as for the time spent below the lowest threshold (<800 ppm). The data are aggregated for all four schools and the total duration, per day, of the differing duration events is presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The advice published by SAGE and the UK Department for Education provide a reference for assessing the indoor air quality and the ventilation capacity in educational environments. At the time of this study CO_2 monitors were not widely used in schools but there were growing calls to implement them, with SAGE et al. [12] highlighting the potential to actively use CO_2 monitors to manage ventilation. From December 2021 CO_2 monitors started to be deployed to schools giving teachers and pupils the potential to access real-time displays of CO_2 levels via the government supplied monitors [11]. Using the quoted CO_2 concentration thresholds as a reference point, the classroom occupants, in particular the education staff, could act by taking measures to manually ventilate a space if high CO_2 levels were indicated by the monitors, and thereby reduce potentially adverse consequences that might be associated with poor ventilation. In the context of this guidance, and the UK Government deployment of CO_2 monitors to classrooms, it is worth asking: how frequently and for how long would teachers within these classrooms, have seen CO_2 readings exceed the thresholds, should they have already been in receipt of these display monitors during 2021, and what if those thresholds had been set differently?

The proposed CO_2 concentration thresholds have been used as a basis for performing a parametric analysis of 'events', i.e. instances when threshold CO_2 concentrations are surpassed for a given amount of time. Our study's monitored data was interrogated using a range of values that represent different thresholds (namely, T_{CO_2} = {800, 1200, 1500 and 2000} ppm), therefore covering the range of official recommendations (800, 1500 and 2000 ppm) and further including an intermediate value (1200 ppm).

Using the monitored data, histograms of the number of 'events' per classroom-day, that would have been observed in 2021, were generated and grouped by the event duration; see Fig. 4. In addition to presenting the distribution of the number of events, the total duration (per classroom-day) associated with the various event durations was also computed and plotted in Fig. 5. This latter plot illustrates, for the data from these classrooms during 2021, the minutes per classroom-day associated with each 'event' duration. Both plots illustrate the frequency with which classroom staff would have been prompted by CO_2 display monitors to initiate a response in the form of adjusting the classroom ventilation by opening or closing windows.

Fig. 4 shows that short-duration events – in which the CO_2 concentration rises above a respective threshold and then quickly returns to lower values – are much more frequent than long-duration events, irrespective of the threshold chosen. Some variation between the four weather periods is apparent (from left to right in the four panes), but whether these variations are systematic, chronological or temperature dependent, is not determinable from this presentation and the significance of these variations is also unclear. The number of events occurring per classroom-day does appear to increase during the colder periods. This increase is most noticeable on the low-threshold events (800 and 1000 ppm); for example, the increase in the number of 800 ppm events roughly doubles from 2.0 per classroom-day during 'Warm period 1', to 3.9 during 'Cold 2'. The increased occurrence of higher threshold events is also noticeable — with the count increasing from 0.1 to 0.8 for the 1500 ppm threshold, which represents poor ventilation and the need for mitigating actions according to [12].

By time-weighting these events, Fig. 5 shows that the total duration spent at CO_2 readings above each threshold (as indicated by the respective coloured areas of the histogram) systematically increases chronologically during the latter part of the year across all thresholds. 'Cold period 2' exhibits roughly double the total event time per classroom-day than that of 'Cold period 1' for readings above either 800 ppm or 1000 ppm — this highlights a significant change in the ventilation of these classrooms between March–April 2021 and November–December 2021. The change in the duration of the 1500 ppm events is also particularly notable, as it increases to 49 min per classroom-day during 'Cold period 2'. The increased duration of high-threshold CO_2 events is indicative of lower per person ventilation rates over longer periods. Furthermore, the plot illustrates a noticeable increase of long-duration, relatively low

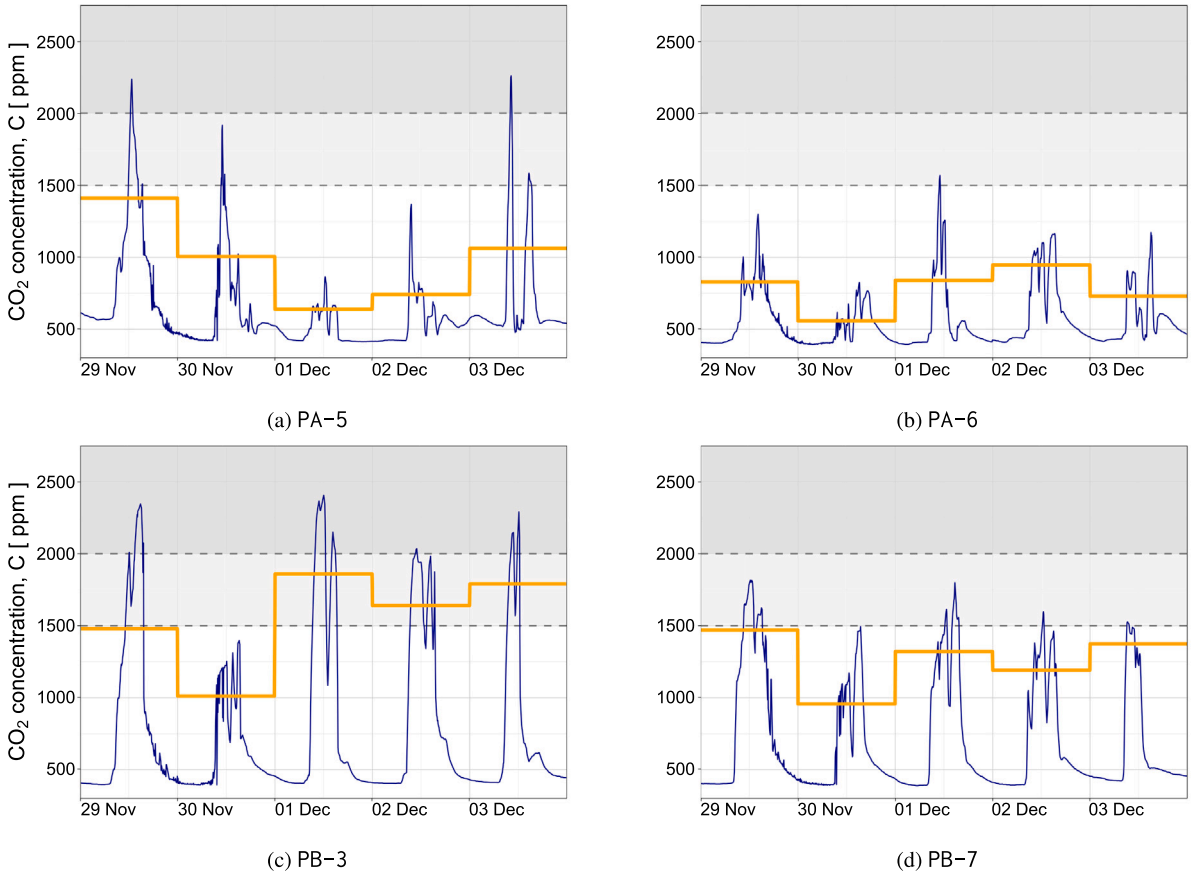


Fig. 6. Temporal variation of the CO_2 concentration for a set of representative classrooms during a weekly period from 'Cold 2'. Blue curves denote the indoor CO_2 levels and yellow horizontal lines the daily mean concentration during classroom occupied hours. Shaded areas correspond to SAGE and the Department for Education's BB101 guidance thresholds ($CO_2 \geq 1500$ ppm and 2000 ppm respectively), which indicate poor ventilation of indoor spaces.

threshold, events (lasting for up to approximately 7 h, or 420 mins) during 'Cold period 2'. Such events are observed for the 800 ppm and to a lesser extent the 1000 ppm threshold. The only exception to the systematic chronological increase of the duration of CO_2 events is presented by 'Warm period 1', which shows less time spent above all thresholds than any other period (including 'Cold period 1').

3.2. Analysis of data from representative classrooms

Along with the seasonal trends identified (Section 3.1), school-to-school variations are also evident within Fig. 3; for example, with the increase of CO_2 concentration appearing more pronounced for the PB primary and SB secondary during the 'Transitional 2' period and the 'Cold 2' period. It is unclear what drives these variations in school-to-school measurements; amongst a host of potentially confounding factors are: differing school characteristics (e.g. occupancy profiles), variations in building design and quality, differences in the approach to managing ventilation in each school.

In addition to seasonal and school-to-school variations, differences are also apparent between the individual classrooms of each given school. The relatively broad spread of each classroom's (mean) CO_2 concentrations around the relevant school-averaged mean, indicates that there can be substantial variation within the same school. From engineering plans of the school sites, showing the location of each monitor, significant variation is apparent even between adjacent rooms even when they had the same number of openable windows and doors.

To investigate these differences, four representative classrooms were selected for further analysis.[4] The chosen classrooms (PA−5 & PA−6 from primary school PA), and (PB−3 & PB−7 from primary school PB) are notionally the same in terms of their floor area and occupancy profiles, and are all naturally ventilated through the same number of openable windows (each having two,

[4] The four classrooms have been chosen to portray some of the different trends identified within the dataset of classrooms monitored in this study, including different combinations of low and high CO_2 and temperature.

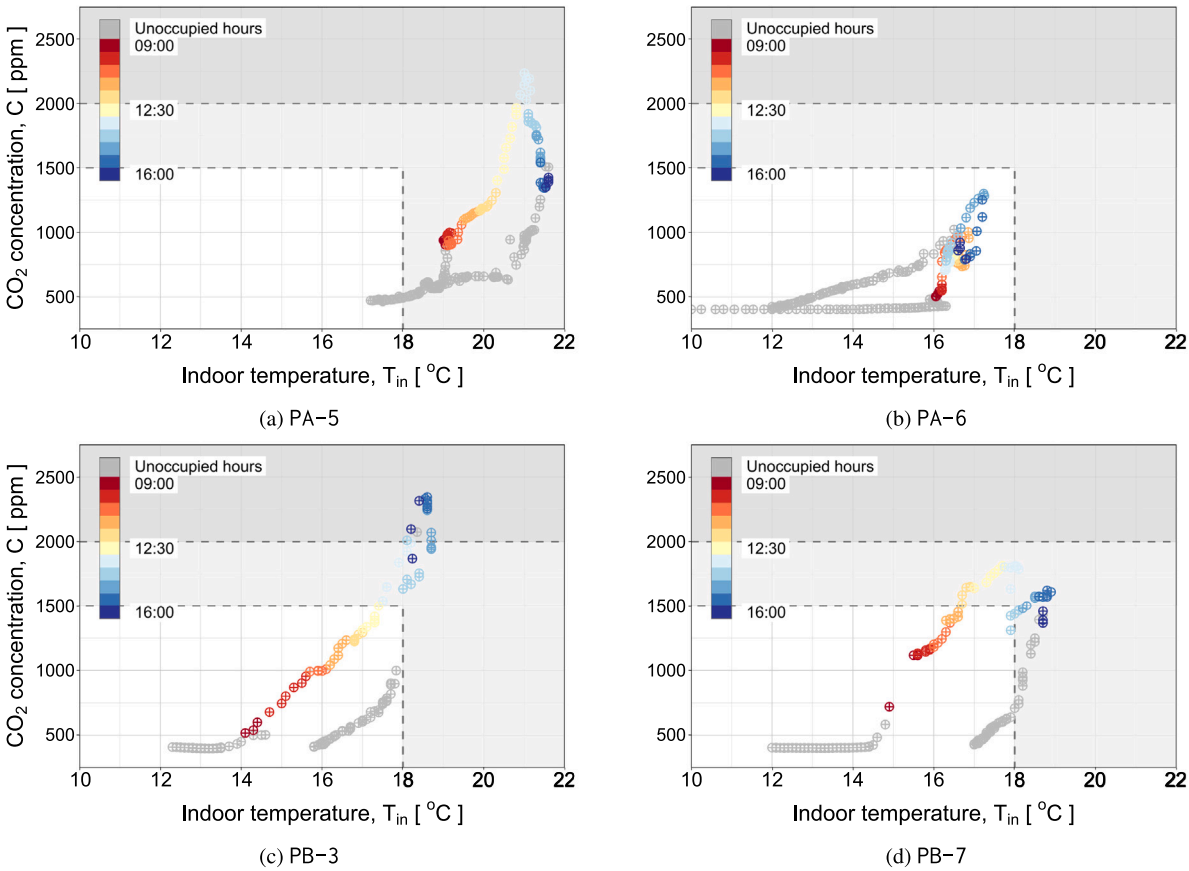


Fig. 7. Scatter plot of CO_2 and the indoor temperature for a representative set of classrooms (PA−5, PA−6, PB−3 and PB−7), during occupied and non-occupied hours on the 29th of November 2021, i.e. the first day of data shown in Fig. 6. The horizontal shaded areas correspond to $CO_2 \geq 1500$ ppm and $CO_2 \geq 2000$ ppm, while the vertical area corresponds to $T_{in} \geq 18$ °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

partially restricted in accordance with the health and safety guidance in the UK) and each having one door. The respective schools reported that no significant interference is expected to the occupancy and activity patterns — i.e. no other year groups visit the chosen classrooms at any point during the day, and activities that could influence the measurements, such as PE lessons do not take place in the monitored rooms. This remained the case in these four schools throughout the study period. As such, around 30 pupils and 2 members of staff are normally expected to be inside these classrooms during occupied hours, except during the breaks when pupils were encouraged to leave the room (weather permitting). The recorded data facilitate a direct comparison of the environmental conditions (at least in terms of temperature, humidity, and CO_2 levels) observed between the two schools as well as between separate classrooms located in the same building.

3.2.1. CO_2 timeseries data

Fig. 6 presents the temporal variation of the indoor CO_2 concentration at the chosen classrooms over five consecutive school days. Along with the timeseries (plotted in blue), the figure also marks the relevant daily mean CO_2 concentrations (as horizontal yellow lines), as computed during school occupied hours. The data were recorded during a week from 'Cold period 2', when differences in ventilation behaviour are most prominent.

The top half of Fig. 6 contains data for classrooms PA−5 and PA−6; both located on the ground floor of Primary School A. The two classrooms see significant variations in the recorded carbon dioxide levels throughout the week. All the daily mean values of CO_2 during classroom occupied hours are below the threshold for poor ventilation recommended by SAGE [22], as they remain below the threshold of 1500 ppm (in most cases, well below), however there are a number of days when the mean value is above the SAGE recommended value of 800 ppm. The timeseries of CO_2 see intra-day fluctuations, with peaks during the morning and afternoon hours and troughs at other times, following the changing occupancy that arises during classroom breaks. For classroom PA−5, these fluctuations lead to a noticeable increase of the CO_2 concentrations above the guidance threshold specified in Building

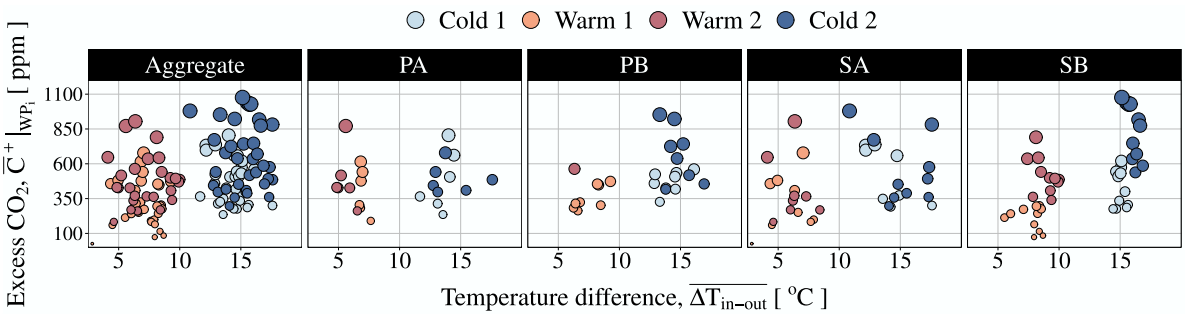


Fig. 8. Mean excess classroom CO_2 concentration plotted against the indoor–outdoor temperature difference for the individual schools, as well as in aggregate. The size of dots corresponds to increasing levels of the $\overline{C}^{+}|_{WP_i}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Bulletin 101 [20]. CO_2 values exceed the 2000 ppm baseline for a consecutive period of ~30 min on the 29th of November and ~25 min on the 3rd of December 2021. In contrast, classroom PA−5 adheres to the BB101 threshold at all times.

The pair of plots on the bottom half of Fig. 6 have been drawn with data from school PB. In this school, classrooms PB−3 and PB−7 display increased daily means during the same weekly period — often surpassing the poor ventilation threshold of 1500 ppm recommended by SAGE and EMG [22]. This is in addition to noticeably higher CO_2 concentration peaks in the case of PB−3, with values well above 2000 ppm for relatively longer time spans in contravention of Department for Education [20] — 1 h and 55 min on the 29th of November, 3 h and 25 min on the 1st of December, as well as 50 min and 30 min on the 3rd of December. A time lag is also observed in the late afternoon, with the CO_2 concentrations only gradually returning to the baseline ambient levels over a period of a few hours, when the two classrooms are not occupied. The data suggest that there is generally poorer per person ventilation in the classrooms within this school. Compared to PB−3, the accumulation of CO_2 in PB−7 is more restrained; the classroom experiences lower daily means on average (at or below 1500 ppm during the entire weekly span) and truncated CO_2 peaks that do not surpass the 2000 ppm baseline at any given time. Hence, in contrast to PB−3, classroom PB−7 adheres to the Department for Education's guidance for ventilation and air quality [20] throughout.

3.2.2. Relationship between CO_2 and indoor temperature (T_{in})

The differences between the four classrooms can also be examined by investigating the variations in the thermal environment. Fig. 7 presents a scatter plot of the CO_2 concentrations and the indoor classroom temperatures throughout the first day shown in Fig. 6 (29th of November 2021). Within Fig. 7 data recorded during classroom occupied hours are marked with differing colours to represent the time of the day and those recorded during non-occupied hours are marked in grey.

The marked difference in CO_2 concentration between PA−5 and PA−6 is immediately obvious within the top two panes — PA−5 which experiences relatively high CO_2 whilst maintaining considerably warmer temperatures (17–22 °C compared to 10–17 °C in PA−6). Centralised heating systems were reported as being in use during the day in both classrooms within this school. This trend of higher ventilation of CO_2 being generally accompanied by decreased indoor temperatures is less pronounced in Primary School B (PB). PB−7, which is located on the first floor of the building appears to be kept marginally warmer, and maintained slightly lower CO_2 levels than in PB−3 (which is on ground floor).

In Fig. 7, the CO_2 ramp-up during the morning school classes and its subsequent decrease in the afternoons is apparent. A Pearson correlation yields values of the correlation coefficient varying between 70% and 85% during occupied hours, thus signifying that the two variables, CO_2 and classroom temperature, vary positively with one another during the cold seasons.

3.3. Mean excess CO_2 concentrations

Fig. 8 compares the mean CO_2 concentration above outdoor ambient levels (taken to be 400 ppm), herein 'excess CO_2' and denoted $\overline{C}^{+}$, and the mean indoor–outdoor temperature difference for each classroom averaged over each of the weather periods. Data from each school is presented in four individual panes (on the right hand side) within the figure and shown in aggregate within the first pane — in all panes, the weather period is highlighted by colour. The two 'Transitional' periods have been excluded from these plots for conciseness, with its values ranging between the two groups of data.

The aggregate data indicates that, on average, mean excess CO_2 concentration for the colder weather periods is generally higher than that of the warmer weather periods. The only school which forms an exception is school PA, that school being an apparent anomaly and highlighting the variability with the UK school stock. In addition, what is also, more subtly, evident is that, for the data from three of the schools and the data in aggregate, the dark blue data from the 'Cold 2' period exhibits higher excess CO_2 than the light blue data from the 'Cold 1' period (we evidence the statistical significance of these observations in Section 3.4). This finding indicates that between these two weather periods, for which the mean outdoor temperatures was broadly the same (Table 2), a greater level of per person ventilation was achieved during the 'Cold 1' period.

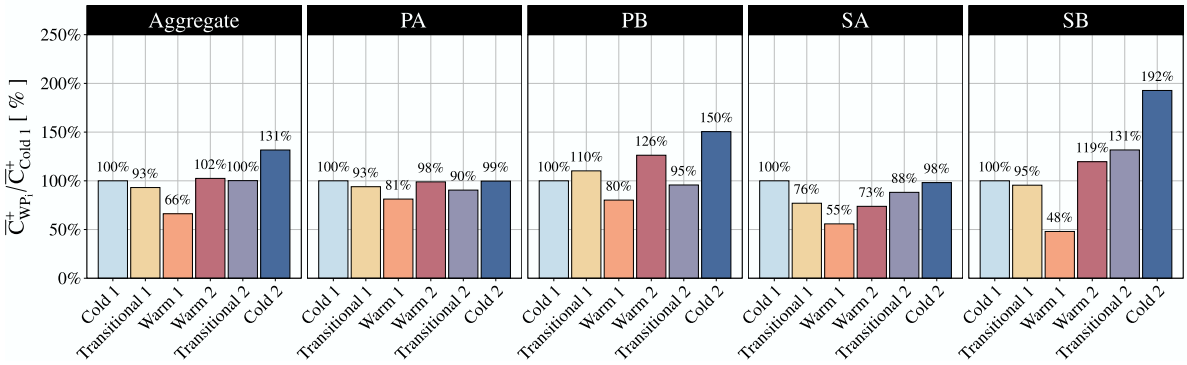


Fig. 9. Variation of the mean excess CO_2 within each school, shown per weather period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the following analysis, we take the data gathered during the weather period 'Cold 1' as a baseline (the data gathered during 'Cold 1' represents relatively low levels of CO_2 within classrooms achieved during a period in which the cold weather made thermal comfort challenging). Fig. 9 presents values of the mean excess CO_2 concentration, $\overline{C}^{+}|_{WP_i}$, normalised by the baseline value measured during 'Cold 1', $\overline{C}^{+}|_{Cold1}$. Seasonal differences and inter school disparities are evident, but the data also reveal the seasonal trend is overlaid by an approximately chronological increase in CO_2 levels during the span of the calendar year.

Examining Fig. 9, especially the left-hand pane showing the aggregate of the all classrooms, it is evident that as the weather warmed through to the end of the academic year (AY) 2020–2021 (i.e. 'Cold 1' to 'Warm 1'), CO_2 levels, on average, decreased — indicating a likely increase in per person ventilation. However, as these schools returned for the new AY 2021–2022 (Warm 2), despite the weather still being relatively warm, there was a marked increase in CO_2 levels; approximately to levels attained during the cold weather of Cold 1 — this pattern has not been observed in other pre-pandemic data sets of CO_2 levels in UK classroom [e.g. 16, which examined data from approximately 50 classrooms measured during periods spanning around five years].

In aggregate, the data during the first term of the AY 2021–2022 (Warm 2 to Cold 2) shows CO_2 levels increasing further, with aggregate CO_2 levels in 'Cold 2' being about 30% higher than in 'Cold 1' whilst the outdoor temperature was, on average, equally cold during these two periods. What warrants future investigation is the difference apparent in the data averaged per school, for which only investigation on a per classroom basis is likely to prove meaningful (see Section 3.2). On average the classrooms in schools PA and SA maintained similar levels of per-person ventilation between 'Cold 1' and 'Cold 2', schools SA and SB managed to approximately double the per-person ventilation during 'Warm 1'. This highlights that whilst the CO_2 levels in some schools were maintained from the start of schooling, to the end of schooling in 2021, other schools exhibit significant increases in CO_2 levels; in none of the study schools were decrease is average CO_2 levels evidenced.

3.4. Statistical significance of $\overline{C}^{+}$ variations

The observed weather period variations (see Section 3.1) may be expected to reflect on the sample distributions of the mean excess CO_2 concentrations; this can be evaluated by using appropriate hypothesis tests to establish whether any such differences can be considered statistically significant. The tests have been performed here for data aggregated over the 36 classrooms examined in this study. Statistical comparisons were made, once again, taking the data of 'Cold period 1' as the baseline conditions (see Section 3.3 for a discussion).

We take the 'Wilcoxon rank-sum test' to compare distributions, via examining the likelihood that the medians can be generated by sampling data from the same underlying distribution, from independent samples that are non-parametric (i.e. not expected to originate from a prescribed probability distribution), and employ also the more widely used 't-test', which assumes an underling normal distribution within the data [an assumption valid under the central limit theorem, when the sample space is sufficiently large, or maximal entropy considerations 23], for an equivalent examination of the distribution means. We acknowledge that the distributions of classroom CO_2 concentrations do not appear to be strictly Gaussian (see Appendix), although the available number of measurements may be adequate in order to satisfy the requirements inherent in the central limit theorem. In both cases, the tests were applied by assuming that the data behave as observation pairs that come from two dependent (paired) populations. For an equivalent examination of the variances of the distributions, we employ an 'F-test', which assumes an underlying F-distribution for the data. The results of all three statistical tests, i.e. the Wilcoxon rank-sum test, t-test, and F-test, are reported as p-values; that is they are probabilities taking value in the range from zero to unity based on the likelihood that by sampling the same population data one can produce the observed differences within the statistics.

The results derived from the statistical tests comparing the data from each weather period to the baseline data from 'Cold 1' are presented in Table 3. The table also contains estimates of the percentile differences in the distribution means and standard deviations, i.e. $\Delta\mu/\mu|_{Cold1} = (\mu|_{WPi} - \mu|_{Cold1})/\mu|_{Cold1}$ and $\Delta\sigma/\sigma|_{Cold1} = (\sigma|_{WPi} - \sigma|_{Cold1})/\sigma|_{Cold1}$, respectively. In the context of

Table 3
Statistical significance of variations in classroom $\overline{C}^{+}|_{WP_i}$.

	$\overline{T_{out}}\|_{WP_i} - \overline{T_{out}}\|_{Cold\,1}$	Distribution averages			Variances	
		$\frac{\Delta\mu}{\mu\|_{Cold\,1}}$	Wilcoxon	t-test	$\frac{\Delta\sigma}{\sigma\|_{Cold\,1}}$	F-test
Return to full schooling in March 2021						
Cold 1/Cold 1	–	0%	1.00	1.00	0%	1.00
Tran. 1/Cold 1	3.0 °C	−7%	0.38	0.50	−4%	0.84
Warm 1/Cold 1	9.5 °C	−36%	<0.01	<0.01	−9%	0.66
Summer break between AY 2020–2021, and AY 2021–2022						
Warm 2/Cold 1	8.7 °C	0%	0.82	0.72	+9%	0.77
Tran. 2/Cold 1	5.9 °C	+3%	<0.01	0.79	+1%	0.75
Cold 2/Cold 1	−0.2 °C	+37%	<0.01	<0.01	+39%	0.05

the hypothesis tests, the CO_2 data broadly display marginal differences to the baseline distribution during 'Transitional 2', 'Warm 2', and 'Transitional 2'; both the Wilcoxon and the t-tests suggest a reasonable probability that the observed medians and means might originate from data of the same underlying distribution. On the other hand, for the data gathered during 'Warm 1' and 'Cold 2', both the Wilcoxon and the t-tests suggest there is an extremely low probability that the observed medians and means might originate from the same underlying distribution. In the case of comparing 'Warm 1' to 'Cold 1' one might attribute the variation to the approximately 10 °C change in the external temperature; however, when comparing 'Cold 2' to 'Cold 1', it is difficult to rationalise such differences arising due to changes in the external temperature.

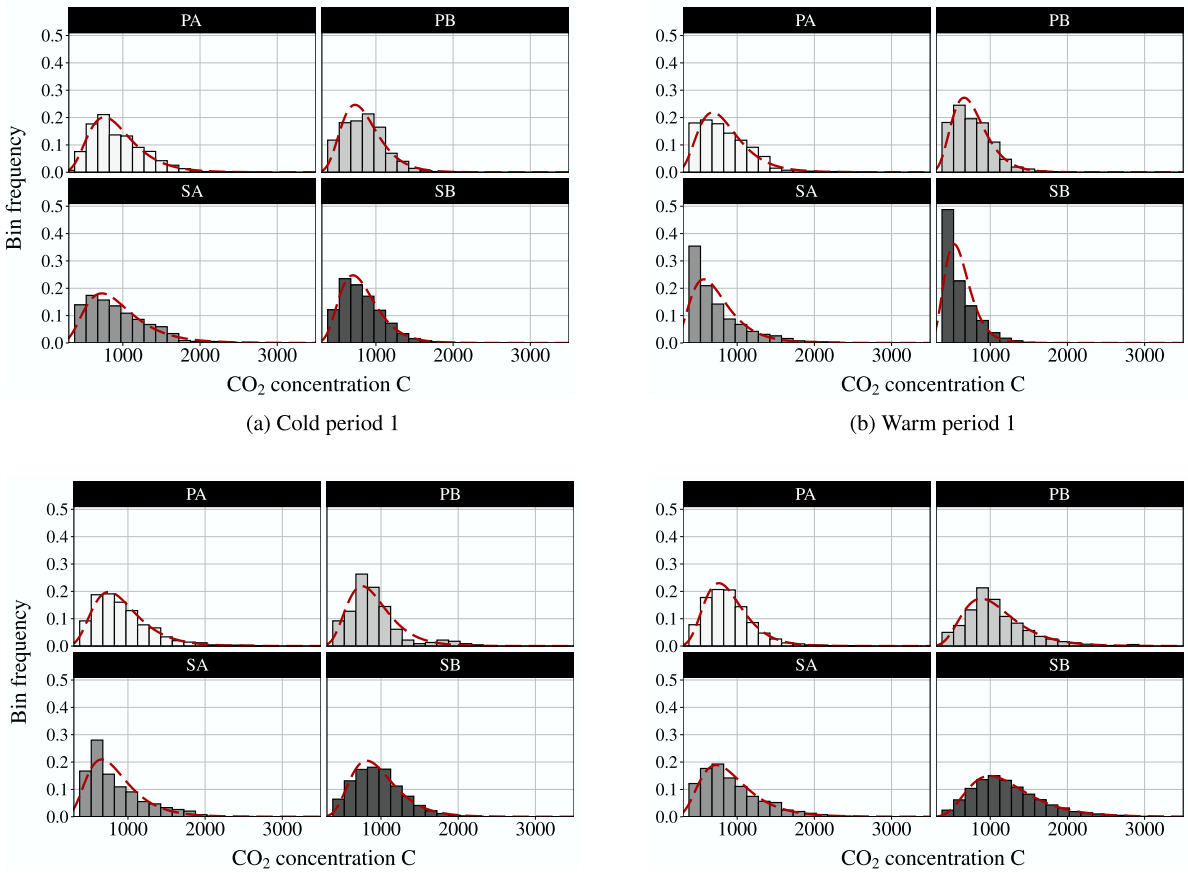
4. Conclusions

Interest in the ventilation of enclosed spaces has grown significantly during the COVID-19 pandemic. This has been particularly relevant for learning environments, due to the importance of schooling and the expectation that the frequent and close contact of individuals within indoor spaces that are not adequately ventilated may play a role in the wider community transmission of SARS-CoV-2, across different age groups and settings.

This study relied on non-intrusive indoor air quality monitors to assess the state of classroom ventilation during the span of the 2021 calendar year, following the reopening of schools from the 'second wave' of COVID-19 infections within the UK. Environmental data were acquired from 4 schools and 36 naturally ventilated classrooms and were analysed for seasonal variations in the indoor CO_2 concentrations and temperatures. The analysis confirmed elevated levels of CO_2 during the autumn and winter months. In this regard, our results are very much inline with previous findings in UK classrooms based on environmental data gathered pre-pandemic [e.g. 16]. However, deeper analysis highlights that climatic influences due to seasons seem insufficient to account for the discrepancies in monitored CO_2 levels throughout 2021. Given the fact that this study was performed in schools during a time dominated by the COVID-19 pandemic [with enhanced safety measures enforced and the wearing of face coverings sometimes being required in classrooms for secondary school-aged children during AY 2020–2021, 24], such sources of discrepancies may be related to the pandemic, the experience within the school population and attitudes towards the disease, as well as the guidance and associated safety protocols that were in place from the national level down to the classroom level. In this case, differences in the behaviour of the classroom occupants, and in particular the relaxation of attitudes towards COVID-19 protocols between the last part of AY 2020–2021 [e.g. 24] and the first part of the AY 2021–2022 [e.g. 25], might have led to the evidenced increased CO_2 and the inferred lower levels of per person ventilation within these classrooms. Although these statistically significant changes between, for example, 'Cold 1' and 'Cold 2' are well evidenced, it is important to note that beyond the seasonal variation in outdoor temperature, an analysis of the many and complex potential confounders within operational school classrooms was not possible within the scope of this study. Nonetheless, the analysis of this unique dataset raises research questions which, for the sake of school communities, warrant further investigation and resource.

CRediT authorship contribution statement

Henry C. Burridge: Led the study, Writing – original draft, Edited the manuscript, Provided insights throughout the study. **Stavros Bontitsopoulos:** Led the analysis and data presentation, Edited the manuscript, Provided insights throughout the study. **Christopher Brown:** Provided school liaison and support, Edited the manuscript, Provided insights throughout the study. **Holly Carter:** Advised on behavioural interactions with the schools, Edited the manuscript, Provided insights throughout the study. **Katherine Roberts:** Helped coordinate efforts throughout the projects, Edited the manuscript, Provided insights throughout the study. **Carolanne Vouriot:** Helped coordinate efforts throughout the projects, Edited the manuscript, Provided insights throughout the study. **Dale Weston:** Advised on behavioural interactions with the schools, Edited the manuscript, Provided insights throughout the study, Edited the manuscript, Provided insights throughout the study. **Mark Mon-Williams:** Helped coordinate efforts throughout the projects, Edited the manuscript, Provided insights throughout the study. **Natalie Williams:** Advised on behavioural interactions with the schools, Edited the manuscript, Provided insights throughout the study. **Catherine Noakes:** Oversaw the study design and management, Edited the manuscript, Provided insights throughout the study.



(a) Cold period 1

(b) Warm period 1

(c) Warm period 2

(d) Cold period 2

Fig. 10. Probability density functions of the CO_2 concentration distributions during classroom occupied hours across the four schools of the study. The overlaid dashed red curves correspond to a fitted log-normal distributions.

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.

Data availability

The authors do not have permission to share data.

Acknowledgements

This work was supported by funding from the PROTECT COVID-19 National Core Study on transmission and environment, managed by the Health and Safety Executive on behalf of HM Government, UK. The CO_2 monitors were funded through the Department for Health and Social Care pandemic innovation fund. The authors would like to thank Hershil Patel and Robyn Gautam from the Department for Education and Dawn Salisbury from the Department for Health and Social Care for their continued support and significant contributions throughout this study. We would also like to acknowledge the help and support from STAR Academy Trust, and the support and advice received from the Office for National Statistics. Finally, we wish to acknowledge the useful feedback from three anonymous reviewers who enabled great improvements to the manuscript through their suggestions.

Appendix. Examination of the co_2 distributions

The following provides a comparative assessment of the 'Cold 1' (Mar–May/2021), 'Warm 1' (Jun–Jul/2021), 'Warm 2' (Sep/2021), and 'Cold 2' (Nov–Dec/2021) weather periods. The data presented here are averaged across classrooms and presented per school.

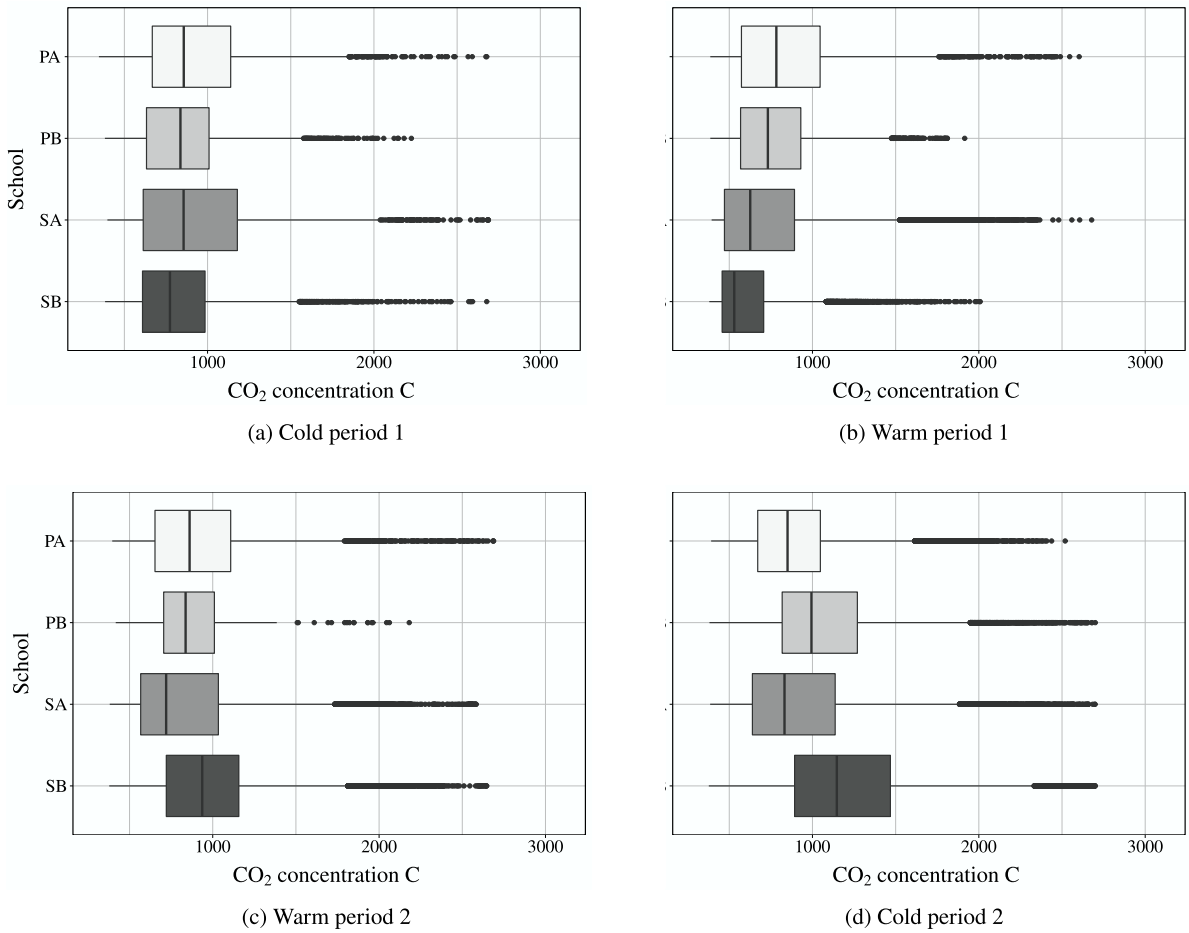


Fig. 11. Box and whisker plots illustrating the CO_2 concentration distributions during classroom occupied hours.

An impression of the CO_2 statistical distributions is provided in Figs. 10 and 11, which present concentration histograms and box plots respectively. Although the sample distributions vary between the individual schools of the study, a positive skewness is observed at all sites across the four weather periods, which signifies a deviation from the classic Gaussian distribution. The deviation is due to the tendency of excess CO_2 to be close to zero, i.e. CO_2 concentrations to be close to the baseline ambient environmental values of around 400 ppm [e.g. 13] both early in the morning and at times of low classroom occupancy.

The weather period-averaged CO_2 increases on average between the four schools by ~ + 13% when comparing 'Warm period 2' and 'Cold 2' (from 910 to 1030 ppm). The equivalent increase between 'Warm period 1' and 'Cold 2' is + 39% (from 740 to 1030 ppm). In both cases, deviations are relatively higher for school SB and lower for PA, indicating a greater seasonal variation in SB. In addition to the increased mean CO_2, the histograms show noticeably longer tails towards higher levels of CO_2 concentrations during the colder periods (particularly during 'Cold period 2'). This is apparent when comparing histograms (b) and (d) (Fig. 10) as well as the equivalent box plots (Fig. 11), with the latter portraying a narrowing of the interquantile range during 'Warm period 1' and a widening during 'Cold 2' (in all cases except PA). This feature, combined with the upwards shift in the concentrations signifies that higher CO_2 (≥1500 ppm) are more frequent during colder months. The more increased occurrences of higher CO_2 concentrations are in line with the expectation of poorer ventilation during the cold season. This is also confirmed from the box plots in Fig. 11, which display wider whisker limits, along with increased instances of 'outliers' (values that are numerically distant from the rest of the data — marked with dots). Both features of the plot illustrate a higher likelihood of elevated CO_2 classroom levels and spikes in concentrations during the colder weather periods.

References

[1] Sky News, COVID-19: Full list of areas where primary schools face indefinite delay in return, 2021, https://news.sky.com/story/covid-19-full-list-of-areas-where-primary-schools-face-delayed-return-12175797.

[2] H.C. Burridge, R.K. Bhagat, M.E. Stettler, P. Kumar, I. De Mel, P. Demis, A. Hart, Y. Johnson-Llambias, M.-F. King, O. Klymenko, et al., The ventilation of buildings and other mitigating measures for COVID-19: a focus on wintertime, Proc. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci. 477 (2247) (2021) 20200855.

[3] L. Morawska, D.K. Milton, It is time to address airborne transmission of coronavirus disease 2019 (COVID-19), Clin. Infect. Dis. 71 (9) (2020) 2311–2313.
[4] R.K. Bhagat, M.D. Wykes, S.B. Dalziel, P. Linden, Effects of ventilation on the indoor spread of COVID-19, J. Fluid Mech. 903 (2020).
[5] R. Corsi, S. Miller, M. VanRy, L. Marr, L. Cadet, N. Pollock, D. Michaels, E. Jones, M. Levinson, Y. Li, et al., Designing infectious disease resilience into school buildings through improvements to ventilation and air cleaning, 2021, https://covid19commission.org/commpub/designing-infectious-disease-resilience-into-school-buildings-through-improvements-ventilation-and-air-filtration.
[6] U. Haverinen-Shaughnessy, D. Moschandreas, R. Shaughnessy, Association between substandard classroom ventilation rates and students' academic achievement, Indoor Air 21 (2) (2011) 121–131.
[7] M.J. Mendell, E.A. Eliseeva, M.M. Davies, M. Spears, A. Lobscheid, W.J. Fisk, M.G. Apte, Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools, Indoor Air 23 (6) (2013) 515–528.
[8] Z. Bakó-Biró, N. Kochhar, D. Clements-Croome, H. Awbi, M. Williams, Ventilation rates in schools and pupil's performance using computerised assessment tests, Indoor Air (2008) 17–22.
[9] Z. Bakó-Biró, D.J. Clements-Croome, N. Kochhar, H.B. Awbi, M.J. Williams, Ventilation rates in schools and pupils' performance, Build. Environ. 48 (2012) 215–223.
[10] D. Clements-Croome, H.B. Awbi, Z. Bakó-Biró, N. Kochhar, M. Williams, Ventilation rates in schools, Build. Environ. 43 (2008) 362–367.
[11] Department for Education, Press release: All schools to receive carbon dioxide monitors, 2021, https://www.gov.uk/government/news/all-schools-to-receive-carbon-dioxide-monitors.
[12] SAGE, EMG, SPI-B, Application of CO_2 monitoring as an approach to managing ventilation to mitigate SARS-CoV-2 transmission, 2021, https://www.gov.uk/government/publications/emg-and-spi-b-application-of-co2-monitoring-as-an-approach-to-managing-ventilation-to-mitigate-sars-cov-2-transmission-27-may-2021.
[13] S.N. Rudnick, D.K. Milton, Risk of indoor airborne infection transmission estimated from carbon dioxide concentration, Indoor Air 13 (3) (2003) 237–245.
[14] H.C. Burridge, S. Fan, R.L. Jones, C.J. Noakes, P.F. Linden, Predictive and retrospective modelling of airborne infection risk using monitored carbon dioxide, Indoor Built Environ. 31 (2022) 1363–1380.
[15] Z. Peng, J.L. Jimenez, Exhaled CO2 as a COVID-19 infection risk proxy for different indoor environments and activities, Environ. Sci. Technol. Lett. 8 (5) (2021) 392–397, http://dx.doi.org/10.1021/acs.estlett.1c00183.
[16] C.V.M. Vouriot, H.C. Burridge, C.J. Noakes, P.F. Linden, Seasonal variation in airborne infection risk in schools due to changes in ventilation inferred from monitored carbon dioxide, Indoor Air 31 (4) (2021) 1154–1163.
[17] A. Kabirikopaei, J. Lau, Uncertainty analysis of various CO2-based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems, Build. Environ. 179 (2020) 107003.
[18] P. Wargocki, N.A.F. Da Silva, Use of visual CO_2 feedback as a retrofit solution for improving classroom air quality, Indoor Air 25 (2015) 105–114.
[19] A. Di Gilio, J. Palmisani, M. Pulimeno, F. Cerino, M. Cacace, A. Miani, G. de Gennaro, CO_2 concentration monitoring inside educational buildings as a strategic tool to reduce the risk of Sars-CoV-2 airborne transmission, Environ Res. 202 (2021) 111560, http://dx.doi.org/10.1016/j.envres.2021.111560.
[20] Department for Education, BB 101: Ventilation, thermal comfort and indoor air quality 2018, 2018, www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings.
[21] Met Office, NCAS British Atmospheric Data Centre, 2006, https://catalogue.ceda.ac.uk/uuid/1bb479d3b1e38c339adb9c82c15579d8.
[22] SAGE, EMG, Role of ventilation in controlling SARS-CoV-2 transmission, 2020, https://www.gov.uk/government/publications/emg-role-of-ventilation-in-controlling-sars-cov-2-transmission-30-september-2020.
[23] A. Lyon, Why are normal distributions normal? Br. J. Philos. Sci. 65 (3) (2013) 621–649.
[24] Education Hub, Why do secondary school and college students have to carry on wearing face coverings? Your questions answered, 2021, https://educationhub.blog.gov.uk/2021/04/06/why-do-secondary-school-and-college-students-have-to-carry-on-wearing-face-coverings-your-questions-on-masks-answered/.
[25] Education Hub, Back to school – what you need to know, 2021, https://educationhub.blog.gov.uk/2021/08/24/back-to-school-what-you-need-to-know//.