Te Tāhuhu o
te Mātauranga
Ministry of Education

Classroom Ventilation: The Effectiveness of Preheating and Refresh Breaks

An analysis of 169 spaces at 43 schools across New Zealand

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Foreword

The New Zealand Ministry of Education's approach to addressing ventilation in schools, as part of its response to the COVID-19 pandemic, has been informed by an evidence-based approach.

Over the last 12 months, the Ministry's COVID-19 ventilation programme, in collaboration with its advisory group of ventilation experts, have carried out series of targeted studies which enhanced the understanding of the role of natural ventilation and informed our ventilation guidance to schools.

In May 2022, the programme initiated a ventilation monitoring initiative which involved continuous monitoring of CO_2, temperature, and relative humidity levels in 43 schools across the country. This report is based on the data collected during this initiative, and focuses on two approaches to encouraging adequate ventilation during cold days:

1. heating classrooms before the start of the school day (preheating) to establish comfortable temperatures and encourage early opening of windows, and
2. taking 'refresh' breaks, in which windows are widely open and the occupants leave the classroom for a short period, while the air refreshes.

The monitoring data has been used to infer how often these actions occur, and what their effect is on CO_2 and temperature levels throughout the school day. The findings add to the body of evidence that is informing our approach to managing ventilation improvements in schools.

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Contents

Executive Summary

The COVID-19 pandemic has highlighted the importance of ventilation as a transmission mitigation strategy. However, there was a widely held concern that a drop in outdoor temperatures during winter may impact thermal comfort in the context of naturally ventilated classrooms. This concern has not been widely investigated by peer-reviewed empirical studies (Sutherland et al., 2022b).

The aim of the Ministry's ventilation monitoring initiative was to assess ventilation performance and thermal comfort by continuously measuring indoor CO_2 levels, air temperature, and relative humidity in classrooms during winter, without obstructing teaching activities.

A total of 43 schools, which represent a broad mix of property attributes and located across the 6 Climate Zones in New Zealand, were selected for the monitoring initiative. The CO_2 monitors were deployed in about 4-6 pre-selected and representative spaces in each school. Data was retrieved from 213 spaces; of these, 44 spaces were excluded, because the initiative concentrated on teaching environments (classrooms) and those spaces were categorised as non-teaching environments (e.g., staff rooms, meeting rooms, etc.).

From the 213 spaces, the data from 169 teaching spaces retrieved for the period 23 May to 26 August 2022 were analysed to ascertain the impacts of inferred human behaviours considered to be able to improve natural ventilation and detected from features of CO_2 and temperature data. This analysis does not (and did not intend to) corroborate independent observation of behaviours.

The key findings were:

- Across all 169 teaching spaces, and for most of the monitored teaching time, CO_2 levels were largely (67% of the time) less than 800 ppm and were within the adaptive comfort temperature range of 18-25 °C (70% of the time). While the indoor air temperatures were similar in all 6 Climate Zones (warmest to coldest), CO_2 levels were higher in colder climates.
- The teaching spaces with more frequent preheating (i.e., heating sufficiently earlier) did experience warmer temperatures when teaching started and likely had better thermal comfort.
- The majority of the teaching spaces appeared to have day-by-day decisions on heating start time, and only a few were frequently preheated.
- A preheating strategy can be useful in lowering CO_2 levels, but only if the room would be otherwise cold when occupancy starts.
- Having *breaks* may have helped bring CO_2 levels down but *refresh breaks* (deliberate opening of multiple doors and windows and preferably also vacating the room, resulting in a much faster CO_2 drop) can help achieve that quicker. The latter can be very important in practice due to the minimal possible interruption to common teaching activities.
- The results showed that the indoor air temperature drop was likely to be limited when both *breaks* and *refresh breaks* occurred.
- *Breaks* seem to have been common, however, **successful** *refresh breaks,* so that a previously occupied space can be flushed quickly with fresh air, appear to have been less frequently applied. This would indicate that, for schools who have elevated CO_2 levels, there remains the opportunity for *refresh breaks* to be adopted to better manage CO_2 levels on an ongoing basis.

The conclusions that this initiative can draw from the analysis are limited because other real-time information such as occupancy, and actions taken directly impacting ventilation were not recorded, given that this initiative was designed not to disturb normal classroom activities. However, the findings generally suggest that having a warmer indoor temperature prior to the start of teaching in the morning and *refresh breaks* can play a positive role in lowering CO_2 levels throughout a teaching day.

1.0 Introduction

During the COVID-19 pandemic, the New Zealand Ministry of Education provided ventilation guidance to schools, primarily through its website 'Te Mahau'. This guidance was informed by a range of empirical studies (Ackley et al., 2022; NIWA, 2022; Sutherland et al., 2022a; Sutherland et al., 2022b) that have shown that opening windows and doors is the best way to maximize ventilation and reduce the spread of airborne diseases such as COVID-19.

During winter and anecdotally, the motivation of occupants to open windows in naturally ventilated classrooms and other spaces is generally quite low. Studies (Beisteiner & Coley, 2002b; Gao et al., 2014; Heebøll et al., 2018) suggest that the reasons why adequate ventilation may not be achieved in naturally ventilated classrooms during winter include poor siting of windows, difficulty in opening windows due to broken handles, and occupants may likely not open the windows due to possible air drafts, fear of being cold and concerns of wasted energy. Hence, while naturally ventilated classrooms may be capable of providing enough fresh air to effectively manage CO_2 and temperature levels, occupants may not avail themselves of this capability.

While we have an increasing awareness of the role of good ventilation in reducing COVID-19 risk, the possible impact of ventilation as a heat loss path is often misunderstood. In addition to heating systems, there are other sources of heat generation in classrooms such as heat generated from the body through metabolic gains, equipment, and heat from the sun over the course of a day. This means that provided more modest levels of ventilation are achieved in winter (e.g., through partially opening windows), these sources of heat will typically compensate for any building fabric losses (i.e., heat losses through openings and other losses through the building envelope).

To inform and refine the COVID-19 ventilation strategies for New Zealand schools, aimed at maintaining comfortable indoor temperatures while achieving good ventilation, CO_2 and temperature data collected from 43 schools across the length and breadth of New Zealand has been analysed to establish:

- Does *preheating* (i.e., heating sufficiently earlier, as defined in Section 2.6.2) help with keeping CO_2 at a low level and achieving comfortable indoor temperature in teaching environments during winter?
- Do *refresh breaks* (i.e., deliberate opening of multiple doors and windows and preferably vacating the room, as defined in Section 2.5.2) help with reducing CO_2 levels without compromising thermal comfort?

Literature generally suggests that purging is effective in decreasing CO_2 concentration without modifying the comfort conditions. For example, a study by (Beisteiner & Coley, 2002b, 2002a, 2003) carried out measurements of CO_2 levels in primary school classrooms in both winter and summer. It found that during purge ventilation the surveyed classrooms have showed the ability to reduce CO_2, and other contaminants to the recommended levels. Griffiths & Eftekhari (2008), measured CO_2 levels for one week during winter to investigate different ventilation modes in a classroom that has a capacity for 30 pupils. They found that "a purge time of 10 minutes could reduce the CO_2 concentration by 1000 ppm without compromising thermal comfort". This study was carried out in a secondary school classroom, which usually has changes after each lesson. (Jones & Kirby, 2012) stated that during unoccupied periods in classrooms, consideration should be given to purge ventilation to bring indoor CO_2 levels back to ambient levels.

Though these studies were carried out prior to COVID-19, these principles remain relevant to the management of COVID-19 airborne transmission risk. Hence, the aim of this paper was to analyse a wide range of data collected between May to August 2022, to ascertain the impact of purging and pre-heating on ventilation performance and thermal comfort in naturally ventilated classrooms.

2.0 Methodology

2.1 Monitoring Design

This initiative, similar to NIWA (2022) and Ackley et al. (2022), is also intended to unobtrusively investigate ventilation in teaching environments by implementing continuous measurement of CO_2, temperature, and humidity levels.

CO_2 is released by human breath while the teaching spaces are being used and measured in real-time. Since the initiative was designed to not disturb normal classroom activities, other real-time information such as occupancy, and actions undertaken directly impacting ventilation were not recorded. This prevents the conversion of the measured CO_2 readings to the real-time air exchange rate (AER) in "air changes per hour" (ACH), a common metric of ventilation, without uncertainty. Though it is possible to calculate AER by guessing varying combinations of occupancy and metabolic rate, obtaining exact real-time AER is beyond the interest of this initiative.

During winter, enhancing natural ventilation without sacrificing thermal comfort is also an issue of importance/significance to be addressed. Indoor thermal comfort depends on several factors including metabolic rate of occupants, warmth of clothing, air temperature, relative humidity, mean radiant temperature, and air speed. Technical knowledge is required to fine-tune these variables to optimise thermal comfort in teaching environments. The *Designing Quality Learning Spaces (DQLS) - Indoor Air Quality and Thermal Comfort* (V.2.0 2022), which requires (for newly built) or recommends (for existing learning spaces) that a minimum air temperature of 19 ± 1 °C is maintained during occupied hours in winter.

In this initiative, air temperature and relative humidity were recorded using the monitoring kit described in Section 2.3 below. However, only air temperature is investigated further, given that that it is the most well-understood variable, easy to measure, and results in actions being taken accordingly.

It should be noted that the data collected in this initiative was primarily intended to inform the New Zealand Ministry of Education's ventilation and thermal comfort guidance and subsequently documented here, but not originally designed as an assessment study of indoor environment during the pandemic. Hence, the aim was to only summarise the characteristics of the measurement dataset and descriptive findings but not to draw any inferential conclusions about all teaching and other spaces in New Zealand schools.

2.2 Participating Schools

A total of 43 schools across the 6 Climate Zones in New Zealand were selected for the monitoring initiative. The CO_2 monitors were deployed in about 4-6 pre-selected and representative spaces in each school. Data was retrieved from 213 spaces; of these, 44 spaces were excluded because the initiative concentrated on teaching environments (classrooms) and those spaces were categorised as non-teaching environments (e.g., staff rooms, meeting rooms, etc.). The selection of the 43 schools aimed to consider a reasonable number of schools who represents a broad mix of property attributes, being approximately half located in the colder climates.

The geographical locations of the schools and all participating space distributions over all 6 Climate Zones (from Climate Zone 1 to 6, the warmest to the coldest, as defined in New Zealand Building Code H1/AS1, Appendix C, based on climatic data and territorial authority boundaries) are respectively shown in Figure 1 and Figure 2 below:

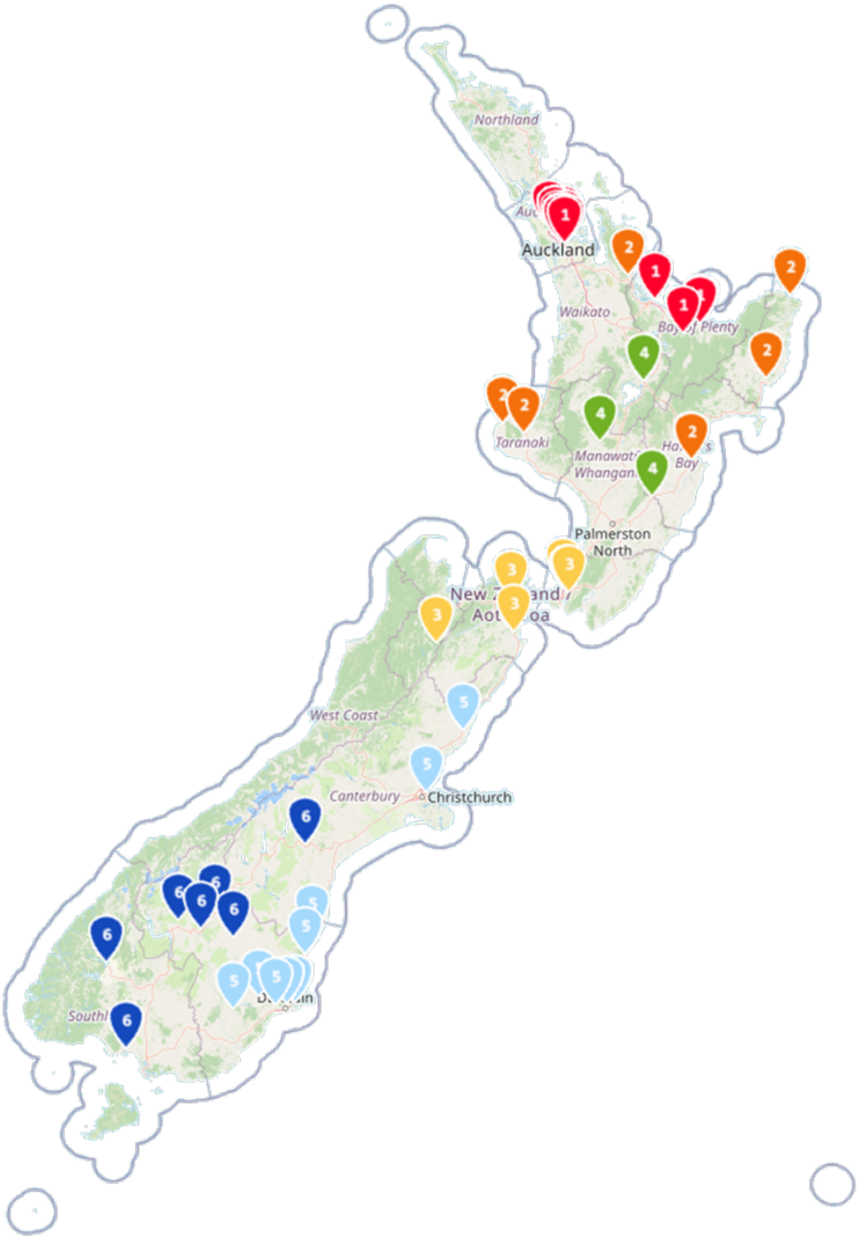


Figure 1: Geographical locations of the participating schools, where the number represents the corresponding Climate Zone (from 1 to 6, the warmest to the coldest).

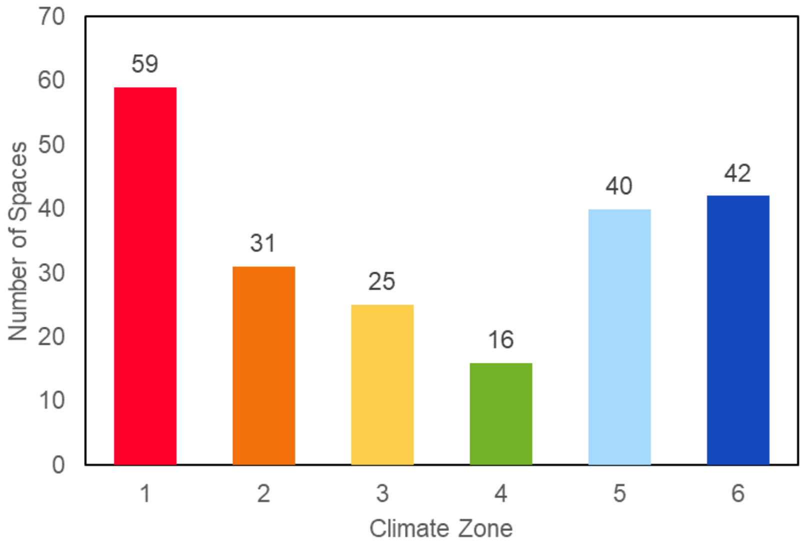


Figure 2: Number of participating spaces in different Climate Zone, from 1 to 6, warmest to coldest. Note that one space failed to upload valid data therefore is not included in this figure.

It can be seen from Figure 2 that, although the participating spaces are not evenly distributed in all 6 Climate Zones, where the warmest Climate Zone 1 has the largest number of spaces, approximately half are located in colder climates (Climate Zone 4-6).

Apart from the CO_2 and air temperature measurements, as a result of other work of the COVID-19 ventilation programme such as the ventilation assessments of certain schools, supplementary data also became available for some spaces, as summarised in Table 1 below.

Table 1: Number of spaces categorised by the types of available information

Description	Count	Percentage
The purpose of the space (e.g., teaching or meeting room)	178	83.2%
Specifically designated as non-teaching space (e.g., staffroom, photocopy room)	44	20.6%
The age range of occupants (e.g., primary student, adults/staff)	210	98.1%
Expected typical occupancy	175	81.8%
Expected activity level (minimal, light, medium, or high)	191	89.3%
Dimensions (length, width, height)	39	18.2%
Location of exterior openings (on the same, adjacent, opposite, 3 or more walls)	39	18.2%
Spaces with valid data uploaded	213	99.5%
Total Participating Spaces	**214**	**100%**

Data from 213 spaces was successfully recorded and uploaded. Of these, 44 spaces were identified as non-teaching environments and were excluded from this analysis. Therefore, as this initiative concentrates on teaching environments, the dataset was reduced down to 169 spaces of interest. The availability of information among the 169 spaces is summaries in Table 2 below:

Table 2: Break down of the available information of the 169 spaces of interest:

Description	Count	Percentage
Purpose of the space (e.g., teaching, meeting)	154	91.1%
Student type (e.g., primary, secondary, or intermediate)	166	98.2%
Expected typical occupancy	159	94.1%
Expected activity level (minimal, light, medium, or high)	159	94.1%
Dimensions (length, width, height)	33	19.5%
Location of exterior openings provided (on the same, adjacent, opposite, 3 or more walls)	33	19.5%
Total Participating Spaces	**169**	**100.0%**

As shown in Table 1 and Table 2 above, the data of space dimensions and the information about the exterior openings was less complete than other, but the sample size of 33 (1, 14, 7, 11 in Climate Zone 1, 3, 5, 6 respectively) still allows to explore the corresponding effects in the future.

The counts of student type and location of exterior openings are summarised in Table 3 and Table 4 below:

Table 3: Break down of the student type of the 169 spaces of interest:

Student Type	Count	Percentage
Primary	110	65.1%
Secondary	35	20.7%
Intermediate	21	12.4%
Unknown	3	1.8%
Total Participating Spaces	**169**	**100.0%**

Table 3 shows that, despite that more than half of spaces were for primary students, the sample size for each of the student types should still enable relevant future investigations.

Table 4: Break down of the location of exterior openings of the 169 spaces of interest:

Location of Exterior Openings	Count	Percentage
Same wall	3	9.1%
Opposite walls	27	81.8%
3 or more walls	3	9.1%
Count of available data	**33**	**100.0%**

Table 4 suggests that most of the spaces of interest should have the capability of obtaining cross ventilation when opening the exterior windows on different walls.

Table 5: Descriptive statistics of occupancy, categorised by student type:

	Primary	Secondary	Intermediate
Count	106	30	19
Mean	26	28	28
Standard Deviation	12	9	10
Min	1	3	10
25%	19	26	27
50% (Median)	27	27	30
75%	31	32	32
Max	88	52	50

Table 5 above suggests that the typical occupancy is roughly the same across all three student type ranges, however, the real-time attendance data during the monitoring is unavailable.

2.3 Data Collection

2.3.1 Indoor Air Temperature and CO_2 Level

To collect the data analysed in this report, each school was sent a set of monitoring kits, including:

- 1 × NETGEAR AirCard 800S Wi-Fi router with a Spark SIM card
- 1 × Aranet base station
- 4-12 × Aranet4 PRO portable air quality monitors (sensors)

The Aranet4 PRO devices are factory calibrated and according to the manufacturer's datasheet, the key device specifications are:

Table 6: Key sensor specifications

Element	Range	Accuracy	Resolution
CO_2	0 – 9999 ppm	± 30 ppm	1 ppm
Temperature	0 – 50 °C	± 0.3 ppm	0.1 °C
Relative Humidity	0 – 85 %	± 3 %	1 %
Atmospheric Pressure	600 – 1100 hPa	-2 hPa / +3 hPa	1 hPa

Specific guidelines on how to set up the devices were included in the kit for the schools.

Figure 3 and Figure 4 below show the device and its typical placement on the classroom walls.

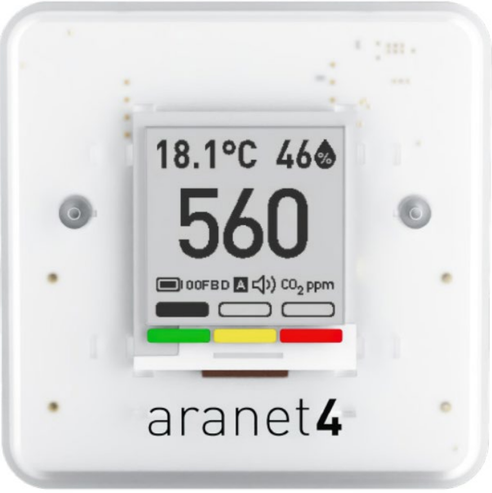


Figure 3: Image of Aranet4 Pro monitor, reproduced from Aranet4 datasheet.

Figure 4: Aranet4 PRO monitors installed on the classroom walls.

The Aranet4 PRO sensors allow taking measurements in four intervals: 1, 2, 5, and 10 minutes. The longest interval of 10 minutes was set by default for most of the sites.

2.3.2 *Outdoor Air Temperature*

The hourly outdoor air temperature was collected by manually downloading the data from NIWA's National Climate Database (CliDB), with the daily outdoor maximum and minimum temperatures collected from Virtual Climate Station Network (VCSN) using Application Programming Interfaces (APIs) provided by NIWA.

The VCSN data is derived from around 150 automatic weather stations from NIWA and MetService. After spatial interpolations, the estimated daily temperature data at the exact locations of schools can be obtained. When a shorter time interval is needed (e.g., an hour), CliDB data is used and resampled by forwardly filling so that the time intervals are the same as the Aranet4 PRO sensors (i.e., 10 minutes). A disadvantage is that the distance from the weather stations to schools varies due to availability, which has the potential to introduce errors. The descriptive statistics and the distribution of the distances can be seen in Table 7 and Figure 6 below:

Table 7: Descriptive Statistics of the Distances (km) from Schools to Nearest Weather Stations

Description	Value
Count	213
Mean distance (km)	29.9
Standard Deviation (km)	32.8
Min (km)	0.3
25% (km)	6.7
50% (Median) (km)	16.7
75% (km)	35.0
Max (km)	128.0

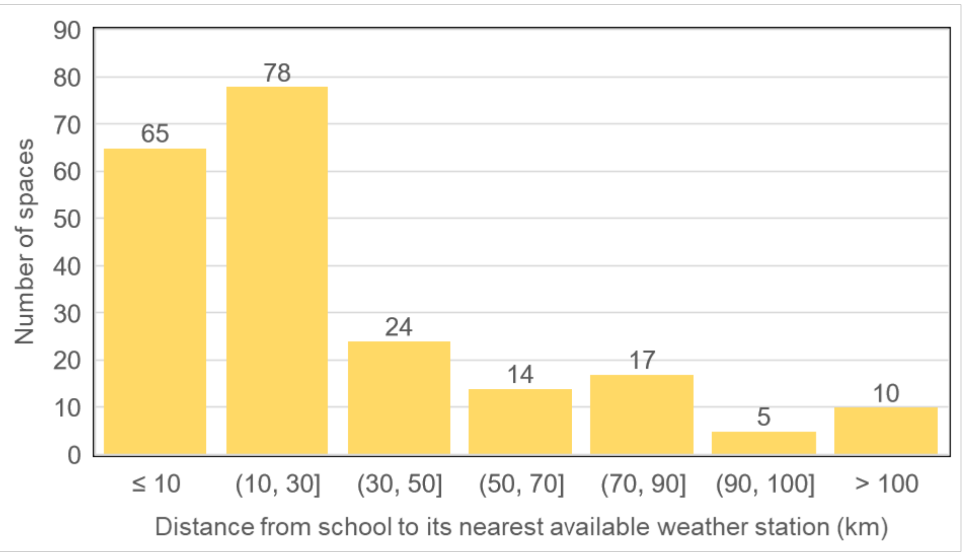


Figure 5: Distribution of distance between all participating spaces and corresponding nearest available weather stations.

As shown in Table 7 and Figure 5, 167 of 213 spaces have the weather station closer than 50 km, where the outdoor data was recorded and used in the analysing. The possible error due to this distance should be minimal.

2.4 Time Scale

Data was analysed for the following teaching days in autumn and winter (*teaching days of interest*):

1. The weekdays from 23 May to 8 July 2022 inclusive, excluding the public holidays of 6 and 24 June.
2. The weekdays from 25 July to 26 Aug 2022 inclusive.

During the teaching days of interest, the number of active sensors can be seen in Figure 6 below:

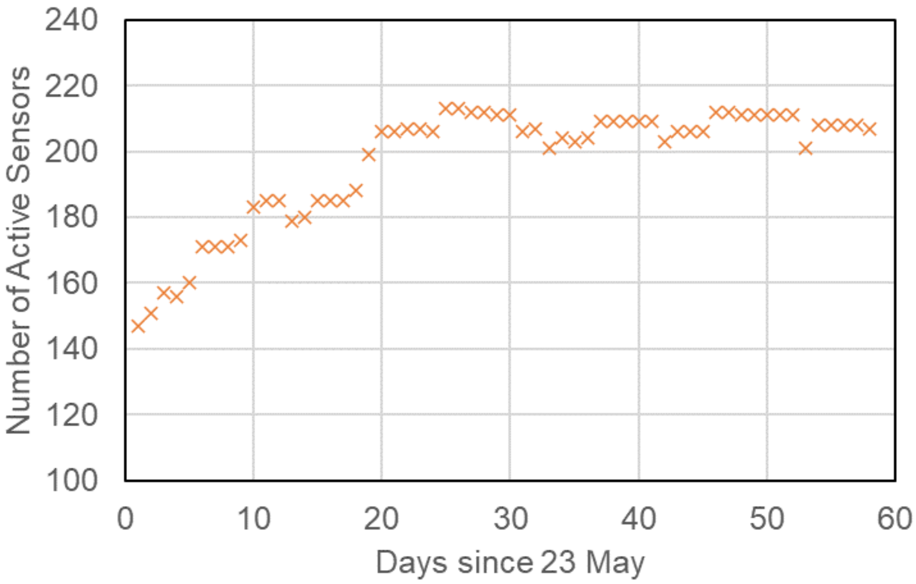


Figure 6: Number of Active Sensors between 23 May and 26 August 2022.

The teaching period of time on a teaching day is designated as 9 am to 3 pm. Though, it is noted that some schools may start teaching before 9 am and end before or after 3 pm. These times are selected for simplicity and consistency.

2.5 Method of Data Analysis

2.5.1 Outlier Detection

Outliers are considered as the observations that largely deviate and appear to be governed by different mechanisms compared to the other observations (Barnett & Lewis, 1984; Hawkins, 1980). These can be caused by naturally occurring errors (e.g., sensors in proximity to windows) and/or artificial errors (e.g., direct exhalation on sensors, faulty sensors, incorrect data processing methods).

In this initiative, the intention is to only focus on the outliers likely caused by direct exhalation, which were unusually high CO_2 levels and sometimes also with high relative humidity readings (Figure 7). The outliers were preliminarily removed by comparing the normalised reading (by adopting the *scaling to range* method: all readings minus the minimum then divided by the difference between the maximum and the minimum) to the rolling median of five previous normalised data points. If the difference is above the threshold of 0.1, the corresponding reading is treated as an outlier and replaced with the rolling median of five previous data points. This was proven to be helpful, as presented in the example below:

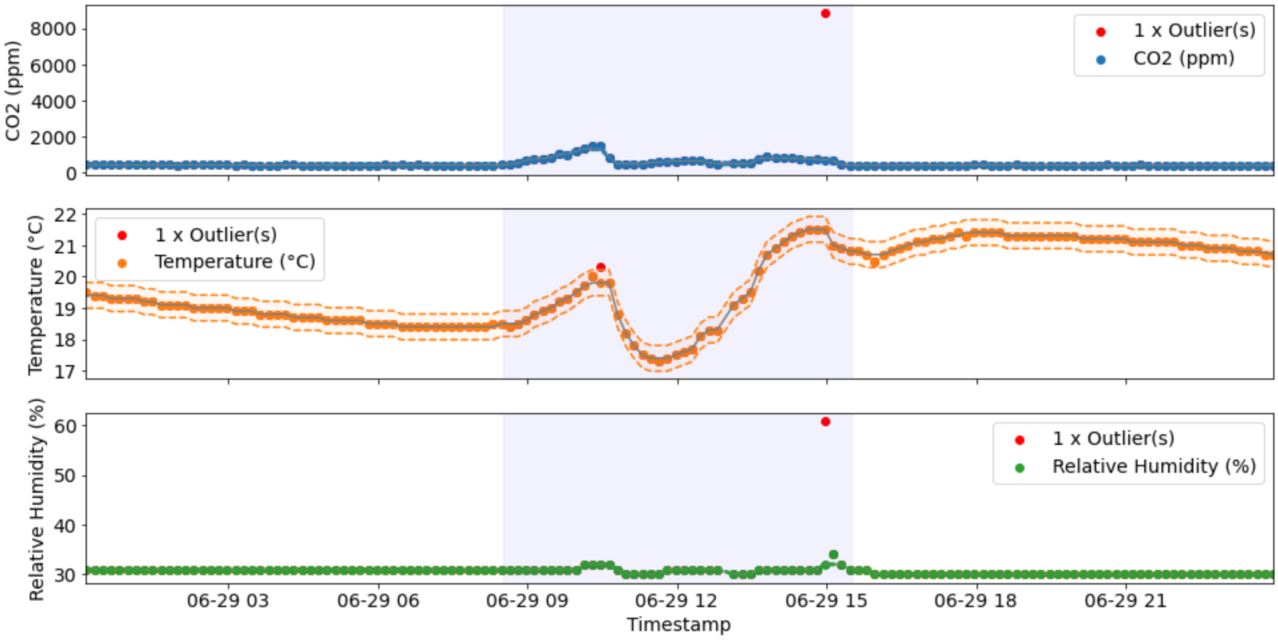


Figure 7: Examples of outliers (the red dots) that were likely caused by direct exhalation. The bands between the dash lines were the prediction intervals. Any observations outside the intervals are considered outliers and are to be replaced with the rolling medians (the grey solid line).

The effects of this method on the datasets are discussed in Section 4.1

2.5.2 *Variable Creation*

To answer the core questions outlined in Section 1, more variables were created to convert the raw CO_2 and temperature readings. In this section, the methods adopted for variable creation are briefly described.

Preheating

The term *preheating* is essentially heating with a time lag between the start time of heating (evidenced by when the indoor air temperature starts to rise) and first occupancy of the day (evidenced by when the indoor CO_2 level starts to increase). An incidence of preheating is one which fits the following criteria shown in Table 8:

Table 8: Criteria used to define the term preheating

Variables to define *preheating*	Condition	Reason
Indoor air temperature	Between 5 am and 8 am, there is an indoor air temperature increase of more than 2 °C, compared to the initial temperature when heating commenced.	• The indoor temperature increase threshold of 2 °C is an arbitrary value. • The time thresholds of 5 am and 8 am are set for consistency, to attempt to exclude unjustified heating start time and the effect of solar gain given sunrise time varied approximately from 6:50 to 8:30 am across the whole initiative.

		- The period in which the temperature rise of 2 °C must occur is not limited as long as the heating start-time can be detected by 8 am.
Outdoor air temperature	The outdoor air temperature rises by less than 1 °C (i.e., 50% of the threshold above), compared to the initial outdoor temperature when heating starts indoors.	- This is also arbitrary and attempts to eliminate the effect of heat loads originating outdoors, regardless of ambient differentials.
Median indoor CO_2 level over a period	Over the period during which the temperature has risen by 2 °C, the median indoor CO_2 level is less than 600 ppm.	- This condition is adopted to identify when a space is occupied, and to avoid including instances when the heating may arise from significant body heat load.

The *preheating* determined by the characteristic of temperature data effectively means **successful** *preheating*, since it is not known whether and when the attempts were made to achieve *preheating*. In this report, unless specified otherwise or emphasising, 'successful' is omitted for simplicity.

The variable *preheating* thus either takes a value of 'true' – there is preheating on the day of interest, or 'false' – there is no preheating on that day.

A *preheated* teaching day in a classroom means that all the above conditions for '*preheating* to be detected have been met on that day. A *frequently preheated* classroom means that preheating was detected on more than half of the teaching days.

The term *heating start time* is defined as the time stamp when the indoor air temperature starts to increase since 5 am. Then the term *typical heating start time* of a certain space is defined as the median of all observed *heating start times* of this space.

The term *start temperature* is defined as the indoor air temperature at the closest recording time to 9 am on a teaching day of interest.

Breaks and Refresh Breaks

A *break* is detected when there is a drop in CO_2 level over time, indicating a change in occupancy, ventilation, or both. Once a decrease in CO_2 concentration is observed, the effective air exchange rate may be obtained by fitting the time series of CO_2 levels to a formula representing the natural decline expected when there is no occupancy, and the outdoor CO_2 level is a constant 450 ppm. The data used for fitting run from the time when the CO_2 level starts to drop until it increases again, or the teaching day ends.

Due to the rather long measurement interval of 10 minutes, when using this method, there may be not enough data points for fitting reliably, e.g., a drop in the CO_2 level over 5 minutes following an increase – in this case, the effective air exchange rate will be underestimated after fitting the only two available data points. Obtaining the real-time air exchange rate is not of interest in this initiative, but it is still considered to be able to identify a CO_2 level drop as a break. The reference to time is not restricted for better coverage of data, i.e., the fitting process will be conducted over any drop in the CO_2 level during teaching time.

Then a *break* is defined as an instance when the obtained effective air exchange rate is no less than 1 ACH. Note that this method suggests that each of the CO_2 decreases, which might be caused by a stoppage of activity and/or increased ventilation while the activity continues, is essentially treated as a *break*.

A *refresh break* is an instance in which the effective air exchange rate is above 5 ACH, and the starting CO_2 is above 800 ppm, suggesting the likely deliberate opening of multiple doors and windows and the room being possibly vacated. When attempting to flush a previously occupied space, more than 5 ACH of ventilation can bring 2000 ppm of CO_2 down to about 1100 ppm in less than 10 minutes.

Note that both *break* and *refresh break* determined by the feature of CO_2 data effectively means **successful** *break* and **successful** *refresh break*, since it is not known whether and when the attempts were made to achieve *break* or *refresh breaks*. In this report, unless specified otherwise or emphasising, 'successful' is omitted for simplicity.

The terms *early morning, late morning, lunch,* and *afternoon break/refresh break* are defined as the *break/refresh breaks* occurring at 8.30-10.30 am, 10.30-12.00 am, 12.00-1.30 pm, and 1.30-3.00 pm respectively.

2.6 Aggregate Data

Based on the raw data reported by each Aranet4 Pro sensor and the created variables, the daily data during teaching hours in each space can be aggregated by taking mean or median depending on the distribution of the variable of interest. To do this, three filters have been applied:

1. At least 4 hours of measurements must have been reported in a single teaching day, otherwise, it may suggest that the sensor has a significant connectivity issue on that day and the corresponding dataset may fail to capture useful information and should be disregarded.
2. The overall CO_2 concentration has to increase before 10 am, meaning that the space is occupied from the morning. This criterion helps to exclude the teaching days that does not conform to the preferred period of teaching activity between 9 am and 3 pm, which could skew the results.
3. Daily median CO_2 has to be above the threshold of 600 ppm. This is to attempt to exclude spaces when the occupancy is very low, or it is not used at all. It should be noted that this method brings the risk of mistakenly disregarding spaces with very good ventilation.

Based on the raw or the daily data, the data by space was aggregated by taking mean or median of all measurements during teaching time in each space, or calculating the fraction (e.g., fraction of the teaching days when *preheating* is detected), depending on variable. The data by school was subsequently aggregated based on the data by space.

2.7 Analytic Methods

Since this document only aims to report descriptive statistics, the analysis procedures are as follows:

1. Determine what dataset is used, e.g., aggregate dataset by space, and visualise (plot) the relevant variables if useful.
2. Where the relevant variables are quantitative, report counts, mean, standard deviation, minimum (min), 25th, 50th (median), 75th percentiles, and maximum (max).
3. Depending on the research question and variable characteristics, determine which hypothesis to test.
4. Report hypothesis test statistics and effect size where possible and determine whether the null hypothesis is likely to be rejected.

2.8 Limitations

This initiative is limited to autumn and winter conditions, and to spaces which are naturally ventilated, i.e., spaces which have ducted mechanical or mixed-mode ventilation were excluded.

In different teaching environments, the ventilation capability varies, according to variables such as the room dimensions, the number and size of openable exterior windows and doors, etc. Also, the people who control the ventilation (usually the teachers) have variable tolerance levels relating to temperature, drafts and outdoor noise with differing responses impacting decision making on opening or closing windows.

These variables were either incomplete or intentionally not recorded in this initiative. Hence, there are two major assumptions:

1. All spaces of interest have ventilation capabilities which are adequate to achieve the desired CO_2 levels, i.e., there are always sufficient exterior windows that can be opened wide enough. The rationale being they will have all been built to New Zealand Building Code (NZBC) requirement, which throughout its history has mandated the current window opening ration as current NZBC.

2. All detected events of preheating and *refresh breaks* (as defined in Section 2.6.2) were non-incidental, i.e., all events were deliberate although they may not necessarily be for achieving better ventilation (e.g., it is possible that the preheating detected in a certain space was applied only for obtaining a warmer temperature before the teaching started).

Before and during the period of data collection, advice was circulated to all schools, including advice on preheating and using refresh breaks (meaning the **attempt** or the **action** “to clear the air by fully opening all the windows and doors, preferably while having everyone exit the room”, and should not be confused with the term (successful) *refresh break* defined in 2.5.2).

No control group received different advice. However, after inspecting the dataset, by assuming that all events of preheating and *refresh breaks* were due to the intervention instead of the previously existing behaviours of the occupants, the advice was found to have been applied unevenly across all monitored spaces, and not necessarily consistently applied in a certain space over the period of the initiative. Therefore, depending on the research question, a control group naturally arises in those spaces where either or both strategies were not applied, i.e., the spaces where preheating and *refresh break* were rarely or never detected.

In this initiative, to concentrate on investigating the core questions described in Section 1, the effects of the intervention (i.e., encouraging the schools to adopt the advice of preheating and *refresh breaks*) will not be assessed.

The other potential issue, which can be significant, is misclassification. For example, if the definitions of preheating and refresh break in Section 2.6.2 have faults, such that some data was falsely detected or overlooked, i.e., false positive or false negative. Sensitivity analysis can be of help with addressing the potential issue, which will be included in the next publication of this initiative.

3.0 Results

3.1 Outliers

In Figure 7 above, the example of obvious outliers likely due to direct exhalation is shown. During the process of outlier removal, it was noted that, as shown in Figure 8, some CO_2 readings (such as the two marked in red) were also treated as outliers by the method described in Section 2.6.1, but appear to be not caused by direct exhalation and therefore seem to be unjustified.

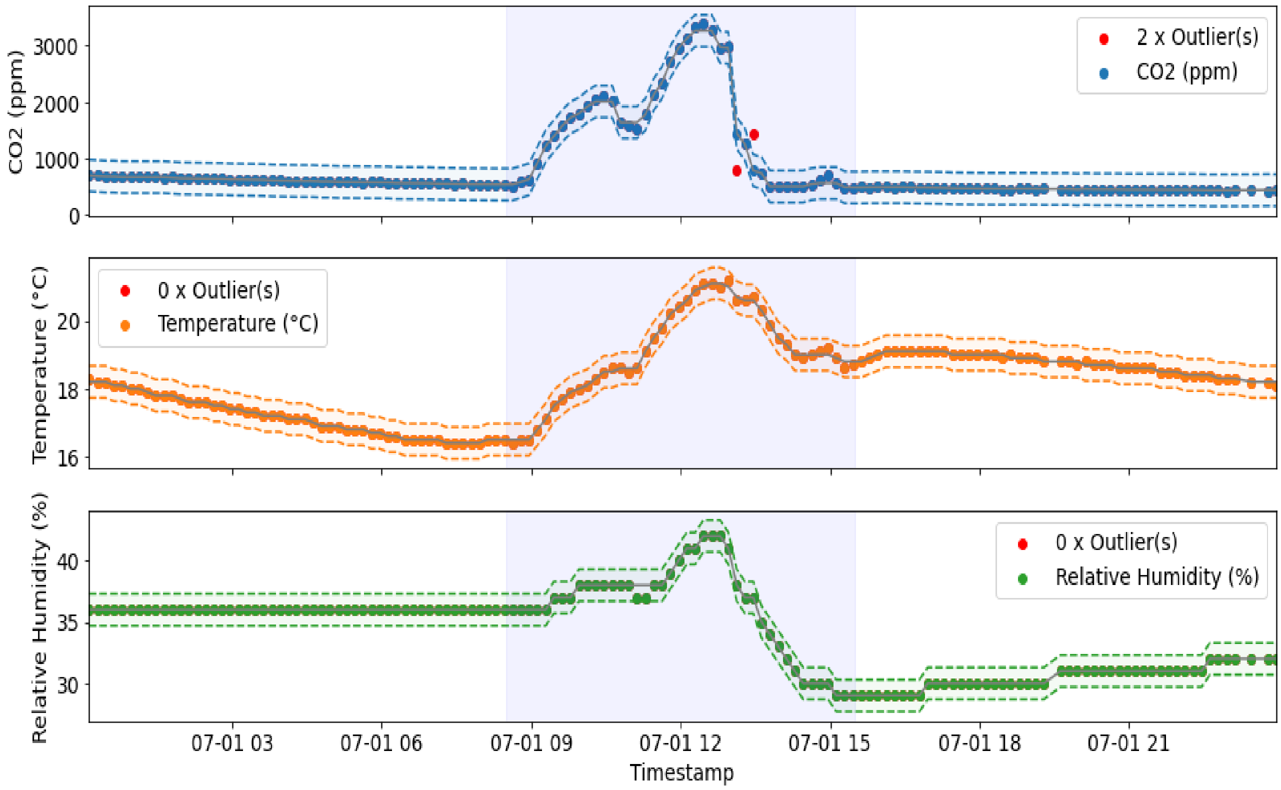


Figure 8: Examples of outliers (the red dots) that were likely caused by naturally occurring errors.

Table 9: Comparison of the typical datasets before and after outlier removal:

(a) CO_2 readings from Figure 7:

Description	With Outliers	Without Outliers
Count of observations	143	143
Mean (ppm)	553	496
Median (ppm)	441	441
Standard Deviation (ppm)	729	199
Min (ppm)	381	381
Max (ppm)	8876	1478

(b) CO_2 readings from Figure 8:

Description	With Outliers	Without Outliers
Count of observations	141	141
Mean (ppm)	835	835
Median (ppm)	569	569
Standard Deviation (ppm)	693	693
Min (ppm)	430	430
Max (ppm)	3404	3404

As shown in Table 9, the outlier removal method described in Section 2.6.1 appears to have the strongest effects when the extreme CO_2 readings due to direct exhalation were present, but have negligible effects on the dataset where direct exhalation on sensors seems to be unlikely. It can be seen that the two columns of Table 9b are identical. This is because that the two outliers happen to be 'symmetrical' to the two rolling medians used to replace the outliers with respect to the datapoint in-between.

Among the data recorded during teaching time, approximately 11% of the CO_2 readings and 4% of the temperature readings are considered outliers and replaced with rolling medians. The binned scatter plot shown in Figure 9 suggests that the outlier detection method becomes rather sensitive when the daily median CO_2 is lower. An alternative method or a higher threshold/tolerance may be of help to improve this.

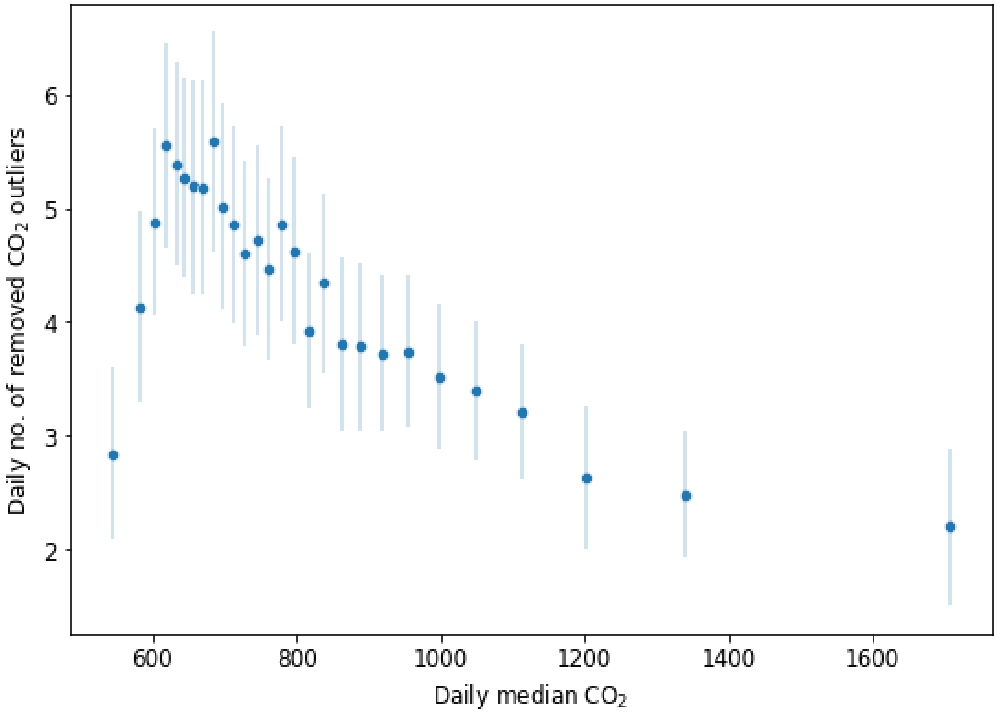
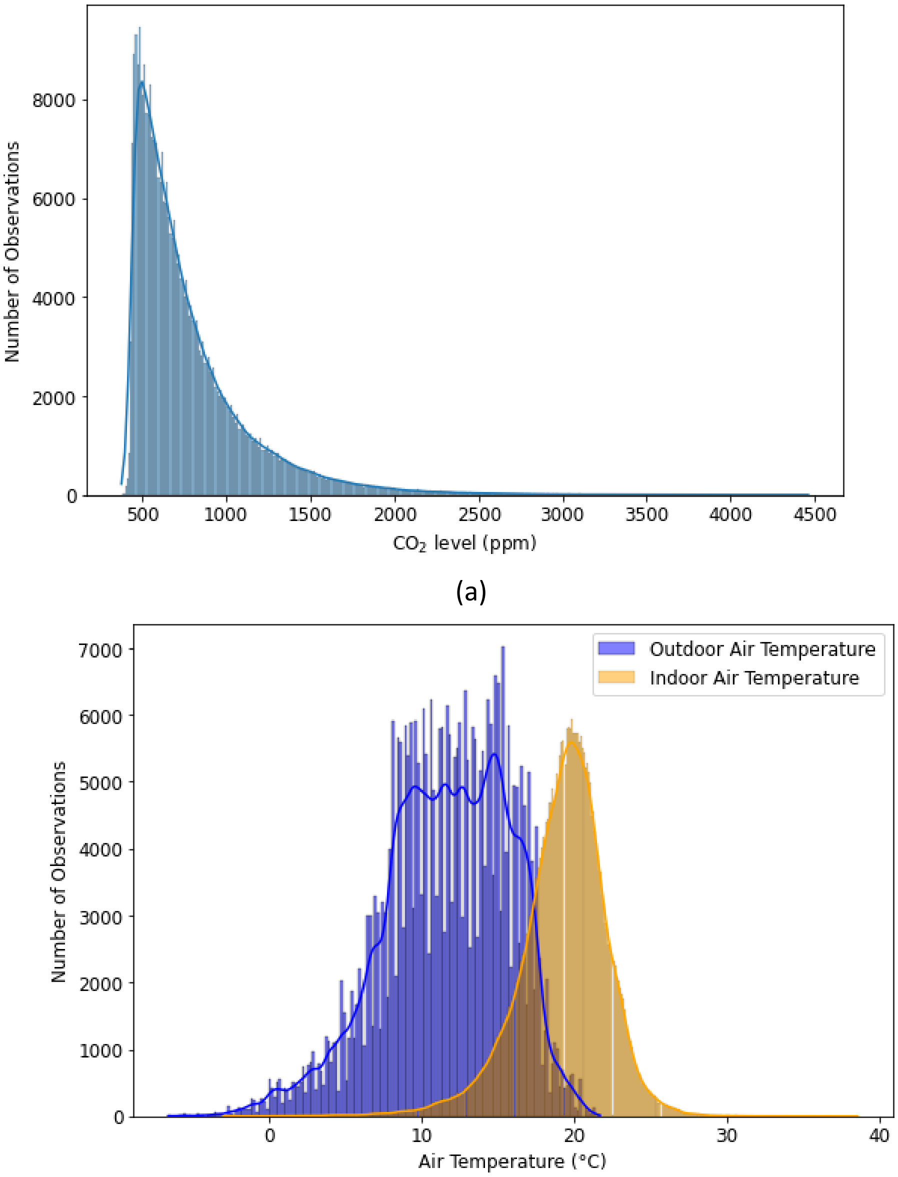


Figure 9: Binned scatter plot of the number of detected outliers in the daily dataset over the daily median CO_2 level.

3.2 Overall Observations

The histograms and the descriptive statistics of raw CO_2 and air temperature data over the whole dataset of the measurements taken during teaching time (i.e. excluding all measurements taken outside 9 am – 3 pm or during weekends, public and school holidays) in the 169 teaching spaces (i.e. excluding all non-teaching spaces) are shown in Figure 10 and Table 10 below.



(a)

(b)

Figure 10: Distributions of Raw Data Recorded during Teaching Time across 169 Spaces of Interest: (a) CO_2 Level, (b) Indoor Air Temperature.

As shown in the histograms above, the distributions of raw CO_2 and indoor air temperature data are heavily right-skewed and slightly left-skewed respectively. The outdoor air temperature data is rather scattered. For simplicity, the indoor air temperature data is assumed to be normally distributed.

Table 10: Descriptive Statistics of All CO_2 Levels (ppm) and Indoor Air Temperature (°C) Across 169 Spaces of Interest, Recorded During the Teaching Time of Interest

Description	CO_2 Level	Indoor Air Temperature	Outdoor Air Temperature
Count	343503	343503	343503 (after resampling)
Mean	777	19.2	11.6
Standard Deviation	352	2.9	4.2
Min	374	-3.0	-6.6
25%	535	17.7	8.9
50% (Median)	668	19.5	11.9
75%	896	21.1	14.8
Max	4462	38.6	21.7

In Table 10, it is noted that a minimum temperature of -6.6 °C was recorded. On checking the raw data, these extreme temperature readings were observed with very low CO_2 levels, suggesting that, at the time when the data was being recorded, there were likely either no occupants, or the spaces were not used as typical teaching environments and should be disregarded, following the filtering method described in Section 2.7.

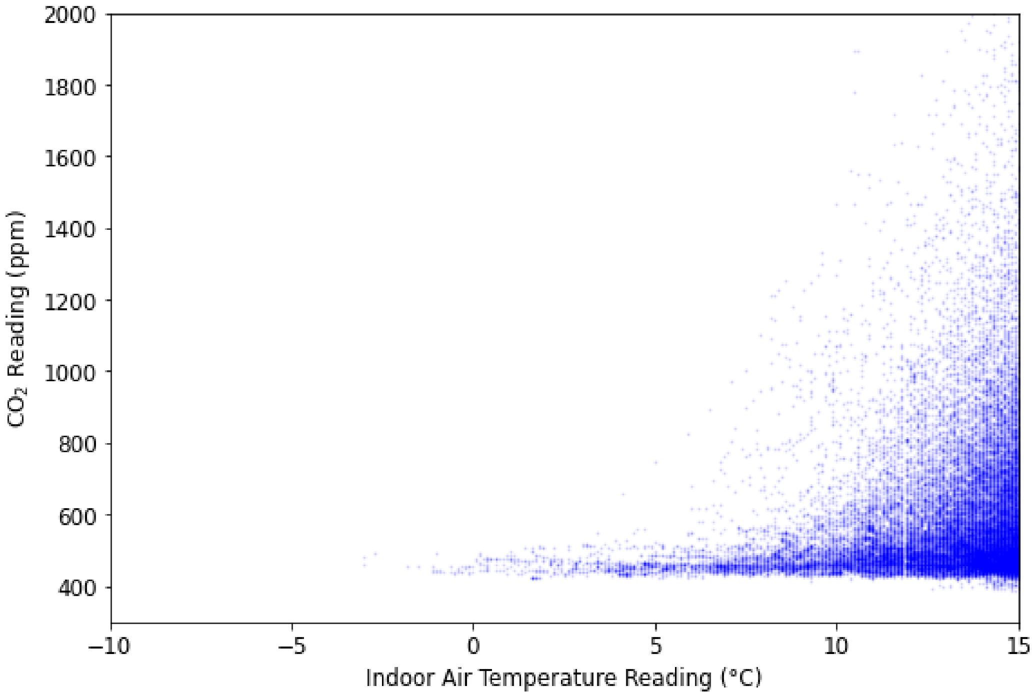


Figure 11: Scatter Plot of CO_2 Data Over Indoor Air Temperature lower than 15 °C.

Since the spaces of interest are not evenly distributed over all 6 Climate Zones, the median CO_2 Levels and the mean indoor air temperatures are broken down into Climate Zones in Table 11.

Table 11: Descriptive Statistics of All CO_2 Levels (ppm) and Indoor Air Temperature (°C) Across 169 Spaces of Interest During the Teaching Time of Interest, Sorted by Climate Zones

	CO_2 Levels (ppm)			Indoor Air Temperature (°C)		
	Median	75%	Max	Mean	Min	25%
Climate Zone 1	619	789	4327	19.2	5.2	17.6
Climate Zone 2	664	863	3909	19.8	6.2	18.1
Climate Zone 3	656	865	4172	19.7	1.2	17.9
Climate Zone 4	692	941	2986	19.6	5.9	17.6
Climate Zone 5	706	984	4462	19.5	0.9	17.6
Climate Zone 6	714	1013	4188	19.7	-3.0	17.8

Note: *the 75th percentile and the maximum of CO_2 levels are used to reveal the upper bounds; the 25th percentile and the minimum of indoor air temperature are used to show the lower bounds.*

Table 10 and Table 11 suggest that across all spaces of interest, for most of the teaching time, the CO_2 level was less than approximately 1000 ppm, and the indoor air temperature was in the comfortable range according to DQLS V.2.0 2022. It is also noted that some spaces did experience elevated CO_2 levels. While the indoor air temperature is about the same in all Climate Zones, CO_2 levels were higher in the colder Climate Zones.

3.3 Preheating

Typical Heating Start Time

The distribution of typical heating start time (defined in Section 2.6.2) is shown in Figure 12 below:

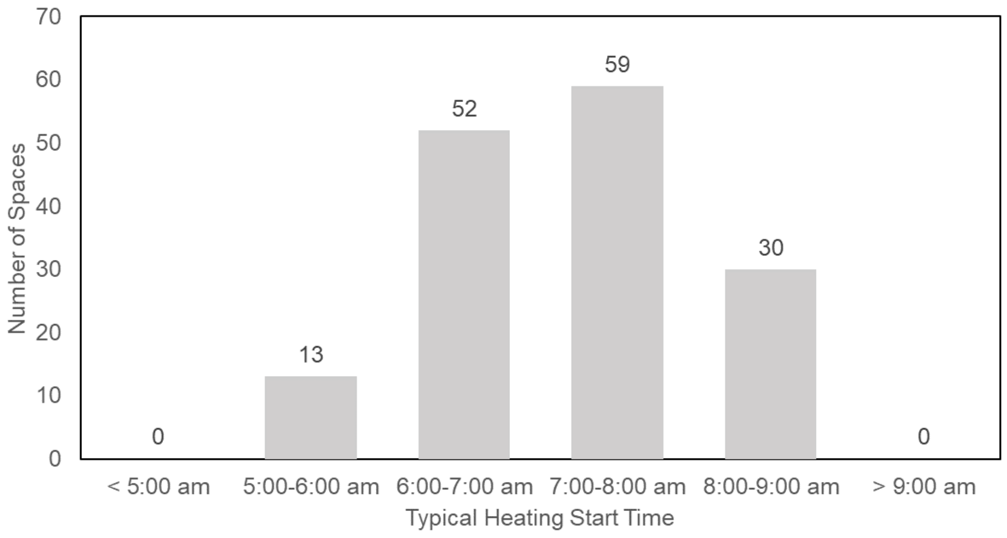


Figure 12: Distribution of Fraction of Teaching Days with Preheating Detected.

As shown in Figure 12 above, most spaces appear to be heated between 6.00 am and 8.00 am.

Fraction of teaching days with preheating

As defined in Section 2.6.2, preheating represents the time lag between heating (reflected by the rise of indoor air temperature) and occupancy (reflected by the increase of CO_2 level).

In certain spaces a fraction of teaching days with preheating can be calculated by:

$$\text{Fraction of Teaching Days with Preheating} = \frac{\text{Number of Teaching Days with Preheating}}{\text{Number of All Teaching Days with Valid Data}}$$

The calculated fraction distribution can be seen in Figure 13 below:

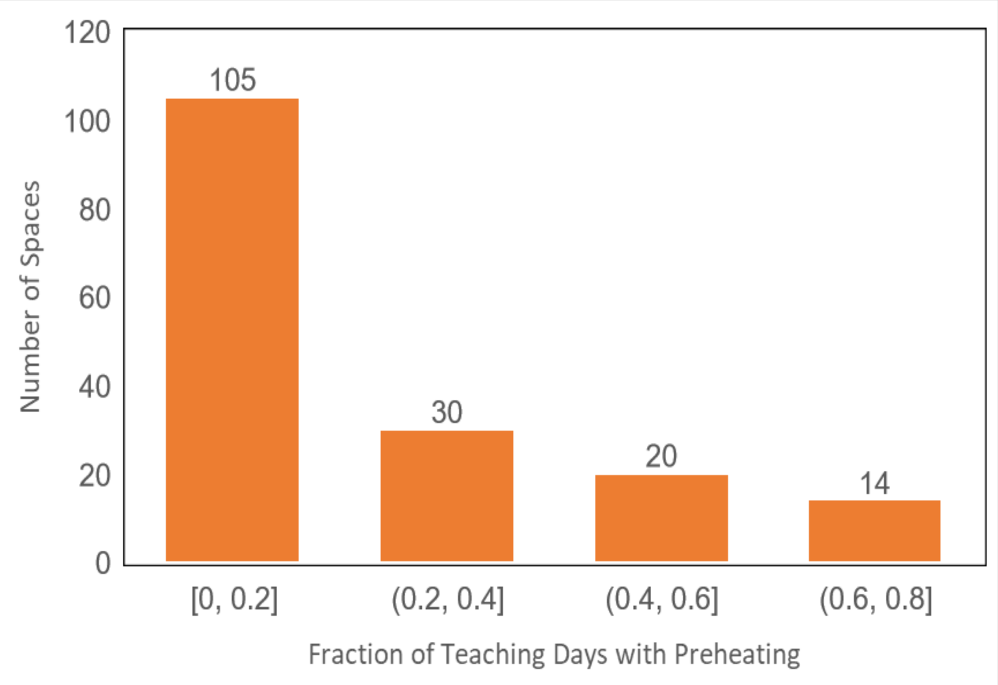


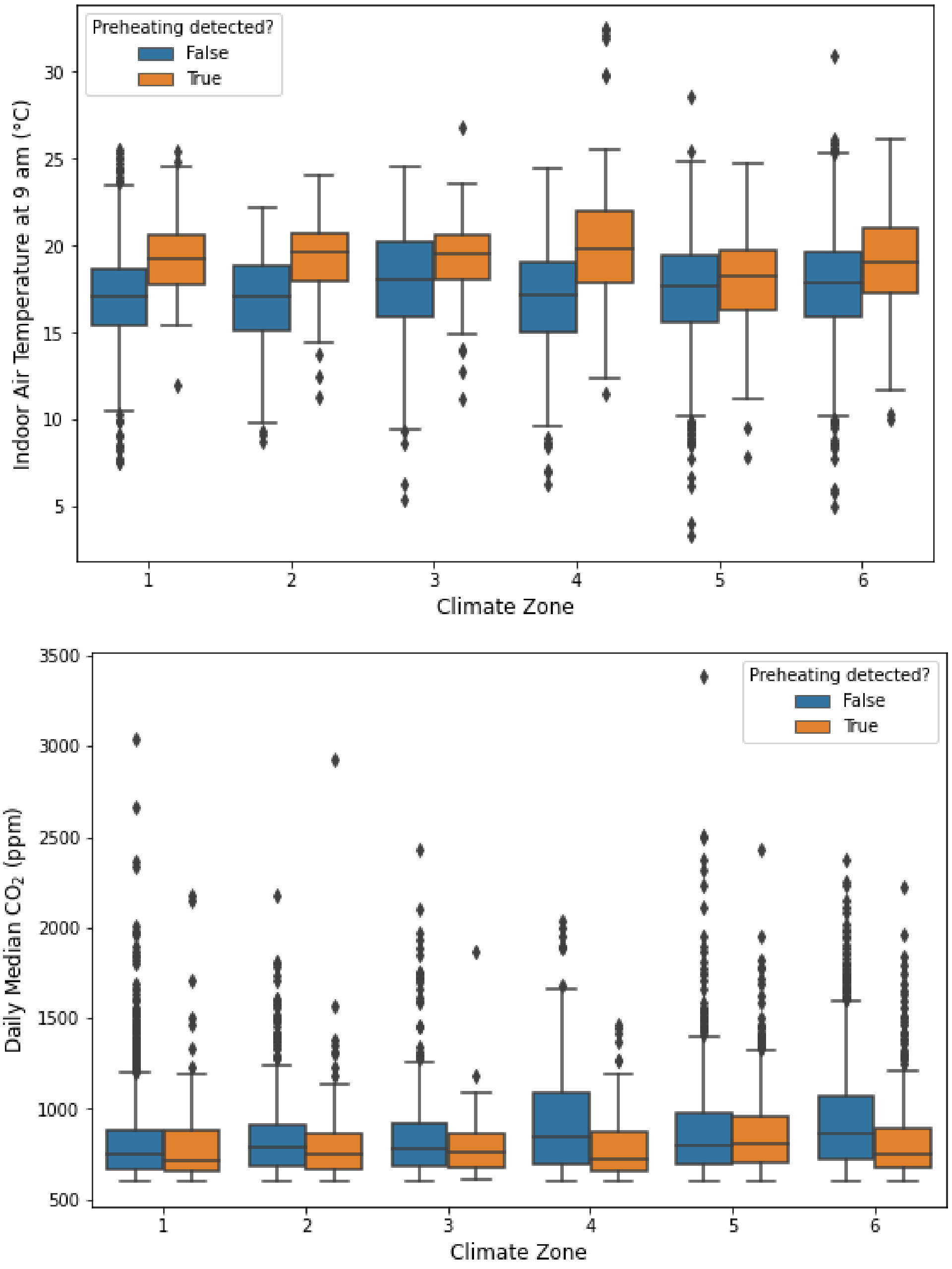
Figure 13: Distribution of Fraction of Teaching Days with Preheating Detected.

It can be seen in Figure 13 that few spaces implemented the preheating strategy. Varying fractions indicate that some spaces might have highly variable heating strategies, i.e., decisions on when to heat are being made day-by-day subject to the factors like weather.

Preheating vs. Start Temperature and CO₂

To visually compare the effects of preheating on the indoor air temperature when teaching started, using the data aggregated by day (all valid teaching days from 169 spaces), box plots are used (Figure 14).

(a)

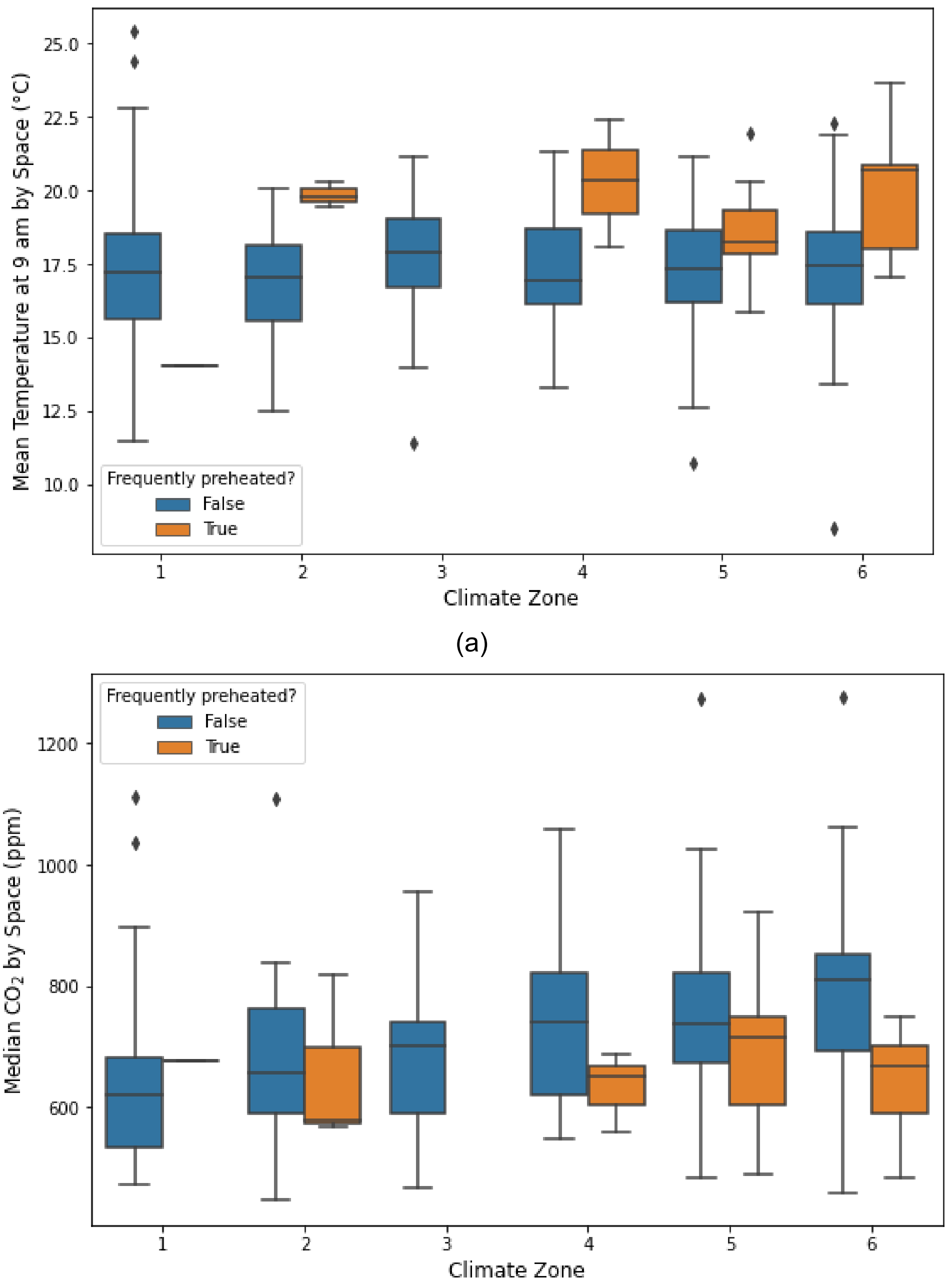


(b)

Figure 14: Daily (a) indoor air temperature at 9 am (typical teaching start time) and (b) median CO_2 levels when preheating was detected compared to when preheating was not detected.

It can be seen that when preheating was detected, the indoor air temperature at 9 am was likely to be higher (warmer and likely better thermal comfort) than that when preheating was not detected, i.e., preheating was effective in raising the temperature at the start of the day, as expected. Preheated and non-preheated spaces have similar daily median CO_2 levels.

To statistically estimate the effects of preheating, the data aggregated by space is used. Plots similar to Figure 14 can be obtained:



(a)

(b)

Figure 15: Box plot of (a) mean indoor air temperature at 9 am and (b) median CO_2 levels in frequently preheated spaces compared to the rest of the spaces. The absent box suggests a low sample size.

Since the start temperature and the median CO_2 by space are considered to be normally and non-normally distributed respectively, independent t-test and Wilcoxon Rank-Sum tests are adopted, where the null hypothesis is that the preheating essentially made no difference. The test results are summarised in Table 12 below.

Table 12: Test statistics of whether the preheating has effects on the start temperature and the median CO2

	Mean Indoor Air Temperature at 9 am (°C)			Median CO_2 Levels (ppm)		
	Test statistic	p-value	Effect Size	Test statistic	p-value	Effect Size
Climate Zone 1	NaN	NaN	NaN	-0.76	0.45	0.10
Climate Zone 2	-2.79	0.01	1.69	0.33	0.74	0.06
Climate Zone 3	NaN	NaN	NaN	NaN	NaN	NaN
Climate Zone 4	-2.11	0.05	1.35	1.14	0.25	0.29
Climate Zone 5	-2.03	0.05	0.62	1.27	0.20	0.18
Climate Zone 6	-2.68	0.01	1.00	2.67	0.01	0.41

NaN: not a number, due to low sample size.

The results suggest that: the effect of preheating on the mean start temperature is rather clear (minimum effect size, Cohen's d, larger than 0.5, highlighted with green colour under Mean Indoor Air Temperature at 9 am (°C)) and statistically significant; whereas the effect on the median CO_2 is unclear except for spaces in the Climate Zone 6 (effect size, r = test statistic / square root of sample size, between 0.30-0.5, highlighted with green colour under Median CO_2 Levels (ppm)), suggesting a moderate effect on lowering median CO_2 (Tomczak & Tomczak, 2014).

Start Temperature vs. Median CO_2

The summarised daily data is used to explore the relationship between the start temperature and the daily median CO_2 level. A binned scatter plot (Cattaneo et al., 2021b, 2021a) is adopted for visualisation:

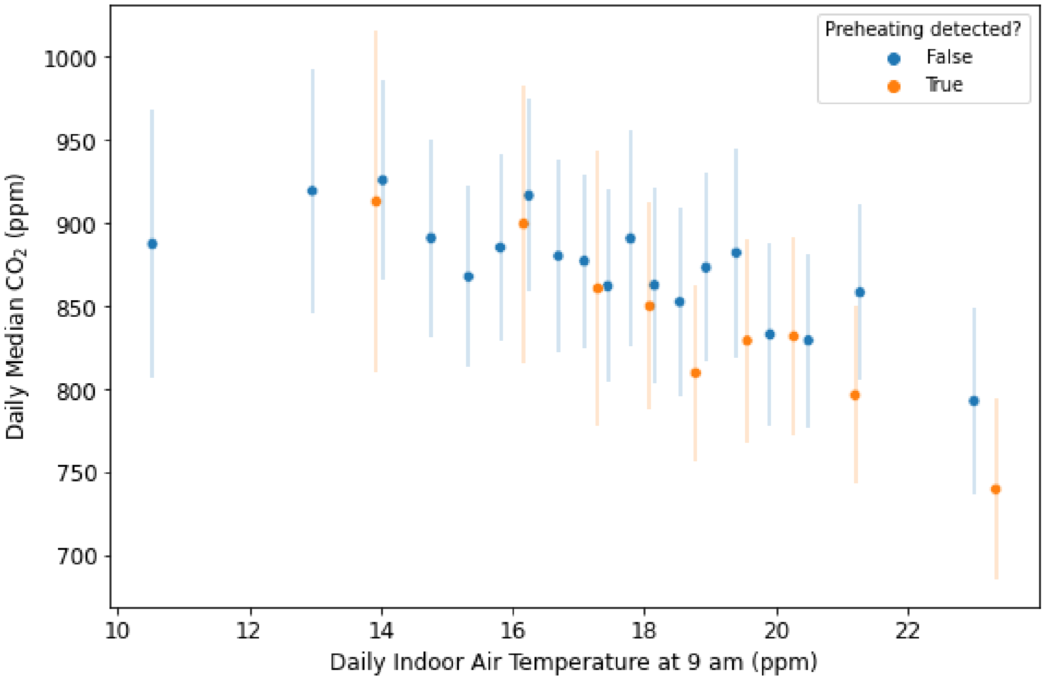


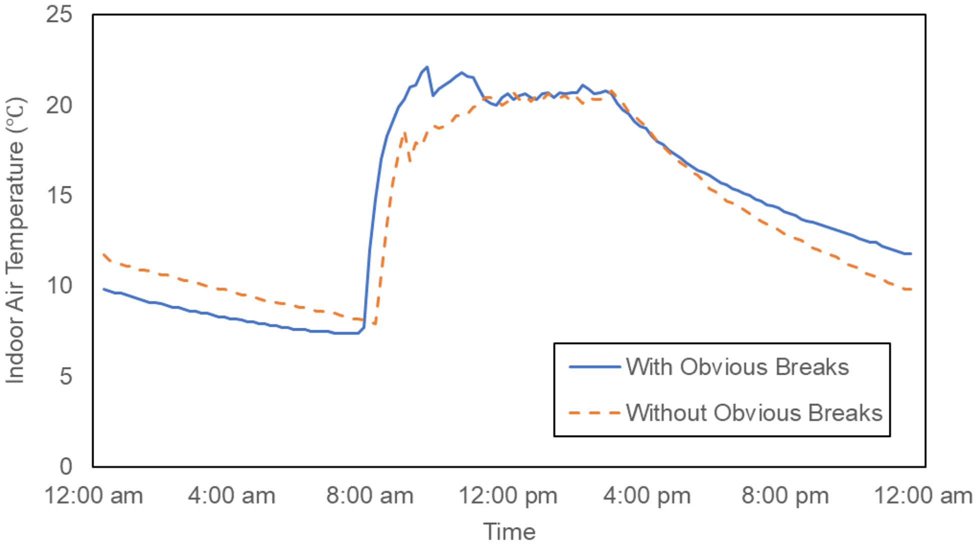
Figure 16: Binned scatter plot of the daily median CO_2 level over start temperature.

The daily median CO_2 level appears to decrease when the start temperature increases, but the plot also suggests that preheating seems to have made no difference, or was only applied to spaces that needed it and rendered their daily median CO_2 levels similar to that of other spaces. Preheating was likely to have the same effect as a warm day or being in a warm climate when other factors are the same.

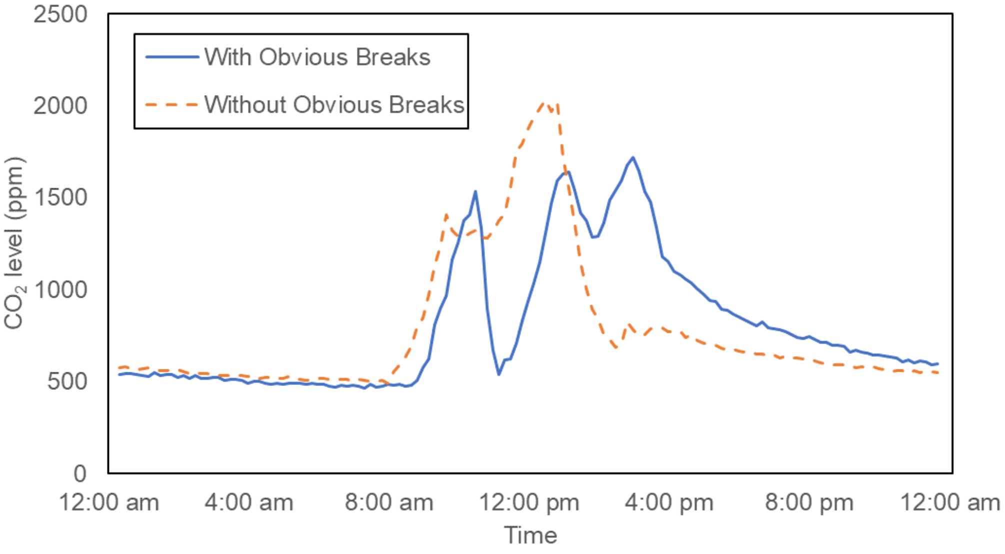
The Spearman rank-order correlation coefficient is adopted to measure the monotonicity of the relationship between the starting temperature and the daily median CO_2 level. The reported p-value is less than .001, and the effect size (Spearman's ρ) is -0.16, suggesting that the relationship is likely to be weak (Rea & Parker, 2014).

3.4 Breaks and Refresh Breaks

The typical effect of a refresh break can be seen in Figure 17 below, where the CO_2 and indoor air temperature readings in the same space during two continuous teaching days (16-17 June) are plotted.



(a)



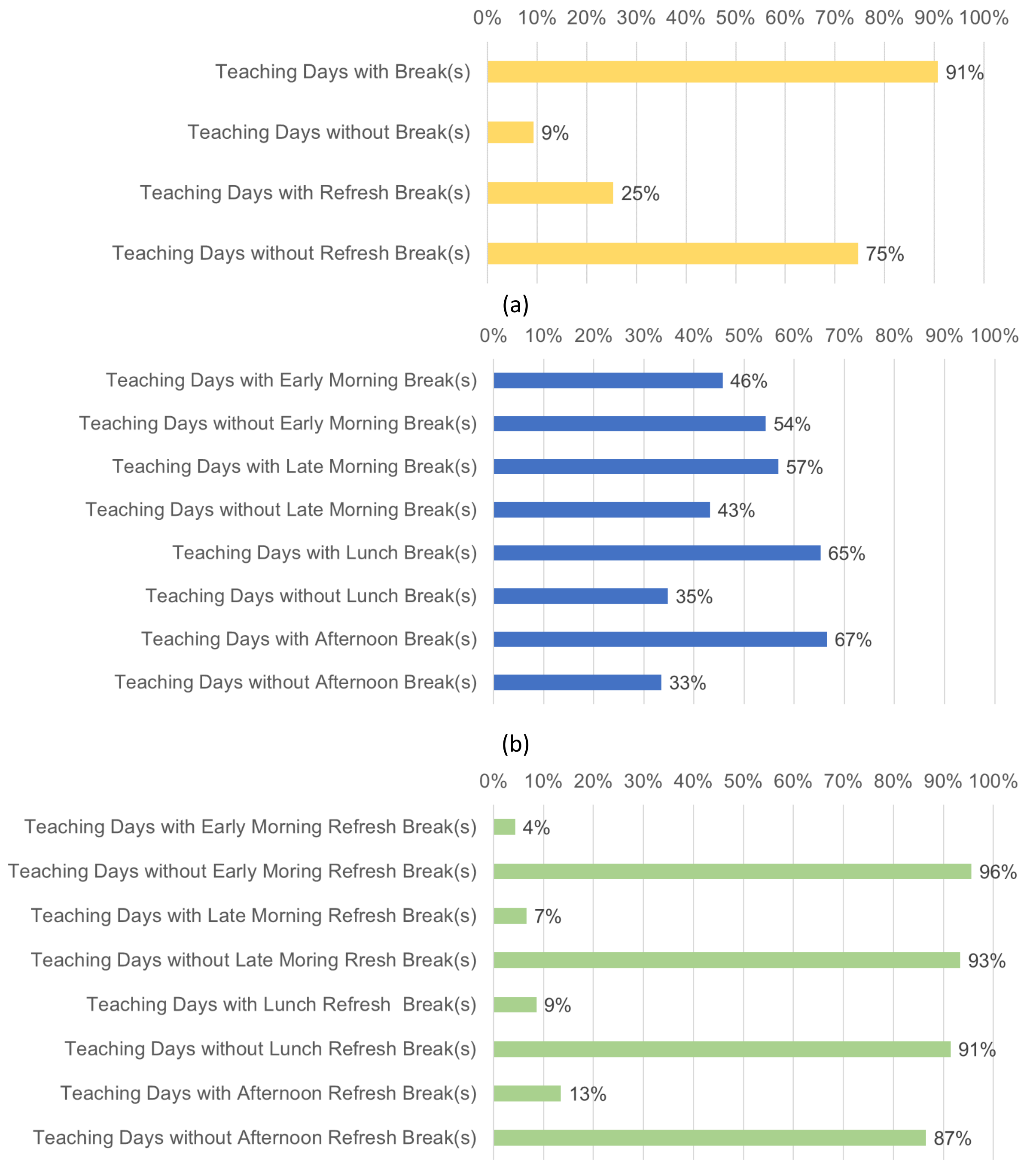
(b)

Figure 17: (a) indoor air temperature and (b) CO_2 readings in the same space during two continuous teaching days, where the blue solid lines and the orange dash lines represent the measurements taken on 16 and 17 June respectively.

In Figure 17 (b), At around 10:30 am, a quick drop of CO_2 was detected, calculated to be effectively 5 ACH indicating an air refresh break had been actioned. The plot shows that the refresh break helped with keeping the CO_2 level low on that day. Meanwhile, in Figure 17 (a), the indoor air temperature appears to have been hardly affected by the additional air exchange.

Breaks vs. Refresh Breaks

The summarised daily data is used to investigate whether the teaching spaces experienced *breaks* and *refresh breaks*.



(c) Figure 18: Percentages of 5314 valid monitored teaching days where breaks and refresh breaks are detected

The plots above show that, even though most of the teaching days had *breaks*, few experienced *refresh breaks*. While the *breaks* appear to have happened through a teaching day, the *refresh breaks* seem to have more likely occurred in the afternoon.

A *frequently breaking space* is defined when the number of *breaks* per day is above one. Similarly, A *frequently refresh-breaking teaching space* is defined when the number of *refresh breaks* per day is above one. The counts of these two types of spaces are summarised in Figure 19 below.

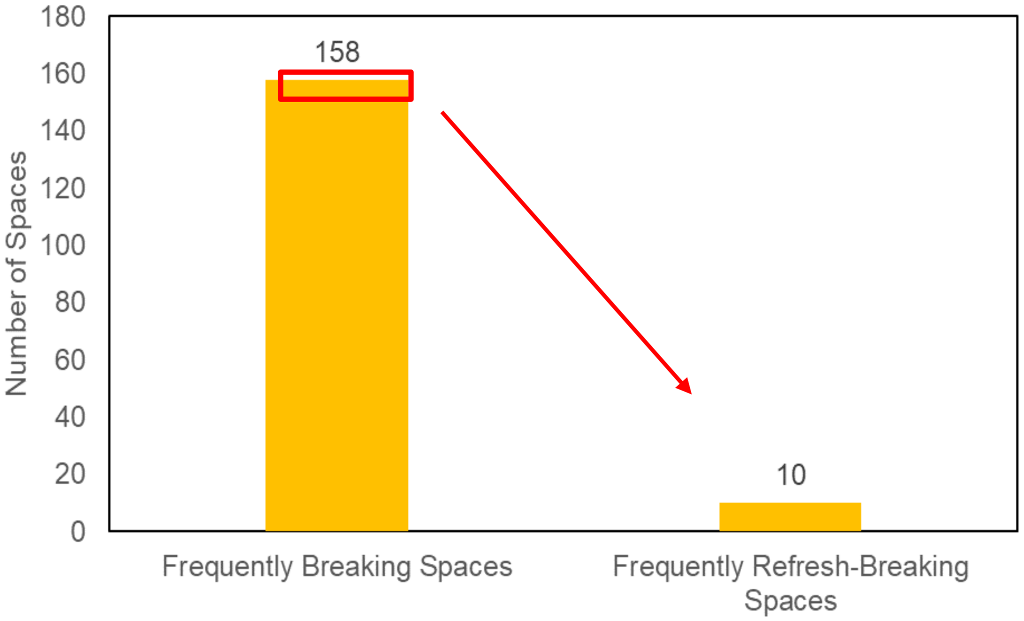
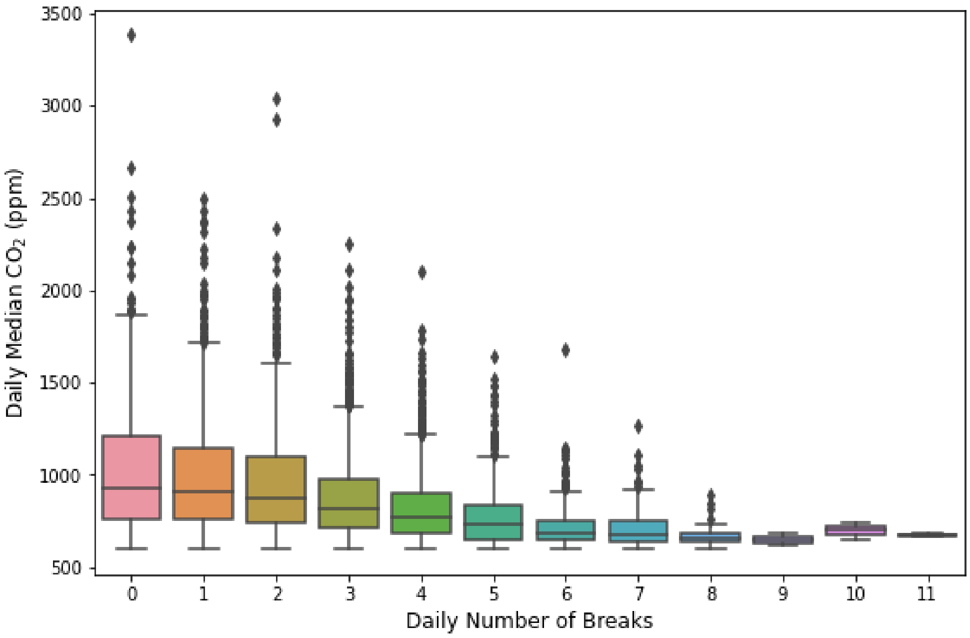


Figure 19: The number of frequently breaking spaces compared with frequently refresh-breaking spaces, among 169 spaces in total. For clarity, the red box and the arrow indicate that only 10 out of 158 spaces with frequent breaks were considered to have frequent refresh breaks

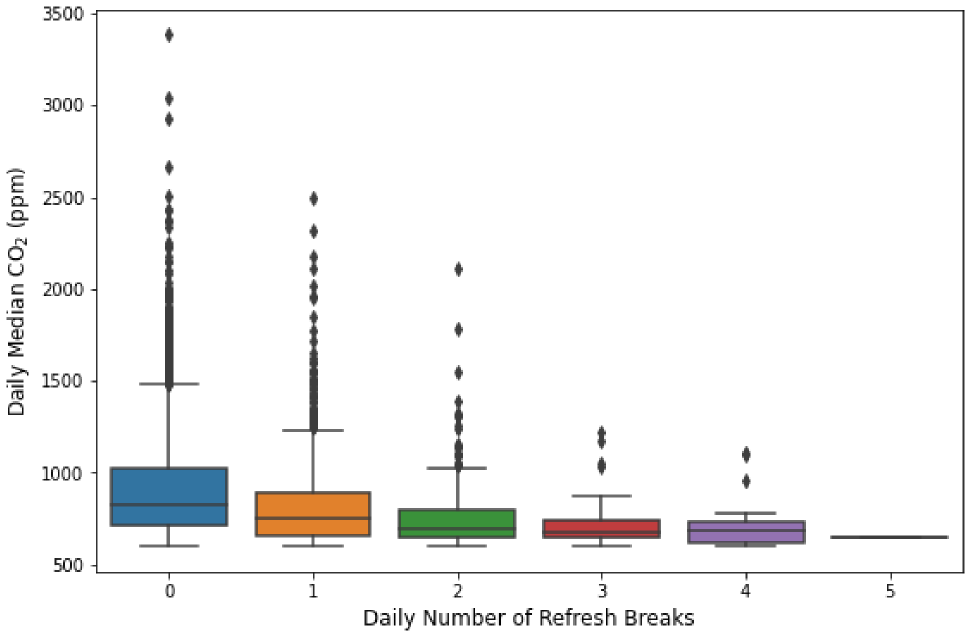
The figure above also suggests that, while most of the spaces seem to have *breaks* frequently, few adopted the method of refresh break to flush the space with fresh air.

Breaks vs. Median CO_2 and Mean Indoor Air Temperature

Due to the definitions, days which have more *breaks* and/or *refresh breaks* also tend to have lower CO_2 levels, as shown in Figure 20 below.



(a)

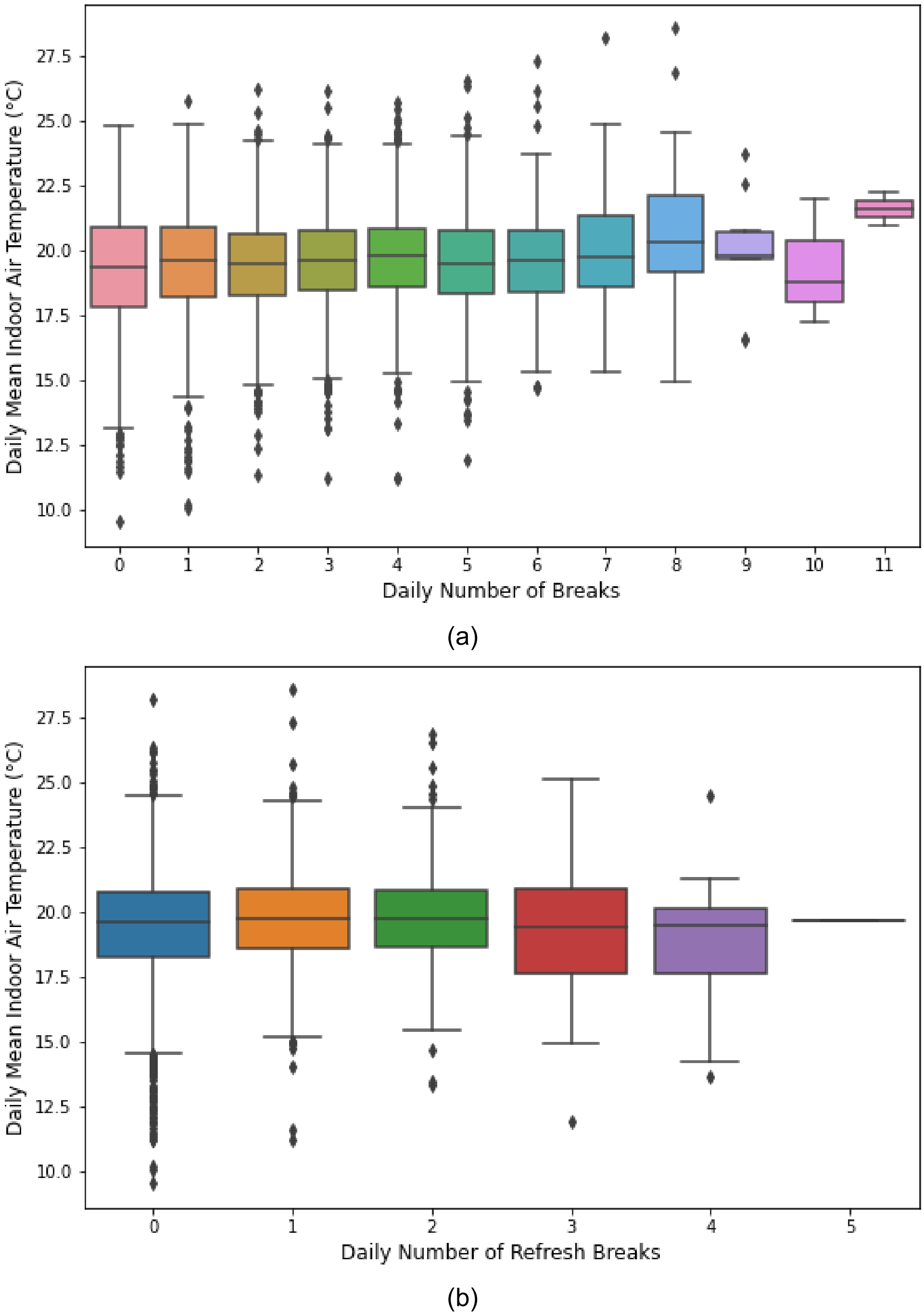


(b)

Figure 20: Box plots of the daily median CO_2 over the daily number of (a) breaks and (b) refresh breaks.

The Spearman rank-order correlation coefficients between the daily median CO_2 level and the number of *breaks* and *refresh breaks* are -0.39 and -0.23, suggesting that more *breaks/refresh breaks* and lower daily median CO_2 levels likely occurred at the same time and the relationships are likely to be moderate (Rea & Parker, 2014).

The same approach is used to investigate the relationship between the daily mean indoor air temperature and the number of *breaks/refresh breaks*.



(a)

(b)

Figure 21: Box plots of the daily mean indoor temperature over the daily number of (a) breaks and (b) refresh breaks.

The Pearson’s correlation coefficients between the daily mean indoor air temperature and the number of *breaks/refresh breaks* are 0.04 and 0.003, suggesting that frequent use of *breaks* and/or *refresh breaks* was unlikely to be detected on days with lower daily mean indoor air temperature.

4.0 Discussion

In this initiative, real-time data of CO_2 level and indoor air temperature in teaching spaces was collected to investigate how ventilation performs. This section presents further interpretation based on the results shown in Section 3 and attempts to better answer the two core questions about preheating and refresh breaks set in Section 1.

4.1 Interpretation of Overall Observations

Due to the obvious limitations discussed in Section 2.2, it is impossible to obtain the real-time performance of ventilation in the monitored teaching spaces without uncertainty. The *Designing Quality Learning Spaces (DQLS) Indoor Air Quality and Thermal Comfort* (V.2.0 2022) adopts the concentration of CO_2 as a proxy for ventilation effectiveness and sets the CO_2 thresholds of 800, 1250, and 2000 ppm as design criteria of new/refurbished teaching spaces, which corresponds to approximately the air exchange rates of 6, 3, and 2 ACH, or the fresh air supply rates of 10, 6, and 4 L/s/person in a typical NZ classroom.

The thresholds of 800, 1250, and 2000 ppm have also been adopted to quickly assess whether a space is well ventilated when it is occupied (Ministry of Education NZ, 2022). This initiative is therefore also adopting the thresholds to assess how ventilation performs during the time scale of interest. Table 13 below shows the frequency at which CO_2 readings exceeded these thresholds:

Table 13: Number of CO_2 datapoints collected in the 169 monitored teaching spaces during teaching time, and the percentages of this data when the CO_2 level was above each thresholds

Description	Number of CO_2 Data	< 800 ppm	≥ 800 ppm	≥ 1250 ppm	≥ 2000 ppm
Climate Zone 1	93332	76.1%	23.9%	4.9%	0.6%
Climate Zone 2	41544	68.2%	31.8%	7.4%	1.3%
Climate Zone 3	36969	69.0%	31.0%	6.5%	1.1%
Climate Zone 4	33861	63.4%	36.6%	11.3%	1.0%
Climate Zone 5	59317	60.4%	39.6%	12.1%	1.5%
Climate Zone 6	78480	59.4%	40.6%	14.5%	1.9%
Overall	**343503**	**66.6%**	**33.4%**	**9.4%**	**1.2%**

Note that the percentages do not add up to 100% as the data exceeding 800 ppm include the data exceeding 1250 ppm, which also include the data exceeding 2000 ppm. The breakdown of the CO_2 data is summarised in Table 14 below, for easy reference:

Table 14: Number of CO_2 datapoints collected in the 169 monitored teaching spaces during teaching time, and the percentages of this data when the CO_2 level was in a certain range

Description	Number of CO_2 Data	< 800 ppm	800-1249 ppm	1250-1999 ppm	≥ 2000 ppm
Climate Zone 1	93332	76.1%	19.0%	4.3%	0.6%
Climate Zone 2	41544	68.2%	24.4%	6.1%	1.3%
Climate Zone 3	36969	69.0%	24.5%	5.4%	1.1%
Climate Zone 4	33861	63.4%	25.3%	10.3%	1.0%
Climate Zone 5	59317	60.4%	27.5%	10.6%	1.5%
Climate Zone 6	78480	59.4%	26.1%	12.6%	1.9%
Overall	**343503**	**66.6%**	**24.0%**	**8.2%**	**1.2%**

Since each of the processed datapoints were taken over the same 10-minute time interval, the percentages shown in the Table 13 and Table 14 above can be interpretated as the fraction of the monitored teaching time when the CO_2 concentration exceeded the thresholds, or was in a specific range.

It was recommended (Ministry of Education NZ, 2022) that actions should be taken to improve ventilation once the CO_2 level exceeds 800 ppm. Tables 13 and 14 shows that approximately 60-76% of the monitored teaching time, the CO_2 levels were maintained below 800 ppm and for approximately 85-95%, it was maintained below 1250 ppm. Schools located in colder climates were more likely to experience elevated CO_2 levels, i.e., lack of efficient ventilation or fresh air supply assuming that the teaching spaces were used similarly. Therefore, needed more ventilation interventions. These results generally suggest that there was sufficient fresh air more than half to three-quarters of the teaching time across all monitored teaching spaces, while actions may still have been needed to achieve better outcomes, especially in colder climates.

Factor reliance (e.g., dimensions of the space, occupancy, types of activity, etc.), determines whether the ventilation is effective, which can only be confirmed once the CO_2 level sustains at a certain level (at steady state or equilibrium). For example, the CO_2 reading of 600 ppm does not mean the ventilation is effective if it eventually will reach and be sustained at > 2000 ppm when other factors remain constant. In some poorly ventilated rooms reaching 2000 ppm, the CO_2 level may not stabilize and continuously rise until there is an intervention. Similarly, an elevated CO_2 level such as > 2000 ppm does not necessarily mean that the ventilation available in the teaching space is insufficient if the space is inappropriately used (e.g., over occupied, or used for an indoor PE class on wet days).

Methods (Wells, 1955; Riley et al., 1978; Buonanno et al., 2020a, 2020b; Mikszewski et al., 2021) exist to potentially estimate the infection risk due to **airborne** pathogens (not including the transmission via surface/fomite or larger droplets which settles fast due to gravity) in a teaching space if the CO_2 level is known as a proxy. The calculations used in such methods are typically informed by clinical data such as that in Teyssou et al., 2021. However, the accuracy also heavily depends on information such as the real-time number and the viral load emission rates of infectious occupants, the infectious quantum of the variant being spread at the time of interest (e.g., Omicron BA.2), the exposure time, and population susceptibility, etc. This level of information is unavailable in the present initiative. These methods also commonly assume that the air in a space is well-mixed, which it may not be, or may not be some of the time. Advanced modelling methods such as Computational Fluid Dynamics can be of use to address this issue but are expensive to run and require greater expertise to obtain reliable results.

In this initiative, and due to lack of real-time information about occupants, the actual effectiveness of ventilation and the risk of airborne infection remains inconclusive. However, the CO_2 measurements can still be justifiably treated as a proxy for the real-time level of fresh air, and avoiding elevated levels of CO_2 without sacrificing thermal comfort remains the general goal.

A breakdown of indoor air temperature data is given in Table 15 below. The results suggests that for approximately 70% of the teaching time in the spaces of interest, the indoor air temperature was in the range of 18-25 °C recommended in DQLS V.2.0 2022. However, as stated in Section 2.1, the thermal comfort is not solely determined by the air temperature. A temperature slightly lower or higher than this temperature range does not necessary mean that the occupants will feel uncomfortable. Even if in the range of 18-25 °C, an occupant may still subjectively feel uncomfortable, especially if other factors become significant, e.g., strong draughts.

Table 15: Number of indoor air temperature data collected in the 169 monitored teaching spaces during teaching time, and the percentages of this data when the temperature was in a certain range

Description	Number of Temperature Data	< 15 °C	15 - 18 °C	18 - 25 °C	25 - 30 °C	> 30 °C
Climate Zone 1	93332	5.6%	25.1%	68.1%	1.2%	0.0%
Climate Zone 2	41544	5.6%	18.8%	73.8%	1.7%	0.1%
Climate Zone 3	36969	8.1%	18.2%	73.0%	0.7%	0.0%
Climate Zone 4	33861	9.8%	19.0%	69.5%	1.6%	0.2%
Climate Zone 5	59317	9.7%	19.7%	69.7%	0.9%	0.1%
Climate Zone 6	78480	7.2%	19.7%	71.5%	1.6%	0.0%
Overall	**343503**	**7.3%**	**20.8%**	**70.5%**	**1.3%**	**0.10%**

4.2 Effects of Preheating

As described in Section 1 and 3.3, a proposed intervention to indirectly lower the CO_2 level is to provide better thermal comfort via preheating. For this to succeed, there must be a lag between the rise of temperature and of occupancy.

In Section 2.5.2, the method used to define preheating is described. The conditions essentially are:

1. Sufficient increased indoor air temperature applied between 5 am and 8 am
2. This increase starting before the beginning of occupancy
3. This increase not being attributable to external/ambient factors, i.e., outdoor (including solar) sources or early occupancy

This method is of use when generating the results shown in Section 3.3, but may also result in false positives and/or false negatives. A false positive means that a preheating is mistakenly detected. One scenario which may cause this is where a cleaner works in a classroom early morning, using the heating while present, and then turning it off when leaving. This may lead to a sufficient increase in temperature that preheating is detected. However, the temperature may drop later, so that there is little effect on the start temperature. An example is shown in Figure 22 below:

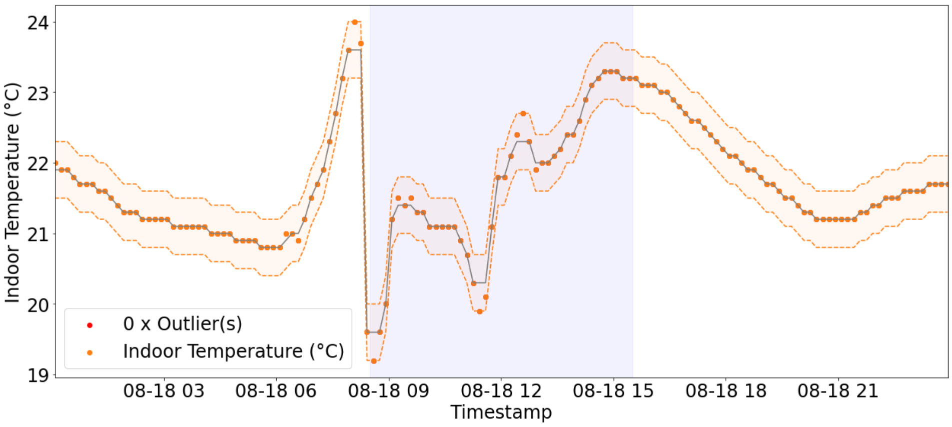


Figure 22: Measurements over a teaching day in a certain teaching space, where the indoor air temperature increased in the early morning and then dropped quickly, resulting in a net temperature change of less than 2 °C from 5 to 8.30 am.

In Figure 22, the temperature clearly increased from 6 am but then dropped just before 8.30 am, resulting in even lower indoor temperature than that when the falsely detected 'preheating' began.

A false negative means that a preheating is mistakenly missed. One scenario which may cause this is if indoors heating between 8 and 8.30 am helps increase the indoor temperature before the start of occupancy. Preheating would not be detected, as the method of detection only considers temperature data up to 8 am. The falsely undetected preheating might have an effect on when the occupants choose to increase ventilation, hence may affect CO_2 levels.

As this initiative did not record or survey real-time occupancy or occupant actions, it is impossible to eliminate false positives and false negatives. Also, the actual reason for sudden temperature drops, like that in Figure 22, cannot be known.

The results shown in Section 3.3 show no clear relationship between the implementation of preheating and lower CO_2 levels. However, the data shows that more frequently preheated teaching spaces did experience warmer start temperatures. It is possible they were providing better thermal comfort, encouraging earlier ventilation (and hence lower CO_2 levels) than they would have if not preheated.

Thus, it is suggested that preheating can be useful in lowering CO_2 levels, but only if the room would be otherwise cold when occupancy starts, i.e., when preheating helps with improving thermal comfort in the morning.

On the other hand, as human decisions on window opening strongly impact the CO_2 level and are based on a number of factors (including for example perception of the nuisance due to drafts or outdoor noise), warmer start temperatures will not always result in a reduction in median CO_2.

The majority of the monitored teaching spaces appear to have had decisions on heating start time made day-by-day. As only a few were frequently preheated, data is scarce.

4.3 Effects of Breaks and Refresh Breaks

Apart from the method of preheating, the other method proposed to have positive effects on lowering CO_2 levels is having *refresh breaks*. In Section 2.6.2, *breaks* and *refresh breaks* have been defined. The definitions and the results shown in Section 3.4 suggest that *breaks* were likely to have helped bring CO_2 levels down but *refresh breaks* can help achieve that quicker. This is the reason why this initiative prefers the latter. The shorter time to flush a used space could be valuable in practice due to its lesser interruption to common teaching activities.

The common concern is that thermal comfort may be compromised after *refresh breaks*. However, other studies (Griffiths & Eftekhari, 2008; Ackley et al., 2022; Sutherland et al., 2022) and the results in Section 3.4 showed that the indoor air temperature drop was limited when *refresh breaks* were detected, possibly due to thermal inertia and other factors.

Even though *breaks* seem to have been common, successful *refresh breaks* by deliberately opening multiple doors and windows, attempting to flush a previously occupied space with fresh air, have been less frequently observed. This may suggest that a *refresh break* can be rather difficult to achieve as it requires the combined actions of vacating the room and opening exterior windows and/or doors. A CO_2 monitor, such as the one used in this initiative, may help the occupants (e.g., teachers and students) be aware of when actions such as a *refresh break* are beneficial.

Teachers have teaching duties along with many other responsibilities. It may not be feasible to solely rely on teachers to track the CO_2 readings from time to time while teaching and to decide whether a classroom should be preferably vacated, and the windows or doors should be opened. Similar to the lunch break, the idea about *refresh breaks* may be more effective if it can be implemented at standardised times, e.g., vacating classroom and leaving all windows and doors opened at 10.30 am, 12.00 pm, and 1.30 pm, with the awareness that this does not serve as a one-size-fits-all solution. For example, the early morning *refresh break* at 10.30 am should be earlier if a teaching day starts earlier. Note that the standardised times just mentioned are for example only. The use of more *refresh breaks* may be effective in spaces where CO_2 levels are stubbornly high.

5.0 Conclusion

It is widely accepted that natural ventilation brings fresh outdoor air indoors, replacing and diluting the stale air, and can therefore help lower the risk of airborne disease infection, not only COVID-19. In winter, due to the concerns of being cold, the time the class spends indoors is extended and the exterior windows and doors tend to be closed more often, resulting in reduced air quality and higher risks of infection by airborne pathogens.

This ventilation monitoring initiative attempted to unobtrusively assess the real-time performance of ventilation in 169 teaching spaces from 43 schools in all 6 New Zealand Climate Zones by continuous measurement of CO_2 and temperature levels. In summary, the key findings were that:

- Across all teaching spaces, approximately 60-76% and 85-95% of the monitored teaching time, the CO_2 levels were maintained below the threshold of 800 ppm and 1250 ppm respectively. This infers that there was sufficient fresh air more than half to three fourths of the teaching time across all monitored teaching spaces, while actions may still have been needed to achieve better outcomes, especially in colder climates.
- For most of the monitored teaching time, the teaching spaces were also within the adaptive comfort temperature range of 18-25 °C (70% of the time). While the indoor air temperatures were similar in all 6 Climate Zones (warmest to coldest), CO_2 levels were higher in colder climates.
- Warmer temperatures were observed in the teaching spaces where preheating was detected more frequently. Therefore, preheating can be a good heating strategy for achieving better thermal comfort.
- In the teaching spaces where the indoor air temperature at the start of the teaching day was likely to be lower when preheating was not detected, it is suggested that the preheating strategy may be useful in lowering CO_2 levels by providing better thermal comfort in the morning.
- The heating start time in the majority of the monitored teaching spaces seems to vary on daily basis. Frequent preheating was observed in few spaces.
- *Refresh breaks* can help flush a used room quicker. This can be crucial in practice due to the minimal possible interruption to teaching activities but may not be implemented easily. *Refresh breaks* with standardised times may be a better solution.
- The indoor air temperature drop was observed to be limited when *breaks* or *refresh breaks* occurred.
- Successful *breaks* were observed to have been common across all monitored teaching spaces, whereas it appears that successful *refresh breaks* were much less frequently detected.

The conclusions that this initiative can draw from the analysis is limited because other real-time information such as occupancy, and actions taken directly impacting ventilation were not recorded, given that this initiative was designed not to disturb normal classroom activities. However, the findings generally suggest that having a warmer indoor temperature prior to the start of teaching in the morning and *refresh breaks* can play a positive role in lowering CO_2 levels throughout a teaching day.

The real-time measurements are still ongoing till the end of the 2022 calendar year, so that a complete dataset of approximately half of a year can be obtained. Further analysis may investigate the effects of variables such as climate on ventilation performance, and a comparison across different seasons.

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