

Ventilation and Air Quality in 18 School Classrooms - Rapid Study

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Contents

Executive summary	6
1 Introduction	9
1.1 Background	9
1.2 Scope.....	9
2 Methods.....	11
2.1 Study design.....	11
2.2 Study timing	11
2.3 School and classroom selection	12
2.4 Measurements and observations	14
2.5 Experimental protocols.....	18
2.6 Data quality control	20
2.7 Converting CO ₂ into Air Changes per Hour for Control Study data	21
2.8 Assessment goals.....	21
3 Results	26
3.1 Assessment of ventilation during Occupied Classroom teaching periods.....	26
3.2 Determinants of classroom CO ₂ levels.....	28
3.3 Control study	34
3.4 Mitigation.....	36
3.5 Study limitations	39
3.6 Recommendation for further study.....	40
4 Conclusions and Recommendations	45
1: Can typical classrooms achieve sufficient ventilation naturally?	45
2: Are windows and doors being used during class time to achieve sufficient ventilation?	45
3: Can temporary ventilation boosts help?.....	46
4: CO ₂ monitoring.....	46
5. What if natural ventilation is insufficient?	46
5 Acknowledgements	48
6 Glossary of abbreviations and terms	49

7	References.....	50
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Appendix A	Occupied classroom results	51
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Appendix B	Manual Observation Survey Form.....	85
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Tables

Table 2-1:	Summary of classrooms observed in this study.	13
Table 2-2:	Specifications of the sensors used in the Hau-Hau monitor.	14
Table 2-3:	Theoretical CO ₂ concentrations in typical classroom.	23
Table 3-1:	Fraction (and total number in brackets) of observed periods assessed as having good/marginal/poor ventilation for each classroom.	28
Table 3-2:	Recommended study settings and the questions they can be used to address.	42

Figures

Figure 2-1:	A Hau-Hau monitor, alongside a dashboard showing data from ten monitors in the Control Study room.	15
Figure 2-2:	Example of Hau-Hau monitor placement in one of the occupied study classrooms.	15
Figure 2-3:	Google Earth image of Epuni School with the Control Study room in the foreground.	16
Figure 2-4:	Sketch of the Epuni School block including the Control Study room (pale blue) indicating one external and three internal doors.	17
Figure 2-5:	Sketch side view of the Control Study room indicating position of "front" (left) and "top" (right) windows.	17
Figure 2-6:	The "front" windows and external door at the Control Study room.	18
Figure 2-7:	The "top" windows at the Control Study room.	18
Figure 2-8:	Distribution of the standard deviation of CO ₂ across all 10 Control Room monitors as a function of time elapsed since CO ₂ release for all test.	20
Figure 2-9:	Modelled relationship between infection risk, ACH and CO ₂ in a typical classroom.	22
Figure 2-10:	Modelled relationship between ACH and CO ₂ after 1 hour and in the steady-state.	24
Figure 2-11:	Time (mins) for CO ₂ to rise to 90% of steady state in typical classroom.	24
Figure 2-12:	Example of how a model is used to estimate steady-state CO ₂ by extrapolating observed data.	25
Figure 3-1:	Number of periods assessed per classroom for which steady-state CO ₂ levels were estimated	26
Figure 3-2:	Fraction of observed periods assessed as good/marginal/poor ventilation as a function of "open-ness" (doors/windows open).	27
Figure 3-3:	Fraction of observed periods assessed as good/marginal/poor ventilation for each classroom.	27
Figure 3-4:	Example CO ₂ data for one day from one classroom.	30
Figure 3-5:	Example of CO ₂ accumulation across multiple periods.	32

Figure 3-6:	Example of CO ₂ kept low during continuous occupancy through the use of cross-flow ventilation.	32
Figure 3-7:	Relationship between opening area and air change rate for tests with natural ventilation configuration.	35
Figure 3-8:	Modelled CO ₂ concentration for the baseline classroom scenario.	37
Figure 3-9:	Comparison of modelled CO ₂ for typical classroom with ACH = 1 (baseline) and ACH = 5.	37
Figure 3-10:	Modelled impact of introducing high-ventilation (ACH=10) during break and lunchtime	38
Figure 3-11:	Modelled impact of introducing 15-minute high-ventilation (ACH=10) flush between every occupied period.	38
Figure 3-12:	Modelled impact of keeping the classroom vacant for alternate periods	39

Executive summary

The Ministry of Education has oversight of over 2500 schools across New Zealand, including owning the property of around 2100 state schools. In October 2021 the Ministry of Education initiated the Ventilation in Schools COVID-19 Response Programme (**COVID-19 Ventilation Programme**, or **CVP**). CVP's objective is to minimise the airborne transmission of SARS-CoV-2, the virus that causes COVID-19, by improving ventilation strategies, systems, and practices in schools without detracting from education delivery or learning outcomes.

Whereas various authorities (WHO¹, CDC², ASHRAE³, etc.) have recommended ventilation performance criteria as one strategy for reducing airborne transmission in indoor spaces, when this Programme started there was limited evidence on the achieved and achievable performance of New Zealand classrooms.

A rapid observational study was therefore established to collect indicative data to establish:

- What levels of ventilation can be achieved in a typical classroom using different door and window opening configurations?
- What levels of ventilation are routinely being achieved in a range of occupied classrooms representing some of the more common classroom design types?
- What is the indicative performance of some supplementary ventilation technologies (specifically an exhaust fan a supply fan and a prototype “assisted natural ventilation system)?)

This was an urgent study restricted to observations in schools over a single week meaning that all data are indicative and all conclusions tentative rather than comprehensive. Only a limited number of classrooms, and a limited range of ventilation behaviours or practices, were observed.

The focus of this study was on ventilation. This study did not observe presence of any pathogens in schools, nor make any observations of health-related outcomes. Easily measured levels of carbon dioxide (CO₂) were used to provide an indirect measure of ventilation. Although the relationship between infection risk and CO₂ is non-linear, complex and dependent on the volume and use of the room, concentrations below 800 parts per million (ppm) are recommended as an approximate indicator for the management of the risk of COVID-19 transmission in classrooms.

The study consisted of two parts:

- An “Occupied Classroom” observation study in which levels of CO₂ (from human breath) were measured for between one and five days (29th November – 3rd December 2021) in 18 classrooms representative of common standard classroom types. This was a “passive” study in that there was as little interference with the normal operation of the classroom as possible.
- A “Control Room” study, in which a vacant classroom was used to measure air change rates (using a CO₂ release method) under a non-comprehensive selection of different ventilation conditions (door and window openings, and some repeats under different weather conditions), including brief trials of two technologies to enhance ventilation.

¹ World Health Organisation

² Center for Disease Control (US)

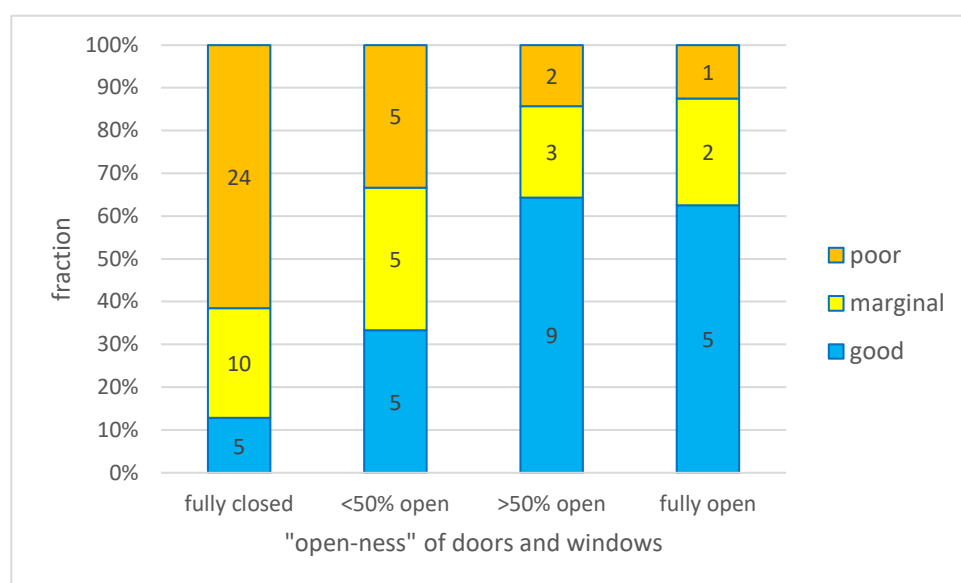
³ American Society of Heating, Refrigerating and Air-Conditioning Engineers

Given the relatively small sample size in this study, the data are under-powered to detect any relationship between typical CO₂ and classroom block type, volume, location or school age group.

Out of 84 observed teaching periods:

- 31% of observed periods were classed as having “good” ventilation⁴.
- 36% of observed periods were classed as having “marginal” ventilation⁵.
- 31% of observed periods were classed as having “poor” ventilation⁶.

Variability in CO₂ was best explained by variations in ventilation practices and behaviour, with levels indicative of poor ventilation much more common when windows and doors were closed and vice versa.



In general, the observations showed that:

- A wide range in ventilation performance was observed between and within classrooms.
- Good ventilation was achieved in most classrooms when doors and/or windows were opened.
- The best results (with CO₂ kept below 800 ppm) were associated with crossflow between multiple openings fully opened.
- Half of the classrooms achieved high ventilation (CO₂ below 800 ppm) at some point, and the rest may have been able to achieve it. (Whether the rest could not or just did not during the study remains unknown.)
- CO₂ levels were also reduced using internal doors to larger unoccupied indoor spaces thus increasing the dilution volume.

⁴ Defined as having a steady-state CO₂ concentration below 800 ppm

⁵ Defined as having a steady-state CO₂ concentration between 800 and 1500 ppm

⁶ Defined as having a steady-state CO₂ concentration above 1500 ppm

- Control study data indicated that the use of an exhaust fan may increase overall ventilation, especially by stabilising crossflow when double openings are used.

In general, the observational results indicate that high CO₂ (and potential infection risk) was largely driven by three **operational** issues:

- Low air exchange rates, especially in the morning, due to doors and windows remaining fully or mostly shut
- Greater build-up of stale air (if air change rates remain low) in the case of extended continuous occupancy (e.g., over an hour or over “double” teaching periods)
- Failure to adequately remove stale air through high ventilation between occupancy periods.

These observations, supported by some simplified modelling, suggest a range of mitigations are available, with the most effective likely to be a permanent increase in ventilation. This is most easily achieved through maintaining crossflow throughout the day. This may not be practical during hot, cold or wet weather unless the adverse effects of weather are otherwise mitigated. Methods to achieve this are beyond the scope of this study but are recommended for urgent future research by MoE or other science providers.

If crossflow is achievable but acceptable only for short periods, this should be exploited to periodically purge the classroom of stale air, for instance during regularly scheduled breaks. Another option of similar effectiveness is to use the school timetable to avoid double-periods and periods of extended occupancy.

Although it cannot be confirmed that our Control study room was able to achieve sufficient ventilation through natural crossflow alone, our study scope preventing us from establishing this for other classrooms. High air change rates were not observed in 8 out of 18 classrooms. Although this does not confirm that they could not achieve high ventilation, it is plausible that many classrooms around the country may not. Outside of the summer months, and in inclement weather, depending on the climate zone, it may not be desirable to have natural ventilation through multiple openings without excessive heat loss or other disruption. For these reasons we trialled using a fan to enhance ventilation.

A prototype **Assisted Natural Ventilation System** (ANVS) was tested providing various combinations of boosted exhaust or supply ventilation, air recirculation (with HEPA filtration).

Although highly limited, our results suggest an **exhaust fan** may make crossflow stronger and more reliable or provide some minimal ventilation when the room is otherwise sealed.

The use of a **supply fan** alone was only tested once showing a modest improvement in ventilation.

Based on only a single test (room sealed) **the combination of a supply fan and exhaust fan** provided no significant benefit over using an exhaust fan alone.

The **full ANVS** (exhaust and supply fan, with partial air recirculation through a HEPA filter) was tested with four room configurations (fully sealed, door only, front windows open slightly, and door fully open plus top windows open slightly). Relative to no ANVS, air change rate was slightly reduced in two of the tests, and slightly increased in the other two tests. Due to the very small sample, we consider these results to be indicative but inconclusive.

1 Introduction

1.1 Background

The Ministry of Education has oversight of over 2500 schools across New Zealand, including owning the property of around 2100 state schools. In October 2021 the Ministry of Education initiated the Ventilation in Schools COVID-19 Response Programme (**COVID-19 Ventilation Programme, or CVP**). CVP's objective is to minimise the airborne transmission of SARS-CoV-2, the virus that causes COVID-19, by improving ventilation strategies, systems, and practices in schools without detracting from education delivery or learning outcomes.

Whereas various authorities (WHO⁷, CDC⁸, ASHRAE⁹, etc.) have recommended ventilation performance criteria as one strategy for reducing airborne transmission in indoor spaces, when this Programme started the actual and achievable performance of New Zealand classrooms was largely unknown. An estimated 90 % of classrooms in New Zealand are naturally ventilated, mainly through opening doors and windows. It is through the practice of door and window opening that achieved performance may be much lower than achievable performance.

Most existing classrooms were built using standard designs based on the 1950's – 1980's "school block" principle, and these standard designs are spread across the country, although more recent builds have a unique design with emphasis on spaces that support flexible styles of teaching and learning (MoE, 2011).

An initial understanding of the current ventilation performance of classrooms was needed to be able to develop ventilation strategies. Time pressure was imposed by the need to develop suitable strategies or recommendations before the onset of winter. A rapid observational study was therefore established to collect indicative data to establish:

- What levels of ventilation can be achieved in a typical classroom using different door and window opening configurations?
- What levels of ventilation are routinely being achieved in a range of "occupied" classrooms representing some of the more common classroom design types?
- What is the indicative performance of some supplementary ventilation technologies?

1.2 Scope

The major limitation of this study was its urgency to outline a range of measures that need to be considered in preparing for reopening of schools in early 2022. This therefore meant that the observational work had to be completed before the end of the 2021 school term in mid-December. This restricted observations to a single week, a limited number of classrooms, and a limited range of ventilation behaviours or practices were observed. However, the data provides indicative results on the ventilation performance in the studied classrooms.

⁷ World Health Organisation

⁸ Center for Disease Control (US)

⁹ American Society of Heating, Refrigerating and Air-Conditioning Engineers

The focus of this study was on ventilation. This study did not observe presence of any pathogens in schools, nor make any observations of health-related outcomes.

2 Methods

2.1 Study design

Direct measurement of ventilation of an indoor space is relatively obtrusive (involving substantial noisy machinery and replacement of doors or windows) and conventionally conducted when the space is unoccupied. This approach was considered inappropriate to meet our objectives.

A very commonly used alternative is to use continuous measurements of carbon dioxide (CO₂) from which ventilation can be inferred. CO₂ can be measured unobtrusively using small, silent electrical sensors.

This method can be used in a controlled setting where CO₂ is released into the room (e.g., from a gas canister) and the decay in concentration observed as the gas is removed from the space by ventilation. From this the “air changes per hour”, a common metric of ventilation, can be calculated for different ventilation configurations.

Human breath also emits CO₂ at a variable rate related to age and activity. In occupied rooms where the exhalation rate is unknown, ventilation can still be inferred from CO₂ measurements with rapid changes and lower levels of CO₂ corresponding to high air change rates and vice versa.

CO₂ also has two additional advantages:

- It can act as a proxy for exhaled virus aerosol (both have the same source – human breath – and are dispersed in the air in the same way).
- There are existing guidelines for CO₂ levels to inform the design of newly built classrooms to avoid potential effects of reduced attention and learning associated with high levels of CO₂.

To study both achieved and achievable ventilation performance in classrooms without disturbing normal classroom activities, our chosen study design consisted of two parts:

- A “Occupied Classroom” observation study in which CO₂ levels were measured for between one and five days in a representative range of classroom types. This was a “passive” study in that there was as little interference with the normal operation of the classroom as possible.
- A “Control Room” study, in which a vacant classroom was used to measure air change rates (using a CO₂ release method) under a non-comprehensive selection of different ventilation conditions (door and window openings, plus some repeats under different weather conditions), and including brief trials of two technologies to enhance ventilation.

2.2 Study timing

The field study took place during the five days from 29th November to 3rd December 2021 inclusive. During this time most of the country (including the three study sites – see below) were at Level 2 in

the COVID-19 Alert system¹⁰. Level 2 applied when there was low risk of community transmission in the area. This meant that, except for advice against certain high-risk activities like singing in large groups, school classrooms were being used normally.

2.3 School and classroom selection

2.3.1 School selection

Schools were selected based on:

- Covering different major climate zones of New Zealand (MoE, 2022)
- Providing access to some of the more common naturally ventilated classroom building typologies found across New Zealand (MoE 2013), one of which could be dedicated to the Control Room study for a week
- Open with significant student numbers during the study (which was late in term 4 during COVID-19 Alert level 2)
- Not in COVID-19 Alert level 3 locations (Auckland, Northland and Waikato at the time of the study)
- A mixture of primary and secondary schools
- Able to confirm willing participation at short notice.

The following schools were selected:

- Aurora College, Invercargill (climate zone 6) – Occupied Classroom study only
- Taupo Nui a Tia College, Taupo (climate zone 4) - Occupied Classroom study only
- Epuni Primary School, Lower Hutt (climate zone 3) – Occupied Classroom and Control Room studies.

2.3.2 Classrooms selected and data coverage

The **Control Room Study** was conducted in Room 1 at Epuni School. This room is of the “Open Air” block type.

Three classrooms were selected for the **Occupied Classroom study** at Epuni School, 10 at Taupo College and 5 at Aurora College (i.e., 18 in total).

Due to logistical constraints, monitoring did not begin at Aurora College or Taupo College until Tuesday 30th November 2021.

Thursday 2nd December was a teacher-only day at Taupo College and Friday 3rd December was a teacher-only day at Aurora College. For this reason, some monitors were re-allocated to rooms which were going to be occupied during those days, including a few non-standard rooms (reception, staffroom, gym, sickbay).

¹⁰ <https://covid19.govt.nz/about-our-covid-19-response/history-of-the-covid-19-alert-system/>

By the end of the study monitoring had been conducted in 25 rooms (3 in a primary school and 22 in secondary schools) covering 10 classroom types in total, with 49 day-long classroom datasets in occupied classrooms in normal use and 62 in total. A full list of monitored rooms is provided in Table 2-1.

Table 2-1: Summary of classrooms observed in this study.

School	Classroom	Block type	Estimated volume / m ³	total	#days data Normally occupied days	Teacher-only day
Epuni School (climate zone 3)	ES-3	Open Air	287	5	2	n/a
	ES-5	Avalon	206	5	5	n/a
	ES-6	Avalon	403	5	3	n/a
Taupo College (climate zone 4)	TC-D18	NS	292	2	2	0
	TC-D3	NS	225	2	2	0
	TC-D8	NS	unknown	2	0	1
	TC-E1	DHS	256	2	2	0
	TC-E4	DHS	183	2	1	1
	TC-F8	PA	310	2	2	0
	TC-F9	PA	310	4	3	1
	TC-Gym		Unknown	2	1	0
	TC-H4	KH	Unknown	4	3	1
	TC-Music		199	2	1	1
	TC-N14	NEL6	325	4	3	1
	TC-Reading Room	NEL10	244	2	2	0
	TC-Sickbay		unknown	1	1	0
	TC-Staffroom		270	2	1	1
Aurora College (climate zone 6)	AC-M26	S68/2	245	4	3	1
	AC-M30	S68/2	398 (660) ¹¹	4	3	1
	AC-M6	S68/1	246	3	3	0
	AC-7HK	S68/1	401	3	3	0
	AC-S16	S68/1	345	4	3	1
	AC-S19	S68/1	390	1	0	1
	AC-M24	S68/1	341	1	0	1
	AC-Reception		306	1	0	1

¹¹ A sliding door can be opened to combine with adjacent room giving the larger volume

2.4 Measurements and observations

2.4.1 Instrumentation

Measurements in all classrooms were conducted using Hau-Haus.

A Hau-Hau (pronounced 'Hæʊ¹²') is a low-cost air quality monitor built by Hau-Hau Ltd. in Auckland. The Hau-Hau:

- Contains the following sensors (specification in Table 2-2):
 - Carbon dioxide (Senseair K30FR using NDIR)
 - Particulate Matter, PM_{2.5} and PM₁₀ (Honeywell HPM115SO optical scattering)
 - Temperature and relative humidity (Bosch BME280).
- Records measurements at a user-defined rate.
- Sends data to a cloud server using a 3G USB modem dongle.
- Is mains powered (placing some limitations on where each unit can be placed).
- Does not have any data display, however a dashboard is available for the project team to view and download live and recent data.

Table 2-2: Specifications of the sensors used in the Hau-Hau monitor.

Sensor	Parameter	Range	Resolution	Accuracy
Senseair K30FR	CO ₂	0 – 5000 ppm	1 ppm	±30 ppm
Honeywell HPM115SO	PM _{2.5}	0 – 1000 µg m ⁻³	1 µg m ⁻³	±15 %
Bosch BME280	T	-40 to 85°C	0.01°	±0.5 °C
	RH	0 – 100 %	0.008 %	±3 %

¹² Using Oxford dictionaries pronunciation guide.
https://www.oxfordlearnersdictionaries.com/about/english/pronunciation_english



Figure 2-1: A Hau-Hau monitor, alongside a dashboard showing data from ten monitors in the Control Study room.

2.4.2 Locations and settings of instruments

The Hau-Haus default to record data every minute. For most of the measurement campaign they were reset to record data every 5 seconds.

Hau-Haus were deployed in pairs in each **Occupied Classroom Study** classroom. This provides a degree of back-up in case of failure or tampering, but also can provide some insight into data quality and variability within the classroom. Due to limitations placed by availability of power sockets, and the desire to minimise impact on classroom activity, Hau-Haus tended to be placed on tables or shelves on opposite walls.

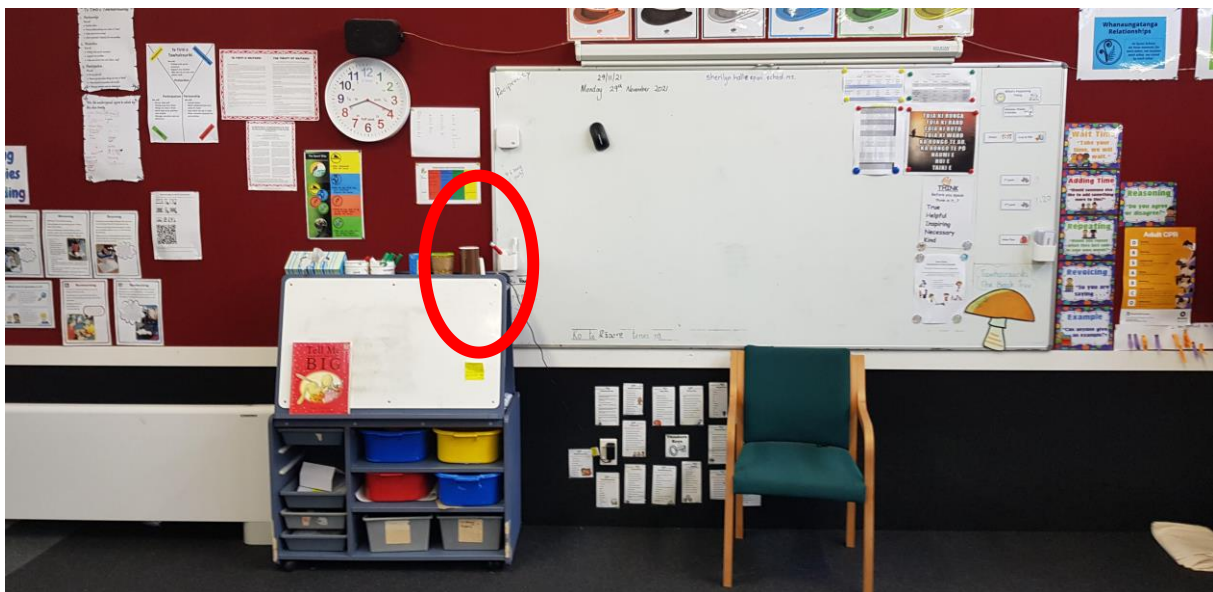


Figure 2-2: Example of Hau-Hau monitor placement in one of the occupied study classrooms.

At least nine Hau-Haus were deployed in the **Control Study** classroom in an approximately rectangular grid pattern. This design was chosen to enable the state of mixing of air in the room to be understood, and especially the time for a CO₂ release to mix evenly across the volume.

In both studies, all Hau-Haus were deployed at approximately table height. Analysis of air mixing times (see below) show that this did not impact the calculation of air change rates and eliminate this from being a limitation of the study.

2.4.3 Configuration of the control study classroom

The Control Study room was at the end of a block of four classrooms facing the school's playground (Figure 2-3 and Figure 2-4).



Figure 2-3: Google Earth image of Epuni School with the Control Study room in the foreground.

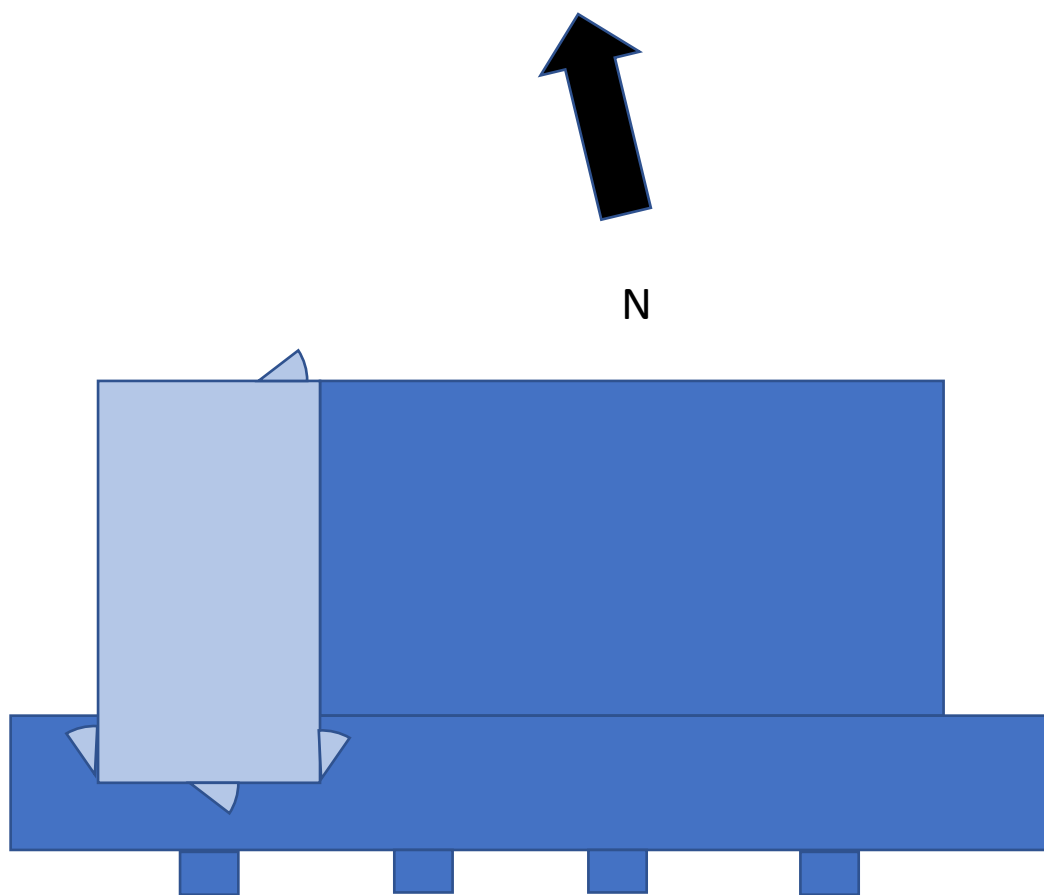


Figure 2-4: Sketch of the Epuni School block including the Control Study room (pale blue) indicating one external and three internal doors. Not to scale.

The Control Study room had a single external door, next to which were 2 rows of 6 windows, individually-openable up to $\sim 20^\circ$ (Figure 2-6). On the opposite side of the room were 8 elevated windows, which could be opened in two sets of 4 up to $\sim 30^\circ$ (Figure 2-7). Three internal doors at the back of the classroom were kept closed throughout the entirety of the study.

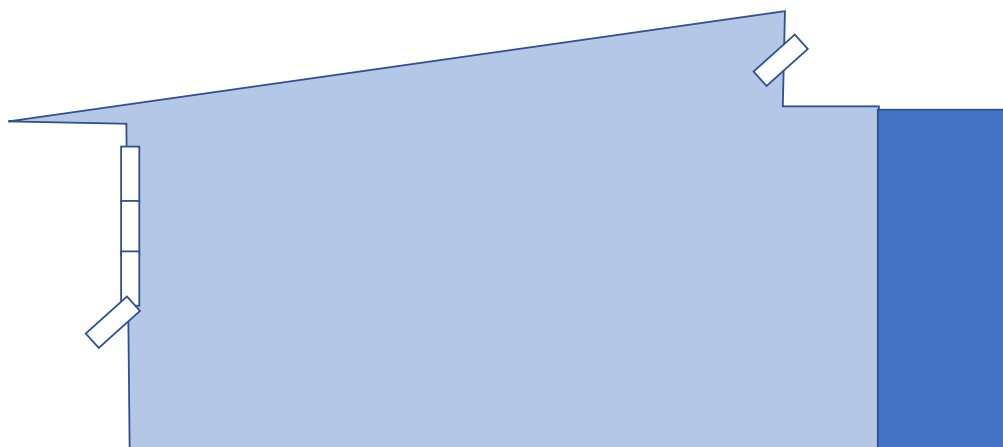


Figure 2-5: Sketch side view of the Control Study room indicating position of "front" (left) and "top" (right) windows. Not to scale.



Figure 2-6: The "front" windows and external door at the Control Study room.



Figure 2-7: The "top" windows at the Control Study room.

2.5 Experimental protocols

2.5.1 Occupied Classroom observations

In each Occupied Classroom Study school, a team of two observers were tasked with visiting each study classroom on a regular basis (ideally at least once every period or hour) to make additional observations. These observations were made without entering the classroom to avoid disrupting classroom activities or introduce a “Hawthorne” effect where the feeling of being observed changes behaviour.

Observations were recorded in an online survey form (presented in Appendix B) on tablets with mobile data enabled:

- Number of adults and children present in the room

- Subjective measure of degree of door and window opening on a 5-point scale (from 1 for 0% open to 5 for 100 % open)
- Subjective measure of activity levels of the occupants (on a 5-point scale from 1 to 5)
- Air flow in/out of the room through an available opening (using a handheld anemometer where available)
- Noise levels (using a handheld noise meter where available)
- Any other pertinent observations made in written note form.

2.5.2 Control study protocols

A series of tests were conducted covering a wide range of ventilation settings and configurations. Due to the rapid time-constrained nature of the study this was partially pre-planned but included a degree of adaptation during the study.

In brief, each test consisted of the following stages:

- The room configuration (doors, windows, occupants, fans, etc.) was set
- CO₂ was released briefly (up to 5 seconds) using a manually operated fire extinguisher in the centre of the room. An approximately 6-minute period was allowed for the CO₂ to evenly mix within the room (established using the grid of sensors in the room, see below). The extinguisher method was replaced by a CO₂ bottle release for the final day of testing.
- CO₂ decay was further observed, and the room configuration held constant a further 10 – 20 minutes, after which the configuration was changed to the next test, continuing until the CO₂ was 90% removed.
- The method was repeated until all tests were complete.
- Several methods for generating aerosol were also trialled but were deemed to not be successful.

By having ten Hau-Haus set in a grid pattern across the room it was possible to observe the mixing time of air in the room, and hence, the consistency of each monitor. Figure 2-8 shows how the standard deviation of CO₂ across all monitors converged on a minimum value within approximately 6 minutes over all tests (corresponding to a wide range of ventilation configurations). This is consistent with our study design protocol in which a mixing time of 6 minutes had been assumed, i.e., data captured within this 6-minute period was not used for estimating air change rates.

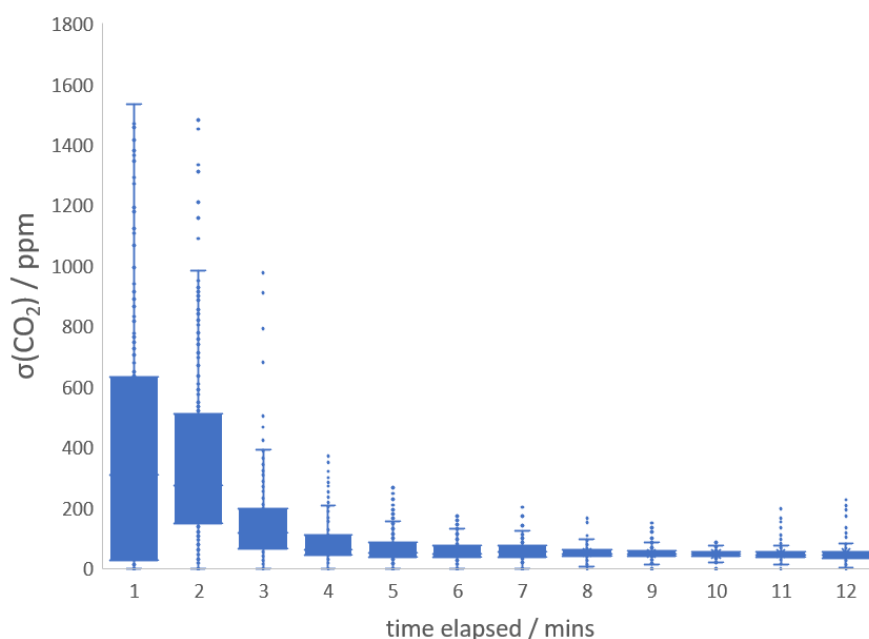


Figure 2-8: Distribution of the standard deviation of CO₂ across all 10 Control Room monitors as a function of time elapsed since CO₂ release for all test.

Other than the baseline “fully sealed” (doors and windows closed) configuration, a further 50 tests were conducted that yielded usable results. Due to several repeats these 50 tests covered 29 configurations. Although not comprehensive (in that not all possible configurations available were tested) the tests did cover various combinations of:

- External door open/closed
- 4 or 8 (out of 8) external upper windows opened slightly or fully (i.e., enabling variation in opening area)
- Between 4 and 7 (out of 12) external lower windows opened slightly or fully (i.e., enabling variation in opening area)
- Prototype “Assisted Natural Ventilation System” (ANVS), incorporating various combinations of exhaust fan, recirculated and HEPA-filtered air

Most configurations were tested between one and three times, between which meteorological conditions may have changed.

2.6 Data quality control

The Hau-Hau instruments occasionally “freeze”, recording the same CO₂ reading until re-started. An alert code was written and used by experimenters on the ground to re-start instruments as required. After the study the data were reviewed, and repeated “frozen” measurements were discarded. This affected <1 % of the data. Gaps in the data were left rather than patched.

Each Hau-Hau has a unique offset. This was corrected for by assuming all monitors in the same school should report the same concentration between midnight and 3am. All data were adjusted to report 420 ppm during this period.

The Hau-Haus have a default time resolution of one minute. However, from Tuesday this was re-set to 5 seconds. For the purposes of this analysis, however, data was averaged back to one-minute intervals.

2.7 Converting CO₂ into Air Changes per Hour for Control Study data

The data were split into “tests”, meaning periods when the room configuration was constant using manual records made at the time, with adjustments made to test start and end times to align with step-changes in the CO₂ data.

Offset-adjusted CO₂ (see above) was converted into an instrument-adjusted “excess” CO₂ (i.e., above background) by subtracting a reference concentration (an assumed background concentration of 420 ppm) from every value.

Adjusted room-excess data from all functioning Hau-Haus in the control room was averaged to generate a single representative measure of room excess CO₂.

Air change rate was then calculated for each test based on a linear fit of the natural logarithm of mean excess CO₂ against time elapsed for each test.

15 out of the 29 test configurations were repeated (8 once and 7 twice). The maximum variance in the calculated air change rate between repeat tests was 27 %, and the mean variance was 10 %. Some variance is to be expected due to limitations in the sensitivity of the method, but also due to the influence of meteorology on air exchange. The small scale of this study means we are not able to apportion the observed variance to methodological limitations or meteorology. However, the low variance relative to our objectives means that all data was retained.

2.8 Assessment goals

2.8.1 Setting assessment goals

This study sought to evaluate ventilation rates relative to goals considered appropriate to managing the risk of transmission of COVID-19 in classrooms.

It must be understood that ventilation provides a continuum of protection against the risk of infection and that there is no threshold level of ventilation that will reduce risk to zero.

Air change rates are difficult to measure directly and unobtrusively. Conversely, it is relatively easy to measure the impact of air change rates on a tracer gas that is released indoors at a moderately steady rate. Carbon dioxide (CO₂) is widely used for this purpose as it is steadily emitted within human breath (at a rate that is not constant but related to a person’s age and activity level), yet is relatively constant outdoors (so long as combustion or other CO₂ sources are avoided).

Figure 2-9, based on a simple model of air and heat exchange in a typical classroom, plus the presence of a single individual infectious with SARS-CoV-2 virus, indicates the basic relationships between air changes per hour (ACH, as a measure of ventilation), levels of CO₂ in the room, time elapsed and relative infection risk. This model assumes the room had fully fresh air at the start of the

modelled period, and that occupancy, activity rates (and hence exhalation) and ventilation remain constant.

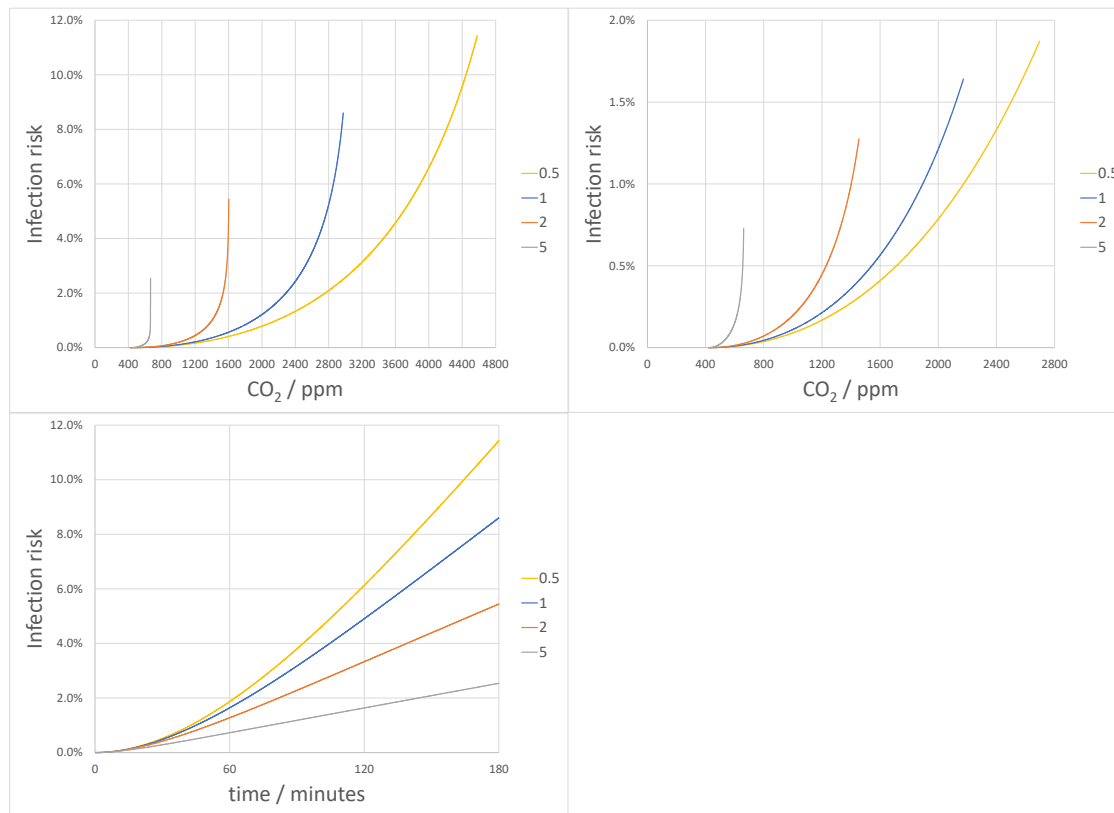


Figure 2-9: Modelled relationship between infection risk, ACH and CO₂ in a typical classroom. Left: over 3 hours, Right: over 1 hour. Legend refers to ACH values.

From this figure it follows that:

- Infection risk increases with exposure time
- Infection risk can be reduced by increasing air change rates (ACH)
- CO₂ values are related to ACH and infection risk
- CO₂ values tend towards a steady-state value
- The steady-state is reached in approximately 1 hour if ACH ~2 - 3, more quickly for higher ACHs and more slowly for lower ACHs.

A convention has been established that for “typical” classrooms of 200 – 250 m³ volume and accommodating up to 30 students, **air change rates of 5 h⁻¹ or better is an achievable target to minimise infection risk** (Allen and Ibrahim 2021).

In any given occupied room, CO₂ levels will tend towards a steady-state concentration that is a function of the emission source strength, air change rate and classroom volume. In a typical classroom an air change rate of 5 h⁻¹ will tend to lead to CO₂ levels stabilising at approximately 800 ppm. Therefore, **a steady-state CO₂ concentration below 800 ppm is widely used as an imprecise but easily measured indicator of good ventilation.**

As well as CO₂ providing a proxy indicator of ventilation¹³, CO₂ is also used as a proxy for the concentration of virus-containing aerosol in the room if a known proportion of the occupants were infectious. Good ventilation will remove any contaminant in the air with an indoor source, such as particulate matter and virus-containing aerosol and therefore reduce indoor concentrations.

The risk of infection of another occupant would then be a function of the CO₂ concentration and the duration of exposure. In practice this means that if the CO₂ concentration is constant (e.g., steady state has been achieved) then the risk rises linearly so long as exposure continues. Thus, not only does a concentration of 800 ppm not pose zero infection risk, but the risk over 6 hours is approximately 6 times that over one hour.

A steady-state CO₂ concentration above 1500 ppm is also widely used as an indicator of poor ventilation (e.g. SAGE, 2020, HSE, 2022). Values between 800 ppm and 1500 ppm therefore indicate “marginal” ventilation.

2.8.2 Use of steady-state CO₂ as a metric of ventilation

This simplistic approach also assumes the period begins with concentrations at a background level. However, if the room has been previously occupied CO₂ levels can accumulate and no longer directly reflect the air change rate at that time.

It must be noted that the CO₂ target values mentioned above apply to the **steady-state** concentration. At air change rates above ~2.5, this steady state will be below 1000 ppm and will be reached within an hour (a typical length of a teaching period). For air change rates below ~2.5, however, the time to reach steady state will be longer than an hour and **the steady state concentration could be much higher than the concentrations observed within that hour** (see Table 2-3). This provides a general rule-of-thumb that if CO₂ concentrations have stabilised in under an hour then the room is well-ventilated, and vice versa.

Table 2-3: Theoretical CO₂ concentrations in typical classroom. Assumed volume 220 m³, 25 occupants with a CO₂ exhalation rate of 3 ml s⁻¹ and initial (background) concentration of 420 ppm.

Air change rate / h ⁻¹	Steady -state CO ₂ / ppm	Time to reach 90 % of steady state / mins	CO ₂ concentration after 1 hour / ppm
0.5	3470	276	1651
1.0	1945	138	1402
2.0	1183	69	1087
5.0	725	28	723
10.0	573	14	573

¹³ strictly speaking the rate of change of CO₂ in response to a change in emission or ventilation is an indicator of the air change rate

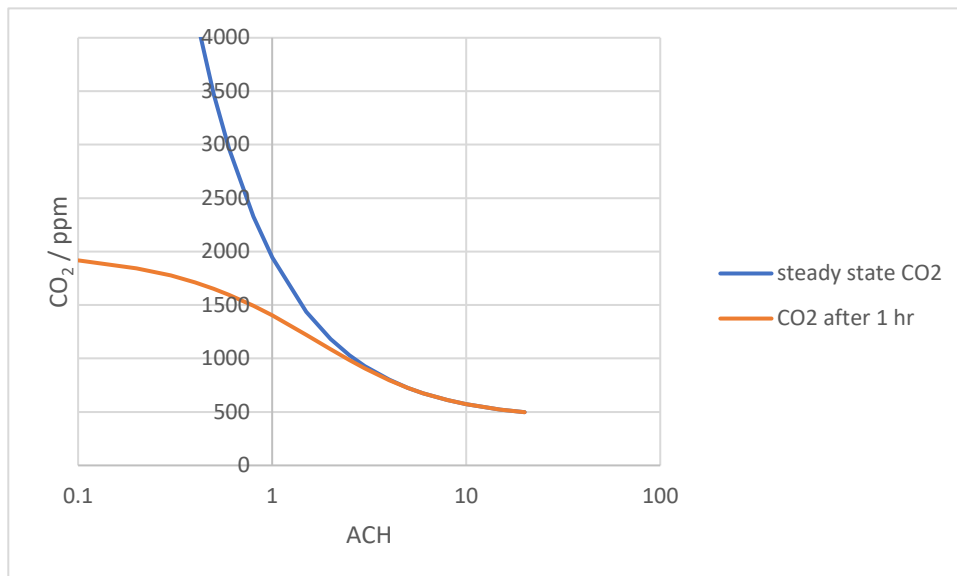


Figure 2-10: Modelled relationship between ACH and CO₂ after 1 hour and in the steady-state..

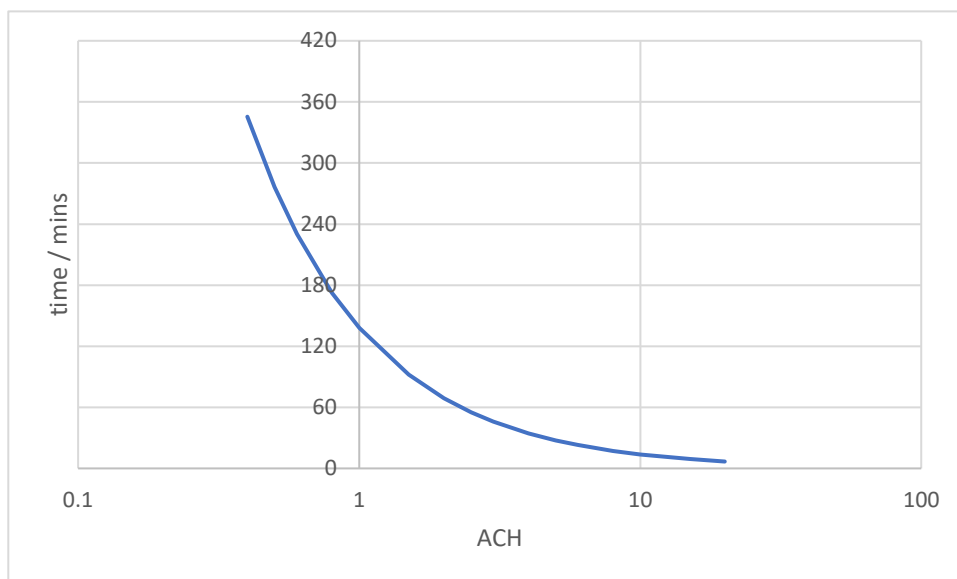


Figure 2-11: Time (mins) for CO₂ to rise to 90% of steady state in typical classroom.

2.8.3 Method to estimate steady-state CO₂

To use CO₂ data to provide a more robust evaluation of ventilation conditions, we assess each observed teaching period in terms of the steady-state CO₂. In many cases, the CO₂ concentrations did not reach a steady state during that teaching period. In this case the CO₂ data was extrapolated beyond the end of the classroom period by assuming an exponential function (using Excel Solver). This is illustrated in Figure 2-12, using an example from our observational dataset. This method introduces a degree of uncertainty, nevertheless the aim was simply to categorise each period as

having either “good” (steady-state < 800 ppm), “marginal” (800 – 1500 ppm) or “poor” (>1500 ppm) ventilation. Where ventilation conditions clearly changed during the period, assessment was conducted on the period during which the data conformed to a consistent exponential form.

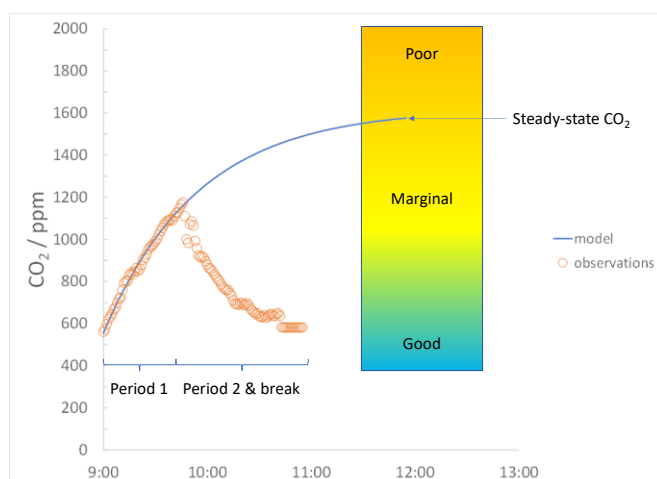


Figure 2-12: Example of how a model is used to estimate steady-state CO₂ by extrapolating observed data. Based on Aurora College room M26, 30th November 2022, periods 1 and 2.

3 Results

3.1 Assessment of ventilation during Occupied Classroom teaching periods

To evaluate ventilation, we restricted analysis to teaching periods where occupancy was either visually confirmed as being more than five people, or this was inferred from high CO₂ readings. Lunchtimes and breaks have been excluded from this analysis.

In Figure 3-1, steady-state CO₂ levels were estimated for 84 teaching periods across 17 classrooms, and the number per classroom varied from 1 to 11.

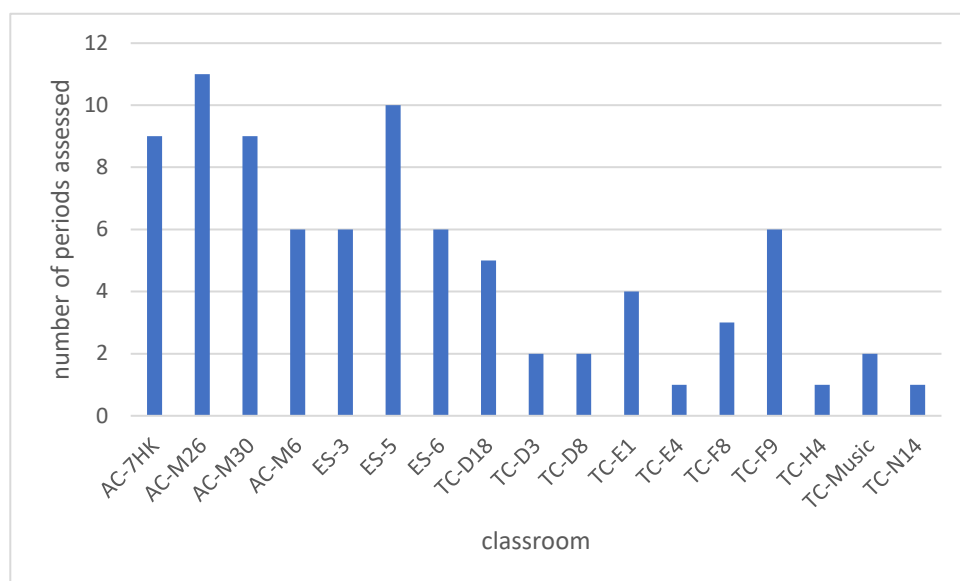


Figure 3-1: Number of periods assessed per classroom for which steady-state CO₂ levels were estimated

In summary,

- 31% of observed periods were classed as having “good” ventilation.
- 36% of observed periods were classed as having “marginal” ventilation.
- 31% of observed periods were classed as having “poor” ventilation.

For 76 of those periods we also recorded a subjective score (1 to 4) based on visual observations of the degree of “open-ness” of the room.

Figure 3-2 shows how that fraction varied with “open-ness”, with >60 % of periods with significant door or window opening achieving “good” ventilation.

Only one observed classroom was assessed as “poor” whilst having high open-ness. This was Epuni School (2nd Dec, period 1 – see Appendix A), where three doors were observed to be open. However, high activity levels amongst children was noted by our observers.

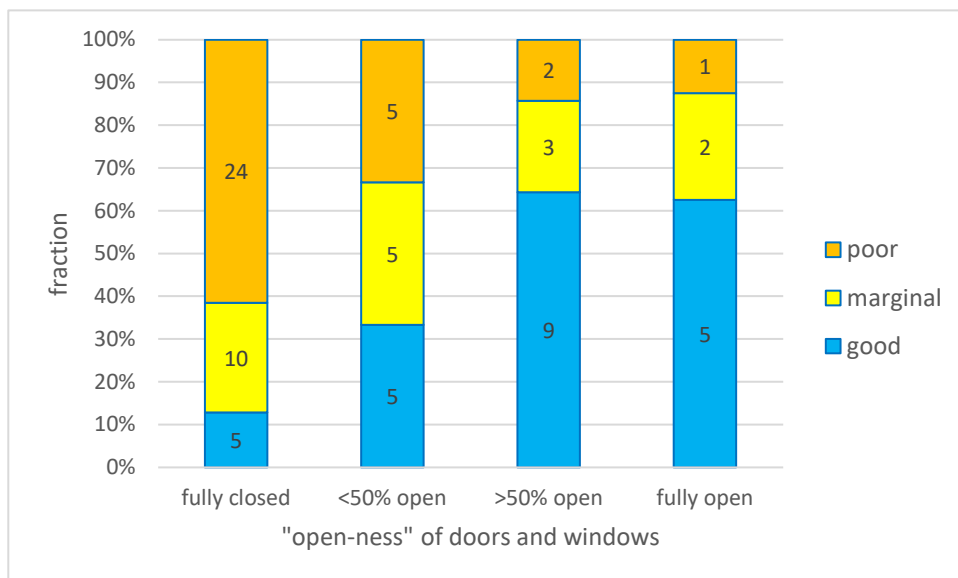


Figure 3-2: Fraction of observed periods assessed as good/marginal/poor ventilation as a function of "open-ness" (doors/windows open). Open-ness of 1 = doors/windows closed, 4 = several doors/windows fully open. Numbers indicate number of periods in each class.

Figure 3-3 and Table x) show the same data as shown in Figure 3-2, but broken down by classroom. Care should be taken in interpreting this figure, as the number of periods assessed in each classroom varied from 1 to 11. Nevertheless, 6 classrooms spanned good, marginal and poor ventilation, clearly indicating that these classrooms are capable of a wide range of ventilation performance. Two classrooms were assessed only as good (E4 and H4), although this relates to only a single observation.

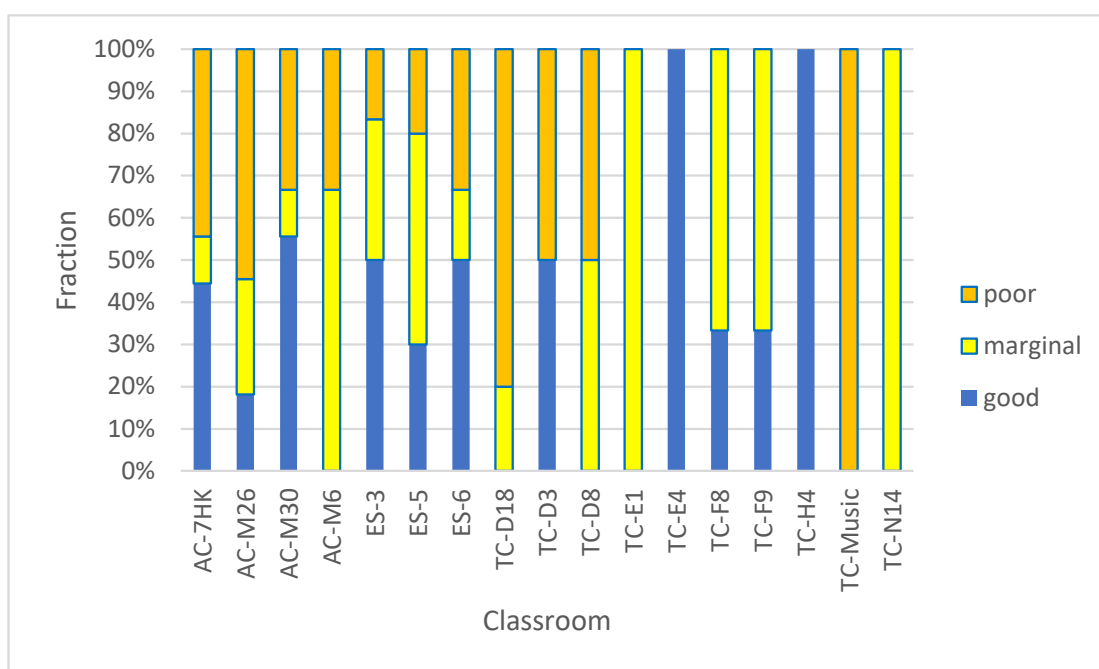


Figure 3-3: Fraction of observed periods assessed as good/marginal/poor ventilation for each classroom. Note number of observations per classroom varies from 1 to 11 (see Figure 3-1).

Table 3-1: Fraction (and total number in brackets) of observed periods assessed as having good/marginal/poor ventilation for each classroom.

classroom	Good	Marginal	poor
AC-7HK	44 % (4)	11 % (1)	44 % (4)
AC-M26	18 % (2)	27 % (3)	55 % (6)
AC-M30	56 % (5)	11 % (1)	33 % (3)
AC-M6	0 % (0)	67 % (4)	33 % (2)
ES-3	50 % (3)	33 % (2)	17 % (1)
ES-5	30 % (3)	50 % (5)	20 % (2)
ES-6	50 % (3)	17 % (1)	33 % (2)
TC-D18	0 % (0)	20 % (1)	80 % (4)
TC-D3	50 % (1)	0 % (0)	50 % (1)
TC-D8	0 % (0)	50 % (1)	50 % (1)
TC-E1	0 % (0)	100 % (4)	0 % (0)
TC-E4	100 % (1)	0 % (0)	0 % (0)
TC-F8	33 % (1)	67 % (2)	0 % (0)
TC-F9	33 % (2)	67 % (4)	0 % (0)
TC-H4	100 % (1)	0 % (0)	0 % (0)
TC – Music	0 % (0)	0 % (0)	100 % (2)
TC-N14	0 % (0)	100 % (1)	0 % (0)

Given the relatively small sample size in this study, the data is under-powered to detect any relationship between typical CO₂ and classroom block type, size, location or school age group. In our view, variability in CO₂ is well-explained by variations in ventilation practices and behaviour (described more fully in the sections below).

3.2 Determinants of classroom CO₂ levels

3.2.1 Assessment limitations

In this section an attempt is made to synthesise and identify key patterns in the full dataset, which is visualised with commentary for individual classroom-days in the Appendix. It is important to note that the explanatory data collected (observed ventilation and occupancy) are highly incomplete, consisting of a quick head count and one (or in some cases two) brief subjective observations of

room “open-ness” at a random point during each period. No systematic record of which doors and windows were opened, and by how much, and at what times, was collected (such observations were recorded on occasion and often incompletely). Similarly, the entry and exit times of people was not recorded.

Given the urgency in using this study to inform classroom practice, the analysis presented is not exhaustive. The dataset collected can be analysed further and may yield further lessons beyond what is presented here.

3.2.2 An illustrative example of Occupied Classroom CO₂ data

In general, the CO₂ data followed the expected general patterns:

- Consistently low overnight (indicating zero excess above background).
- Logarithmically rising when occupied, with either...
 - Higher air change rates leading concentrations to rise asymptotically towards a steady-state or equilibrium concentration in an hour or less.
 - Lower air change rates leading to near-linear rises until the room is vacated or ventilation is increased. This usually occurred within an hour, but sometimes longer, but long before concentrations approached a steady state (which could take 4 hours or more).
- Exponentially falling when occupancy was reduced (often to zero) or ventilation increased, either:
 - Slowly (for small increases in air change rate or room is left poorly ventilated when empty)
 - Quickly (for high air change rates, e.g., crossflow).
- Numerous smaller perturbations and disturbances, presumably related to changes in activity (CO₂ exhalation), small changes in occupancy, breathing close to the monitor or other transient changes in air change rates (e.g., gusts, door/window openings).

Many of these features are illustrated in Figure 3-4 (from Aurora College, room 7HK, Tuesday 30th November).

- When in use, occupancy (students and staff) was in the range 14 – 21 (median 16).
- Several brief transient spikes can be seen on this day (which was the first of the study, but not seen on subsequent days) – presumably someone breathing very close to the monitor.
- Air change rates are mostly low - indicated by CO₂ concentrations rising over 800 ppm frequently. The figure clearly shows that before period 5 CO₂ concentrations rose when the room was occupied and fell when it was not. All these periods correspond to manual observations of windows and doors being closed.
- The consequence of having two consecutively occupied periods without a break are seen on this morning, which not only leads to the highest concentration observed in

this classroom but also means that at the start of period 4 the room was still not flushed of stale air with CO₂ at around 600 ppm, despite having been empty for over an hour. This means that approximately 0.5% of air in the room at the start of period 4 was exhaled by occupants during periods 1 or 2.

- The exceptions to this pattern – when high air change rates were in effect - can be seen when CO₂ concentrations suddenly dropped early in period 5. The same thing happened in period 5 on Wednesday and early in period 3 on Thursday (not shown) despite the rooms being fully occupied. These three periods correspond to observations of windows being fully opened. The effect was immediate and dramatic with estimated air change rates well above 5 h⁻¹. This effectively flushed out the accumulated stale air in 6 - 15 minutes and kept CO₂ low for as long as the windows remained open. We do not know the reason why windows were opened at these specific times other than to note that in each case CO₂ levels were above 800 ppm at the start of the period (windows were not opened if CO₂ was below 800 ppm), although of course nobody in the classroom knew this. We can speculate that window opening was in response to rising temperatures, which also suggests that the windows may not have been opened in this way on a cooler day or may have been opened earlier on a warmer day.

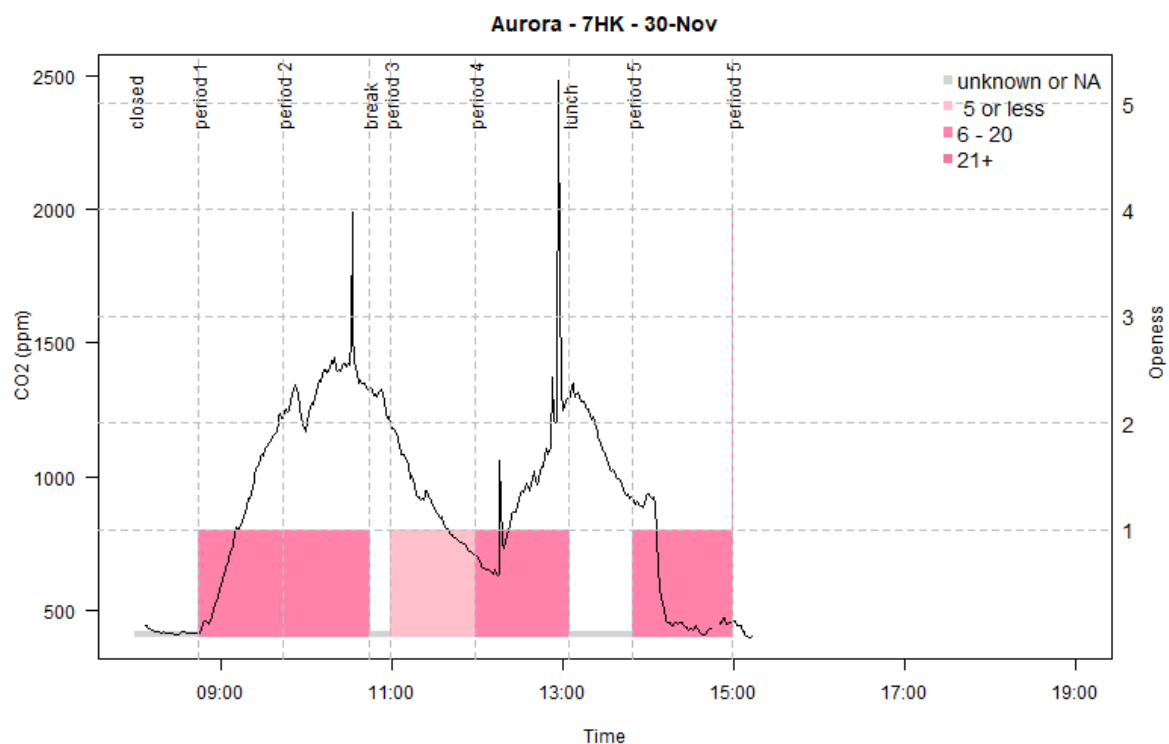


Figure 3-4: Example CO₂ data for one day from one classroom. Black line is 1-minute average CO₂. Rectangular block colour is occupancy (number of people - see legend) and height of the block is a subjective measure of the room's openness, i.e., ventilation.

Similar figures and brief commentary for all monitored classrooms are provided in Appendix A.

3.2.3 Can classrooms achieve higher air change rates?

Data from 10 of our study classrooms provided evidence that high air change rates were possible. This evidence consisted of either CO₂ levels remaining low after doors and/or windows were open, brief but rapid reductions in CO₂ often after a class ended, or permanently low CO₂. This does not mean that the remaining classroom could not achieve high air change rates, just that these were not observed during our study.

3.2.4 Were rooms being “flushed” of stale air during short breaks between teaching periods?

Although our data indicated that many classrooms could be flushed clear of stale air within 15 minutes, we saw only one example of this happening during the shorter break times between scheduled class times. On the contrary, in most cases air change rates tended to remain low during breaks so that classrooms still contained a substantial component of stale air from the previous period when the next period began.

3.2.5 Impact of occupancy patterns

In eight of our study classrooms, consecutively occupied periods led to accumulation of CO₂ for more than an hour.

Note that infection risk for COVID-19 is exponentially related to exposure time. In cases where CO₂ concentrations (as a proxy for viral load) is increasing over time due to poor ventilation, the risk over a double period could be more than double the risk over a single period.

A clear example was observed in Aurora College room M30 where two double periods were separated by a short break (Figure 3-5). Air change rates appear to have been moderate, but CO₂ levels were effectively accumulating for 4 hours reaching 2000 ppm (this high value was also contributed to by relatively high occupancy and activity levels). Levels may have reached 2500 ppm had it not been for the breaktime. Similarly, the ACH during lunchtime was not sufficient to flush the room clear before period 5 which began with CO₂ at ~1280 ppm (or 3% re-breathed air). Note that in this example, windows were finally opened during period 5 allowing CO₂ to fall from 1600 ppm to 1000 ppm. We do not know the reason for the windows being opened at this time, so can only speculate that it was in response to rising indoor temperatures.

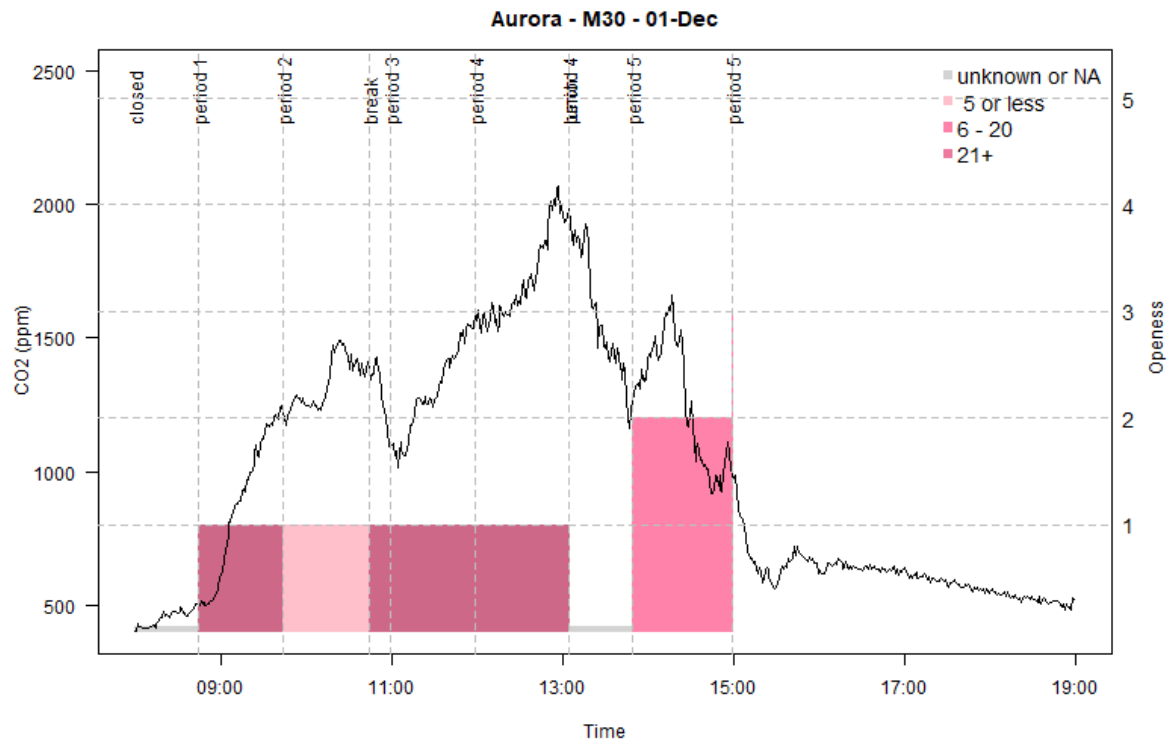


Figure 3-5: Example of CO₂ accumulation across multiple periods.

In contrast, Taupo room F9 was also continuously occupied for 4 hours on Wednesday, but CO₂ levels were kept relatively low due to the introduction of cross-flow ventilation from the end of period 1 (Figure 3-6).

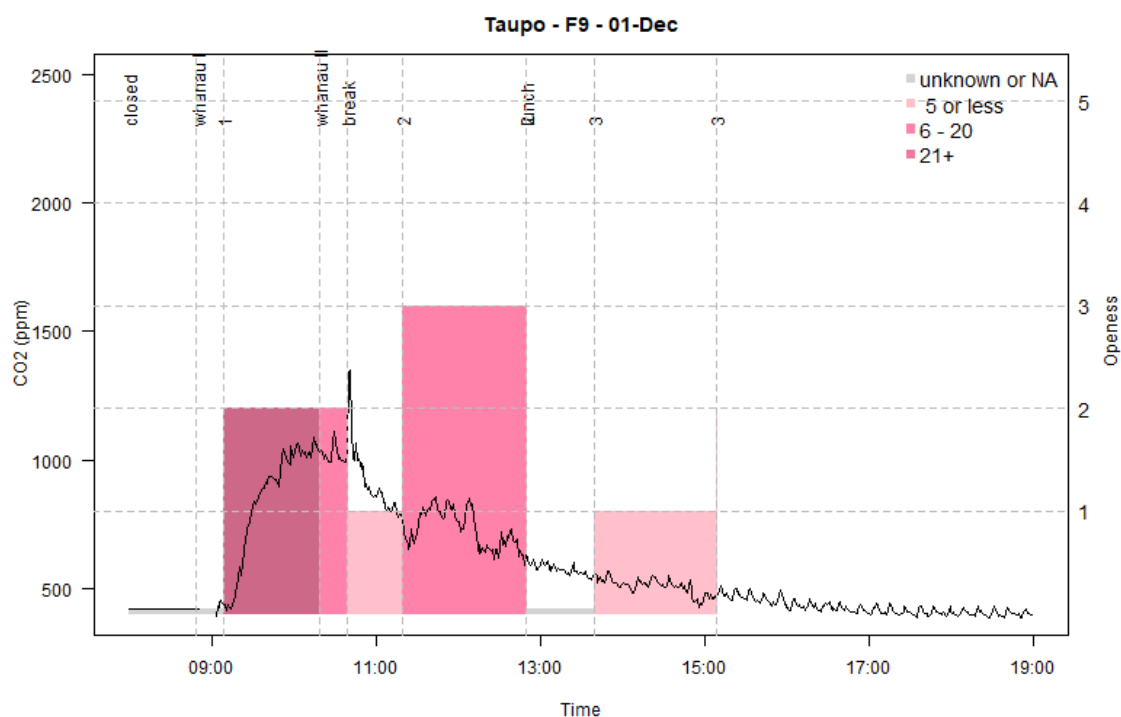


Figure 3-6: Example of CO₂ kept low during continuous occupancy through the use of cross-flow ventilation. Taupo room F9, Wednesday. Single door open during period 1, double doors open thereafter.

3.2.6 Influence of adjoining spaces

In some of our study classrooms we inferred the influence of exchange of CO₂ between the study classroom and adjoining indoor spaces. This could happen in two ways:

- In seven of our study classrooms a door was opened into a (presumably) less-occupied space (another classroom, a corridor, communal space, or in one case a hall), effectively increasing the dilution volume of the classroom. This was evidenced by a reduction in CO₂ concentrations, sustained for as long as the door was kept open. Although effective in suppressing concentrations in the study classroom this raises the risk of additional exposure in those adjoining spaces if they are likely to be occupied for any significant period, and/or are poorly ventilated.
- In some cases, there was suggestive evidence of the opposite effect with the open door allowing air with a higher CO₂ concentration from the adjoining space to enter the room being studied, thereby raising its concentration too. This cannot be confirmed due to the lack of monitoring in the adjoining spaces.

3.2.7 Primary versus secondary

Primary classrooms had slightly higher occupancy (median of 20 as opposed to 16 for secondaries) and may be expected to have higher activity rates (although our subjective observations did not corroborate this). Any increases in CO₂ exhalation rates because of these factors may be offset by lower exhalation rates in general in younger children. In our limited study there was no systematic effect of higher (or lower) CO₂ concentrations in primaries relative to secondaries, or vice versa.

3.2.8 Summary of findings from Occupied classrooms

Our quantitative observations indicated that:

- Approximately one third of observed classes had poor ventilation, one third had good ventilation and one third were marginal.
- Ventilation performance was not consistent for most classrooms, but varied between periods, indicating a major influence of room use and ventilation practice.

Furthermore, a selection of non-systematic and qualitative observations was suggestive that:

- Good ventilation was achieved in most classrooms when doors and/or windows were opened.
- The best results (with CO₂ kept below 800 ppm) were associated with crossflow between multiple openings
- CO₂ levels were also suppressed by the use of internal doors to larger unoccupied indoor spaces thus increasing the dilution volume

In general, our results indicate that high CO₂ (and potential infection risk) was largely driven by three phenomena:

- Low air exchange rates, especially in the morning, due to doors and windows remaining fully or mostly shut.

- Greater build-up (if air change rates remain low) in the case of extended continuous occupancy (e.g., over an hour or over double teaching periods).
- Failure to adequately remove stale air through high ventilation between occupancy periods.

3.3 Control study

This section presents both summary findings and key observations pertinent to the management of classroom ventilation. It should be noted that these results are specific to one classroom in one study in the early summertime. Results (especially for higher air change configurations) are likely to vary with meteorological conditions. However, it is likely that the general patterns observed will be consistent.

3.3.1 Effect of natural ventilation

- Our results clearly showed that a wide range of air change rates (from 0.7 to 17) – straddling either side of the recommended goal - were achievable with natural ventilation, indicating the importance of ventilation configuration.
- When the doors and windows were closed (baseline configuration) we observed the lowest air change rates of ~0.7.
- **Natural ventilation** with openings on more than one façade of the room (thereby inducing **cross-flow**) was approximately 4 - 5 times more effective than openings on a single façade for the same opening area (Figure 3-7). In general, crossflow provided more than 4 ACH and single façade openings provided less than 4 ACH, indicating that crossflow is a necessary condition to meet ventilation goals (in that room at that time).
- For both cross-flow and single façade openings, the air change rate appeared to be broadly proportional to the **total door/window opening area**¹⁴ (Figure 3-7). In this classroom the best performance (12 ACH) for double facade openings was achieved by fully opening the top and front windows – giving the largest opening area. Using a combination of one set of windows plus the door (reducing the opening area) gave “borderline” performance of 4 – 8 ACH with the top windows performing better. This may also be because the top windows opened more fully but this cannot be confirmed from our limited testing. Opening doors or windows only by a “crack” was not sufficient, providing no more than 1 ACH for a single façade opening or 2 ACH for a double façade opening. From this it follows that it is important to be able to **fully open openings on two or more facades** to achieve the recommended air change rate from natural ventilation alone. Anything less will provide reduced protection (noting that winds and temperature gradients were relatively low in this study, higher values could improve ventilation, but the degree is currently unknown).

¹⁴ I.e., area of the opening at any given time, not the maximum, or “openable” area

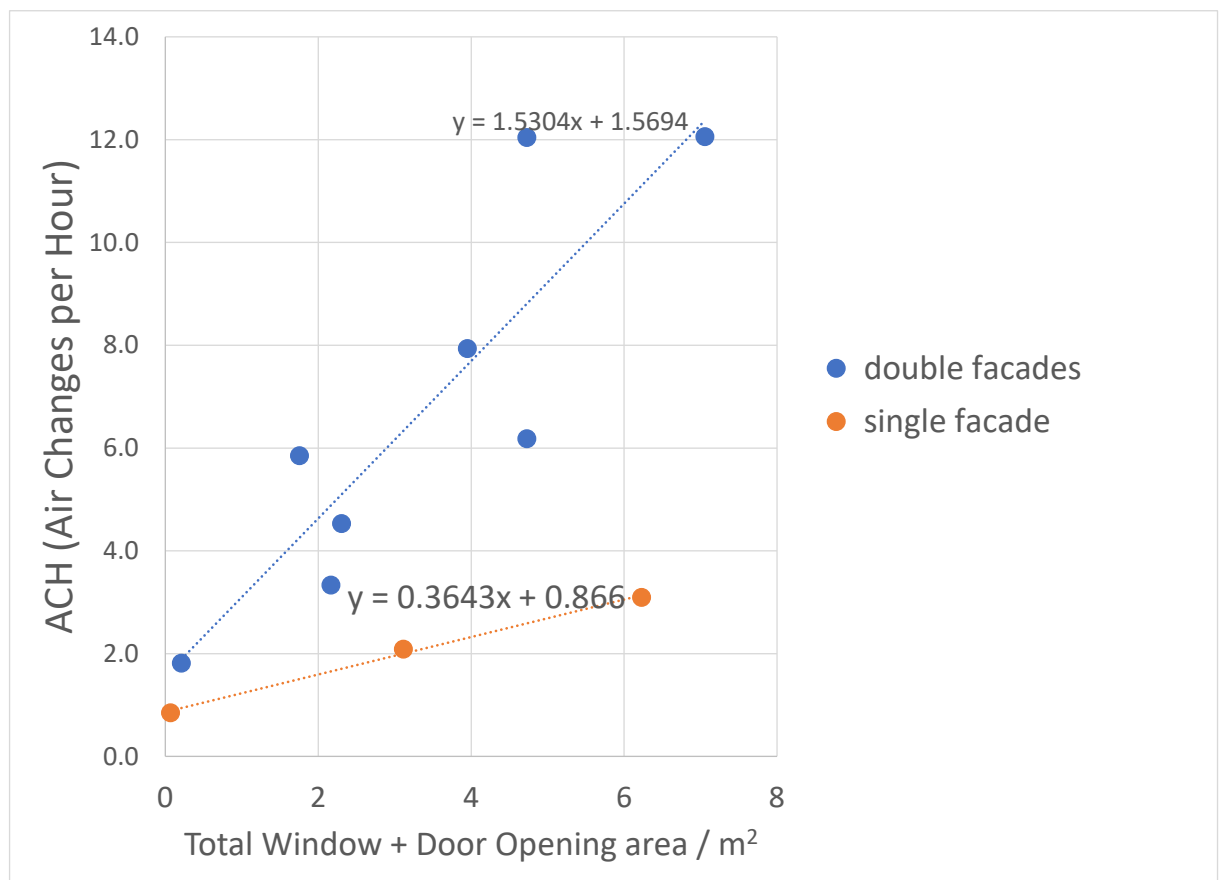


Figure 3-7: Relationship between opening area and air change rate for tests with natural ventilation configuration. "Single facade" = single sets of openings (e.g., adjacent windows). "Double façades" = two sets of openings, consisting of either upper + lower windows; or external door + upper or lower windows.

- Air change rates of 4, 6 and 12 (all achievable with natural cross-flow) corresponded to "purge times" (which we arbitrarily take to mean the time for 90 % of the air to be replaced) of 35, 23 and 12 minutes respectively.

3.3.2 Effect of mechanically assisted natural ventilation

- A prototype **Assisted Natural Ventilation System** (ANVS) was tested that provides various combinations of an exhaust and supply fan, and air recirculation with HEPA filtration.
- The use of the **exhaust fan** only substantially increased the air change rate when the door and 4 front windows were fully opened, from 3 to 12, i.e., raising it above the target. A similar improvement was also evident when the door and top windows were fully open, raising ACH from 12 to 22. A four-fold increase was also observed when the room was fully sealed, raising ACH from 0.7 to 3.0. Two other exhaust fan tests – covering single-opening ventilation - showed much more modest changes. Although highly limited, these results suggest an exhaust fan may make crossflow stronger and more reliable or provide some minimal ventilation when the room is otherwise sealed.
- The use of a **supply fan** alone was only tested once showing a modest improvement in ACH from 2.4 to 3.4 (door open only).

- Based on only a single test (room sealed) **the combination of a supply fan and exhaust fan** provided no significant benefit over using an exhaust fan alone.
- The **full ANVS** (partial exhaust, partial supply and partial recirculation through a HEPA filter) was tested under four room configurations (fully sealed, door only, front windows open slightly, and door fully open plus top windows open slightly). Relative to no ANVS, air change rate was slightly reduced in two of the tests, and slightly increased in the other two tests. Due to the very small sample, we consider these results to be indicative but inconclusive.

3.4 Mitigation

3.4.1 Modelling approach

In this section we provide illustrative examples of four mitigation approaches that could be employed to reduce CO₂ concentrations, informed by the results of the study. Rather than attempt to model every classroom and every day individually we have developed a baseline scenario, roughly based on the Aurora College timetable, that has the key features of a relatively under-performing classroom, i.e.:

- Two consecutive hour-long morning periods
- A 15-minute break
- Two more consecutive hour-long morning periods
- A 60-minute lunch break
- A final hour-long afternoon period.

We assume an occupancy of 20 in each teaching period and zero during break and lunch.

Furthermore, we assume an air change rate of 1.0 throughout the day. Figure 3-8 illustrates the modelled CO₂ concentrations through the day which peaks at 1404 ppm at the end of period 2, 1579 ppm at the end of period 4 and 1344 ppm at the end of period 5.

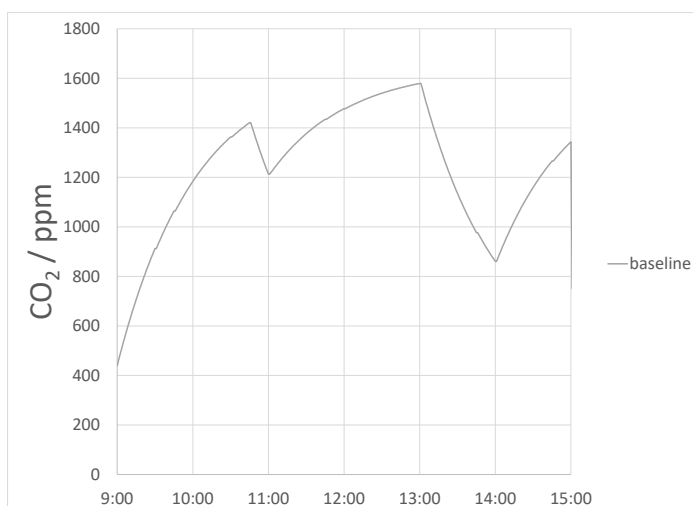


Figure 3-8: Modelled CO₂ concentration for the baseline classroom scenario. Two consecutive hour-long morning periods, 15-minute break, two more consecutive hour-long morning periods, 60-minute lunch break, final hour-long afternoon period).

3.4.2 Modelled scenario 1: Increase ACH from 1 to 5

Figure 3-9 shows that increasing the air change rate across the whole of the day substantially suppresses CO₂, which in this scenario now peaks at 664 ppm (which is the steady state).

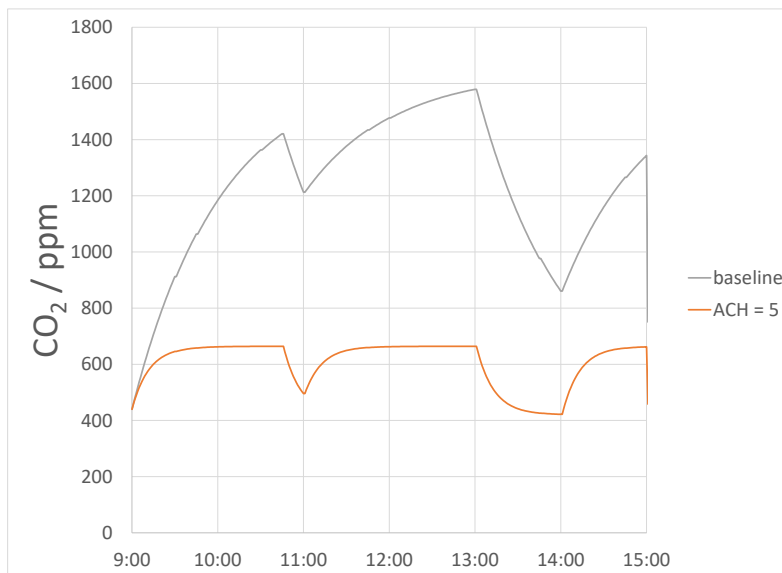


Figure 3-9: Comparison of modelled CO₂ for typical classroom with ACH = 1 (baseline) and ACH = 5.

3.4.3 Modelled scenario 2: “Flush” room clear during breaks

In this case we assume that while raising ACH above 5 is possible, it is not considered viable to achieve continuously, perhaps due to excessive heat loss or disturbance from the weather. In this scenario, therefore, ACH is raised to 10 during unoccupied periods only (i.e., break and lunchtime). Figure 3-10 shows that the effect is to mostly “reset” the classroom when it is unoccupied. However, the room still spends most of the day at a low level of ventilation and peak CO₂ levels are still above 1100 ppm and reaching as high as 1500 at the end of each occupied period.

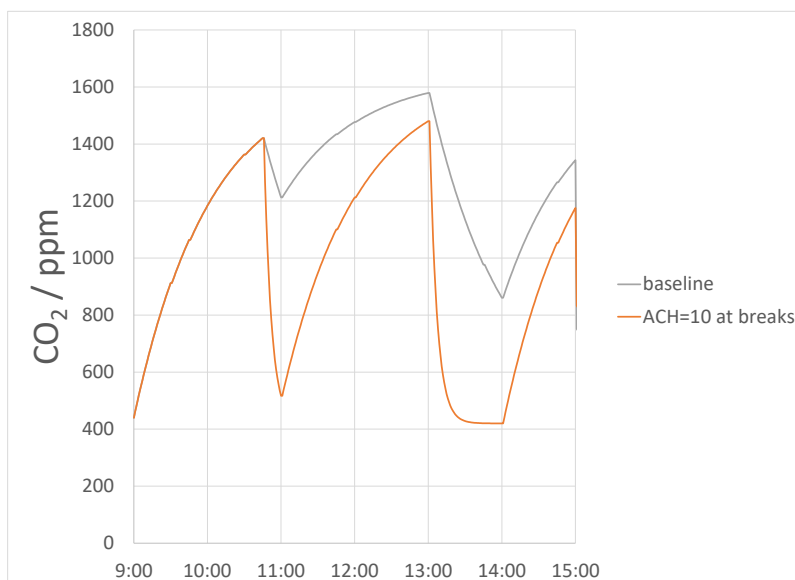


Figure 3-10: Modelled impact of introducing high-ventilation (ACH=10) during break and lunchtime
Assumed ACH = 1 when room is occupied

3.4.4 Modelled scenario 3: Introduce a flush every hour

In this scenario, additional 15-minute “flush” breaks are introduced between the consecutive classes, i.e., between periods 1 and 2 and between periods 3 and 4. Figure 3-11 show that CO₂ is now kept lower for longer and does not exceed 1250 ppm.

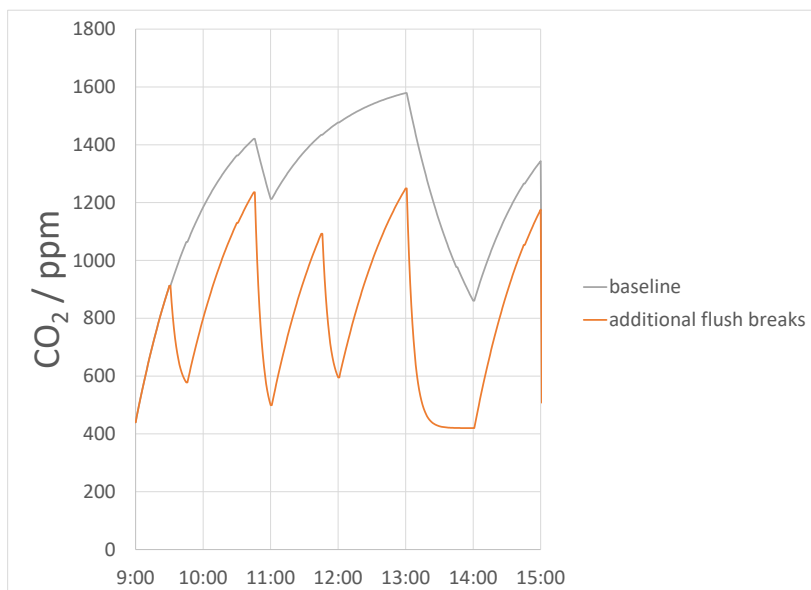


Figure 3-11: Modelled impact of introducing 15-minute high-ventilation (ACH=10) flush between every occupied period.

3.4.5 Modelled scenario 4: Keep classroom unoccupied on alternate periods

This scenario assumes that higher air change rates cannot be achieved in the room. We therefore assume the classroom is left unoccupied during periods 2 and 4. Figure 3-12 shows that the result is to keep CO₂ below 1250 ppm.

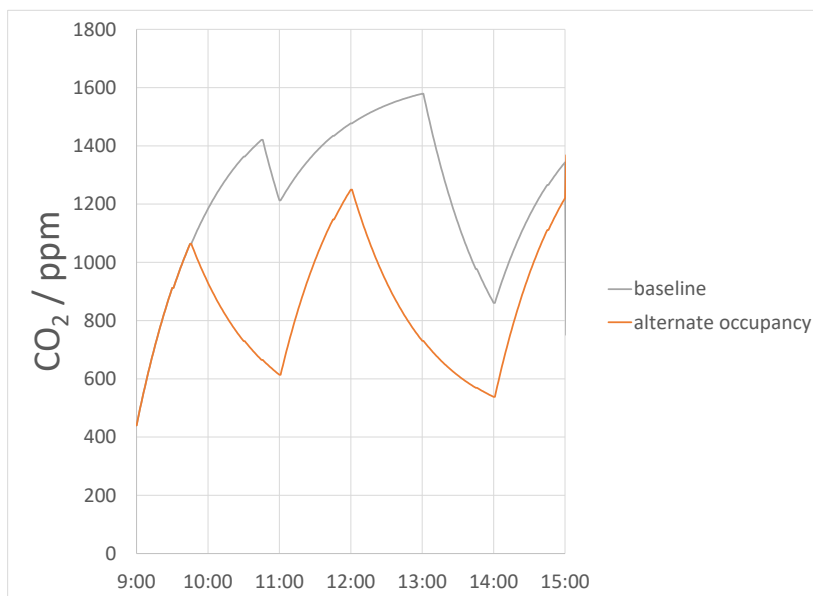


Figure 3-12: Modelled impact of keeping the classroom vacant for alternate periods ACH = 1 throughout.

3.4.6 Synthesis of modelled mitigation options

The scenarios presented in this section show that permanently increasing the air change rate is by far the best option. Our limited study suggests that significant increases in air change rates were achievable with crossflow through multiple openings in many of the observed classrooms. Whether this is a practical option is most likely to depend on negative impacts on thermal comfort and weather intrusion. These impacts are beyond the scope of this study.

The other scenarios were broadly similar in their overall effectiveness in reducing CO₂ concentrations (and, by proxy, any virus in the air) to values between 800 ppm and 1500 ppm.

3.5 Study limitations

Due to the limitations on resources and the urgency of this study, only a limited number of observations were made. In particular, measurements were restricted to between one and 5 days per classroom. Both the results, and past experience indicates that ventilation can vary substantially based on ventilation practice, room use and weather conditions. The study results, therefore, can only be considered to be valid for the week that the observations took place. It is especially pertinent to note that this was in early summer towards the end of a school term disrupted by COVID-19 meaning that temperatures were warm but classroom occupancy and activity patterns may have been lower than normal.

The number of different classrooms that could be sampled was also limited. Although efforts were taken to sample a range of common classroom types this study can in no way be considered a comprehensive study of the relationship between block type and ventilation performance of that type elsewhere (or at other times of the year).

It was not considered practical in this study to systematically observe door and window openings, nor detailed meteorological observations. This study, therefore, cannot causally link ventilation

practice, meteorology and ventilation performance, other than through qualitative, subjective and anecdotal evidence that is suggestive of a relationship, for instance explaining exactly when and why doors and windows were opened or closed.

Some additional observations were made but were found not to aid analysis. Some Live Classroom study observers carried noise meters and handheld anemometers. The intention was to use these to make indicative “spot” measurements of noise (as a potential proxy for activity levels) and air flow through doors or windows. We found no correlation between noise and visually observed activity, and air flow was often too low to measure, or difficult to measure consistently, or the openings could not be reached, or the attempt was considered too disruptive of class activities.

There were significant logistical and practical limitations on where the Hau-Hau monitors could be placed in classrooms (partly related to their being mains powered). In practice, most monitors were placed around 0.6 – 1.0 m above the ground and close to walls on opposite sides of the classroom, away from doors and windows. Although not covered in this report we found minimal differences in CO₂ from monitors paired in this way, however, the degree to which these monitors represent the ventilation of the room as a whole (or variation within the room) has not been explicitly explored.

3.6 Recommendation for further study

3.6.1 Research questions

Our recommendations for further study are based on three themes:

- A. Maximising natural ventilation through good practice
- B. Supplementary solutions for more demanding settings and climates
- C. Effectiveness, evaluation, feedback and learning.

A. Maximising natural ventilation through good practice

We recommend that further research is required to firmly establish what good practice regarding natural ventilation should consist of and identifies and addresses barriers to achieving good practice. Specifically, that work should address the following questions:

- A-1 How consistent or variable are the main findings of this brief study, regarding the impact of opening area and air flow regime on air change rate, over a wider range of carefully documented meteorological conditions?
- A-2 Can the use of supplementary fans enhance the reliability of natural ventilation (in single-sided, crossflow and stack-flow regimes) to consistently achieve the desired air change rates, and how?
- A-3 What are the consequences of enhanced natural ventilation for heat loss/gain, thermal comfort and disturbance of classroom function and learning in classrooms? How will these consequences change in different weather conditions?
- A-4 What is the current state of ventilation rates and practice in schools across the country? Do poorly performing classrooms have any distinctive common characteristics?

B. Supplementary solutions for more demanding settings and climates

We recommend that further research is conducted to clarify and trial additional solutions for situations where natural ventilation alone will not be sufficient to manage infection risk. Specifically, studies should address the following questions:

- B-1 What are effective strategies for compensating for excess heat loss/gain associated with enhanced ventilation?
- B-2 What is the performance of portable air cleaners (i.e., filtration devices of the type being considered by the Ministry) relative to natural ventilation, regarding the reduction of exhaled particles, and how does performance depend on the device's clean air delivery rate and positioning, as well as classroom ventilation configuration?
- B-3 What levels of noise are generated by portable air cleaners at different settings and placement configurations relative to the tolerance for a range of classrooms and classroom activities?
- B-4 Can an "assisted natural ventilation system" (combining supply/exhaust fans and/or recirculating flow with air filtration) deliver improved performance in providing good indoor air quality at an appropriate scale for widespread implementation?

C. Effectiveness, evaluation, feedback and learning

We recommend that further work is conducted to create a strong feedback loop so that the wide range of mitigations and interventions likely to be applied in schools across the country are rapidly evaluated in a robust and systematic manner so that learning can be captured and used to regularly update good practice advice. Specifically, we recommend addressing the following questions:

- C-1 How effective is the presentation of CO₂ data to teachers and school property managers in terms of effective mitigation, and how can effectiveness be maximised?
- C-2 Can air change rates be rapidly and automatically estimated from CO₂ data from classrooms? What are the uncertainties in the estimates? What (if any) supplementary data is required?
- C-3 Is the guidance provided by the Ministry effective? Do schools/teachers follow the advice? If not, why not?
- C-4 Do supplementary technologies deployed in real-live settings achieve the performance targets predicted through controlled studies or manufacturer's claims?

3.6.2 Recommended studies and methods

We recommend that many of the questions above can be combined and addressed in a set of focussed studies:

- Modelling
- A "Control Room" study, very similar to the one described in this report, but extended in time to conduct a wider range of tests, and with some improvements (described below).
- Experimental cohort studies with a few occupied classes, including

- Studies involving human responses and acceptability (e.g., noise tolerance, self-reported comfort)
- Case-control intervention trials of mitigation strategies.
- Classroom surveys over a wide number of schools, including CO₂ monitoring and teacher surveys

Table 3-2 indicates how each study setting relates to the research questions.

Table 3-2: Recommended study settings and the questions they can be used to address.

Study setting	Research questions
Modelling	A-3 Heat loss C-2 Automating Air Change Rate calculation
Experimental control room	A-1 Natural ventilation configurations A-2 Supplementary fans A-3 Heat loss B-1 Mitigating heat loss B-2 Portable air cleaner performance B-3 Portable air cleaner noise generation B-4 Assisted Natural Ventilation System C-2 Automating Air Change Rate calculation C-4 Evaluate technologies
Experimental occupied classroom cohort	B-1 Mitigating heat loss B-3 Portable air cleaner noise tolerance C-1 Effectiveness of CO ₂ data C-2 Automating Air Change Rate calculation C-3 Guidance effectiveness C-4 Evaluate technologies
Classroom surveys	A-4 Current state/practice

Some questions are suited to a two-stage approach where Control Room studies are followed by Experimental cohort studies (e.g., mitigations are tested for technical performance in the Control study and for classroom acceptability in a Cohort study). Consequently, we recommend that at least one Control Room study is begun as a priority. Due to the urgency of this work, potential limitations on access and labour availability during the pandemic, and the likely impact of climate on the results, **we recommend that three Control rooms are established**, one each in the three main climate zones of New Zealand, all following the same experimental protocols. Control room tests would likely last a month but may be repeated or adapted as the seasons change.

3.6.3 Methodological critique and recommendations

During this study we encountered some limitations and here make recommendations for improving future studies.

- Control room studies
 - Whereas a CO₂ “pulse” release method (using either a bottle or fire extinguisher) was simple and reliable, a much slower continuous release offers greater experimental opportunities, including the ability to measure the emission rate (improving the ability to calculate air exchange rate), and the ability to simulate classroom practices. The use of a bottle with a mass flow controller and measured flow rate is recommended or means to calculate the mass emission rate as a secondary option.
 - Our attempts to generate a test aerosol using diffusers and a theatrical fog generator were unsuccessful. These aerosols were either too unstable or too low or too high concentration. We recommend that a constant aerosol source is used that can raise indoor PM₁₀ concentrations into the range 50 – 500 µg m⁻³ (i.e., concentrations common in a home when there is cooking being undertaken) thereby providing a clear signal to evaluate ventilation and filtration interventions.
 - Good metadata is critical. We recommend steps are taken to accurately, consistently and systematically record the timing of all relevant events in the control room, preferably using an automated metadata tool.
 - Tests and room configurations should be planned and scheduled in advance as much as possible.
 - Continuous (at least every 10 minutes) outdoor meteorological observations should be recorded.
 - Outdoor CO₂ should be recorded continuously.
 - The use of a grid of instruments was highly valuable and is recommended.
 - An online dashboard allowing the experimenter to see real-time data and view or download recent data was highly valuable and is recommended.
 - This study used a fan to deliberately provide internal mixing of air in the control room. We did not systematically vary this mixing, nor study the impact of ventilation setting on internal mixing. We recommend this is studied in a control room to provide some understanding of variability in CO₂ across a room in different conditions, thus assisting in monitor placement advice and data interpretation.
 - An ideal situation would be for the control room to be fully remote-controlled, preferably with experiments based in an adjoining room during the tests. This would ensure that the exhalation of experimenters, or experimenters using doors to enter/leave the room thereby disturbing the experiment, is removed. This would greatly reduce uncertainty in emission and ventilation rates. If not feasible,

the tests should be carefully designed to minimise the impact of the experimenters on the results. Furthermore a “red light” or similar system should be considered to minimise the risk of accidental interference by third parties with the tests.

- Occupied classrooms:
 - The use of manual observers who did not enter the room and took only occasional “spot” measurements was a compromise and yielded data of limited value relative to the human resource it used. More robust and automated methods of observing occupancy, activity and ventilation configuration are recommended where they are needed to address the question being studied.
 - If detailed analysis (especially estimation of air change rates) is required, outdoor CO₂ should be recorded continuously.

4 Conclusions and Recommendations

1: Can typical classrooms achieve sufficient ventilation naturally?

- CONCLUSION 1-1: Control study data showed that a classroom designed to have crossflow ventilation (i.e., openings on differing sides of the room), and used in this way, can consistently provide much better ventilation performance, meeting the requirements broadly agreed as necessary for management of COVID-19 (>5 air changes per hour). Using only single-opening ventilation (i.e., relying on a single opening or row of adjacent openings) provides moderate but not sufficient ventilation. Although far from comprehensive, our Occupied Classroom study results corroborated this finding which we expect to be consistent across all naturally ventilated classroom designs.
- RECOMMENDATION 1-1: Property improvements should be considered that will introduce a level of crossflow ventilation in classrooms currently restricted to single-sided ventilation.
- CONCLUSION 1-2: Restricting how wide windows can open has a major impact on ventilation performance. The Control study data showed that the ability to achieve acceptable ACH levels was proportional to the classroom's total window and door opening area. How wide windows can open is often restricted by hinging and opening mechanisms, and security stays.
- RECOMMENDATION 1-2: Finding additional ways to provide secure and safe, yet widely opening windows would significantly benefit classroom ventilation.

2: Are windows and doors being used during class time to achieve sufficient ventilation?

- CONCLUSION 2-1: Air change rates above 5 were shown to be achievable in the Control study, and were inferred in some of the Occupied Classrooms associated with opening of windows and/or doors (although details of which and how many was not recorded) CO₂ was kept below the target of 800 ppm in only one third of the observed occupied classes implying that air change rates in Occupied Classrooms were frequently below 5 ACH (considered low and potentially insufficient). This appeared mainly to be due to doors and windows not being opened insufficiently. Lower ACHs were more common in the morning, with higher ACHs mostly occurring later in the day (it is presumed mainly due to window opening), or on some days not at all.
- RECOMMENDATION 2-1: So long as it is practical to do so and does not adversely impact learning or children's health; increasing ventilation throughout the day and encouraging ventilating the classroom on entering should be encouraged, not just when the room feels warm or stuffy. Further analysis may reveal certain types of rooms for which this is not required, but good ventilation is recommended on a precautionary basis.
- CONCLUSION 2-2: The classroom with the worst ventilation performance had windows deliberately kept shut due to traffic noise.

- RECOMMENDATION 2-2: This highlights the need for alternative ventilation strategies to be investigated and made available where the 'as designed' strategy is not working in practice.
- CONCLUSION 2-3: Some of the better performing classrooms had a door open into a larger indoor volume (such as a hallway). This will substantially increase the dilution volume. This may be an effective means of reducing infection risk, however, great care needs to be taken to ensure that this does not pose an additional risk to users of that larger space, or the classrooms it may connect to. To reduce risk, this larger space also needs to be adequately ventilated.
- RECOMMENDATION 2-3: In situations where full cross-flow and introduction of fresh air is not achievable or effective, linking an occupied space to an adjacent space can dilute indoor contaminants and reduce risk so long as that adjacent space is only rarely or occasionally occupied, and is well-ventilated.

3: Can temporary ventilation boosts help?

- CONCLUSION 3: Once a room was vacated, whether or not doors and windows remained open made the difference between stale air being flushed out (within 6 - 15 minutes at high ACH) or being retained for hours (at low ACH) - potentially still present when the next class began, leading to an accumulating risk. We found the latter situation to be the norm.
- RECOMMENDATION 3: High ventilation throughout the school day is ideal. Planning and adopting regular breaks (particularly between high school teaching periods) where a classroom is briefly vacated with all windows and doors open would be a **major benefit to classroom ventilation**. This would be a more practical approach in cooler conditions or when permanently ventilating an occupied room is impractical.

4: CO₂ monitoring

- CONCLUSIONS 4: CO₂ levels in under-ventilated classrooms tend to exceed 800 ppm within an hour after being first occupied.
- RECOMMENDATIONS 4: This further validates the Ministry's intended approach of focussing on assessing ventilation performance and improvements utilising CO₂ monitoring devices, meeting international practices. CO₂ monitoring provides a quick and easy early warning for problematic classrooms. Occasional breaches of this value, especially if associated with one specific class, may indicate an easily remedied issue associated with the way the space is used (e.g., class occupation numbers too high). Persistent breaches indicate more systematic improvements in ventilation practice or infrastructure are required.

5. What if natural ventilation is insufficient?

- CONCLUSION 5: Although we were able to confirm that our Control study room was able to achieve sufficient ventilation through natural crossflow alone, our study scope preventing us from establishing this for other classrooms. High ACHs were not observed in 8 out of 18 classrooms. Although this does not confirm that they could not achieve >5 ACH, it is plausible that many classrooms around the country may not.

Outside of the summer months, and in inclement weather, it may not be desirable or possible to achieve 5 ACH with natural ventilation through multiple openings without excessive heat loss or other disruption. For these reasons we trialled a very simple prototype Assisted Natural Ventilation System (ANVS) designed to enhance air replacement through crossflow, whilst allowing doors and windows to be partially or fully closed, reducing heat loss and classroom disruption. Due to time constraints the study gathered limited data but did confirm improvements over natural ventilation and/or portable air cleaners for CO₂ and PM.

- RECOMMENDATION 5: The concept of ANVS deserves further pursuit.

5 Acknowledgements

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- Isabel Andrade Beltran, University of Canterbury
- Arden Callagher, Victoria University Wellington
- Swarnali Dihingia, Victoria University Wellington
- Jose Nunez Collado, Victoria University Wellington
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- Daniel Morrish, NIWA
- Elizabeth Somervell, NIWA
- Robyn Phipps, Victoria University Wellington
- Mark Jermy, University of Canterbury
- Vicky Evans, Ministry of Education.

6 Glossary of abbreviations and terms

ACH	Air Changes per Hour
ANVS	Assisted Natural Ventilation System
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CDC	Center for Disease Control (USA)
CO ₂	Carbon dioxide
ppm	Parts per million
SARS-CoV-2	The virus that causes COVID-19
WHO	World Health Organisation

7 References

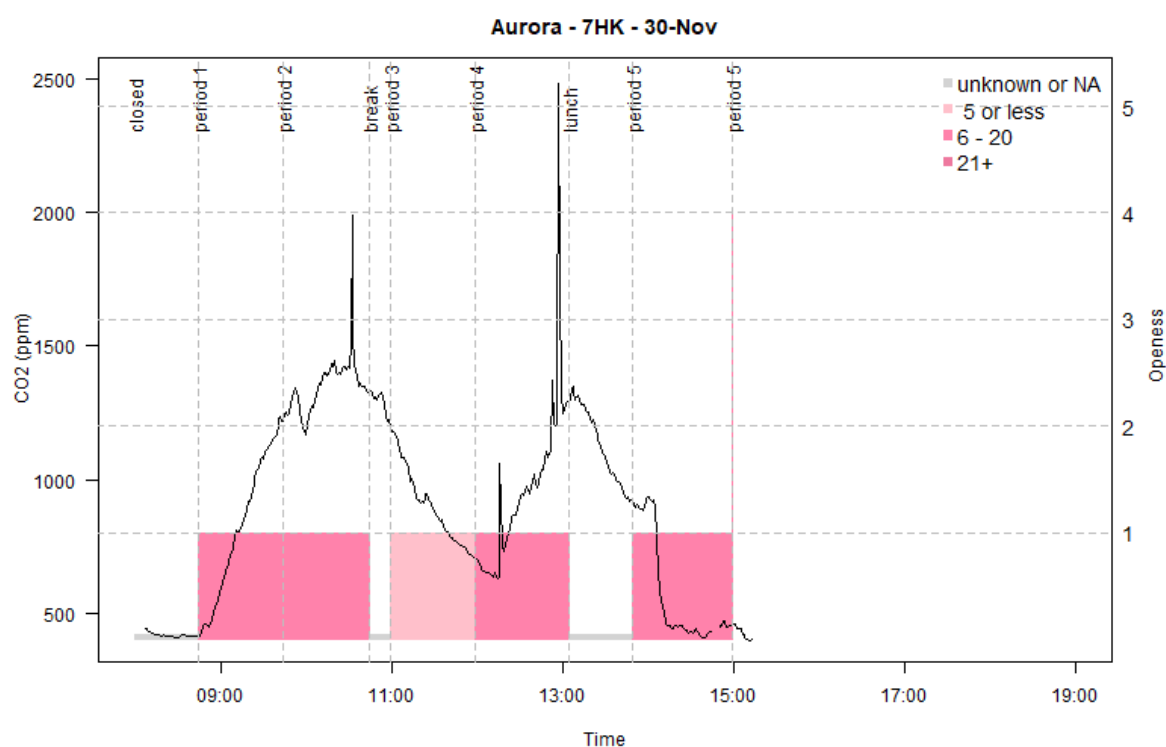
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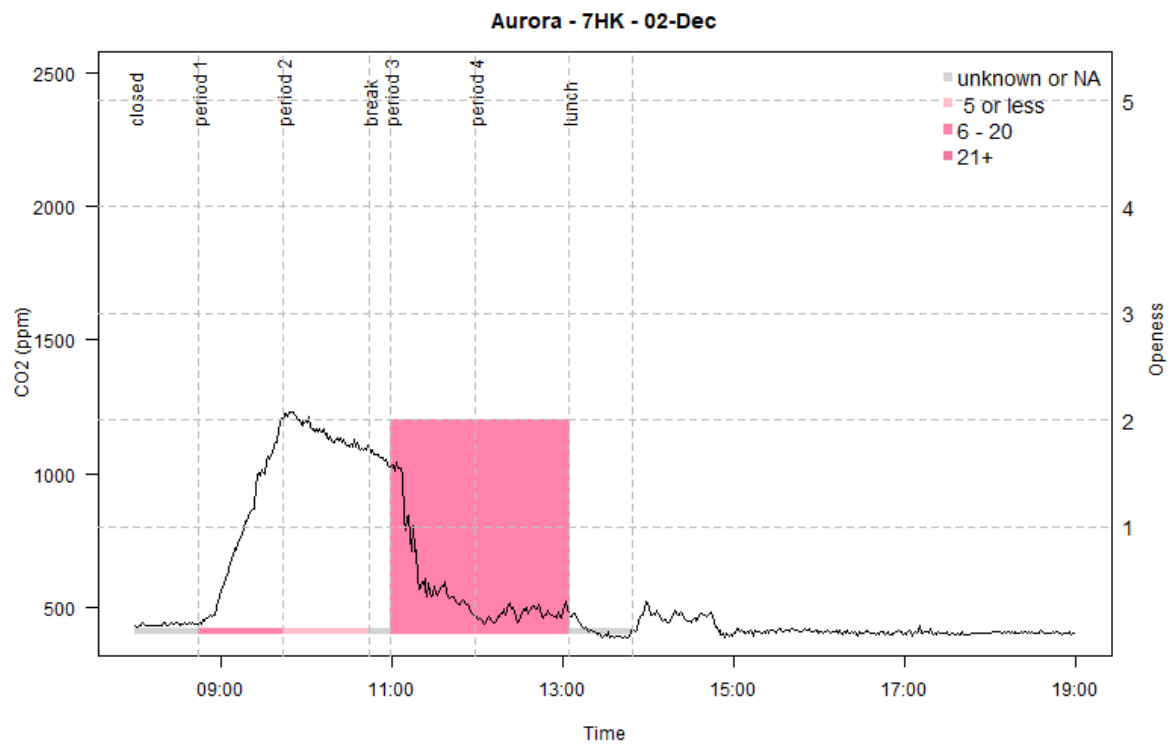
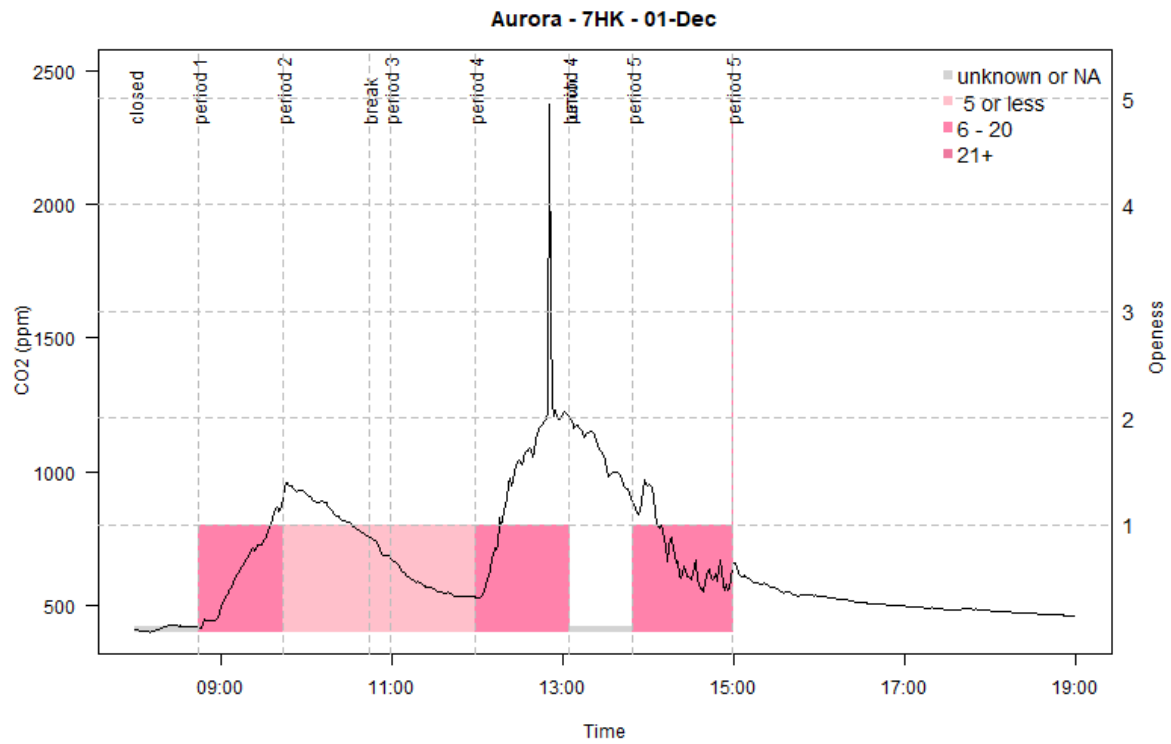
Appendix A Occupied classroom results

Data for each classroom for each day are shown in the figures in this appendix. The classroom name and date are shown at the top of each figure. The black line is the 1-minute average CO₂ (averaged over all Hau-Haus present in that room). The colour of each bar is the number of occupants in the room (if observed). The height of each bar is the subjective measure of openness provided by the observers (1 = all windows and doors closed, 5 = windows and doors opened to maximum degree).

Aurora College – 7HK

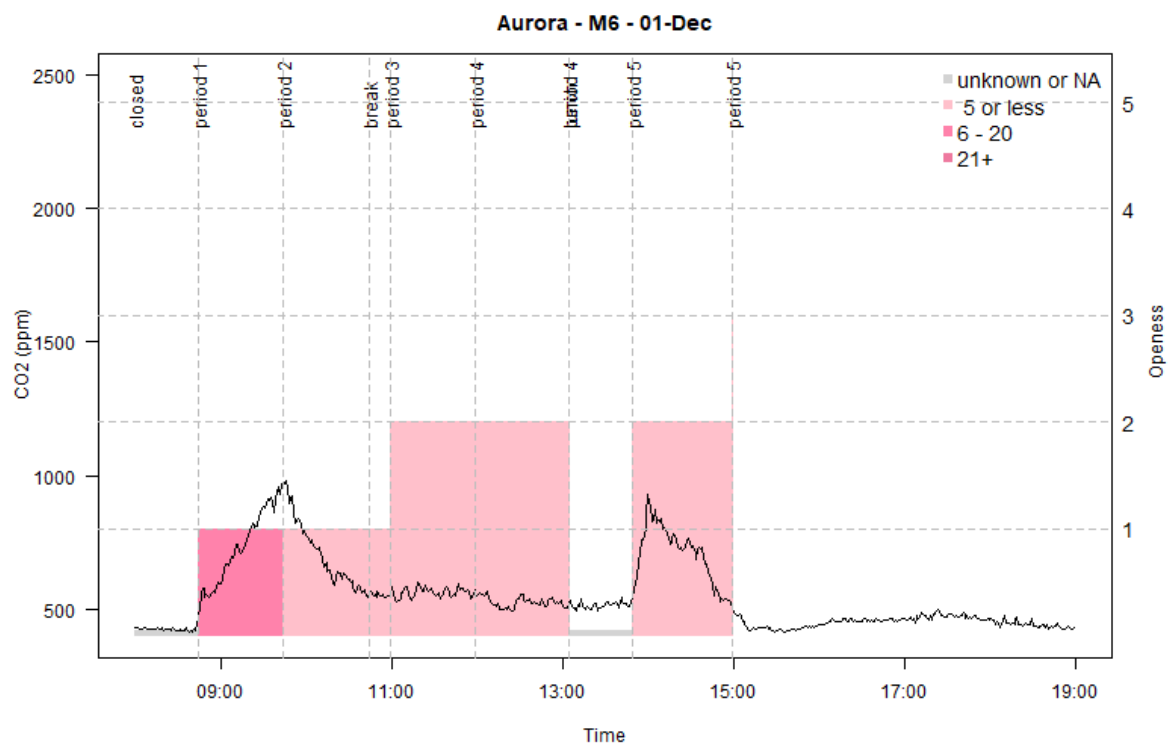
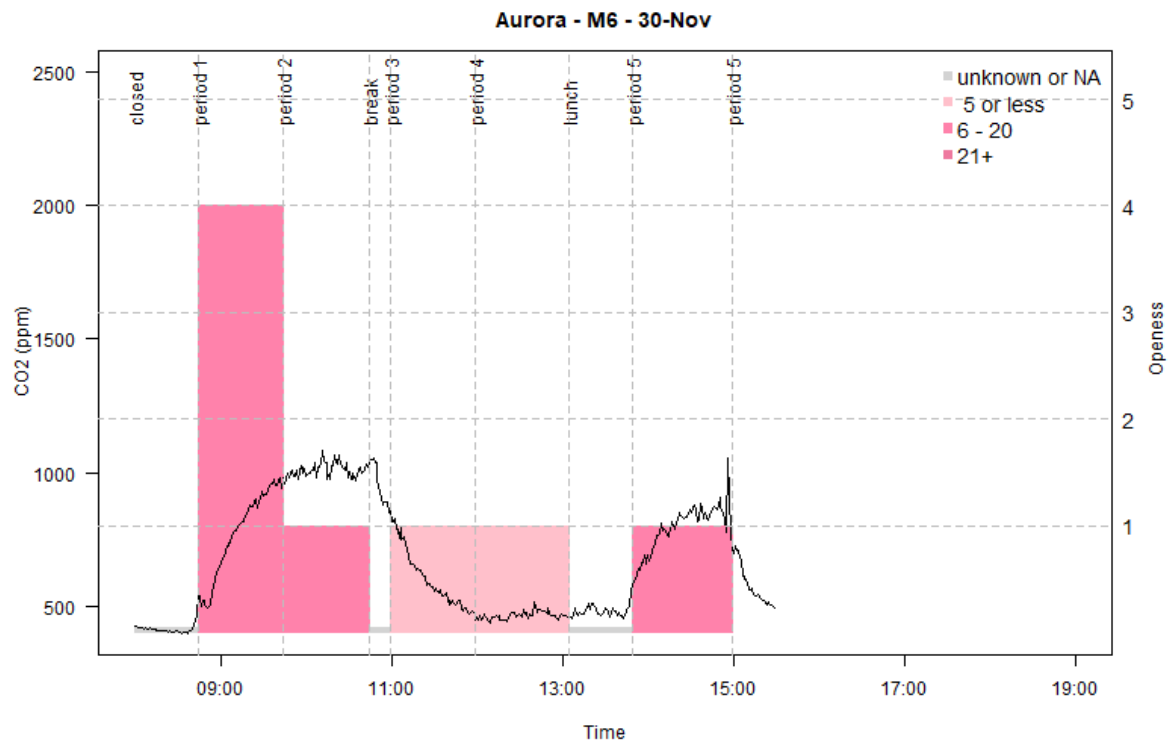
Ventilation rates appear to have been mainly low in this room, with CO₂ regularly exceeding 800 ppm. Our observers reported windows were kept mostly closed. Lack of inter-period flushing, and double periods also contributed to elevated CO₂ levels. However, strong flushing associated with high air change rates and dramatically reduced CO₂ levels were observed three times, corresponding with manual observations of windows being opened (not apparent in the measure of “openness”), indicating the potential for significantly improved ventilation in this room.

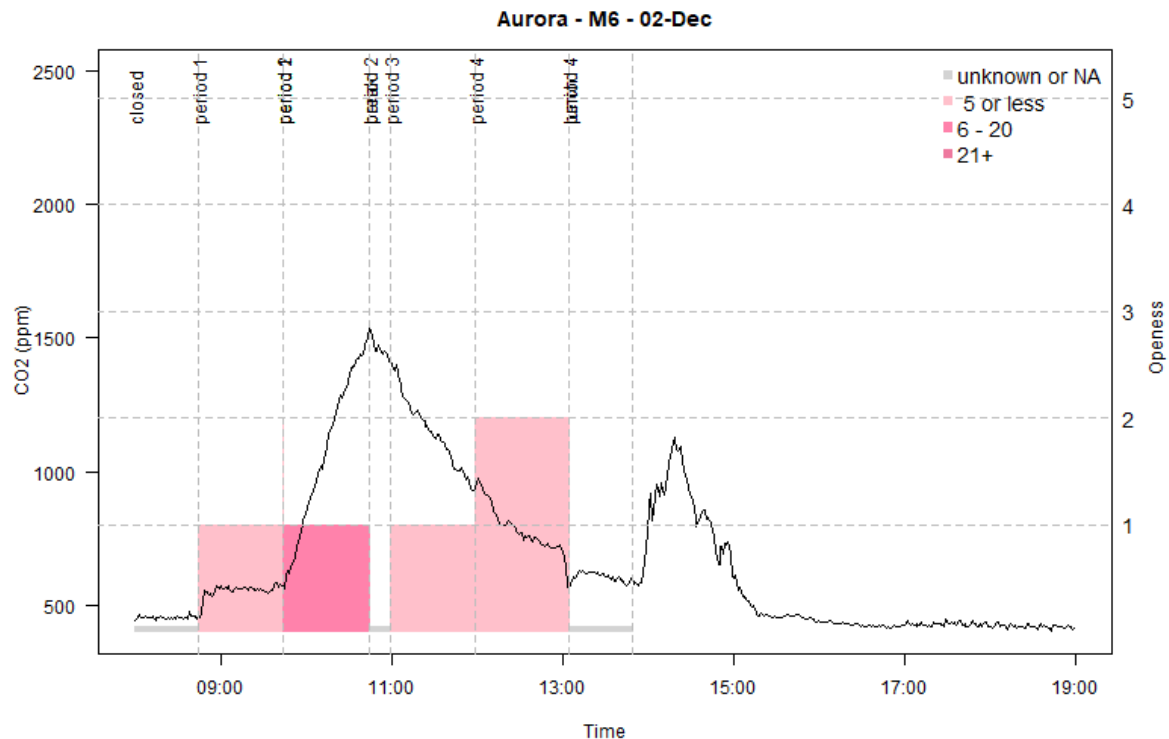




Aurora College – M6

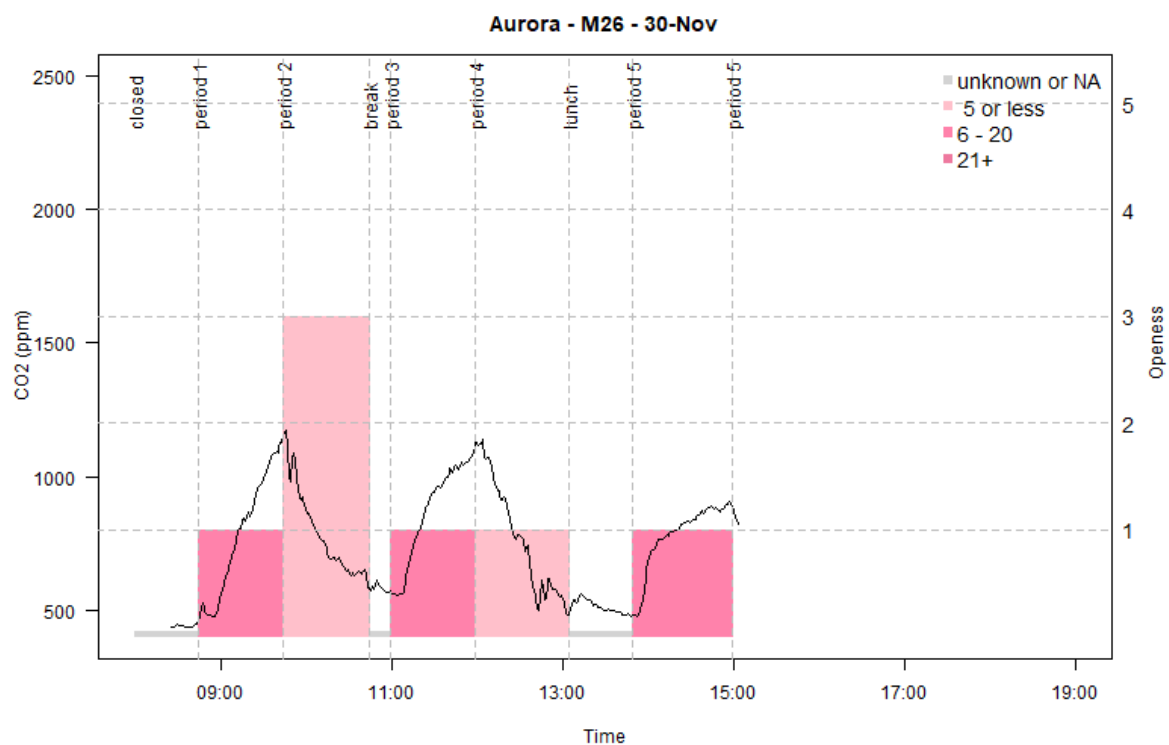
This room was moderately well-ventilated on Tuesday (30th Nov) but less so on the following days. Our observations note windows kept closed most of the time or opened only slightly.

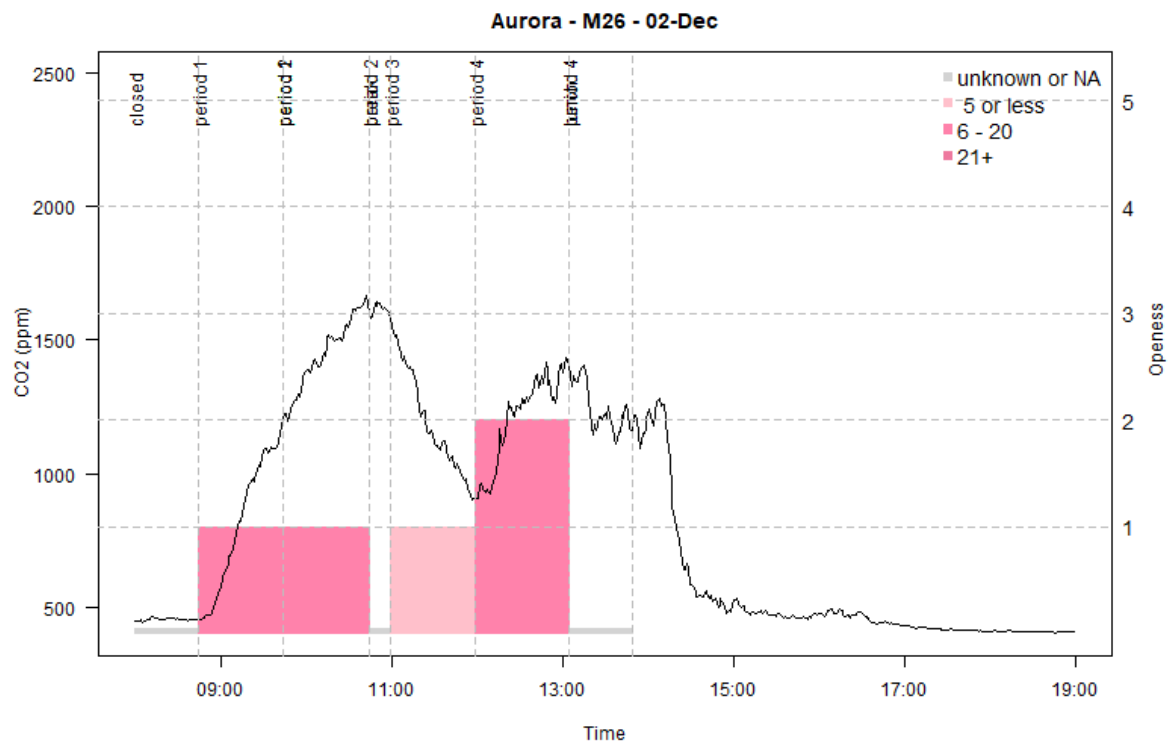
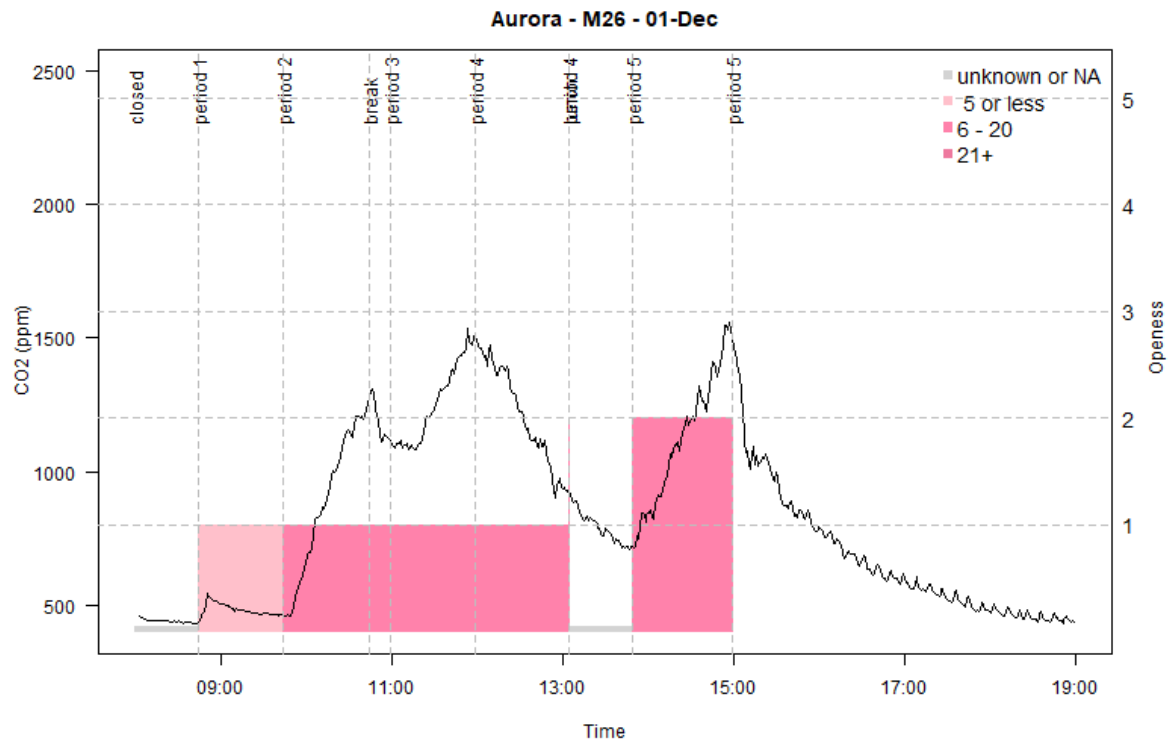




Aurora College – M26

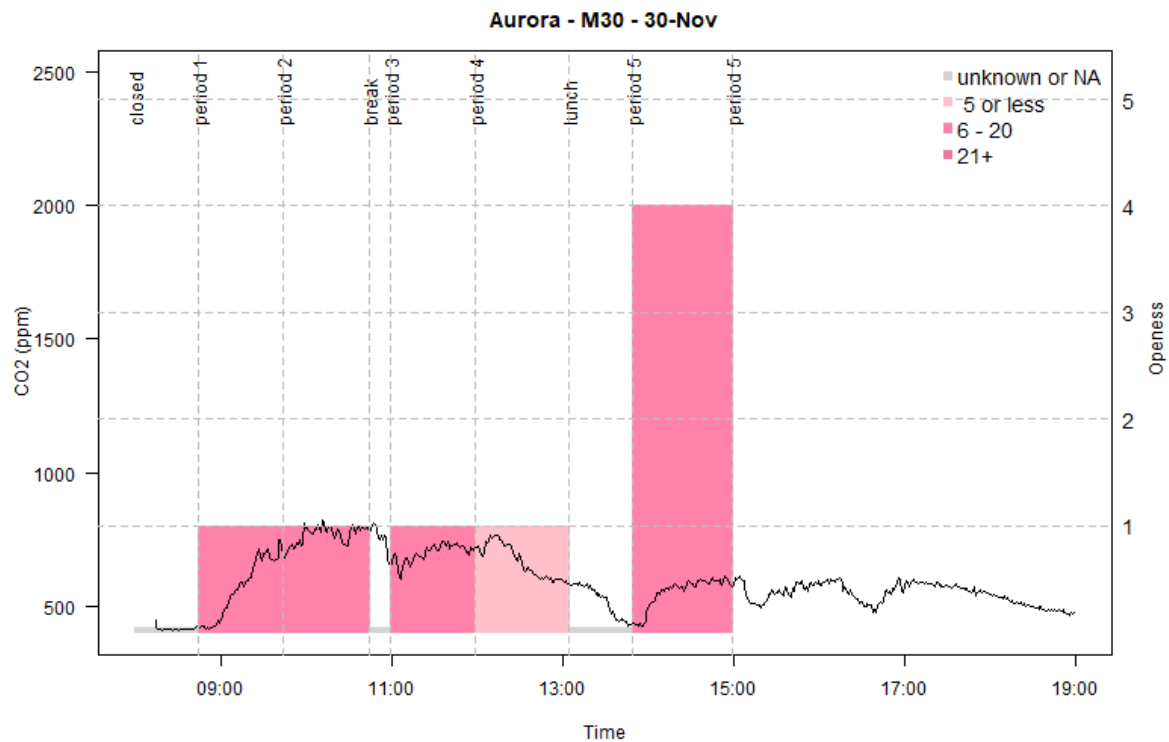
Ventilation rates were generally low to moderate, with CO₂ regularly exceeding 800 ppm. The situation was exacerbated by double periods and low air exchange between periods of occupancy leading to inter-period accumulation of stale air. Our observers did not see windows open at any time, although a door to a corridor was opened on occasion.



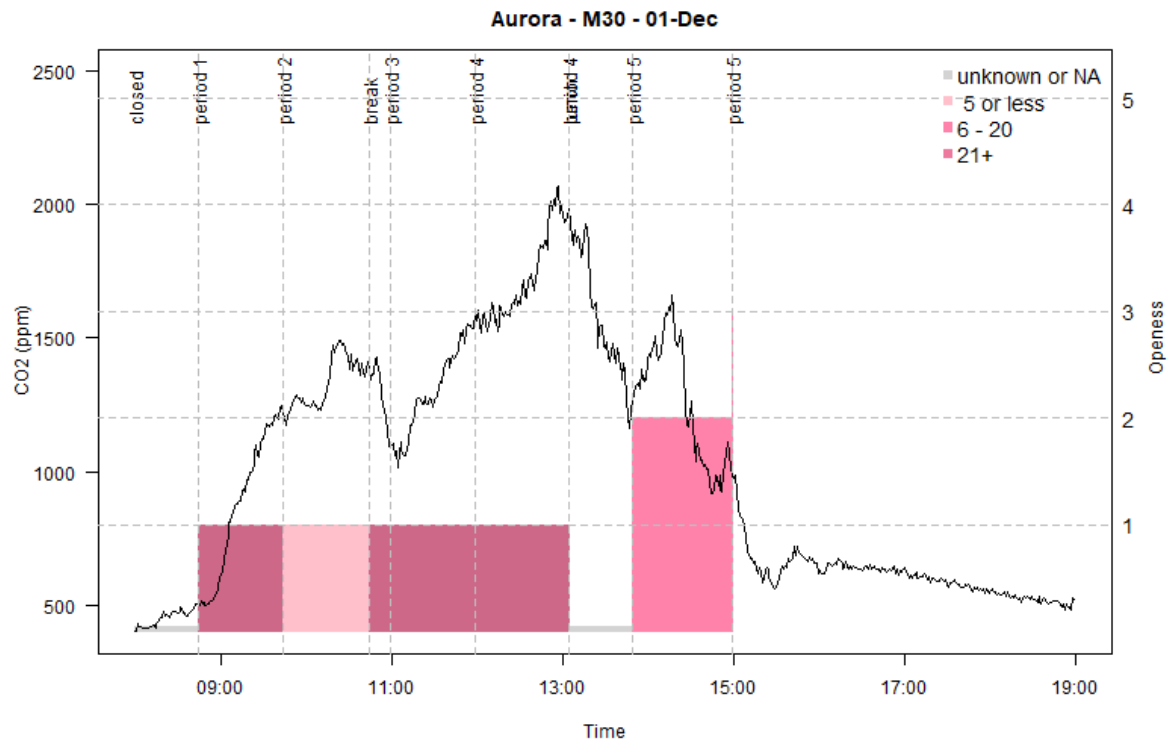


Aurora College – M30

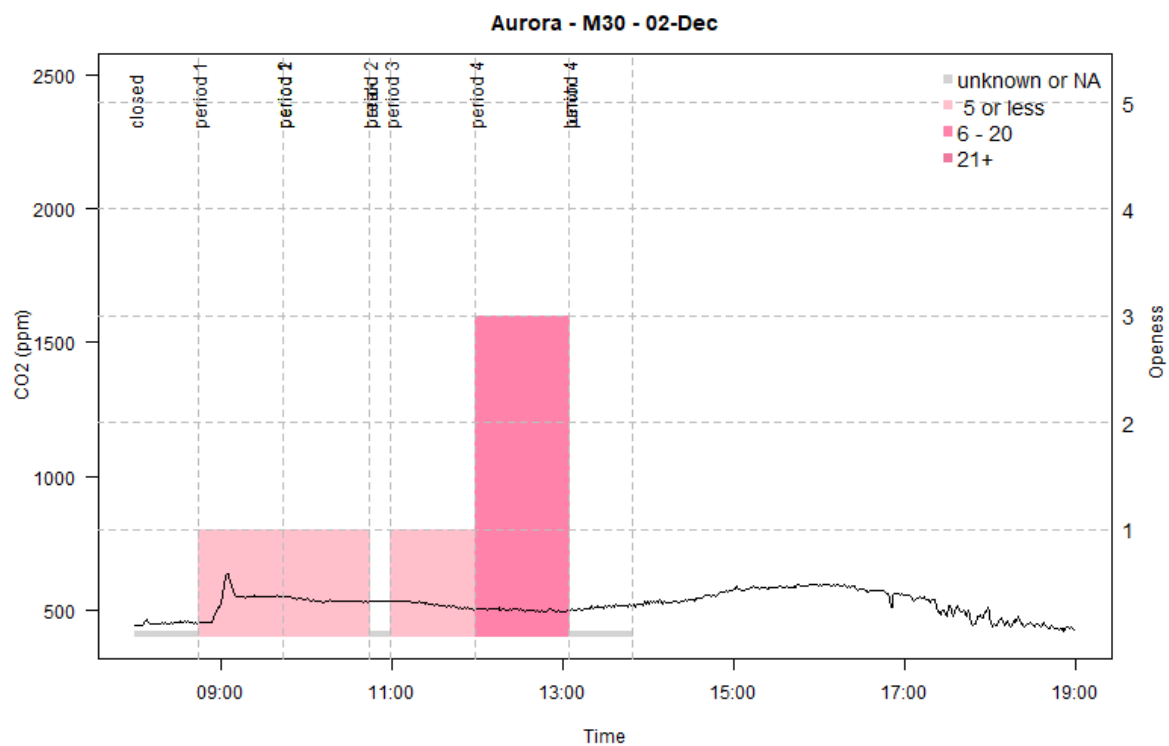
CO₂ levels varied substantially in this room. On Tuesday (30th Nov) CO₂ remained below 800 ppm in the morning, even with windows closed, although this may be helped by relatively low occupancy (12 people). Windows were opened in the afternoon reducing CO₂ levels further.



On Wednesday (1st Dec) occupancy was much higher and windows kept closed until the last period. Continuous occupancy drove CO₂ levels up to 2000 ppm. Although the room was unoccupied over lunch, the opportunity to effectively flush the room was not taken leading to elevated CO₂ at the start of the afternoon teaching period, alleviated first by opening of the corridor door, and later all windows.

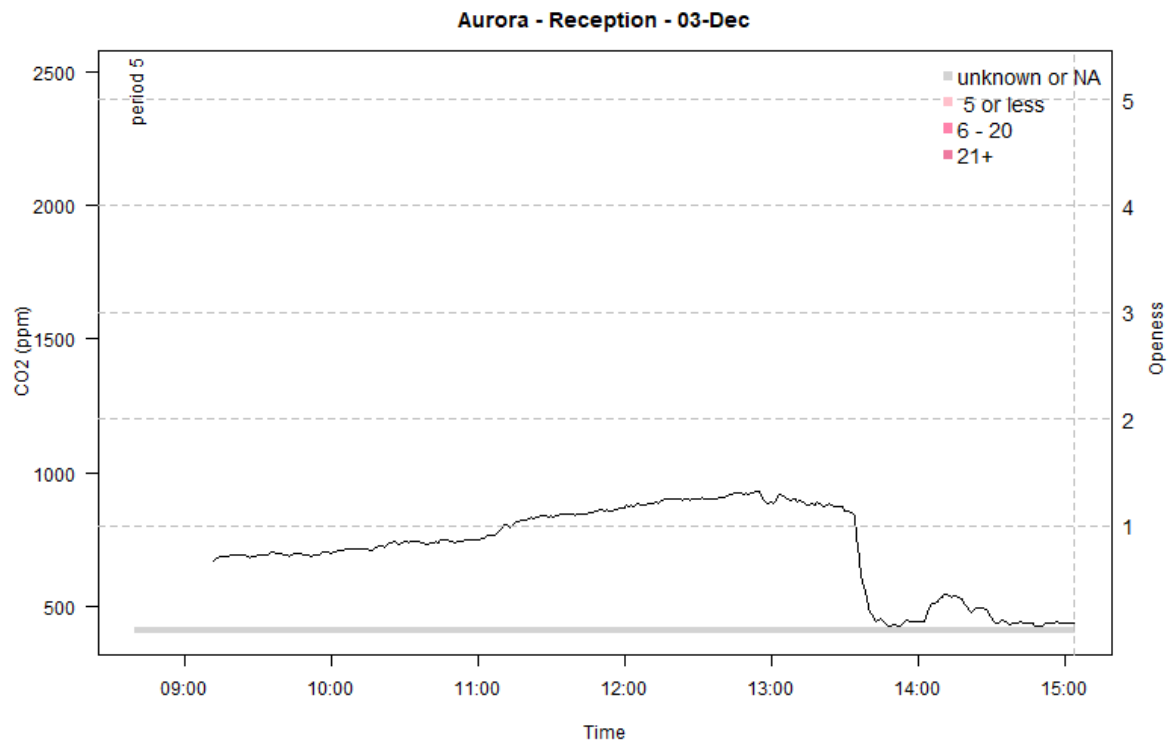


On Thursday, the occupancy rates were very low, and CO₂ also remained low.



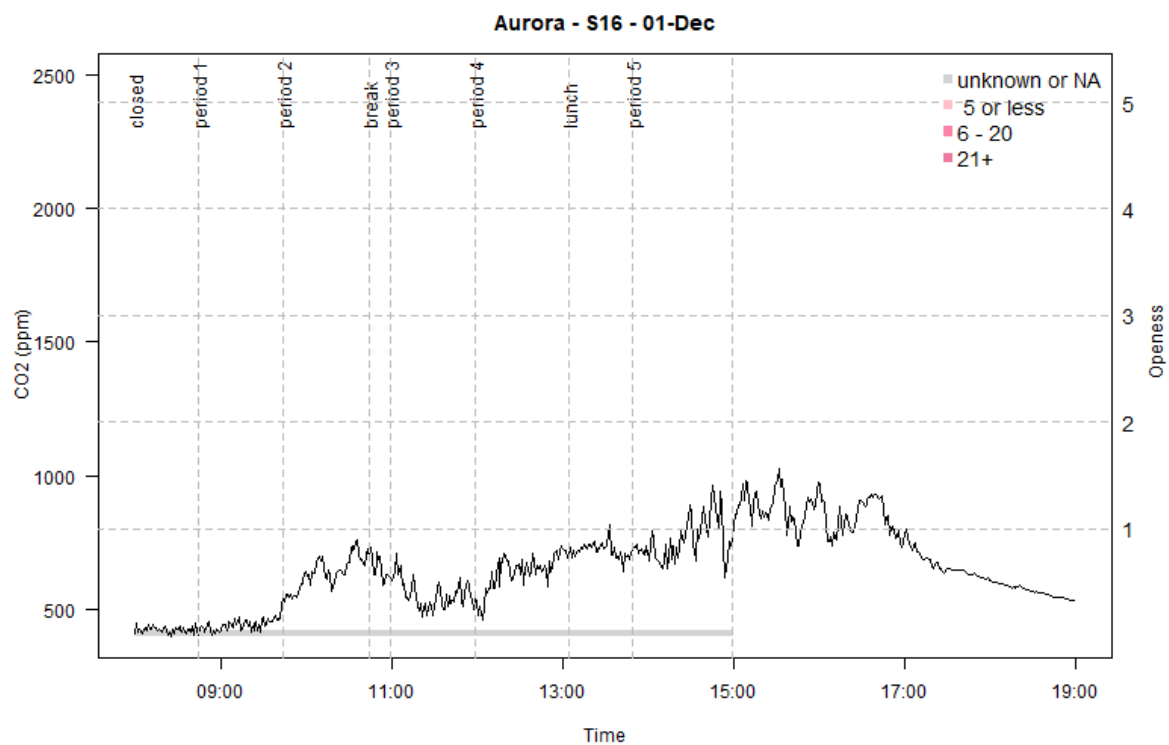
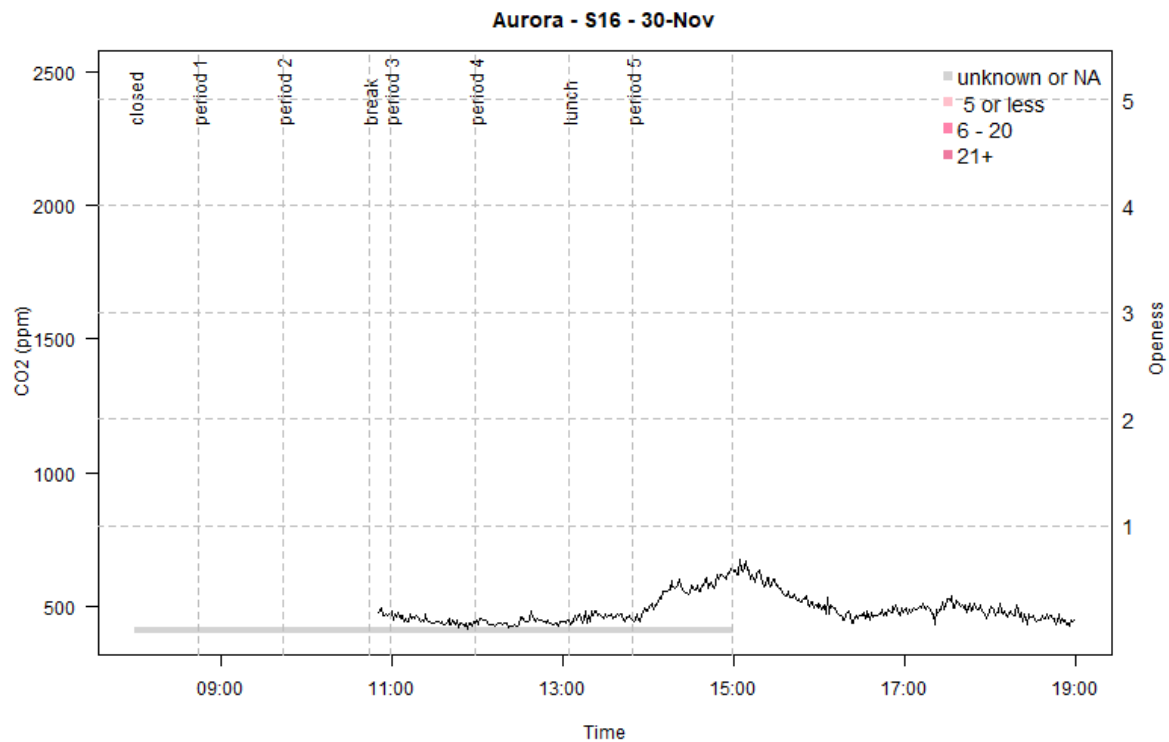
Aurora College – Reception

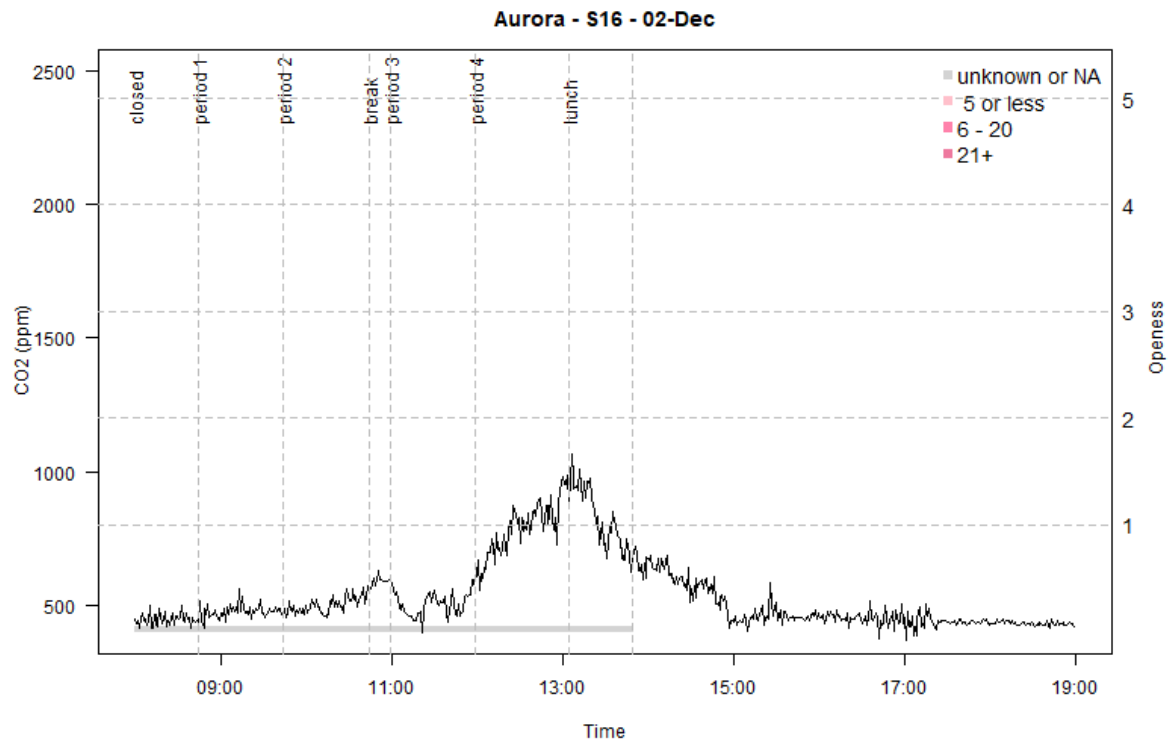
Occupancy and ventilation observations were not made for the reception area. We observed CO₂ levels slowly rising suggestive of low ventilation rates.



Aurora College – S16

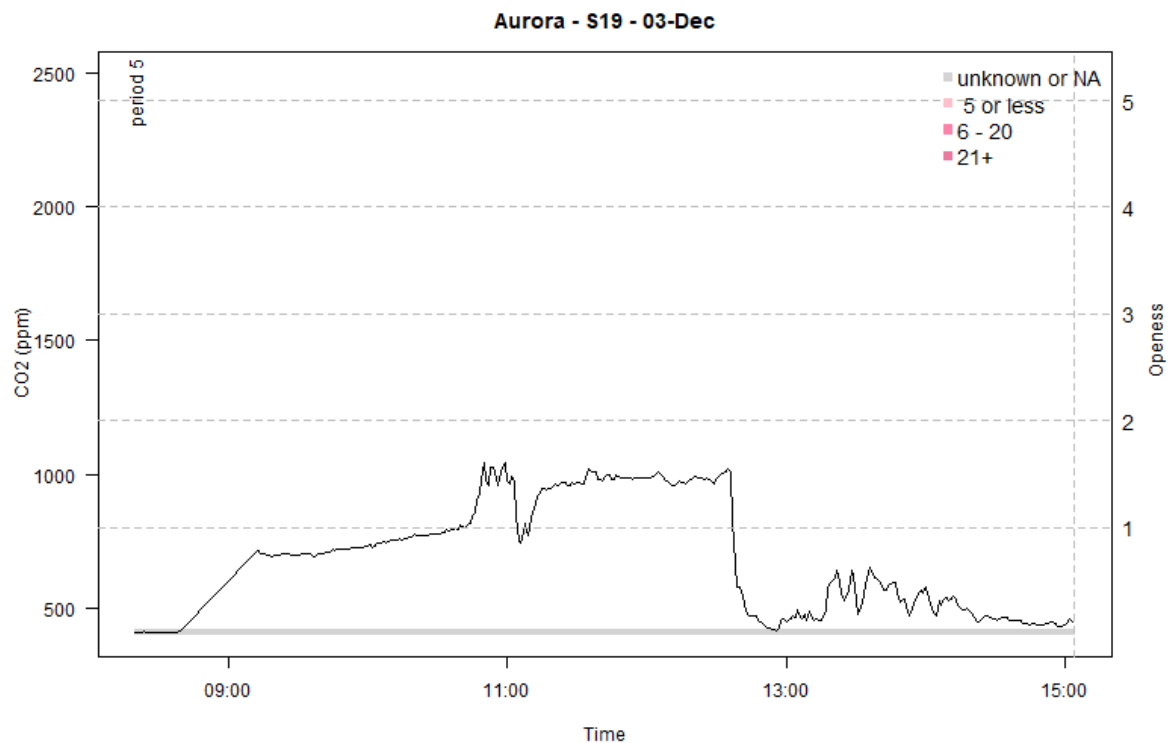
Concentrations remained consistently low (below 900 ppm) in this room, however manual observations were not made of this room, so the reasons cannot be established.





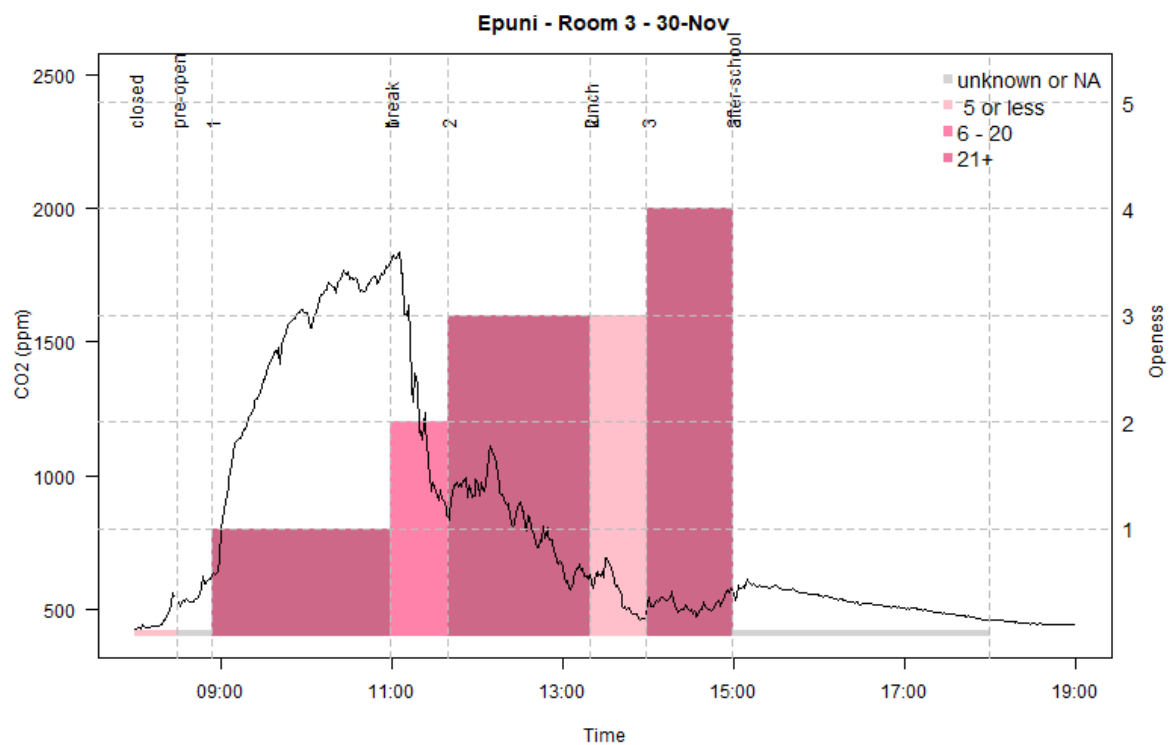
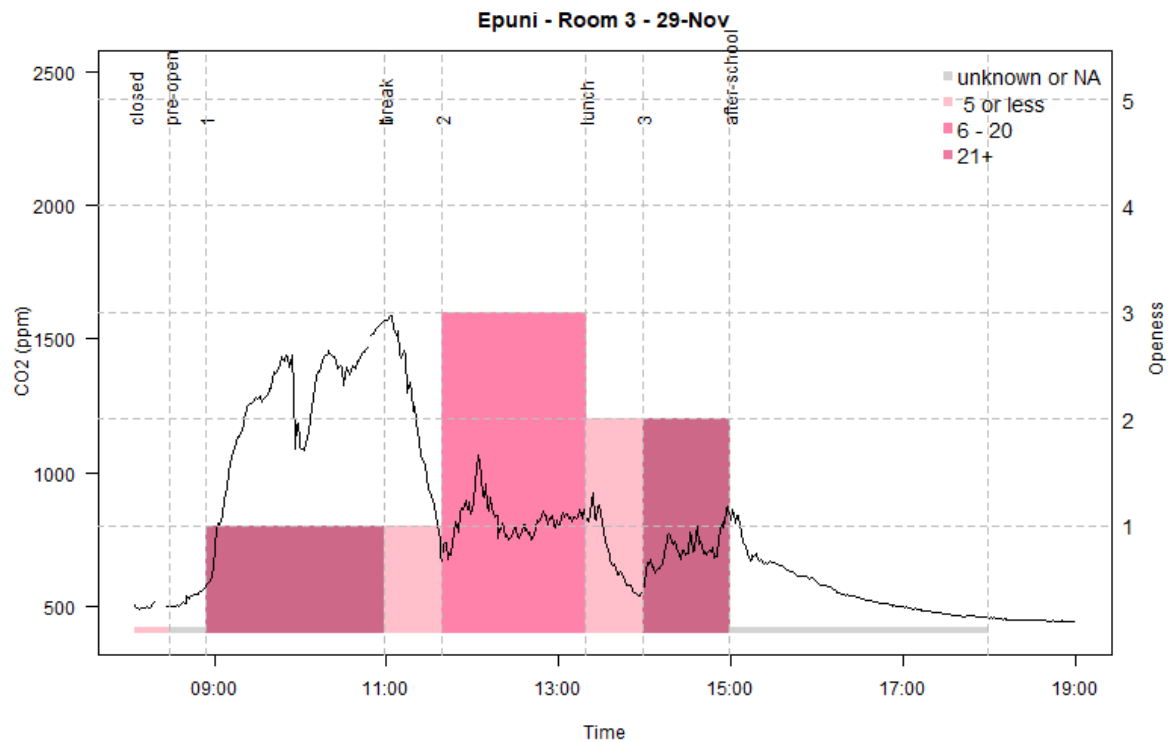
Aurora College – S19

CO₂ only was recorded in this room during the teacher-only day. The results suggest a high air exchange rate observed shortly before 1 pm (sudden drop in CO₂) indicating good ventilation capability.



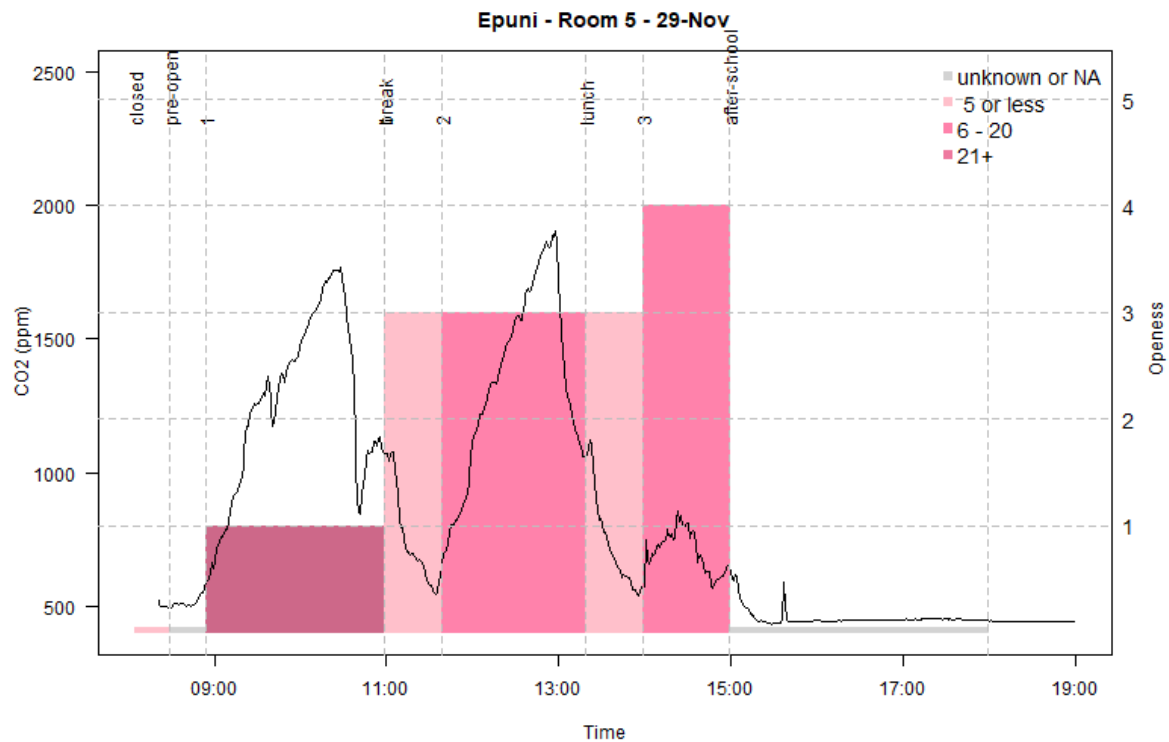
Epuni School – Room 3

This primary school classroom generally had windows closed in the morning up until 11 am to noon, when they were opened.

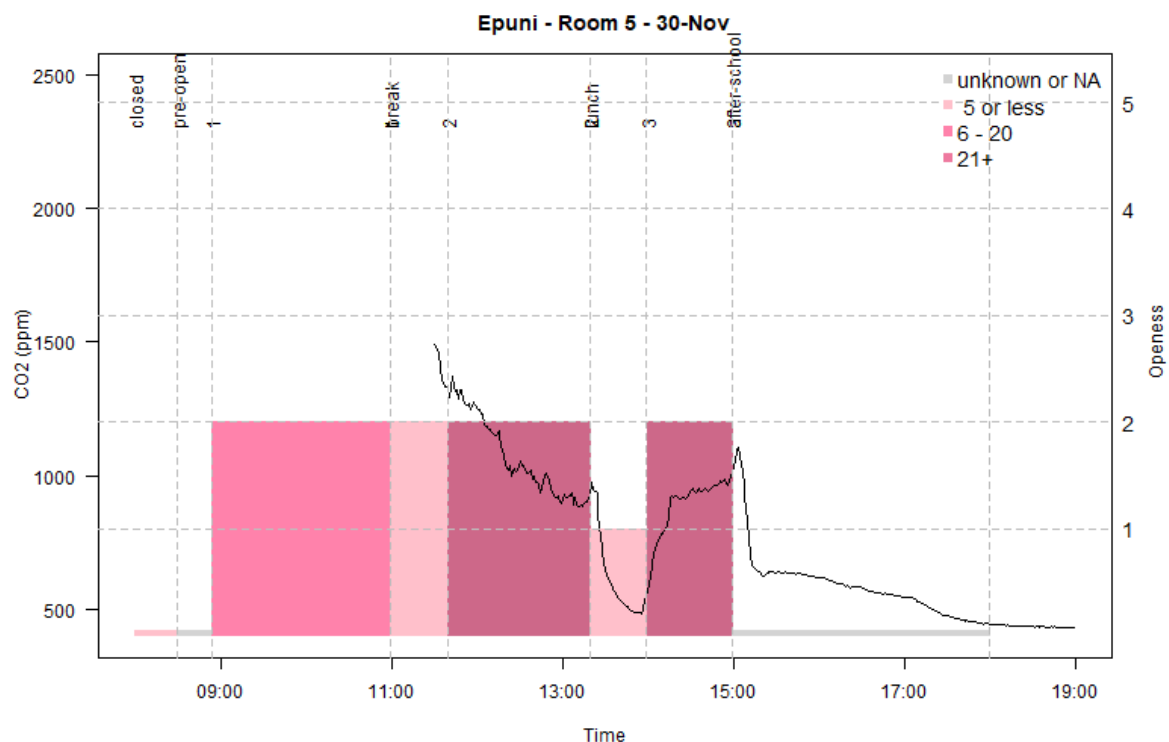


Epuni School – Room 5

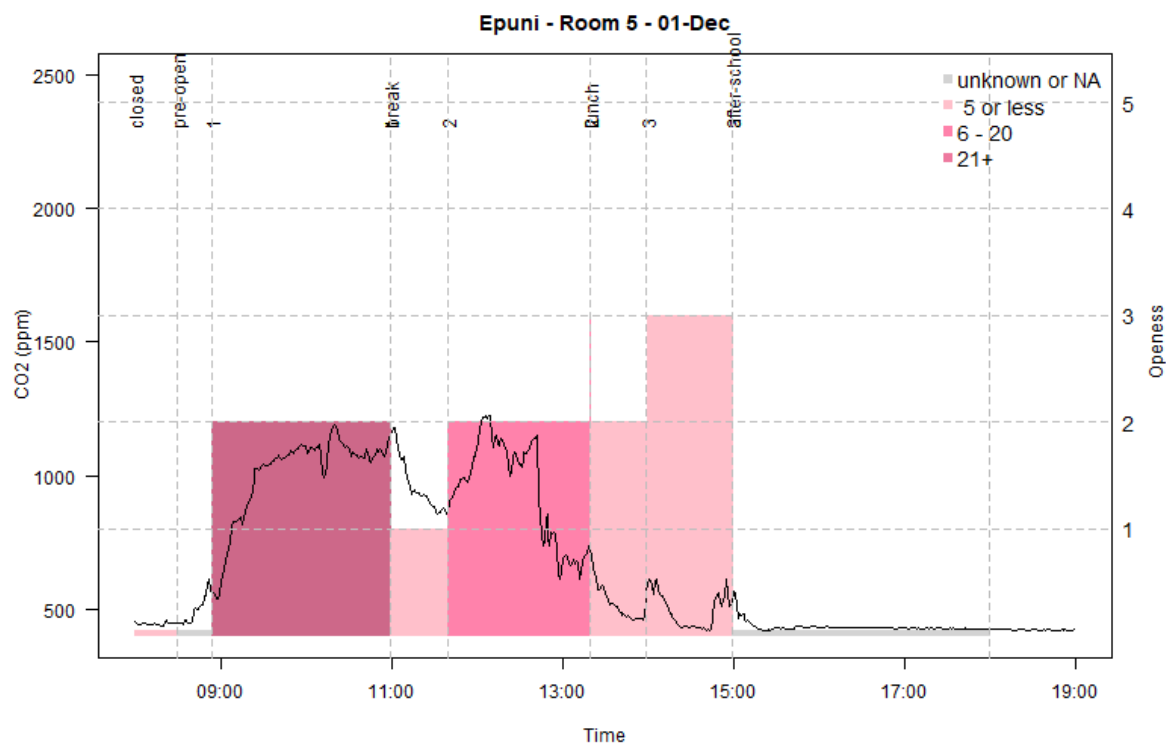
CO₂ levels were quite variable in this classroom, as was ventilation practice. Monday (29th Nov) provides the worst-case with high CO₂ corresponding to windows being shut with the door to the corridor opened from period 2.



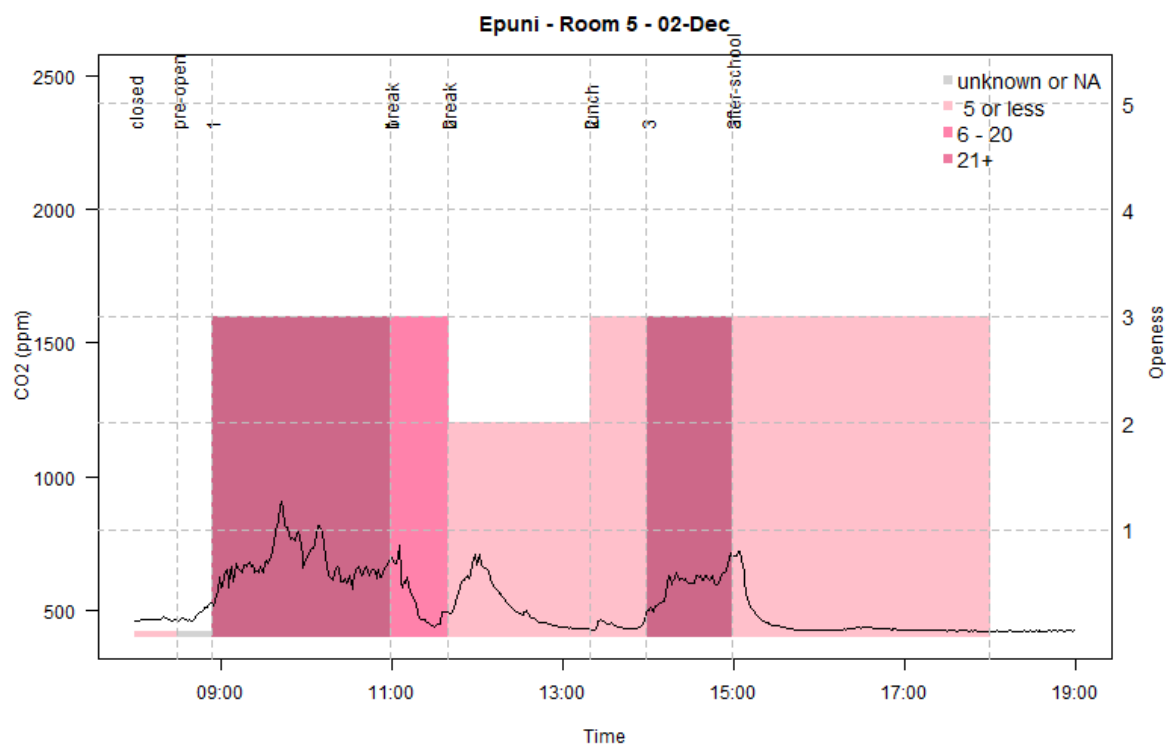
On Tuesday (30th Nov) CO₂ followed a similar pattern with the door to the corridor opened in period 2 but windows remaining closed all day.



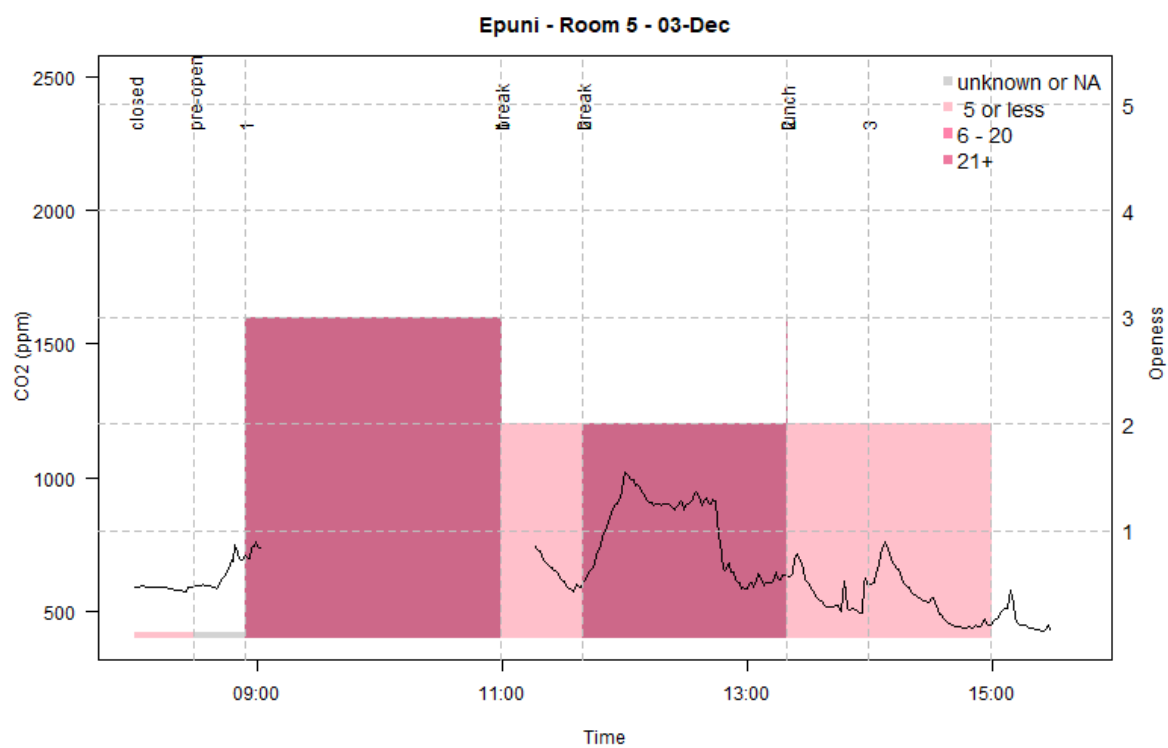
Wednesday (1st Dec) saw similar ventilation practice in the morning, and windows opened from around 1pm, corresponding to lower CO₂ in the afternoon.



On Thursday (2nd Dec) CO₂ levels were much lower all day. Our observers reported crossflow with two doors on opposite sides of the room open.

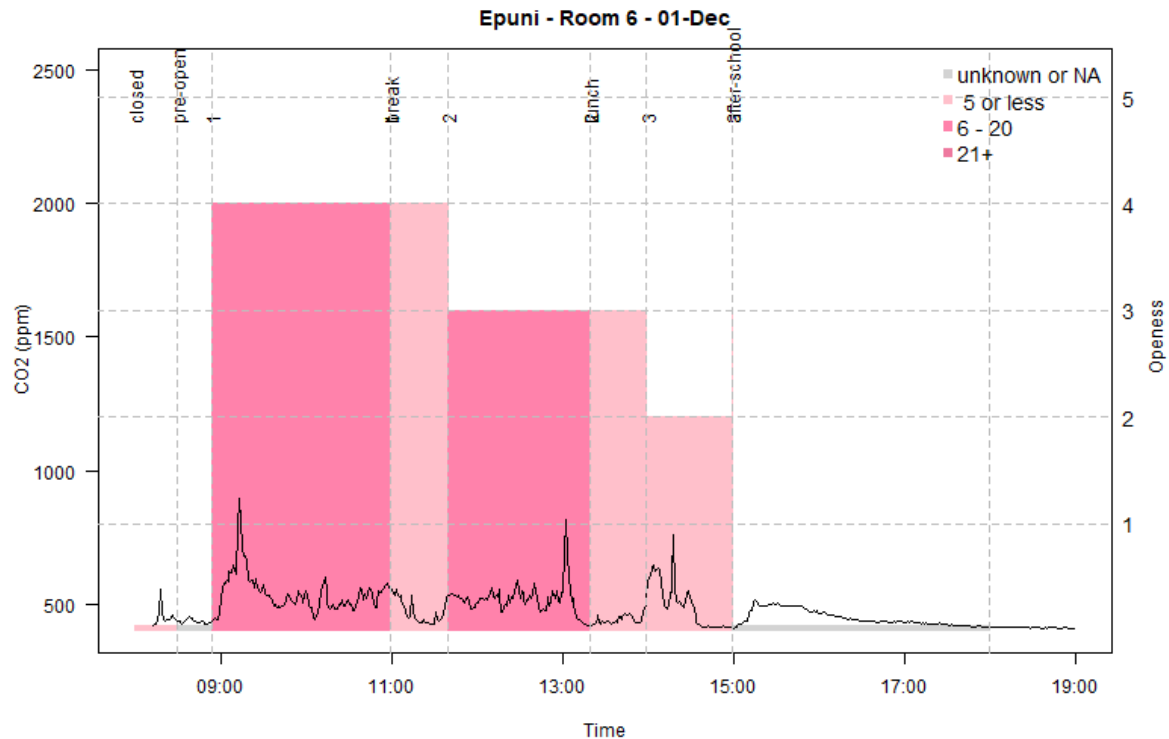


On Friday (3rd Dec) ventilation consisted mainly of the internal corridor door being open (as Tuesday and Wednesday) which seems to have been sufficient to suppress CO₂ levels most of the time.

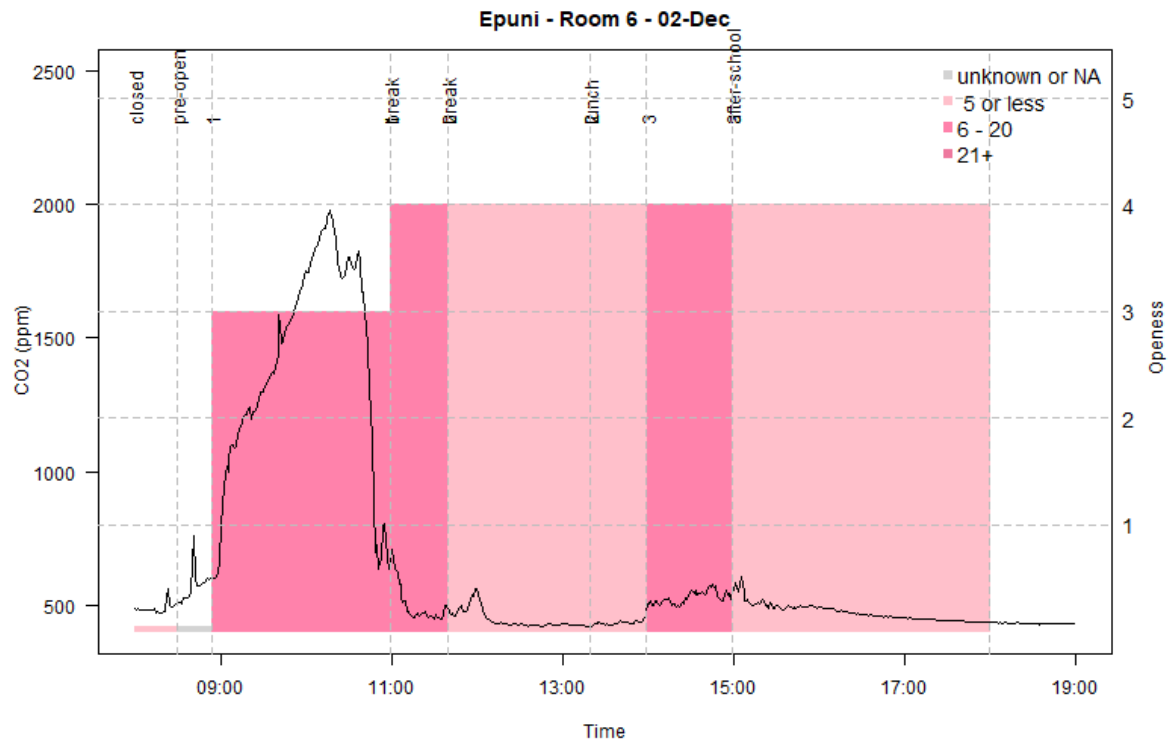


Epuni School – Room 6

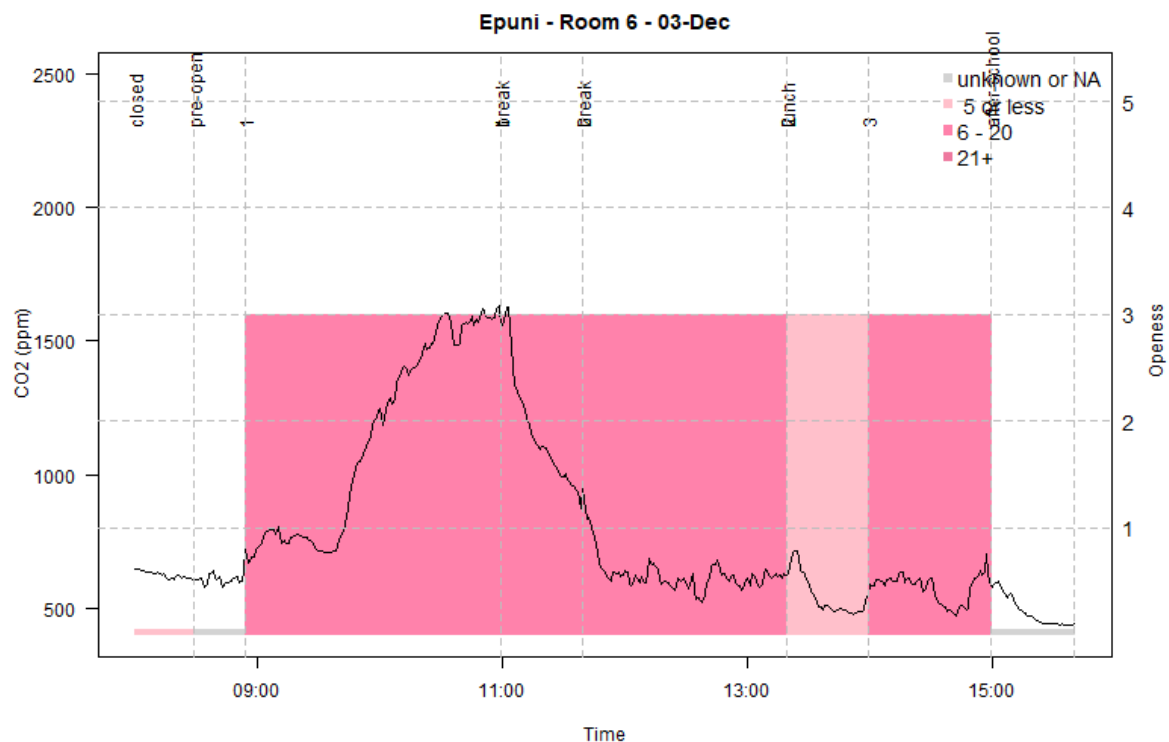
CO₂ levels in this room were quite variable, and its usage was quite complicated. The room had two external doors and one internal door, all of which were frequently open with children regularly entering and leaving. On Wednesday (1st Dec) CO₂ levels stayed low throughout the day indicating good ventilation.



The morning of Thursday (2nd Dec) saw a big change with high CO₂ levels reaching 200 ppm in period 1. Our observations note that all three doors were open all day but also high levels of activity in period 1. The room was mostly empty during period 2.

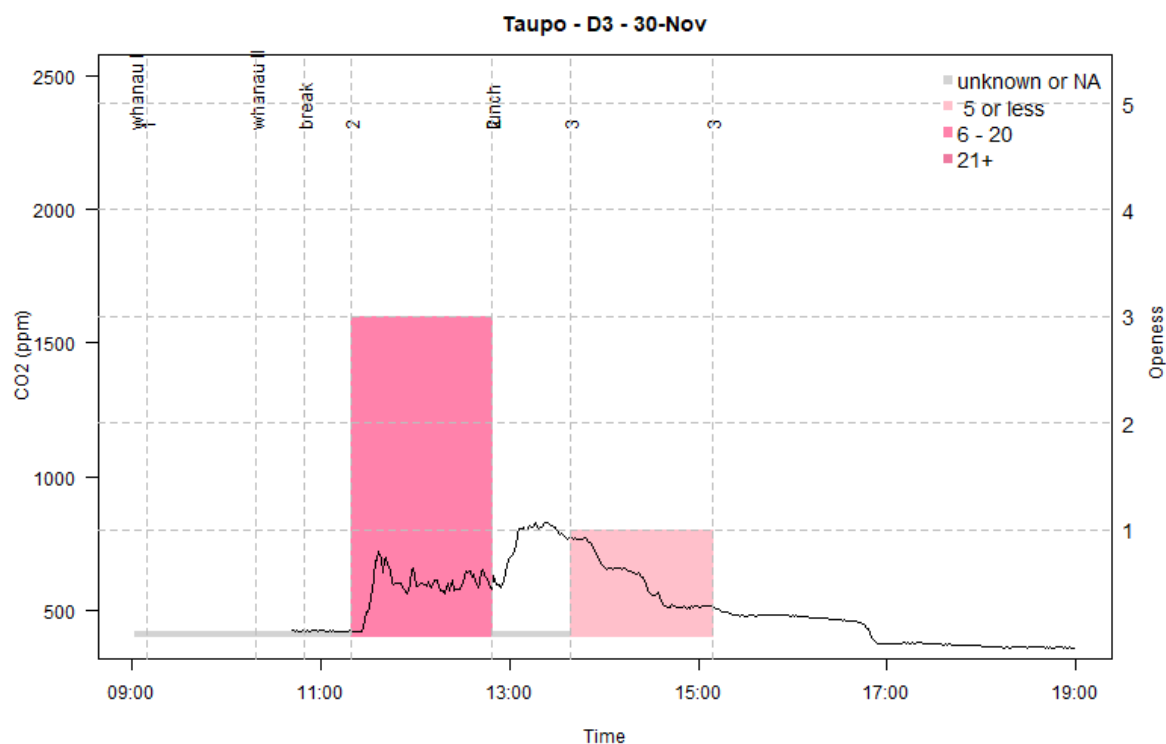


CO₂ levels on Friday (3rd Dec) were also high in period 1 but much lower for the rest of the day. Our records again show all three doors open all day and near continuous occupancy, making these results tricky to interpret. We can only assume the big variation in CO₂ during the day was due to unobserved variables (wind speed, unrecorded window openings, or details in student activity).

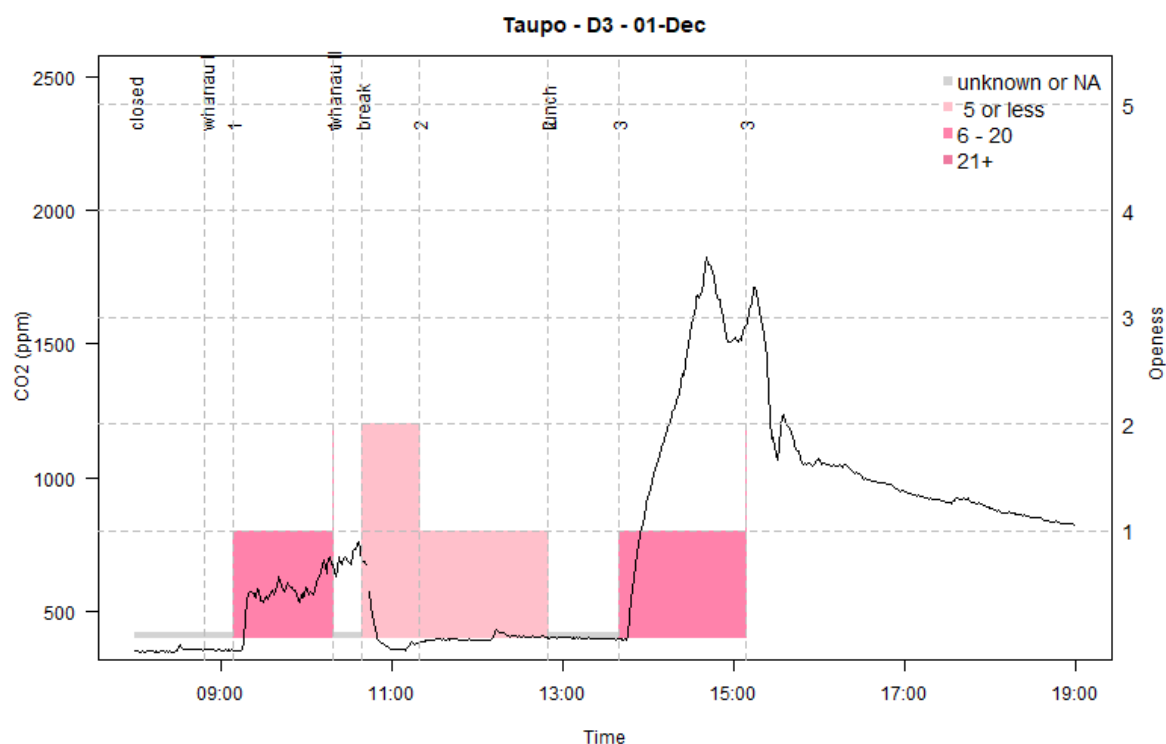


Taupo College – D3

CO₂ stayed below 800 ppm in Taupo College room D3, except during period 3 on Wednesday (1st Dec). Our records show that a sliding door and several windows were open most of the time that the room was occupied, presumably creating a crossflow.

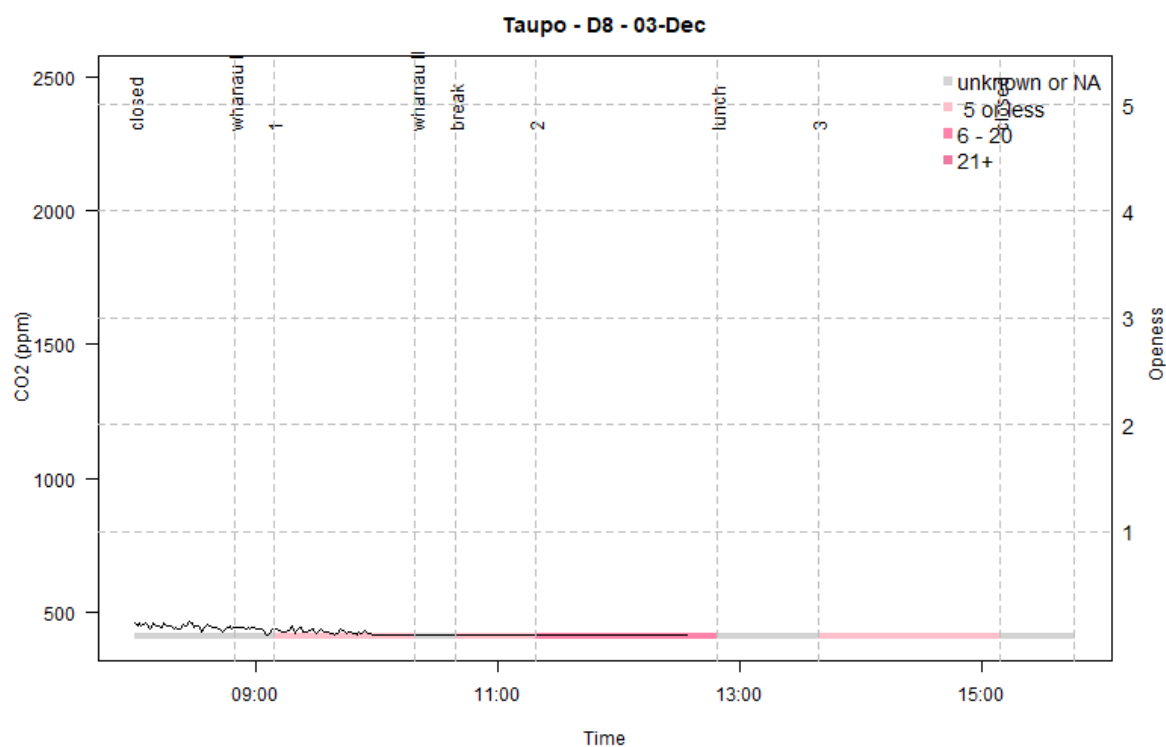
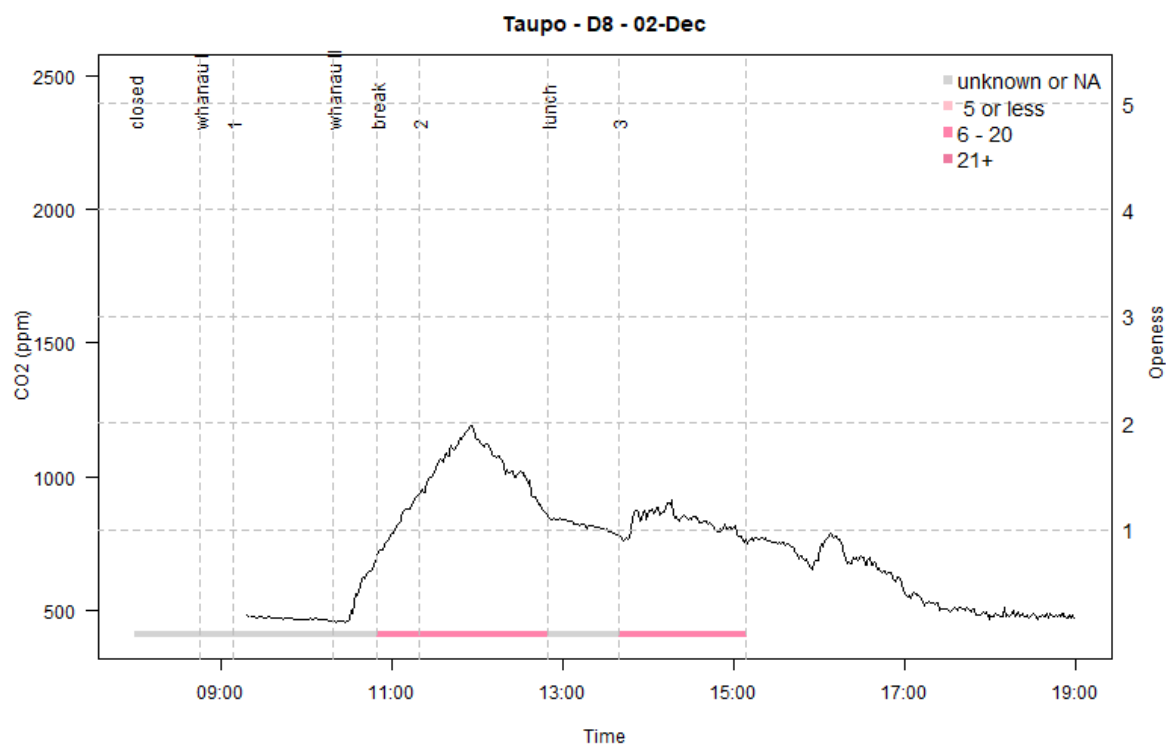


During period 3 on Wednesday all doors and windows were closed for the first 40 minutes, after which a window was opened arresting the rise of CO₂.



Taupo College – D8

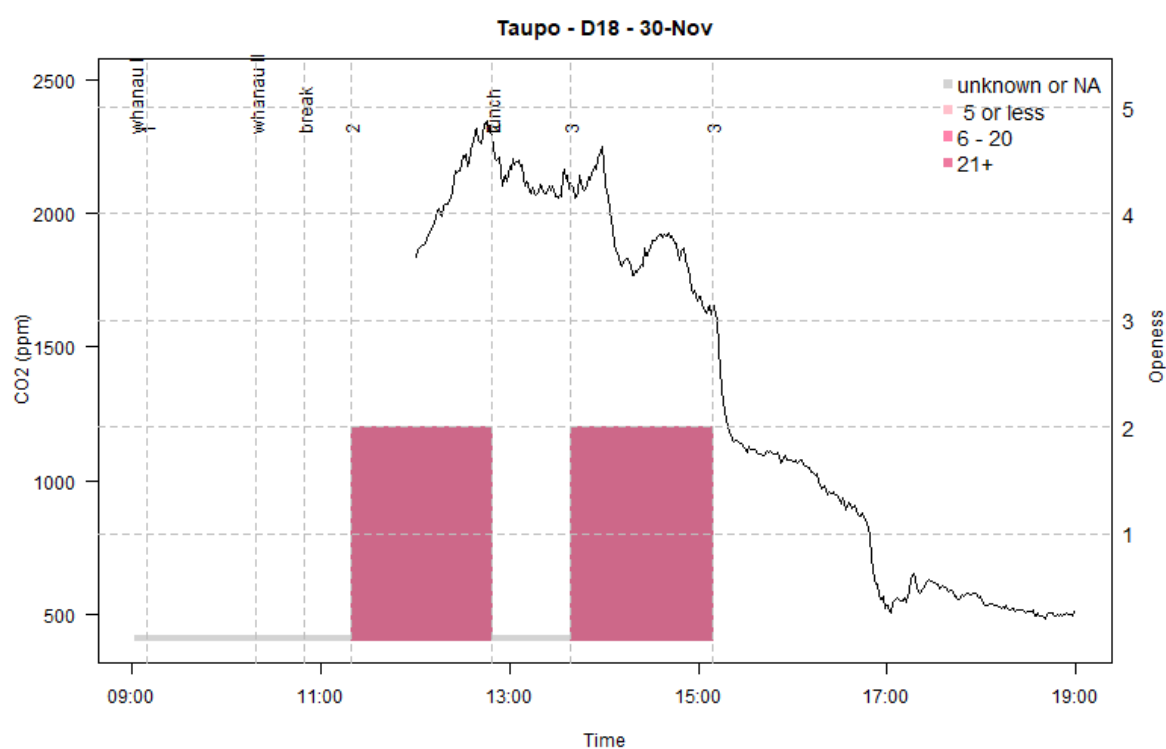
Only a single day of observations are available for room D8, during a teacher-only day. Occupancy was 9 – 14 people. CO₂ slightly exceeded 800 ppm and the slow rise also indicates a low air change rate. Doors and windows were observed to be closed.

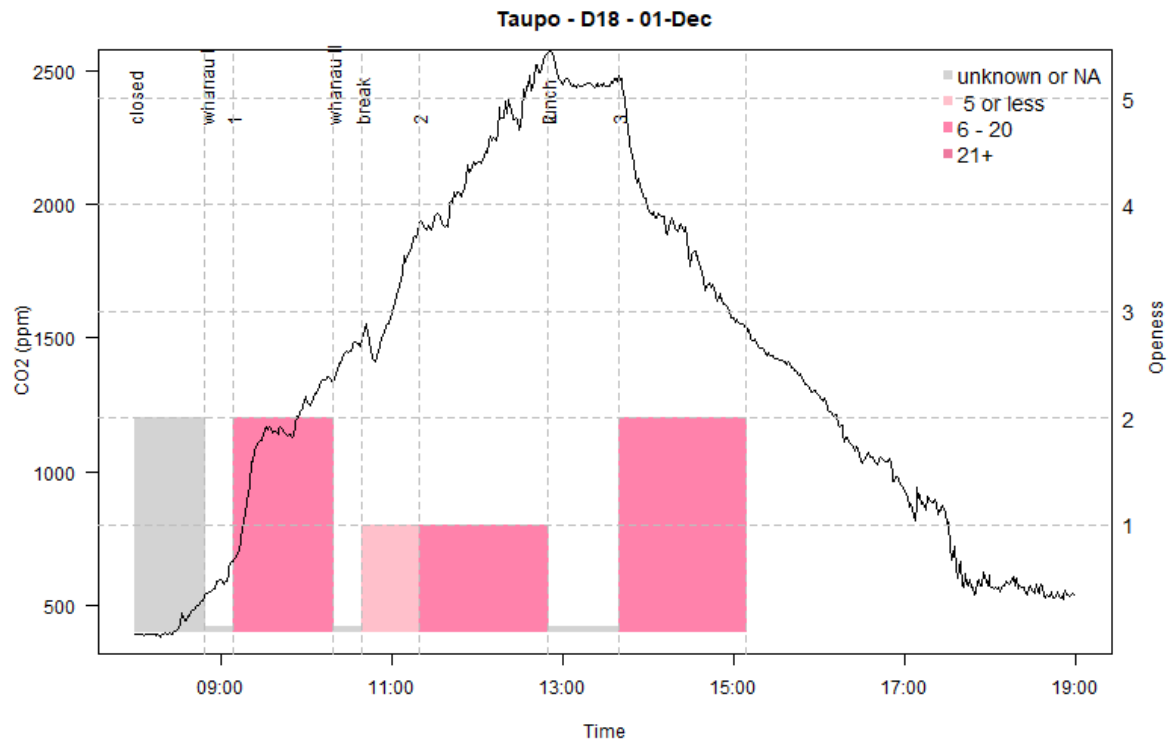


Taupo College – D18

Taupo College D18 was the worst performing room in the study. Although only observed for 1.5 days, on both days CO₂ was observed to rise to ~2400 ppm by lunchtime, before slowly falling from the start of afternoon classes. Low air exchange meant that CO₂ remained elevated until 5pm on Tuesday and 6pm on Wednesday. Our manual observation records show that this was an art room and was occupied during every teaching period over these two days, and moderately high activity levels. It was on the first floor, but **the windows were reportedly never opened due to traffic noise**. Although our observations are made only periodically, they do show that the door to the room was mostly closed in the morning and open in the afternoon, which is probably why CO₂ was observed to fall in the afternoon.

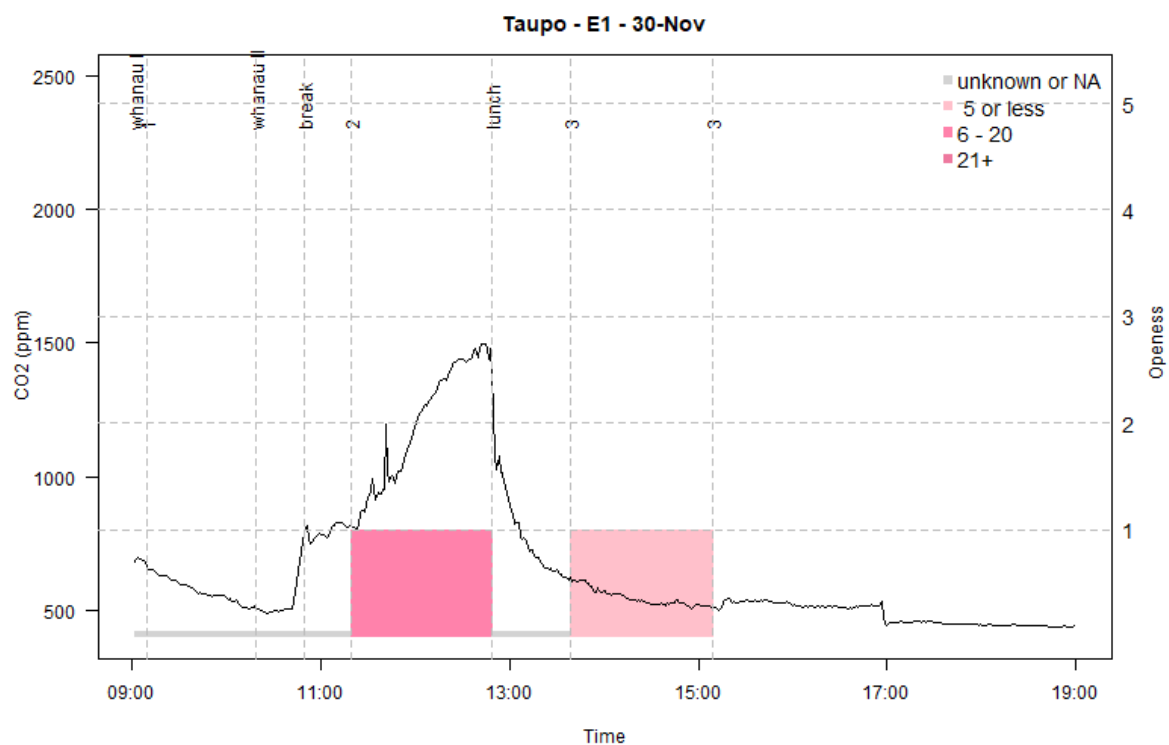
If the opening of windows is not considered acceptable for this room, to improve indoor air quality this room could benefit from keeping the door open all day. If that is not effective, other measures could be investigated (additional ventilation, break-time purges).

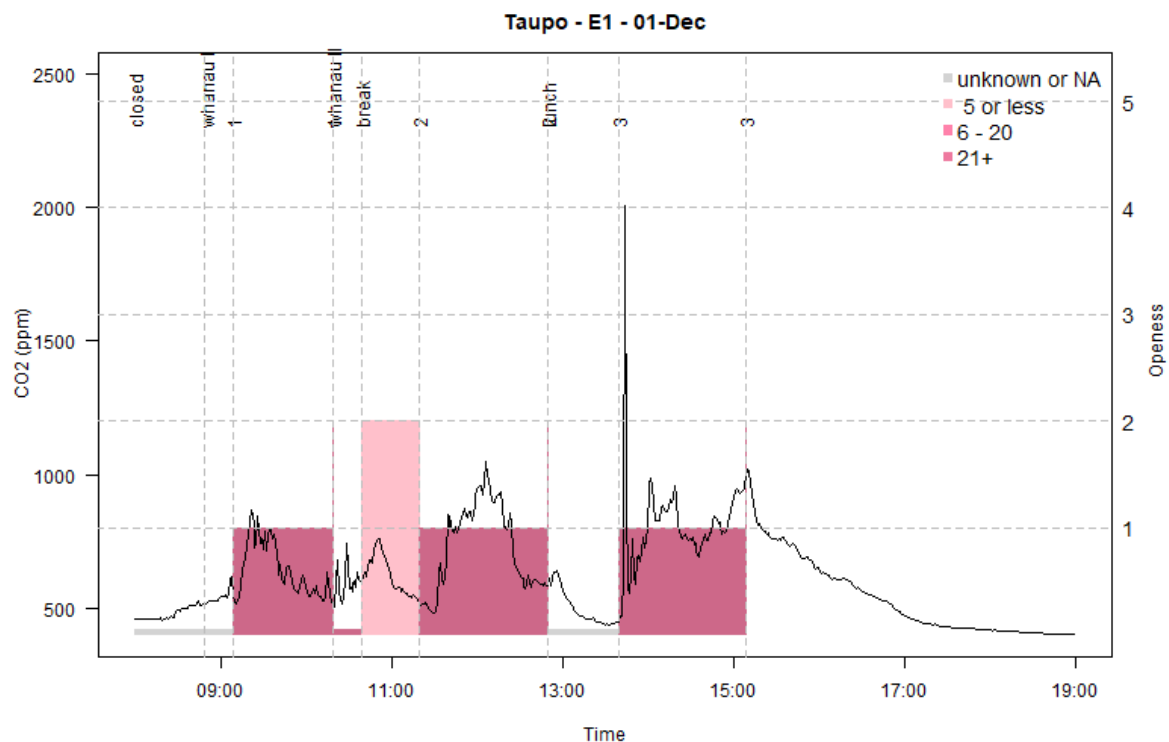




Taupo College – E1

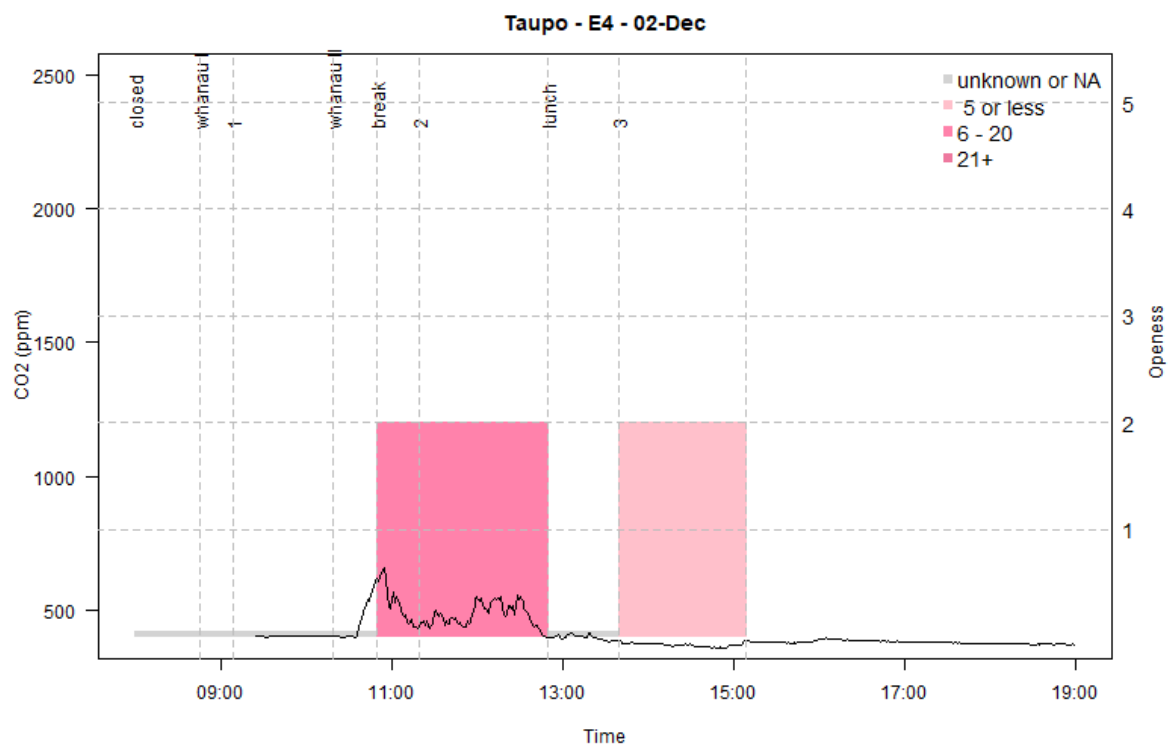
CO₂ was quite variable in this room. The windows were not observed to be open at any time during our study. The room appears to mainly have been ventilated using sliding doors which open to a hallway, presumably expanding the dilution volume. Several sudden changes in CO₂ suggest high air change rates can be achieved in this room.

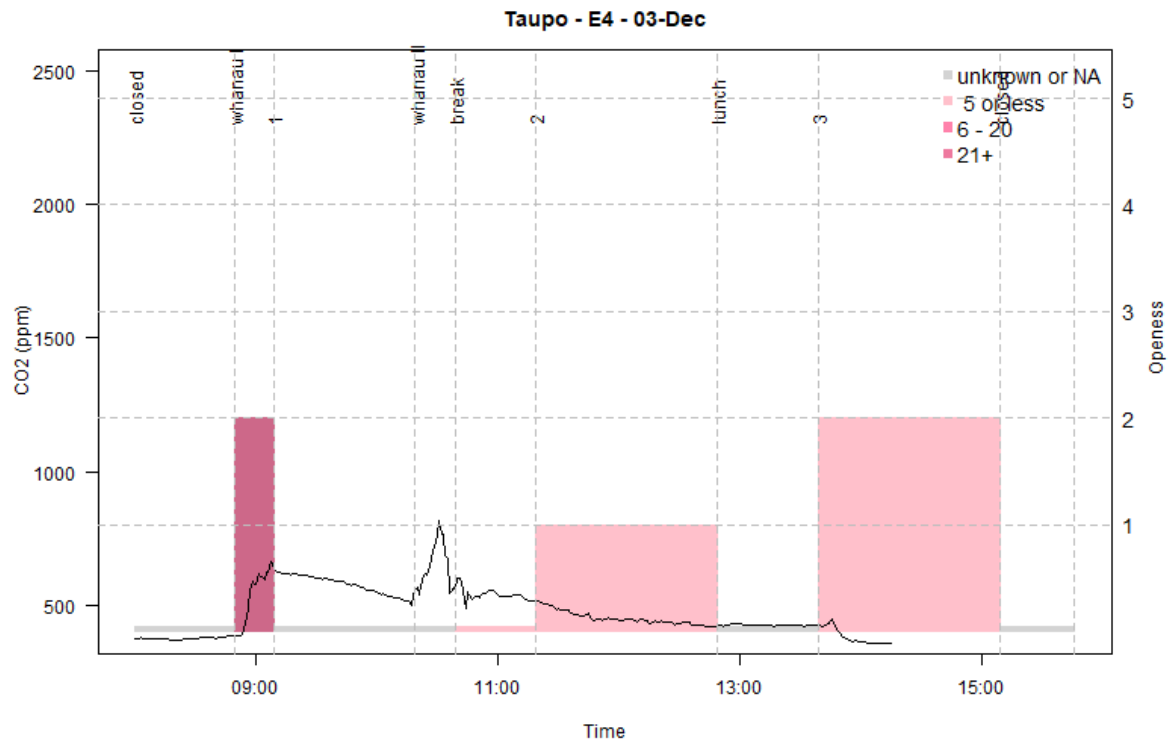




Taupo College – E4

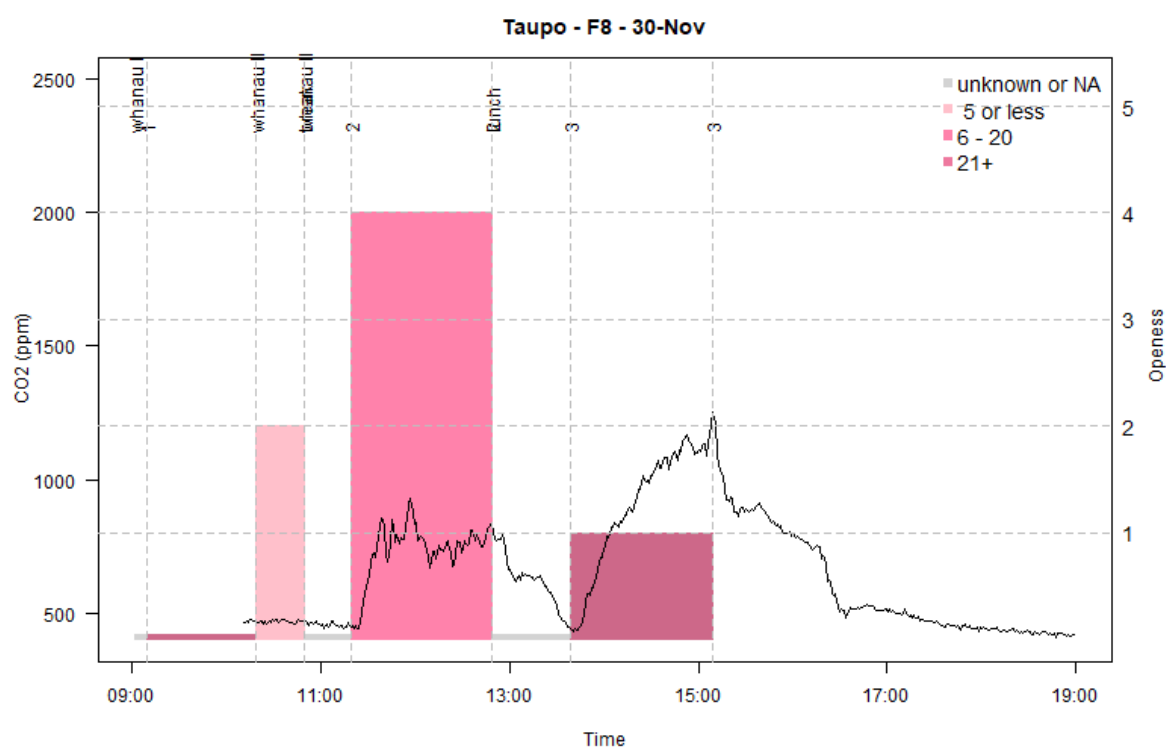
CO₂ remained below 650 ppm in Taupo College room E4. This room had a sliding door which opened to a hallway which was kept open whenever the room was occupied. This appears to have increased the dilution volume and diluted CO₂ to low levels.

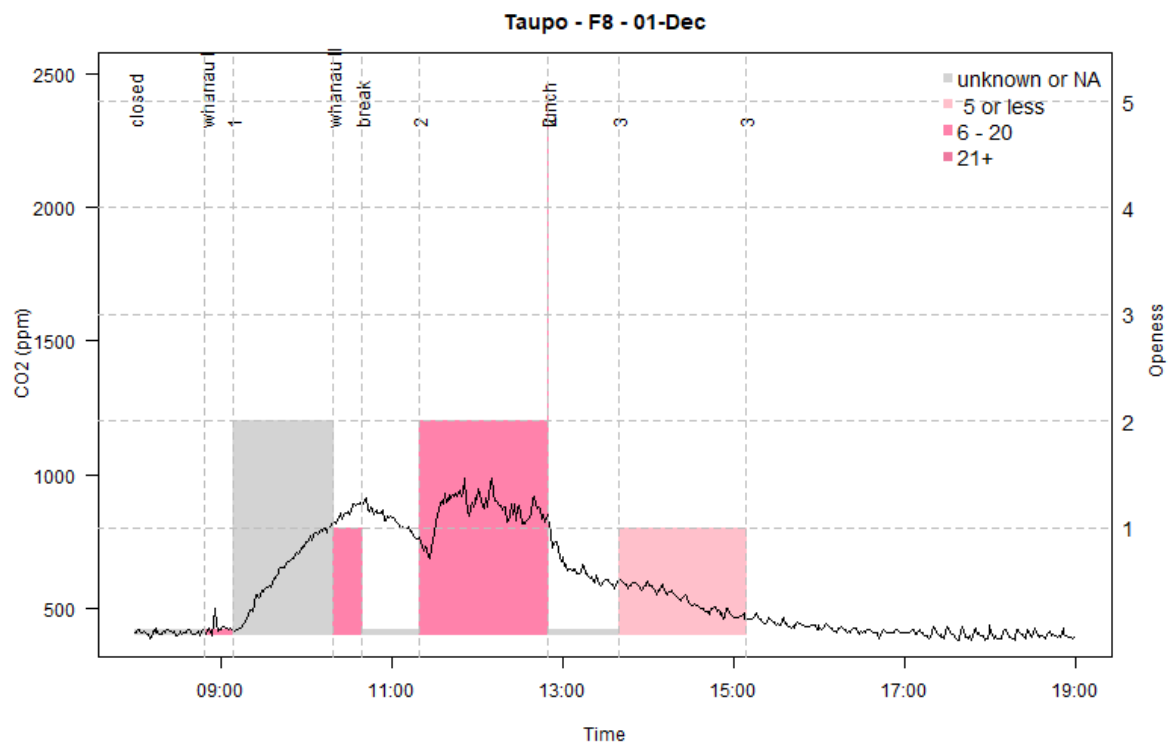




Taupo College – F8

CO₂ stayed below 860 ppm in Taupo College room F8 during the mornings of both Tuesday and Wednesday. On Tuesday (30th Nov) morning the door and windows were mostly open. On Wednesday morning windows were closed but the door to the hallway was open. In the afternoons there were diverging outcomes. On Tuesday afternoon CO₂ rose to nearly 1200 ppm as the doors and windows were closed and 22 people were present. On Wednesday afternoon, doors and windows were fully open at lunchtime and then closed during the last period. The result was that CO₂ fell during lunch and slowly leaked out of the room in the last period. As with room E4, these data indicate that opening the door to the hallway was moderately effective in suppressing the rise in CO₂ concentrations.

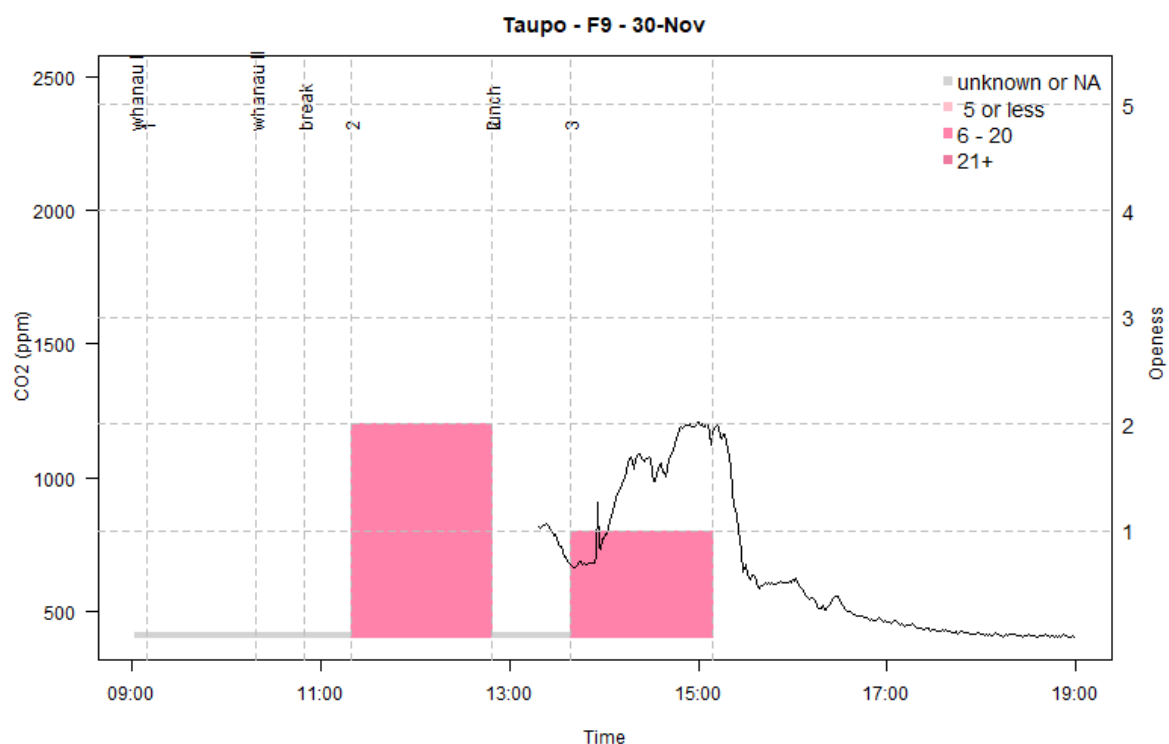




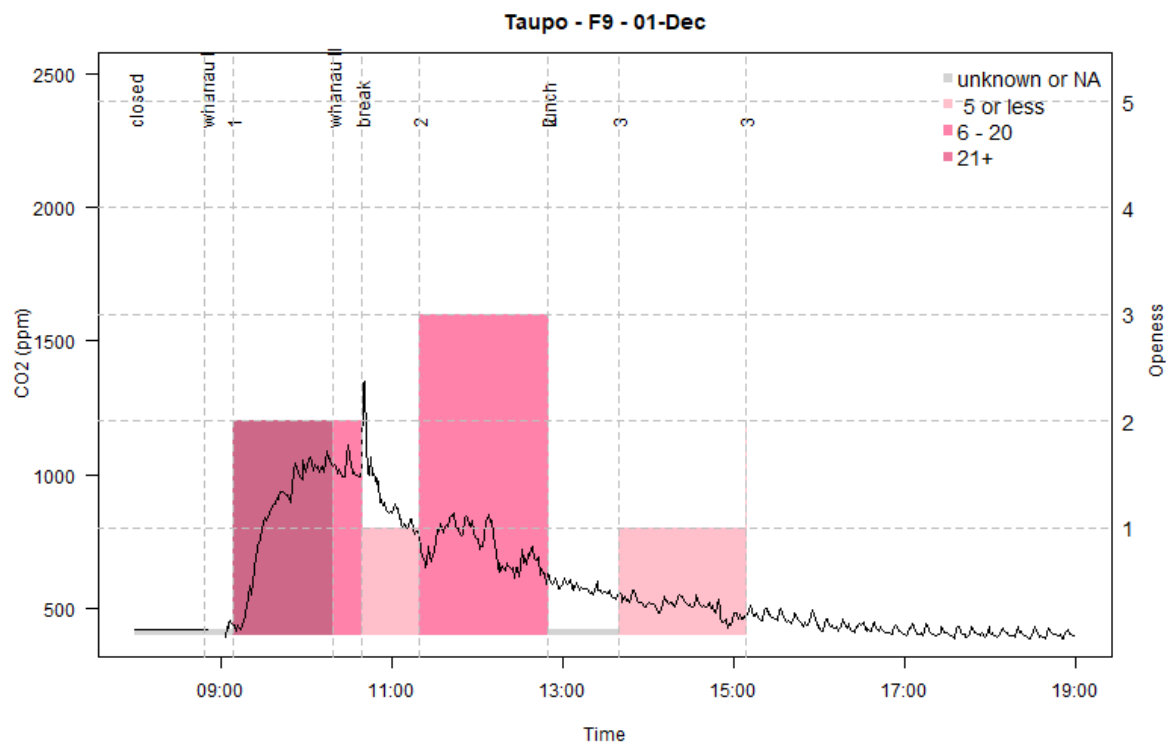
Taupo College – F9

CO₂ levels were variable in this room, exceeding 800 ppm three times. This appears to be related to variability in ventilation. This room has two doors, one external and two internal ones leading to a hallway area and a staff area respectively. Our records show varying combinations of these doors being used to ventilate the space. Windows were only seen open once (period 3 on Friday 3rd Dec).

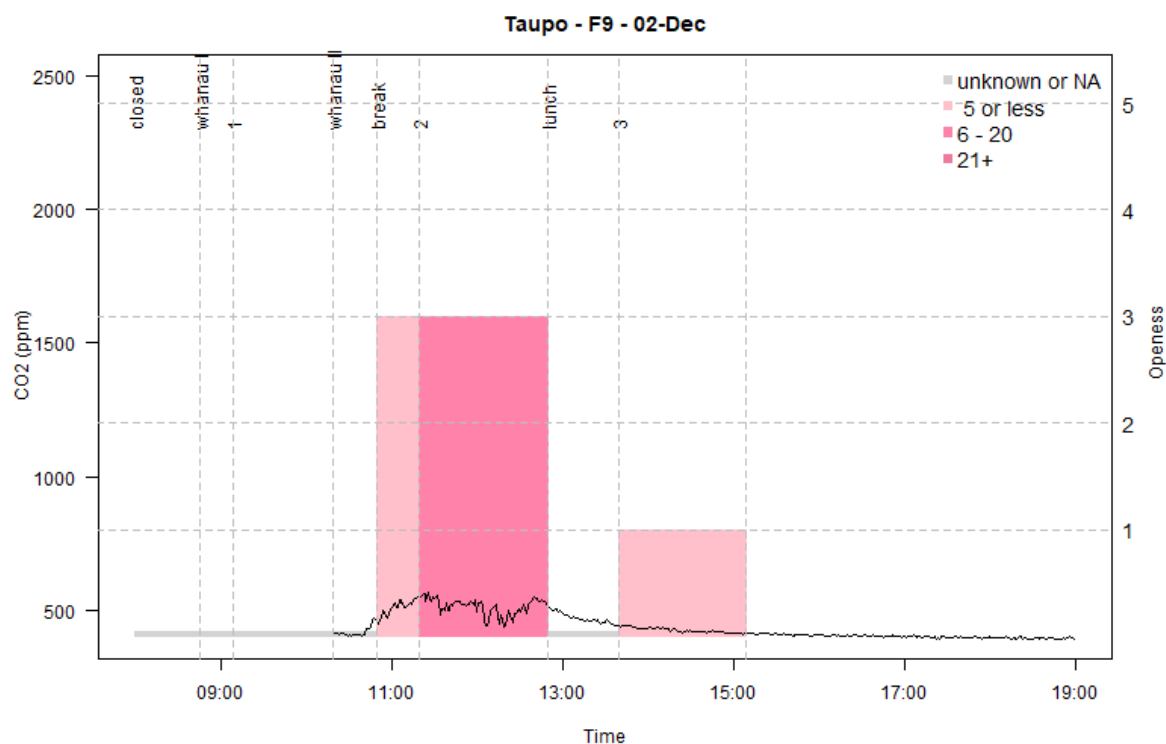
High concentrations on Tuesday afternoon corresponded to only a single door open.



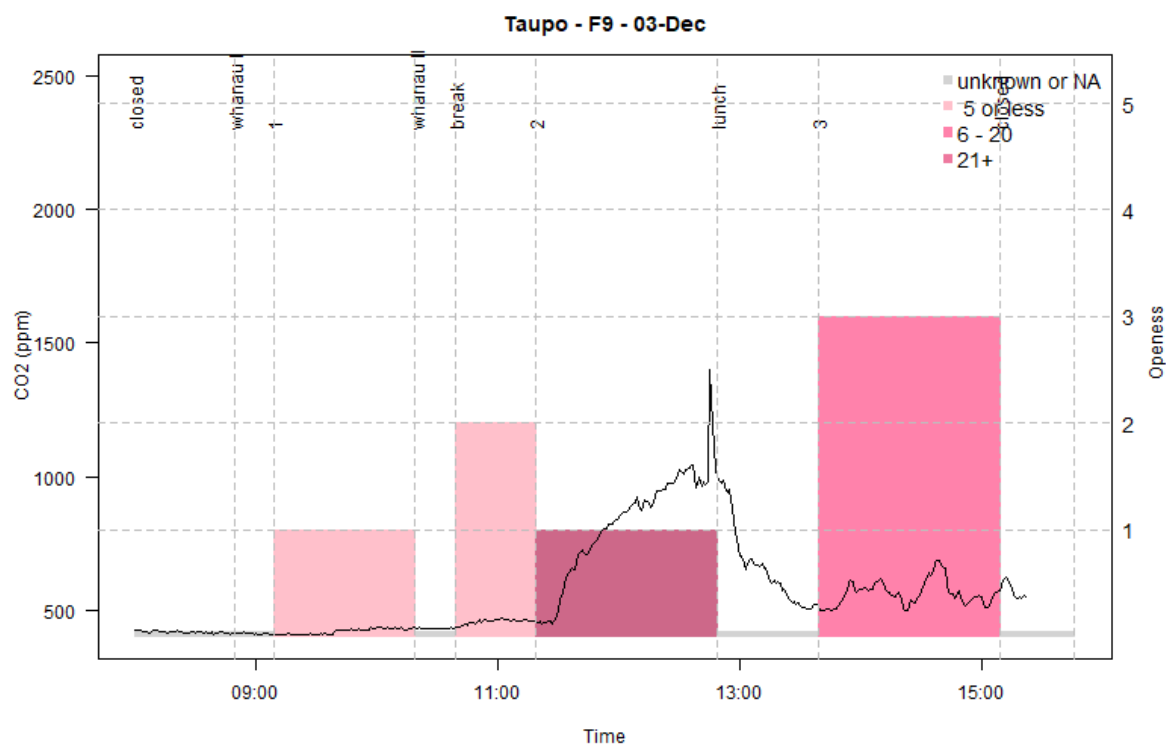
On Wednesday (1st Dec) only one internal door was open during period 1. The external door was opened in period 2. Not only was ventilation progressively increased but occupancy reduced during the day (although the room was continually occupied until lunchtime).



On Thursday (2nd Dec – teacher-only day) all three doors were kept open.

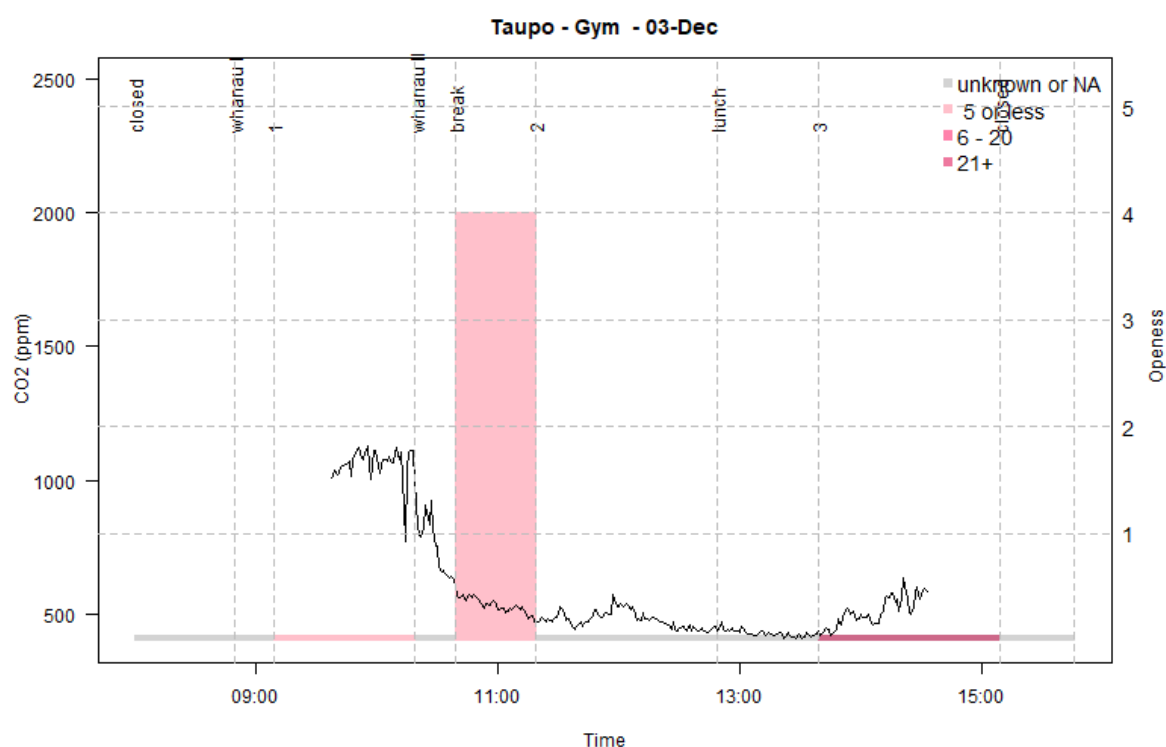


On Friday (3rd Dec) only a single internal door was open during period 2.



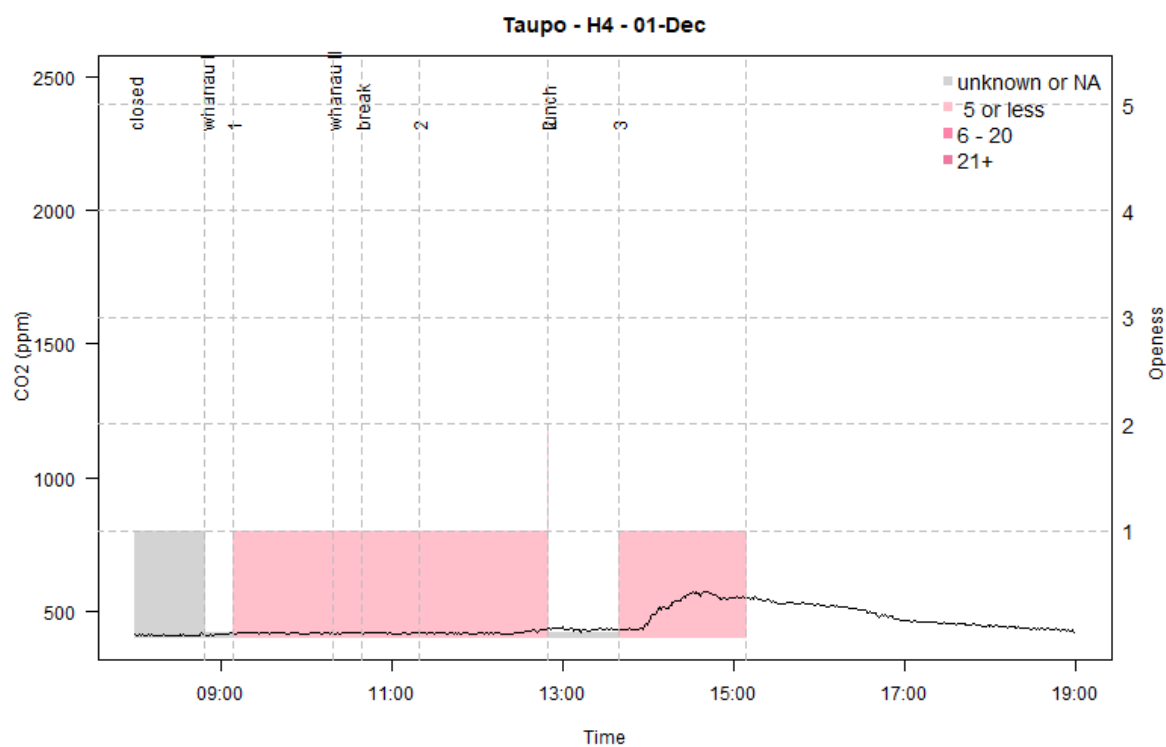
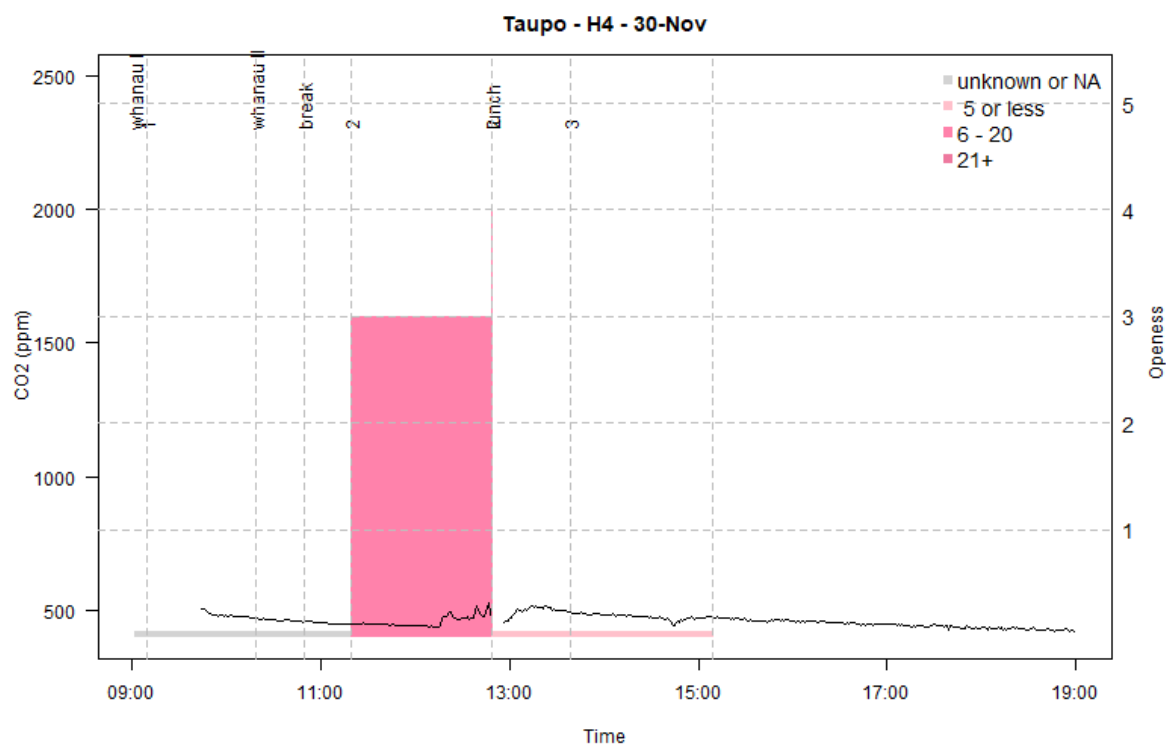
Taupo College – Gym

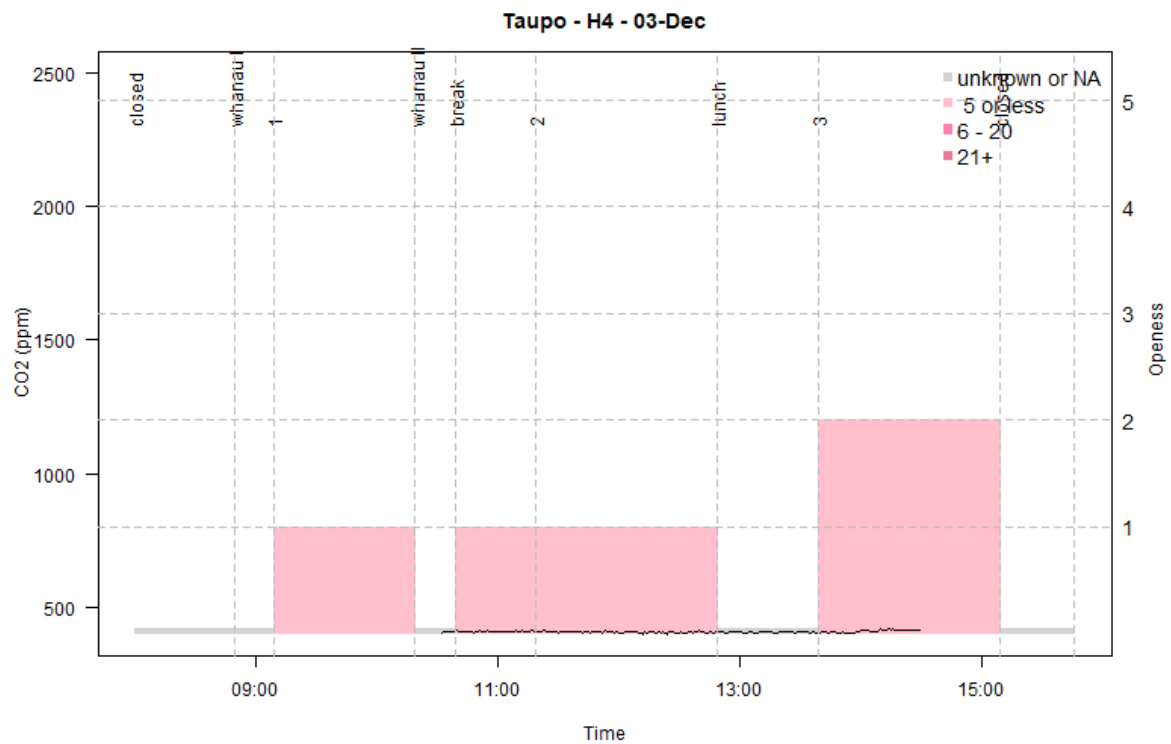
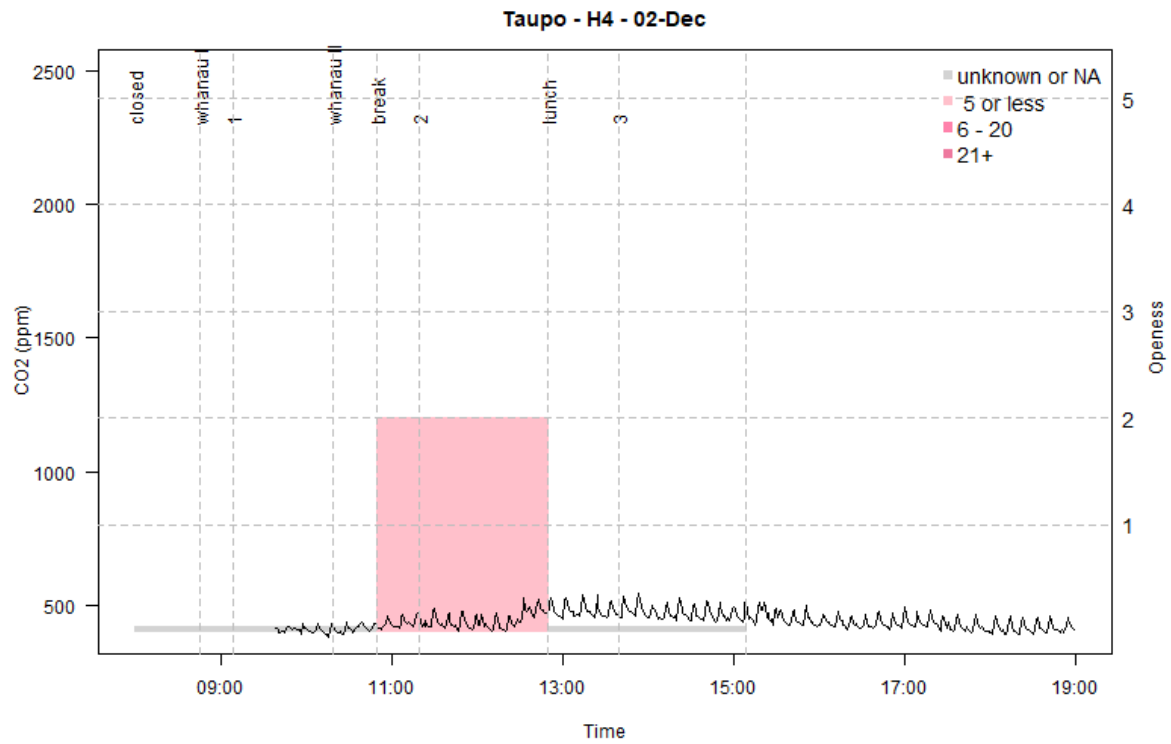
During period 1 the gym was full (an estimated 300 occupants). Four doors (two external, two internal) were open and CO₂ exceeded 1000 ppm. Subsequently CO₂ dropped to very low levels.



Taupo College – H4

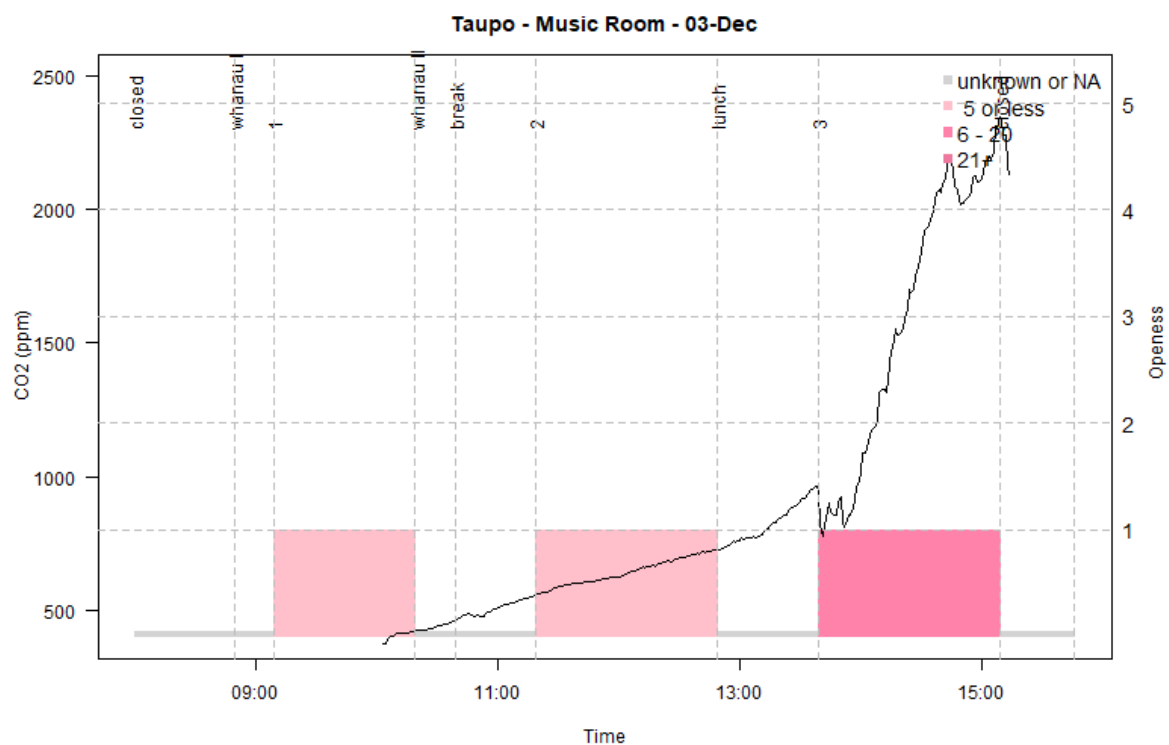
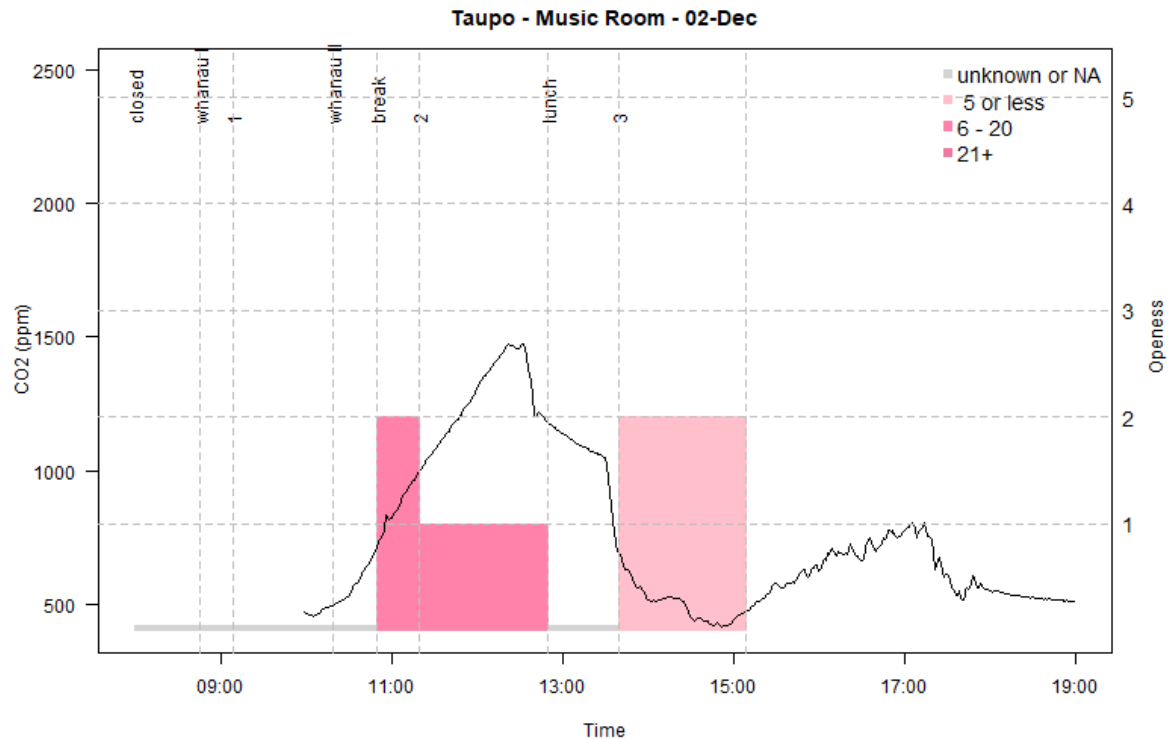
CO₂ levels were very low in H4 throughout the study. Occupancy levels were consistently low and there was at least one door or window opened whenever the room was observed to be in use.





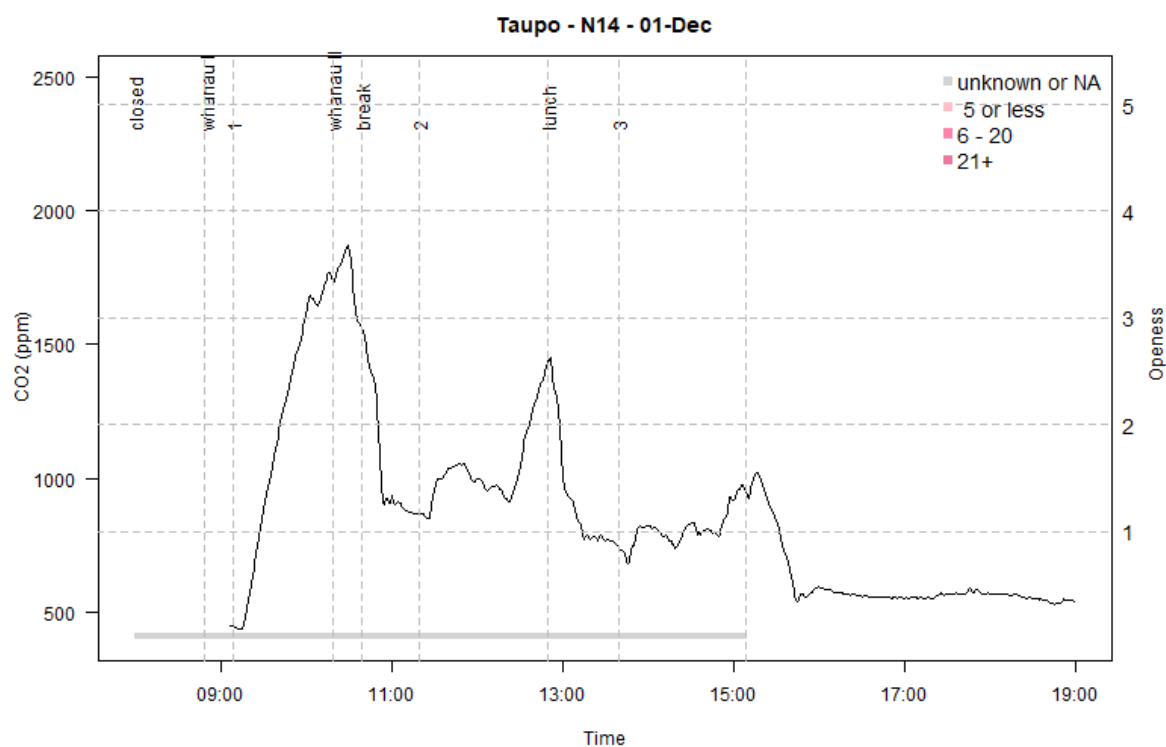
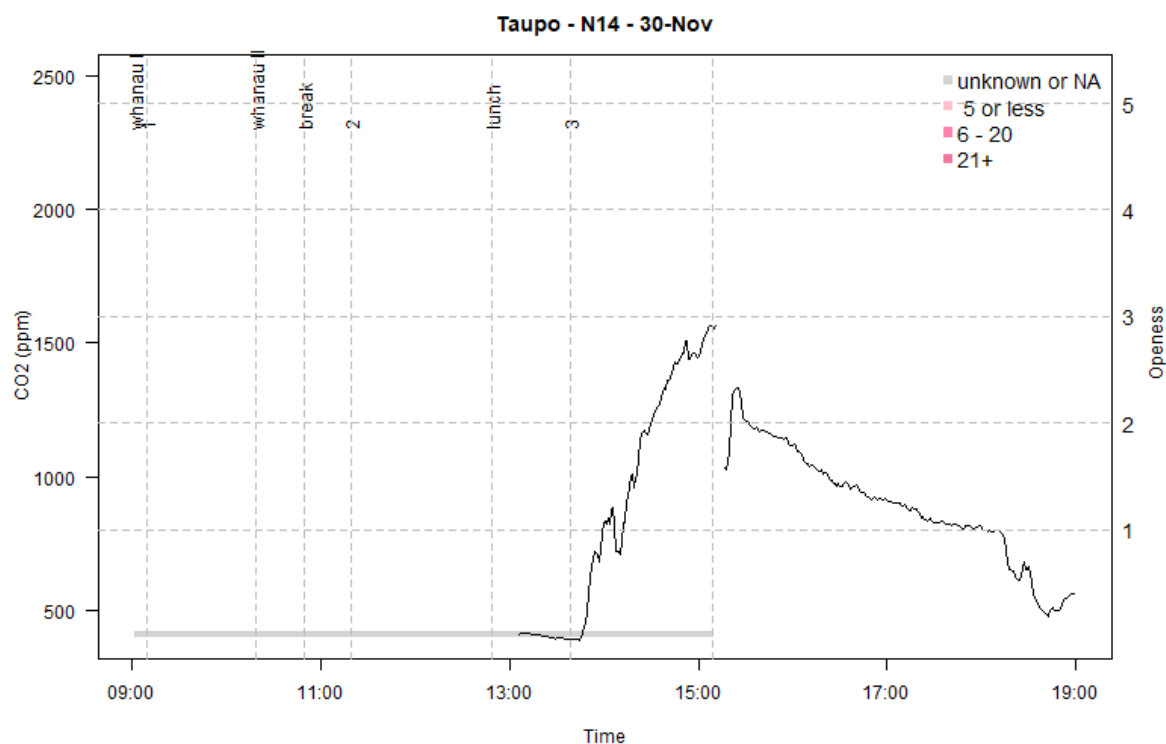
Taupo College – Music Room

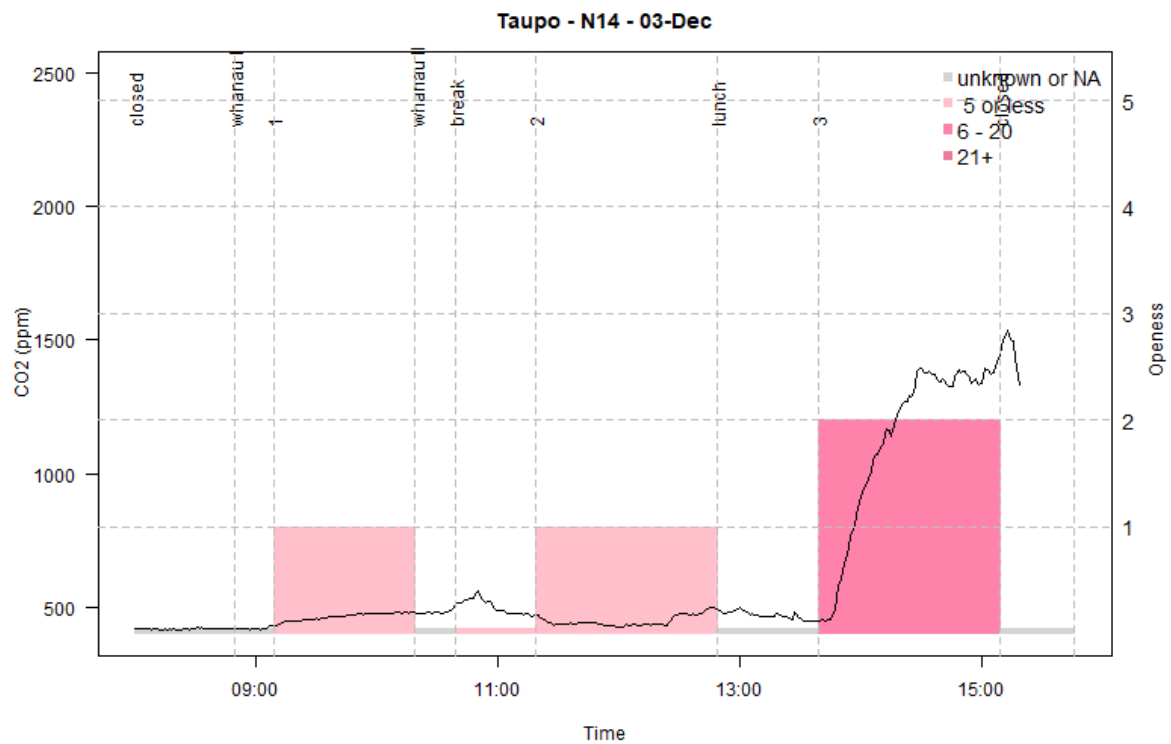
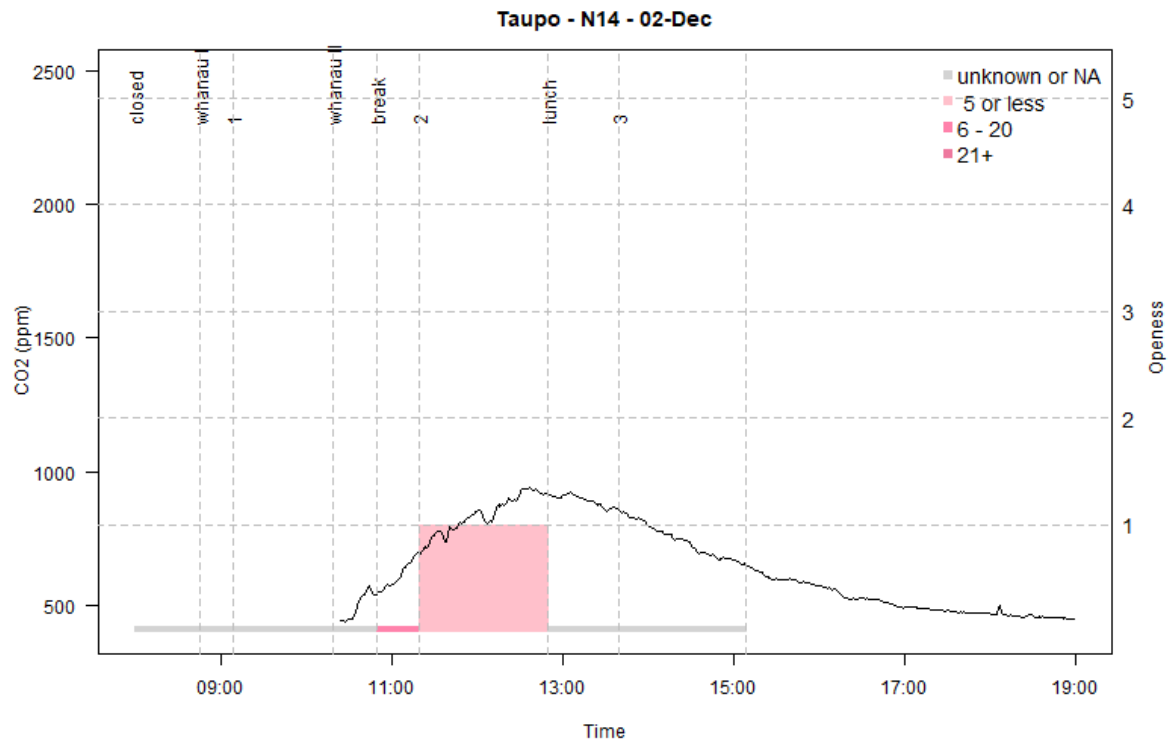
CO₂ rose to 1500 ppm on Thursday morning (9 occupants), and nearly 2400 ppm on Friday afternoon (16 occupants). In both cases **all doors and windows were closed**. A lower CO₂ rise (to 800 ppm) was observed on Thursday after school, however we have no record of the number of occupants or ventilation for this period.



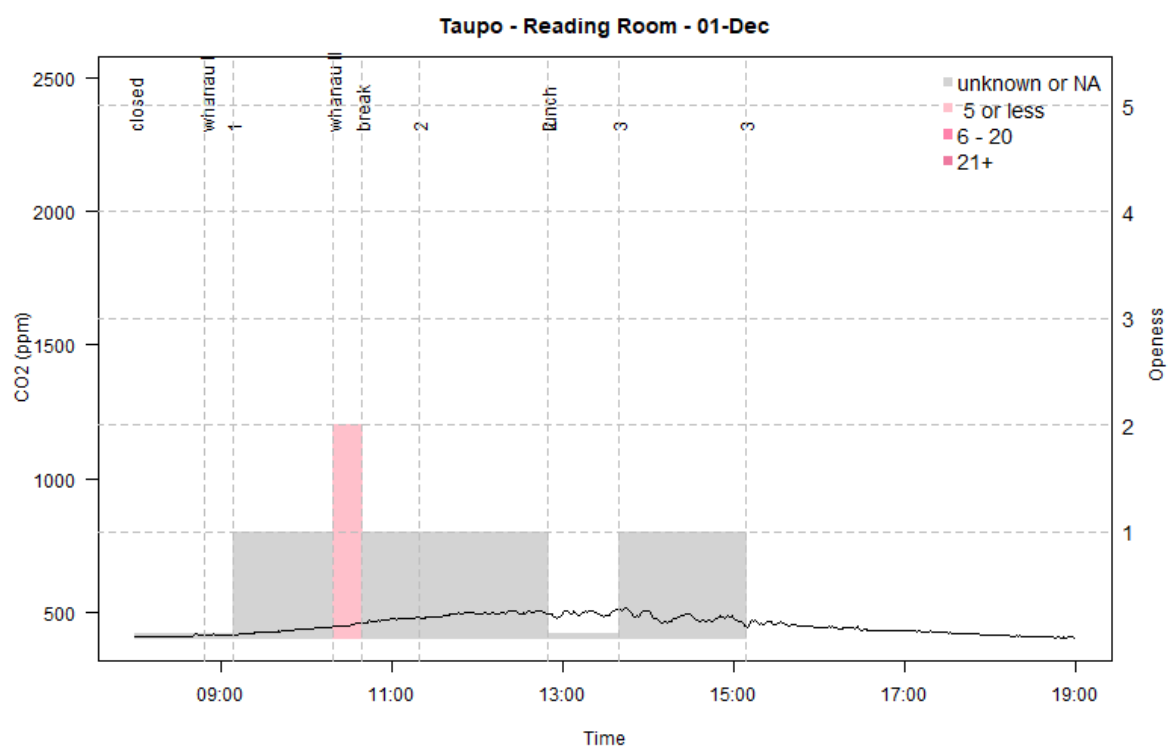
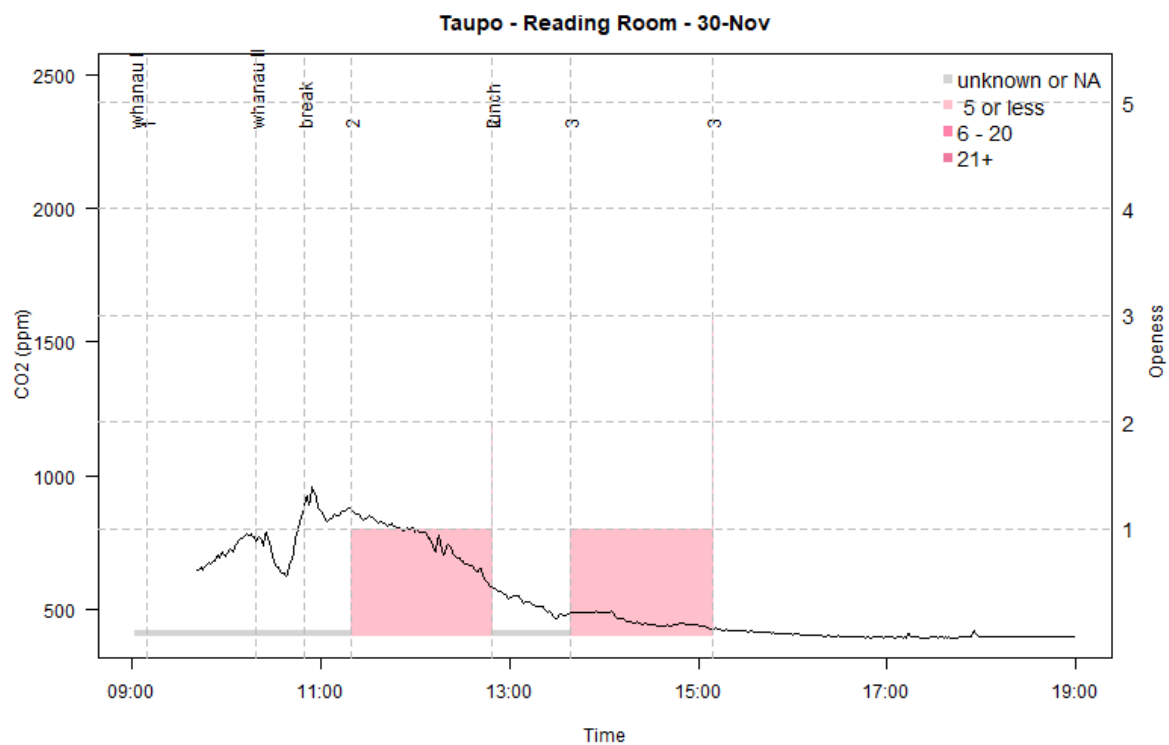
Taupo College – N14

CO₂ exceeded 800 ppm whenever this room was occupied. Manual observations of occupancy and ventilation were not made for the first two days for this room and were insufficiently detailed to explain observed patterns on the last two days.

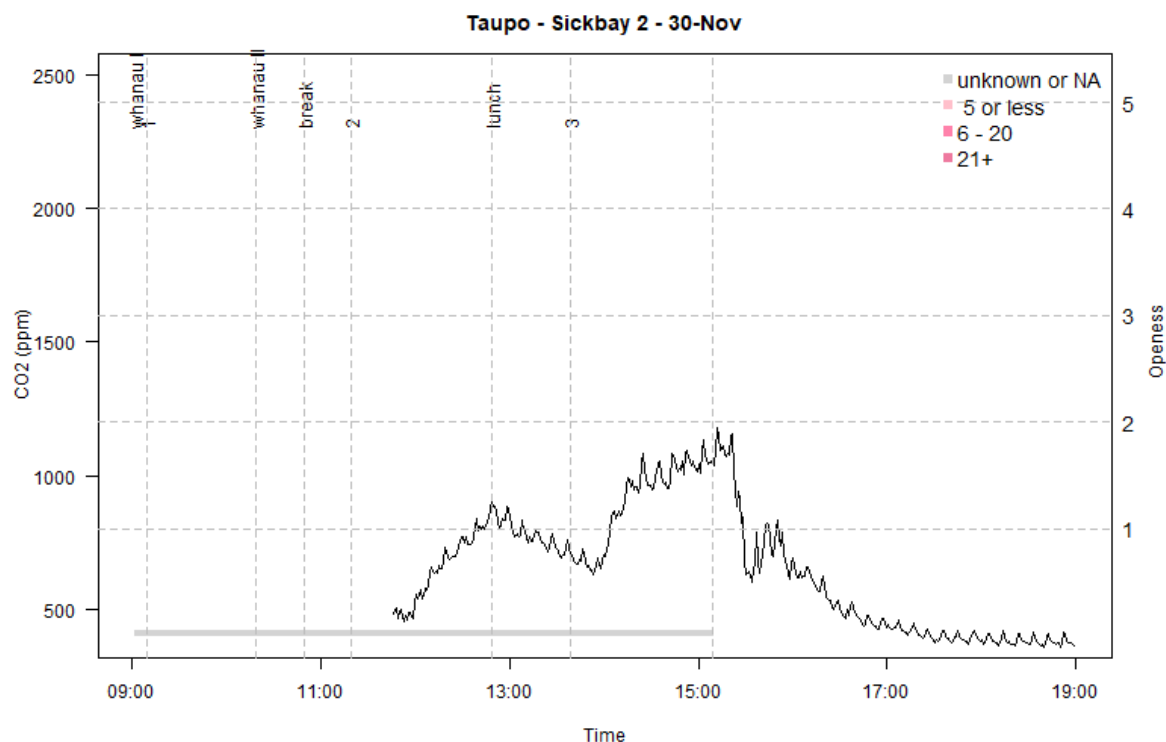




Taupo College – Reading Room

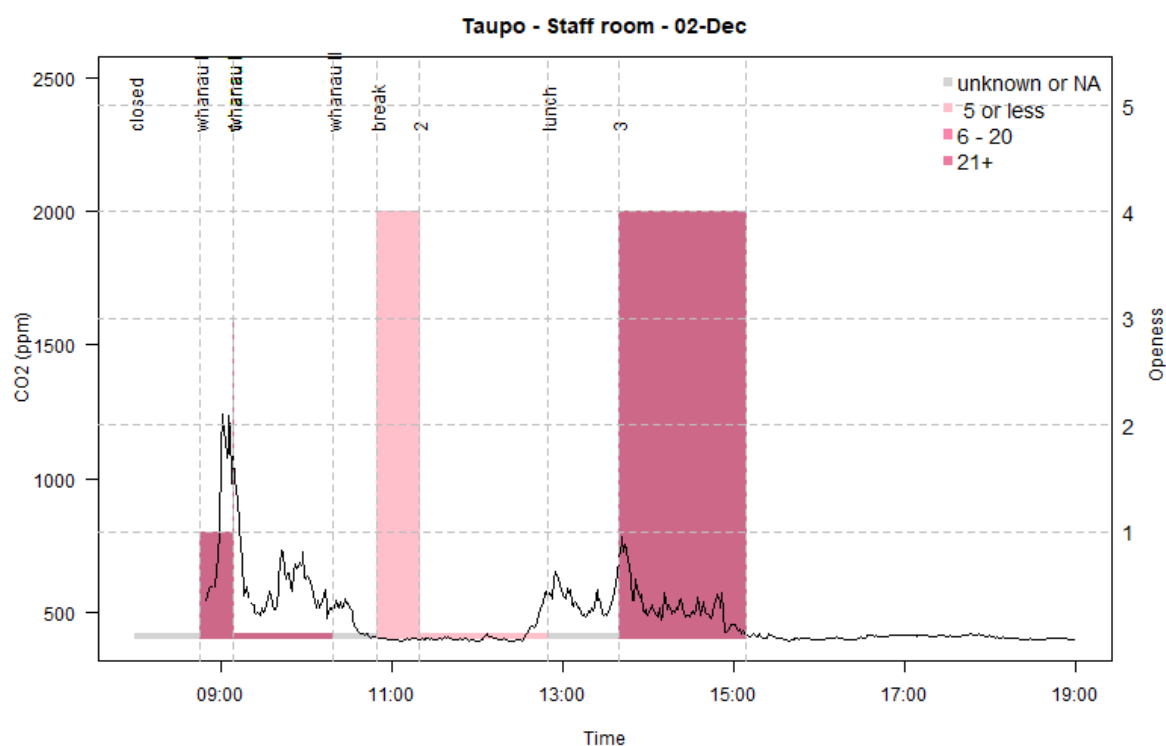


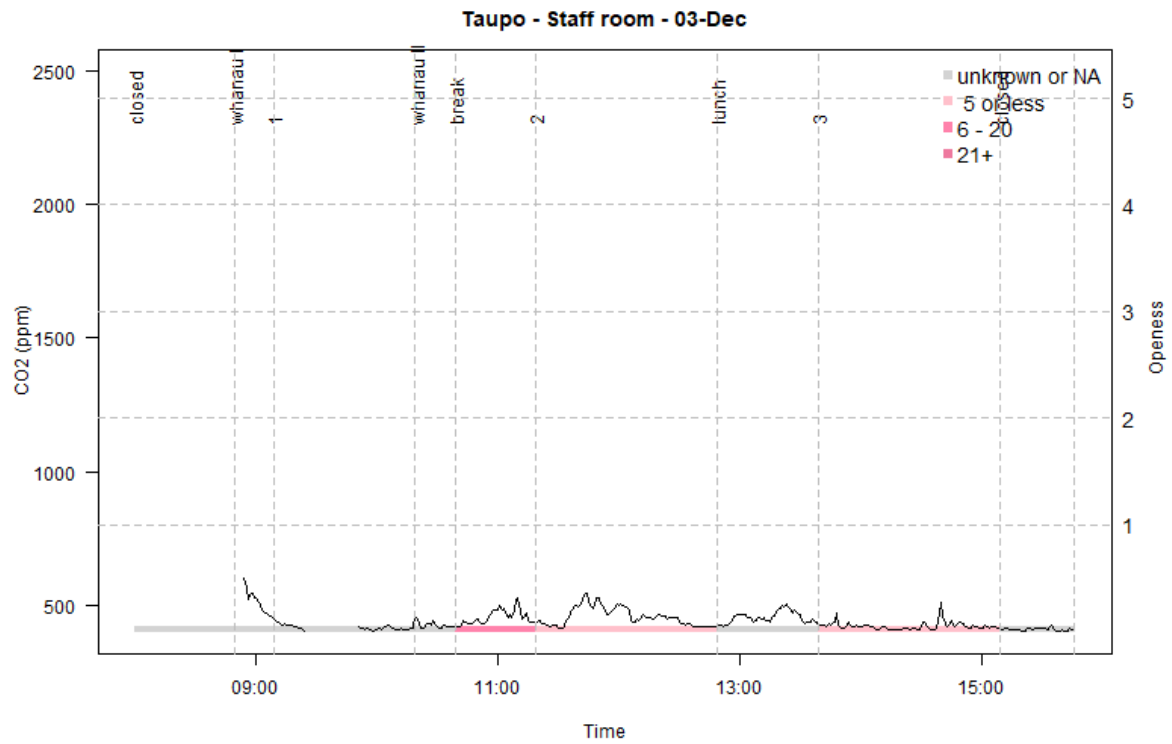
Taupo College – Sickbay 2



Taupo College – Staffroom

High CO₂ was only observed at the start of the day when occupancy was high (50 – 60). Higher CO₂ was observed on Thursday (2nd Dec) compared to Friday. Our observers noted windows closed on Thursday but open on Friday.





Appendix B Manual Observation Survey Form

MoE Ventilation School

Taupo

Classroom*

Select classroom being

Occupan

How many students are*in the

ex:

Excluding yourself, how many adults*are in

ex:

Activi

How active are the occupants*in

(1) (2) (3) (4) (5)

Not very

Very

Exempl

1 Quiet solo work with the teacher talking

2 Slightly louder, or the teacher talking a lot

3 Group work, many occupants talking, some students standing

4 Group singing, lots of loud talking, students moving about the room

5 Dancing, physical exercise or games

Ventilation

How 'open' is the room?^{*}



Not very open



Very open

Examples:

1 0% open. No doors or windows open

2 25% open. The door is open but no windows

3 50% open. The door and one window is open

4 75% open. The door and multiple windows open

5 100% open. Everything is open that can be

Noise Level

ex: 23

Wind speed

ex: 23

Measure wind speed in near the center of the classroom

How many children are masked?

0% 100%

1 2 3 4 5

Comments

Type here...

Go to the HauHaus and scan the codes to check they are working

Submit