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Retrofitting solar air heaters in New Zealand schools – A randomized crossover intervention study

Yu Wang [a,b,1,*], Robyn Phipps [a,c,2], Mikael Boulic [a], Manfred Plagmann [b], Chris Cunningham [d], Gaëlle Guyot [e,f]

[a] School of Built Environment, Massey University, Albany Expressway, SH17, Auckland, 0632, New Zealand
[b] Building Research Association of New Zealand (BRANZ), 1222 Moonshine Road, Judgeford, Porirua, 5381, New Zealand
[c] Wellington Faculty of Architecture and Design Innovation, Victoria University of Wellington, 139 Vivian Street, Wellington, 6011, New Zealand
[d] Research Centre for Hauora & Health (RCHH), Massey University, Wellington, 6021, New Zealand
[e] Cerema, BPE Research Team, 46, Rue St Théobald, F-38080, L'Isle D'Abeau, France
[f] Univ. Savoie Mont Blanc, CNRS, LOCIE, 73000 Chambéry, France

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ABSTRACT

Most New Zealand (NZ) schools rely on natural ventilation and are often inadequately ventilated in winter. NZ school hours typically span from 9 a.m. to 3 p.m. and are well aligned with optimum solar radiation. Existing classrooms could therefore be heated and ventilated using retrofitted solar energy applications. To investigate the suitability of a commercially available solar air heater (SAH) to improve ventilation, a randomized crossover intervention study was conducted in 12 classrooms from six primary schools in Palmerston North, NZ, during the winter of 2014. Typical performance results showed a mean (standard deviation, SD) SAH outlet air temperature of 29.2 (10.4) °C at a mean (SD) velocity of 0.7 (0.3) $m \cdot s^{-1}$. During most school periods (64–99%) classrooms maintained required thermal comfort. The concurrent use of the extant heaters was reduced, and carbon dioxide levels were improved, lowering exposure for occupants. This study confirmed that retrofitting SAHs contributed to improved classroom ventilation, increased thermal comfort and reduced energy use. Optimising performance would require design improvements to improve airflow in order to comply with NZ ventilation and indoor air quality requirements for schools.

1. Introduction

Inadequate ventilation in schools is of public concern [1] as it can negatively affect students' respiratory health [2,3], cognitive performance [4], school attendance [5–7] and learning outcomes [8,9]. The recent COVID-19 pandemic has emphasised the importance of providing sufficient and effective ventilation. Solutions such as particle filtration, air disinfection and avoiding air recirculation have been recommended as key means to reduce the airborne transmission of SARS-CoV-2 and any other airborne viruses containing small microdroplets [10]. To mitigate virus transmission, the strategy of bringing in as much outdoor air as possible to increase the effective ventilation rate without posing safety or health risks while maintaining comfortable indoor temperatures has been recognised as important for schools and classrooms in several countries [11–13].

Measuring indoor carbon dioxide (CO_2) concentration has been widely used to monitor and understand the ventilation characteristics of buildings. The CO_2 produced by people breathing is a useful marker to indicate the bio-effluents generated by building occupants. When the indoor CO_2 concentrations are elevated above the outdoor CO_2 concentrations, well-established tracer gas measurement techniques can be used to study the building ventilation [14]. The generation rates of CO_2 from building occupants have been reviewed based on the human metabolism and exercise physiology, and can be used when estimating ventilation [15]. Persily [16] clarified that the building type and its occupancy must be considered when identify the relevant CO_2 concentrations corresponding to ventilation rate requirements. The ventilation requirements across different countries for different building type have

* Corresponding author. School of Built Environment, Massey University, Albany Expressway, SH17, Auckland, 0632, New Zealand.
E-mail address: yu.wang@branz.co.nz (Y. Wang).
[1] Present address: Building Research Association of New Zealand (BRANZ), 1222 Moonshine Road, Judgeford, Porirua, 5381, New Zealand.
[2] Present address: Wellington Faculty of Architecture and Design Innovation, Victoria University of Wellington, 139 Vivian Street, Wellington, 6011, New Zealand.

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been summarized [17].

In New Zealand (NZ), buildings must comply with the Building Code (NZBC) which requires all occupied spaces in buildings to be provided with adequate ventilation consistent with the maximum occupancy and intended use (clause G4 Ventilation) [18]. Generally, for a naturally ventilated occupied space, natural ventilation must be achieved by providing a net openable area of windows or other openings to the outside of no less than 5% of the floor area; for a mechanically-ventilated occupied space with an estimated maximum occupancy of 50 persons per 100 m^2 floor area, a ventilation rate of 8 $L \cdot s^{-1}$ per person is required to be supplied throughout the occupied zone to achieve an acceptable indoor air quality [18,19].

The NZ Ministry of Education (NZMoE) has produced a series of design quality documents concerning indoor air quality and thermal comfort which require all school buildings (including new buildings and retrofitting projects since July 1, 2022) to meet the following criteria for CO_2 concentration during occupied school periods: i) a recommended daily average of 800 ppm; ii) a maximum daily average of 1250 ppm; and iii) maximum permissible peak CO_2 concentration of 2000 ppm [20]. During the COVID-19 pandemic, the NZMoE provided schools with CO_2 monitoring devices, air purifiers and advice on actions to reduce the CO_2 concentrations when sustained levels are over 800 ppm [21]. Studies conducted during the COVID-19 pandemic have demonstrated that effective ventilation can be achieved in most naturally ventilated classrooms through the implementation of classroom CO_2 monitoring and teacher education [22,23]. However, a contrasting result has been reported [24], indicating that providing a CO_2 monitoring unit to display the current classroom CO_2 concentration, along with advice to open windows, was insufficient to induce behaviour change significant enough to achieve adequate ventilation in classrooms.

High levels of CO_2 in classrooms indicate inadequate ventilation. Inadequate ventilation has been reported in naturally ventilated classrooms in several countries. Batterman et al. found that, in 147 classrooms from 37 American schools, 90% of the median level of CO_2 concentrations during school periods was above 2000 ppm [25]. The result of the SINPHONIE (Schools Indoor Pollution and Health Observatory Network in Europe) study confirmed an inadequate ventilation rate in European schools, where the mean (SD) value of 1433 (856) ppm and median value of 1257 ppm were found in 114 primary schools (340 classrooms in total) from 54 cities in 23 European countries [26]. In addition, Fisk [1] reviewed levels of ventilation during occupied school periods in 3494 classrooms from 1242 schools in 13 countries and found that the average and median of peak CO_2 levels exceeded 1000 ppm in all schools. These findings are consistent the results of another review study conducted by Chatzidiakou et al. [9], which also reported high levels of CO_2 in the school environment.

Most NZ primary school buildings were constructed during the 1950s and 1960s. These buildings are light timber-framed, with extensive single glazed windows, with ceilings, walls and floors uninsulated or insulated to a low level. These school buildings are typically naturally ventilated by the manual opening and closing of windows and doors. Ventilation rates in these naturally ventilated classrooms are frequently lower than the design target value in winter. Surveys undertaken prior to COVID-19 pandemic showed that only between 15% and 40% of teachers were opening windows during their teaching times in winter due to security concerns, outdoor noise and wind [27–29]. Several studies conducted prior to COVID-19 pandemic have also shown that NZ Standard NZS 4303:1990 recommended ventilation rate for classrooms and NZMoE recommended CO_2 concentrations in classrooms are often not achieved [30–36]. A report prepared by Taptiklis et al. reviewed the recent research relevant to the indoor environment in NZ and identified that developing energy efficient ventilation systems that can monitor and respond to the specific needs of the school environment may be required [37] to achieve acceptable indoor air quality in schools.

Research shows that the ventilation rate in mechanically ventilated classrooms is acceptable when the mechanical ventilation system is well designed, well operated and well maintained [38–40]. However, mechanical ventilation systems can be capital and energy expensive [32, 41] and retrofitting such systems in NZ schools would be expensive and beyond school budgets. Therefore, an alternative and affordable method to improve ventilation is needed in NZ schools.

The school hours in NZ typically span from 9 a.m. to 3 p.m. and are closely aligned with the optimum solar radiation [42]. This alignment presents an opportunity for using solar energy applications to heat and ventilate classrooms in winter. The majority of previous investigations into the performance of solar air heaters (SAHs) have been concentrated on design configurations of SAHs to increase energy conversion [43–49]. Field testing of SAHs in real-world conditions remains scant, in particular there has been a lack of studies investigating the SAHs performance under NZ climate conditions. Further, there are few studies investigating the performance of a roof-mounted SAHs. Most importantly, there is a demand for a cost-effective solution for heating and ventilating NZ classrooms, especially during winter.

In this context, a randomized crossover intervention study has been conducted with the aim of investigating the effects of operating a commercially available, roof-mounted SAH on thermal comfort and ventilation in primary schools in winter. The objective of this study is to investigate the change in classroom temperature, relative humidity, CO_2 and extant heater use when operating a roof-mounted SAH. Using renewable energy and solar-assisted thermal systems can decrease the use of non-renewable energy and annual energy costs. However, one of the more challenging problems in NZ primary schools is the low ventilation rate. The measured ventilation rate is typically below the recommended guidelines, especially during the winter. Given this background, this project aims to use a SAH to bring pre-heated air into the classroom to improve thermal comfort and increase the ventilation rate; this intervention is focussed primarily on performance in terms of indoor air quality. Quantifying the energy saved from using the SAH is out of the scope of this paper. This is the first known randomized crossover intervention study to investigate the performance suitability of retrofitting SAHs in schools to improve the indoor air quality.

2. Materials and methods

The conceptual framework and the study design have been described in Refs. [50,51]. Table 1 shows the three stages of this research project, including the input and output variables in each stage. This paper

Table 1
Three stages of the research project. *Source:* Modified from [50,51].

Project Stage	Input	Output
Stage 1 Solar air heater experimental study (see Ref. [52])	**Weather variables:** • Solar radiation • Ambient temperature • Wind speed • Rainfall	**Solar air heater performance:** • Outlet air temperature • Efficiency
Stage 2 Solar air heater field study (see Ref. [51])	**Weather variables:** • Solar radiation • Ambient temperature • Wind speed • Rainfall	**Solar air heater performance:** • Outlet air temperature • Outlet air volumetric flowrate • Efficiency
Stage 3 Change of classroom environments (subject of this paper)	**Weather variables:** • Solar radiation • Ambient temperature • Wind speed • Rainfall **Confounding factors:** • Characteristics of school buildings • Classroom extant heater use • Classroom activities	**Change of classroom environments:** • Temperature • Extant heater use • Relative humidity • Carbon dioxide • Ventilation • Particulate matter

reports the research conducted in Stage 3.

Stage 1 experimentally investigated the SAH performance when it was installed on a custom-made support frame and operated under different air mass flow rates. Results of Stage 1 were reported in Ref. [52]. Stage 2 investigated the SAH field performance when roof-mounted on school buildings. Results of Stage 2 were reported in Ref. [51]. Stage 3 investigates the suitability of retrofitting SAHs in schools and changes in classroom environments arising from the operation of the roof-mounted SAHs, and is the subject of this paper.

2.1. Climate characteristics of study location

This study was conducted in Palmerston North (PN), NZ. Most regions in NZ have a temperate maritime climate (Köppen climate classification: Cfb) [53]. Table 2 shows the summary climate information for PN and NZ [54]. The data are mean annual values for 30 year periods. The rainfall and sunshine hours in PN are lower than the NZ average, while the mean temperature and wind speed in PN are higher than the NZ average.

2.2. School recruitment and participating schools

This study was undertaken in the winter of 2014 (June, July and August). Twelve classrooms from six primary schools participated. The school recruitment process and the criteria that schools met for inclusion have been reported in Ref. [51]. Table 3 summarises the classroom and SAH installation characteristics for each participating classroom.

The volume for all classrooms ranged between 176 m^3 and 314 m^3. The floor areas for all classrooms were between 62 m^2 and 77 m^2. The enrolled student numbers per classroom were between 20 and 30. Students were aged 7–13 years. The density of occupants was between 0.3 and 0.5 person per m^2 of floor area. The student age in the two adjacent classrooms from the same school were very similar, except for School 5. The two adjacent classrooms from the same school have the same type of roofs, windows and heaters. All experimental school buildings were built before 1978 when the requirements for roof, wall and floor insulation became mandatory. This regime required that the thermal resistance for low-rise buildings shall not be less than 1.9 $m^2·K·W^{-1}$ for the roof, 1.5 $m^2·K·W^{-1}$ for the wall, and 0.9 $m^2·K·W^{-1}$ for the floor. While some classrooms may have had some insulation retrofitted, it is inferred that these school buildings had no roof, wall, or floor insulation or were retrofitted to a low level of insulation only. These school buildings were all light timber-framed, single-storey buildings, and were all designed for natural ventilation via single-glazed windows and doors to allow for the flow of fresh air.

Table 2
Mean annual climate information for Palmerston North and New Zealand over 30 years periods [54].

Location and outcomes	Climate parameters					
	Rainfall (mm)	Sunshine (hours)	Temperature			Wind mean speed ($m·s^{-1}$)
			Mean (°C)	Very highest (°C)	Very lowest (°C)	
Palmerston North mean annual	967	1733	13.3	33.0	− 6.0	4.7
New Zealand (NZ) mean annual average	1419	2005	12.4	33.4	− 5.9	3.9
NZ mean annual minimum	360	1532	8.8	28.3	− 15.6	1.7
NZ mean annual maximum	6749	2409	15.7	41.6	0.9	6.1

2.3. The intervention process

At the beginning of the study, one SAH (SV30, SolarVenti Ltd, Thorsoe, Denmark) was installed, as per manufacturer instructions, on the sun-facing roof for each participating classroom, as shown in Fig. 1 (A). The heated air was blown by a photovoltaic panel powered fan into the classroom via the outlet air duct, as shown in Fig. 1 (B).

From the front to the back, the SAH is composed of a transparent double-layer polycarbonate cover, an absorber black felt layer, a perforated aluminium back plate, and an aluminium frame, as shown in Fig. 1 (C). The length, width, and air channel depth of this SAH are 3000 mm, 1020 mm, and 75 mm respectively. The collector gross area and the absorber layer effective area are both 3 m^2. The SAH is equipped with a variable-speed fan (power consumption 5.1 watt), a fan speed controller (regulator), and a 125 mm outlet duct. The fan was powered by an 18-watt photovoltaic panel, and no purchased energy was used for the fan. The polycarbonate cover had a solar transmission of 0.77 and a visible transmission of 0.85. The air inlet holes in the perforated aluminium back plate were 1.5 mm in diameter and arranged in an evenly distributed grid, spaced 15 mm apart. The product description shows that under Danish weather conditions, the maximum air flow of this SAH is 200 $m^3·h^{-1}$, and the estimated average energy production per year is 700 kWh. The schematic view of the SAH has been described in Ref. [52]. The setting up of the SAH for each classroom is shown in Table 3.

In each school, two adjacent classrooms were randomly assigned to an intervention group (SAH installed and operated) or to a control group (SAH installed but not operated). The classroom kept the same intervention or control status for five consecutive weeks. After crossover, the intervention classrooms become control and vice versa for another five consecutive weeks. Fig. 2 shows the flow chart of the intervention. When the classrooms were in the control group, the outlet air duct was sealed to avoid air coming into or getting out of the classroom via the duct.

2.4. Data collection

Temperature and velocity of the SAH outlet air were monitored by a hot wire anemometer at 10-min intervals, 24 hours a day, 7 days a week (24/7), see Fig. 1 (B). The classroom temperature, relative humidity and CO_2 were monitored at 2-min intervals, 24/7. The devices were placed inside a custom-made support structure to prevent tampering by occupants of classrooms and to keep stable monitoring, see Fig. 1 (B). The characteristics of the monitoring devices are shown in Table 4.

The extant heater use status (on-off) in classrooms was recorded by a type K thermocouple connected to a microvolt logger at 5-min intervals, 24/7, see Fig. 3. This temperature logger is with an uncertainty of 0.2 °C [55]. During the study, teachers were free to operate the extant heaters as they would normally do.

The devices were located in the best available location in classrooms. Layout of all classrooms and locations of devices inside classrooms were illustrated in Ref. [51]. All devices were away from the doorway and direct sunlight, and were calibrated and checked before and after the study.

2.5. Data analysis

The data analysis focused on the mean occupied school periods for each day, spanning 6 hours from 9 a.m. to 3 p.m. on weekdays, for the following two reasons: i) to account for any potential time lag between intervention and changes in the classroom indoor environment, and ii) to align with the daily requirements outlined in the NZMoE design documents, which are based on mean occupied school periods [20].

Data are presented for each school individually. Comparisons on the

Table 3
Construction characteristics, student number and age, and solar air heater panel azimuth angle and inclination angle for each classroom. *Source:* Modified from [51].

School (S) Room (R)	Volume (m³)	Floor area (m²)	Student number	Student age (years)	Panel azimuth angle (°)	Panel inclination angle (°)	Year of the school building built	Roof	Windows style	Extant heater type
S1R1	221.0	70	21	8–10	13.5	60.1	1963	Skillion roof	Awning	Central radiator
S1R2	221.0	70	21	8–10	13.5	60.1				
S2R1	212.5	64	28	10–13	17.0	66.0	1973	Skillion roof	Awning	Inverter heat pump
S2R2	230.6	71	27	10–12	17.0	66.0				
S3R1	227.7	70	27	9–11	19.0	58.2	1958	Skillion roof	Louvre	Inverter heat pump and unflued gas heater[a]
S3R2	227.7	70	20	9–12	19.0	58.2				
S4R1	313.6	77	26	8–10	17.5	63.8	1928	Gable roof	Awning	Inverter heat pump
S4R2	295.2	73	22	8–10	17.5	63.8				
S5R1	175.8	65	30	12–13	−18.5	65.0	1953	Skillion roof	Awning, sliding	Electric heater
S5R2	175.8	65	21	10–12	0.0	65.0				
S6R1	182.8	62	21	7–8	−30.0	67.3	1975	Skillion roof	Awning	Central radiator
S6R2	182.8	62	22	7–9	−30.0	67.3				

[a] The unflued gas heater was the secondary heater and was only used occasionally. For example, on a cold winter morning, it was started by the caretaker to warm up the classroom before students arrival.

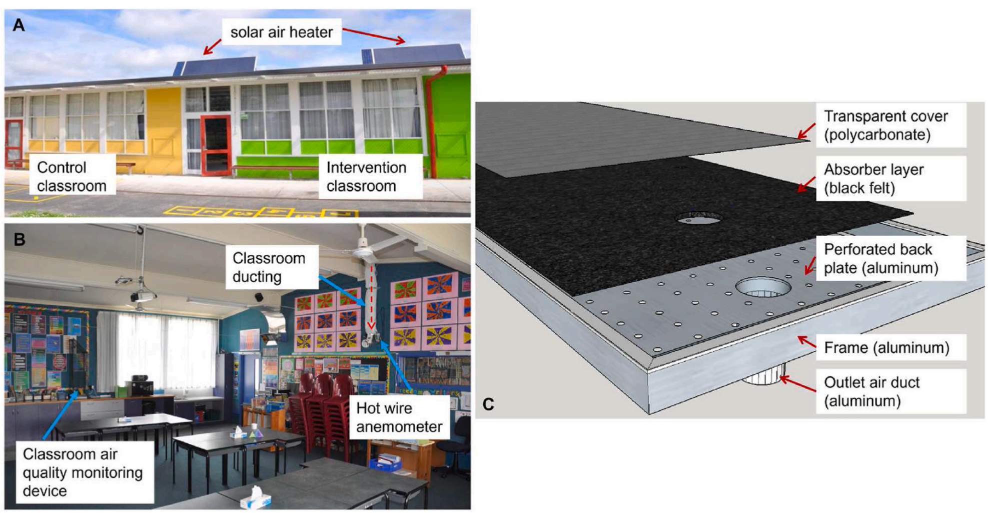

Fig. 1. Solar air heater (SAH) installed on the sun-facing roof of the school building (A); Air duct inside the classroom and locations of hot wire anemometer and air quality monitoring device (B); Exploded view of the SAH (C). Source: Modified from [51,52].

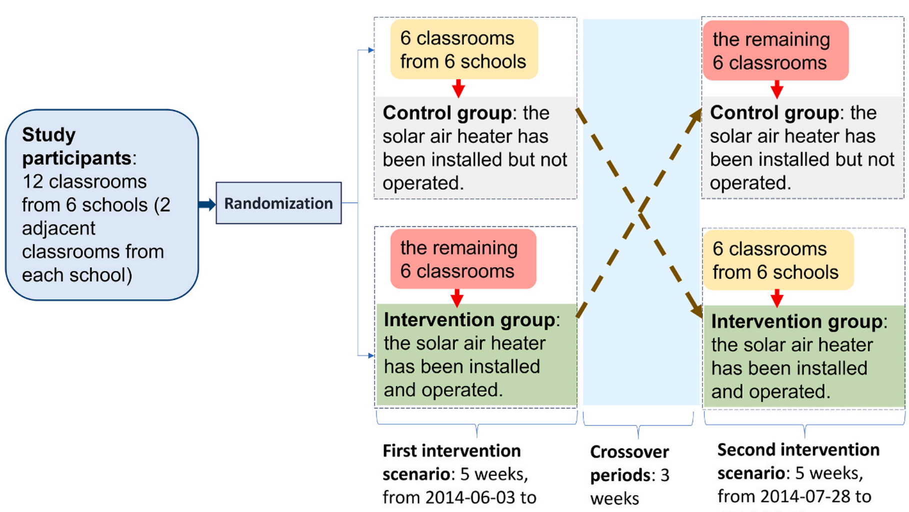

Fig. 2. Flow chart of the intervention.

Table 4
Characteristics of the monitoring devices. Source: Modified from [51].

Device	Monitored parameters	Range	Accuracy
Lutron AM4214SD hot wire anemometer	Outlet air velocity ($m \cdot s^{-1}$)	0.2–25	±5% of reading
	Outlet air temperature (°C)	0–50	±0.8
BW Technologies IAQ3, Gas Probe IAQ monitor	Temperature (°C)	0–40	±0.1
	Relative humidity (%)	0–95	±2
	Carbon dioxide (ppm)	0–10000	±3% of the reading
TSI Model 7545 IAQ-Calc Meter	Temperature (°C)	0–60	±0.6
	Relative humidity (%)	5–95	±3
	Carbon dioxide (ppm)	0–5000	±50
TSI Model 8552 Q-Trak IAQ monitor	Temperature (°C)	0–50	±0.6
	Relative humidity (%)	5–95	±3
	Carbon dioxide (ppm)	0–5000	±50

data collected (temperature, relative humidity, extant heater use and CO_2) from intervention classrooms and control classrooms were made by combining the data under the same intervention status in the first and second intervention scenarios [56]. Data analysis consisted of the following three steps: i) calculate the mean values of temperature, relative humidity and CO_2 during the school periods per day in all classrooms based on the collected 2-mins data, and evaluate the percentage of school periods per day with temperature, relative humidity and CO_2 levels following the NZMoE requirement; ii) test the distribution of daily mean values of temperature, relative humidity and CO_2 in the intervention classroom and the control classroom in each school using Shapiro-Wilk test; and iii) evaluate the efficacy of the intervention with the use of Mann-Whitney U test, as the daily mean values of the temperature, relative humidity and CO_2 are not normally distributed.

In relation to temperature and relative humidity, the NZMoE mandated requirements for the teaching spaces in winter are that the temperature should be between 18 °C and 25 °C, and the relative humidity should be between 35% and 70% [20]. Therefore, the percentage of school periods per day with measures outside these ranges was calculated, and the percentage of school periods per day with temperatures in the 18–25 °C range and relative humidity in the 35–70% range simultaneously was calculated.

The effects of the intervention on classroom ventilation were assessed based on CO_2 concentrations. The percentage of school periods per day with CO_2 concentrations falling into two categories was calculated: i) less than 1250 ppm, and ii) above 1250 ppm. The CO_2 threshold was set up in accordance with the NZMoE's requirement for designing quality learning space [20].

Extant heater use was categorised into four time-based groups: i) early morning (from 12:00 a.m. to 5:59 a.m.), ii) before school (from 6:00 a.m. to 8:59 a.m.), iii) school periods (from 9:00 a.m. to 3:00 p.m.), and iv) after school (from 3:01 p.m. to 11:59 p.m.). For each group, the extant heater use was quantified as the proportion of time during which the extant heater was in operation [57]. The proportion of time during 24-hour periods that extant heaters were in operation was also calculated. In classrooms with two or more extant heaters, the operation of one or more contemporaneously was counted. The extant heater use was not normally distributed according to the Shapiro-Wilk test. The median (interquartile range) values of extant heater use in both intervention and control classrooms were calculated. The Mann-Whitney U test was used to compare the extant heater use in intervention classrooms and in control classrooms [39].

A p-value less than 0.05 was regarded as statistically significant. Data analyses were conducted using the statistical computing and graphics platform programming language R version 4.2.1 [58].

The study design and protocols have been approved by the Massey University Human Ethics Committee (MUHEC 12/49).

3. Results

Table 5 shows the summary of weather data in winter 2014 in PN, including the occupied school periods (9 a.m.–3 p.m. on weekdays) and 24-hour periods (12:00 a.m. to 11:59 p.m.).

During the occupied school periods, the ambient temperature was around 11.5 °C, which was about 2 °C higher than the mean temperature of 24-hour periods. The mean wind speed during the occupied school periods was higher than the daily mean wind speed (4.6 $m \cdot s^{-1}$ vs. 3.8 $m \cdot s^{-1}$).

The study started on June 3, 2014 and ended on August 29, 2014 during the winter season in NZ. Figs. S1–S3 show boxplot of daily school periods temperature, relative humidity and CO_2 based on the 2-mins collected data during both the first and second intervention scenarios (see Fig. 2). To ensure the classroom was occupied, indoor CO_2 concentrations were used as a surrogate of occupancy. In this study, classrooms with a CO_2 level above 450 ppm at all times were considered to be occupied. Table 6 shows the number of occupied school days and the availability of extant heater use data in each school.

The number of occupied school days analysed across all schools was between 45 and 49. The control classroom and the intervention

Table 5
Summary of weather conditions during the study.

Variables	Occupied school periods (9 a.m.–3 p.m. on weekdays)		24-hour periods	
	Mean (sd) (95% CI)	Median (minimum – maximum)	Mean (sd) (95% CI)	Median (minimum – maximum)
Solar radiation ($W \cdot m^{-2}$)	242 ± 144 (228–256)	233.3 (0–647.2)	81 ± 135 (75–87)	0 (0–666.7)
Temperature (°C)	11.4 ± 2.9 (11.1–11.7)	11.5 (0.3–18.7)	9.3 ± 3.9 (9.1–9.5)	9.9 (-1.8–19.4)
Wind speed ($m \cdot s^{-1}$)	4.6 ± 2.8 (4.3–4.9)	4.6 (0–11.3)	3.8 ± 2.6 (3.7–3.9)	3.1 (0–13.9)

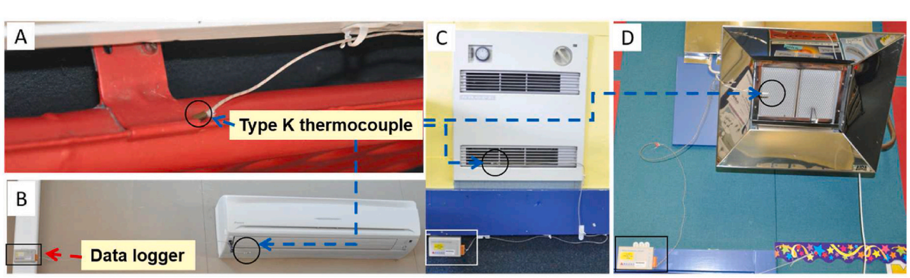

Fig. 3. Thermocouple connected to a data logger to monitor the extant heater use. (A) Central radiator; (B) Inverter heat pump; (C) Electric heater; (D) Unflued gas heater.

Table 6
The number of occupied school days.

School	Number of occupied school days	Dates (MM-DD) where temperature, relative humidity and carbon dioxide data was removed from the analysis[a]	Dates (MM-DD) without extant heater use data[b]
1	45	06-18, 06-19, 08-18, 08-27	06-26, 06-27, 06-30 to 07-04
2	49	NA	06-03 to 06-06, 06-09 to 06-12
3	49	NA	NA
4	48	06-09	NA
5	48	06-03	NA
6	46	06-03, 06-04, 06-05	NA

[a] These dates were removed from the analysis due to the classrooms were not occupied (CO_2 level was not above 450 ppm at all times).
[b] In School 1, extant heater use data logger stopped at 09:15 a.m. on 2014-06-26. In School 2, extant heater use data logger started at 08:35 a.m. on 2014-06-12.

classroom from the same school had the same number of days that the temperature, relative humidity, CO_2 and extant heater use were analysed. Table 7 shows the temperature and volumetric flow rate of the SAH outlet air. The process of calculating the volumetric flow rate is described in Ref. [50].

Across all schools, the SAH mean (SD) outlet air temperature was 29.2 (10.4) °C at a mean (SD) velocity of 0.7 (0.3) $m \cdot s^{-1}$. The mean volumetric flow rate of the SAH outlet air ranged from 25.6 $m^3 \cdot h^{-1}$ to 39.2 $m^3 \cdot h^{-1}$. At least 86% of the time the temperature of the air delivered into the classrooms was above 18 °C.

3.1. Classroom temperature and relative humidity

Figs. 4 and 5 respectively show the boxplot of the mean temperature and relative humidity in classrooms during school periods for each day.

The temperature and relative humidity in all schools are summarized in Table 8.

The median level of mean temperature during school periods per day across all schools fell within the range of 19–22 °C. In five out of six schools, the median level of mean temperature in intervention classrooms was higher than in control classrooms, although the statistically significant difference was only observed in School 4. Furthermore, temperatures in School 4 were lower compared to the other five schools.

The median level of mean relative humidity during school periods per day across all schools was in the 47.9–60.9% range at a temperature between 19 °C and 22 °C. In all schools, no statistically significant differences were found between relative humidity levels in control classrooms and intervention classrooms.

The median level of percentage of school periods per day where the temperature was below 18 °C in all schools ranged from 0% to 16.3%. In School 4, median (interquartile range) levels of school periods per day spent in the temperature below 18 °C were approximately 1.0 (0.5–2.2) hours in the control classroom and 0.6 (0.3–1.1) hours in the intervention classroom. Correspondingly, the control classroom in School 4 had more school periods per day with the relative humidity above 70%, with the maximum value of 2.0 hours.

Across all schools during the occupied school periods, classrooms maintained temperatures within the range of 18–25 °C and relative humidity between 35–70% simultaneously for between 64% and 99% of the time. In School 4, occupants in the intervention classroom experienced 20% more time (roughly 1.2 hours) within the aforementioned temperature and relative humidity ranges compared to the control classroom. However, an opposite result was observed in School 5, where the intervention classroom experienced approximately 8% less time (roughly 0.5 hours) within these temperature and relative humidity ranges compared to the control classroom.

3.2. Use of extant heaters

Fig. 6 presents the distribution of proportion of time that extant heaters were in operation at different parts of a day.

Table 9 shows the median (interquartile range) of the proportion of time extant heaters were in operation at different parts of a day.

The extant heater use before and during the school periods was higher than the other two groups (early morning and after school periods). This result was supported by school activities. Generally, the extant heater was turned on 2 or 3 hours prior to the start of the school (9 a.m.) to preheat the classroom. When the classroom had a comfortable temperature, the teachers turned off the extant heater. It was also found that in some schools extant heaters were in operation in the early morning (before 6 a.m.).

In all schools, median value of proportion of extant heater use during school periods was in the 16–75% range in control classrooms and in the 25–60% range in intervention classrooms. In schools 1, 2, 5 and 6, extant heater use before school (6:00 a.m.–8:59 a.m.) was higher than extant heater use during the school periods. In School 4, the full day extant heater use in the intervention classroom was higher than in the control classroom (9% vs. 6%). In School 5, extant heater use during the school periods in the intervention classroom was statistically significant higher than in the control classroom (35% vs. 16%).

The median (interquartile range) levels of full day extant heater use in the control classroom and in the intervention classroom from School 1 to School 6 were 4.9 (4.3–5.8) hours vs. 4.6 (1.0–5.5) hours, 2.8 (2.0–4.2) hours vs. 2.9 (2.2–3.6) hours, 6.5 (4.7–8.8) hours vs. 5.7 (3.3–7.7) hours, 1.4 (1.0–2.3) hours vs. 2.2 (1.1–3.5) hours, 5.4 (4.1–7.7) hours vs. 6.2 (3.6–10.1) hours, 6.3 (5.4–7.2) hours vs. 6.3 (5.5–7.1) hours. The ratio of the median levels of full day extant heater use in the intervention classrooms to the extant heater use in the control classrooms ranged from 0.87 to 1.56 across all schools.

3.3. Carbon dioxide concentrations

Fig. 7 shows the boxplot of mean CO_2 concentration in classrooms during school periods for each day.

NZMoE requires that the mean CO_2 concentrations in occupied

Table 7
Temperature and volumetric flow rate of the solar air heater outlet air.

School	Variables				
	Temperature (°C)			Volumetric flow rate ($m^3 \cdot h^{-1}$)	
	Mean (SD) (95% CI)	Median (minimum – maximum)	% of time with temperature above 18 °C	Mean (SD) (95% CI)	Median (minimum – maximum)
1	31.7 ± 12 (31.1–32.4)	29.0 (12.6–55.9)	88.1	27.4 ± 8.9 (26.9–27.9)	27.6 (1.1–44.2)
2	29.6 ± 10.7 (29.0–30.1)	26.1 (10.3–52.5)	86.6	30.5 ± 11.4 (29.9–31)	32.7 (1.1–47.7)
3	30.1 ± 10.6 (29.5–30.6)	27.0 (10.8–54.8)	91.0	25.6 ± 13.3 (24.9–26.3)	25.4 (1.1–65.8)
4	28.6 ± 10.9 (28.1–29.2)	25.4 (8.1–55.4)	81.5	39.2 ± 14 (38.6–39.9)	44.9 (1.1–53.9)
5	27.6 ± 7.5 (27.2–28.0)	25.4 (6.4–50.9)	96.3	27 ± 13.7 (26.3–27.7)	28.7 (1.5–76.6)
6	27.6 ± 9.3 (27.1–28.1)	23.6 (15.4–55.4)	97.4	31.8 ± 18.1 (30.8–32.7)	28.3 (1.9–79.4)

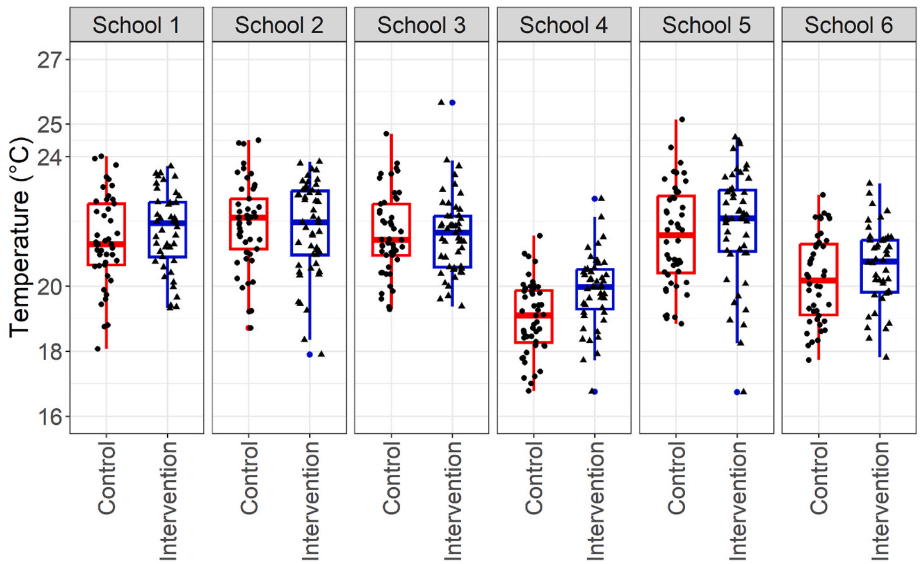

Fig. 4. Boxplot of the mean temperature in classrooms during school periods per day.

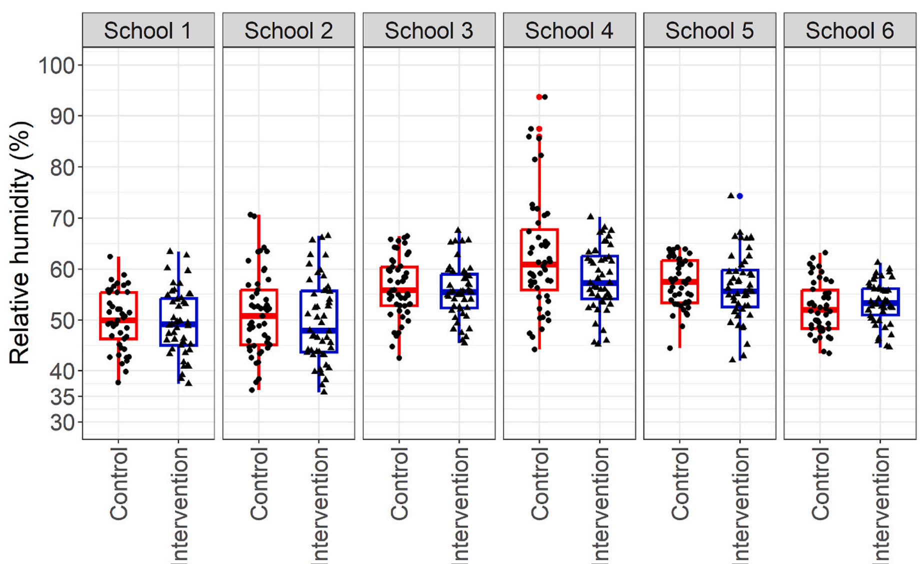

Fig. 5. Boxplot of the mean relative humidity in classrooms during school periods per day.

learning space should be in 800–1250 ppm range during the school periods per day [20]. However, mean CO_2 levels above 1250 ppm were recorded in all schools during school periods per day. CO_2 concentrations above 2000 ppm were also observed in five out of six schools, indicating widespread non-compliance.

Table 10 summaries the mean CO_2 concentrations during school periods per day in all schools, including the median (interquartile range) levels and the percentage of school periods per day with CO_2 concentrations below 1250 ppm and above 1250 ppm. The boxplot of the proportion of time during school periods per day for carbon dioxide within different ranges is shown in Fig. S4.

Amongst all schools, the median level of mean CO_2 concentrations during school periods per day was in the 1015–1921 ppm range in control classrooms, and in the 959–1854 ppm range in intervention classrooms. In three out of six schools (Schools 2, 3, and 4), the CO_2 concentrations in intervention classrooms were lower than in control classrooms, though the statistically significant difference was only observed in School 2.

In five out of six schools, the intervention classrooms had longer exposure times to CO_2 concentrations below 1250 ppm compared to the control classrooms. This outcome was attributed to the operation of the SAH.

4. Discussion

The median level of mean temperature during the school periods per day ranged from 19 °C to 22 °C. The temperature result found in this study was different from a previous NZ school study, which showed that for nine out of 35 Wellington primary classrooms, the mean temperature during school periods per day was below 18 °C, with a range of 13.4–17.7 °C [31]. In contrast to this previous NZ school study, overheating was found in the present study, as indoor temperature levels above 25 °C were observed in all schools except for School 6. To prevent overheating, adjustments to the SAH controller algorithm are required when the indoor temperature exceeds 25 °C.

All classrooms were within the NZMoE recommended temperature (18–25 °C) and relative humidity (35–70%) ranges simultaneously for more than half of the school periods, between 64% and 99% of the time.

Table 8
Summary of the mean temperature and relative humidity in classrooms during school periods per day.

Variables	School	Control classrooms, median (interquartile range)	Intervention classrooms, median (interquartile range)	p-value
Temperature (°C)	1	21.3 (20.7–22.6)	21.9 (20.9–22.6)	0.3
	2	22.1 (21.1–22.7)	22.0 (21–23)	0.84
	3	21.4 (21–22.5)	21.7 (20.6–22.2)	0.95
	4	19.1 (18.3–19.9)	20.0 (19.3–20.5)	**0**
	5	21.6 (20.4–22.8)	22.1 (21.1–23)	0.18
	6	20.2 (19.1–21.3)	20.8 (19.8–21.4)	0.14
Relative humidity (%)	1	50 (46.3–55.4)	49.1 (45–54.2)	0.56
	2	50.8 (45.1–55.9)	47.9 (43.7–55.7)	0.35
	3	55.8 (52.8–60.4)	55.4 (52.3–59)	0.45
	4	60.9 (55.9–67.7)	57.3 (54.1–62.5)	0.06
	5	57.5 (53.4–61.7)	55.7 (52.5–59.8)	0.41
	6	52 (48.4–55.8)	53.3 (51–56.2)	0.26
% of school periods per day with temperature below 18 °C	1	0 (0–1.7)	0 (0–2.2)	0.85
	2	0 (0–2.2)	0 (0–1.1)	0.85
	3	1.7 (0–3.9)	1.1 (0–7.2)	0.69
	4	16.3 (7.8–36.1)	10.6 (5.4–17.9)	0.06
	5	0 (0–7.9)	0 (0–10.4)	1
	6	3.6 (0–17.6)	5 (0–11.1)	0.62
% of school periods per day with relative humidity above 70%	1	0 (0–0)	0 (0–0)	NA
	2	0 (0–0)	0 (0–0)	0.64
	3	0 (0–0)	0 (0–0)	0.23
	4	0 (0–32.6)	0 (0–0)	**0.04**
	5	0 (0–0)	0 (0–0.1)	**0**
	6	0 (0–0)	0 (0–0)	NA
% of school periods per day with temperatures between 18 °C and 25 °C and relative humidity within 35% and 70% simultaneously	1	98.9 (93.9–100)	98.9 (95.6–100)	0.81
	2	94.4 (73.9–100)	92.2 (77.2–99.4)	0.91
	3	96.7 (87.8–98.9)	96.7 (89.4–100)	0.49
	4	64.3 (26.9–86.9)	84.8 (76.8–92.1)	**0**
	5	96.1 (87.6–100)	87.8 (76.2–98.3)	**0.04**
	6	96.1 (81.9–99.9)	94.7 (87.6–100)	0.52

A previous NZ study found a relative humidity level above 60% in classrooms for more than 50% of the school periods [31]. Differences in relative humidity levels between the present study and the previous one might be explained by the higher classroom temperature. In the present study, the mean temperature during school periods was between 18 °C and 25 °C in all classrooms, while the previous study found that 14 out of 35 Wellington primary classrooms had temperature levels below 18 °C for more than 50% of the school periods [31].

Median extant heater use during the school periods was in 16–75% range in all schools. However their use was highly teacher dependant which may explain the observed variation. Teachers also have different work routines. For example in School 5, the teachers in the participating classrooms frequently worked in the early morning and turned on extant heaters for their own comfort.

A study investigating the use of low nitrogen oxide unflued gas heaters in 22 schools in New South Wales, Australia, found that median (interquartile range) school periods per day extant heater use during four weeks was 25.7% (0–47.2%), 30.4% (6.9–47.8%), 16.7% (0–41.7%), and 0% (0–9.7%), respectively, which corresponded to a mean classroom temperature between 9 a.m. and 3 p.m. per day in the 20.5–20.9 °C range [57]. However, as the extant heater capacity and other confounding factors contributed to the classroom temperature, the extant heater use and temperature in classrooms between the results found in the present study and this Australian study is unable to be compared directly.

The CO_2 levels in School 3 and School 5 were higher than in other schools where the four classrooms from these two schools (Schools 3 and 5) had CO_2 levels above 1250 ppm for more than 80% of the school periods. The device used in this study had a maximum CO_2 detection limit of 5000 ppm. This maximum CO_2 level of 5000 ppm was found in both School 3 and School 5. This data was checked and it confirmed that the high level of CO_2 reading was not caused by someone who had exhaled onto the CO_2 sensor, as CO_2 levels above 4800 ppm lasted for from 0.1 hours to 1.2 hours in these two schools in both the control and the intervention classrooms.

There are reasons for the higher levels of CO_2 observed in School 3. Firstly, School 3 consisted of a row of four classrooms. The two participating classrooms were in the middle of the row of four classrooms. There was a cloakroom between the two participating classrooms' main entrance door and outside. This design would limit the cross ventilation and the influx of fresh air from outside. Another drawback of this design is that air with high CO_2 concentrations from adjacent classrooms may flow into other classrooms, negatively impacting classroom air quality, as the finding from Ref. [59] has shown that infiltration between classrooms influences CO_2 concentrations despite the challenge of accurately quantifying this effect. Secondly, thick curtains were observed on the north (sunny) side windows in these two participating classrooms. These curtains were consistently drawn across the windows during winter to minimize heat loss from the classroom. These factors could reduce the fresh air coming into the classroom and consequently result in a higher level of CO_2.

In terms of the high CO_2 levels in School 5, the smaller volume of the classroom and the high density of occupants could be the causes. The volume of the classroom in School 5 was 176 m^3, which was smaller than the other classrooms where the volume ranged from 183 m^3 to 314 m^3 (see Table 3). More importantly, an occupancy of 0.5 person per m^2 of floor area was reached in one of the School 5 participating classrooms while in most of other participating classrooms the density of occupants were approximately 0.35 person per m^2 of floor area. Additionally, the students in School 5 participating classrooms were typically from 10 to 13 years old and older than the students in other participating classrooms, who were 5–10 years old. The children aged from 10 to 13 years old generate higher levels of CO_2 than students aged between 5 and 10 years old, assuming students were at the same level of physical activities [15].

To improve classroom ventilation and thereby providing a healthy learning environment for students, ventilation intervention studies have been conducted in schools. Before the COVID-19 pandemic, intervention studies included but not limited to implementing different ventilation systems [39] and using custom-designed mechanical ventilation devices [40]. Gao et al. [39] reported a mean (SD) CO_2 level of 942 (185) ppm in classrooms equipped with automatically openable windows and an exhaust fan, and 757 (147) ppm in classrooms with a balanced mechanical ventilation system. Rosbach et al. reported mean CO_2 levels of 841 ppm (minimum–maximum: 743–925 ppm) and 975 ppm (minimum–maximum: 887–1077 ppm) in classrooms equipped with a custom-designed CO_2-controlled mechanical ventilation system, when the targeted indoor CO_2 levels were set at 800 ppm and 1200 ppm, respectively [40]. These results indicate that some ventilation approaches can achieve an acceptable ventilation in classrooms. However, the high capital and operation costs are beyond schools budget in most instances.

During and after the COVID-19 pandemic, monitoring CO_2 concentrations along with the windows opening advice have been investigated [60]. The CO_2 concentrations were significantly reduced by opening windows before school starts or during breaks (subject to the windows opening protocols), but it was at the expense of lowering the classroom temperature. In contrast, in the present study at least 80% of the air being brought into the classroom was pre-heated with the temperature above 18 °C.

Overall, inadequate ventilation rates in schools are a worldwide issue. Operating a roof-mounted SAH could play a positive role in increasing the temperature and increasing ventilation, thereby lowering the CO_2 concentrations in classrooms. Although in this study there was likely insufficient airflow to meet CO_2 requirements in all schools, neither did we observe the statistically significant changes in the

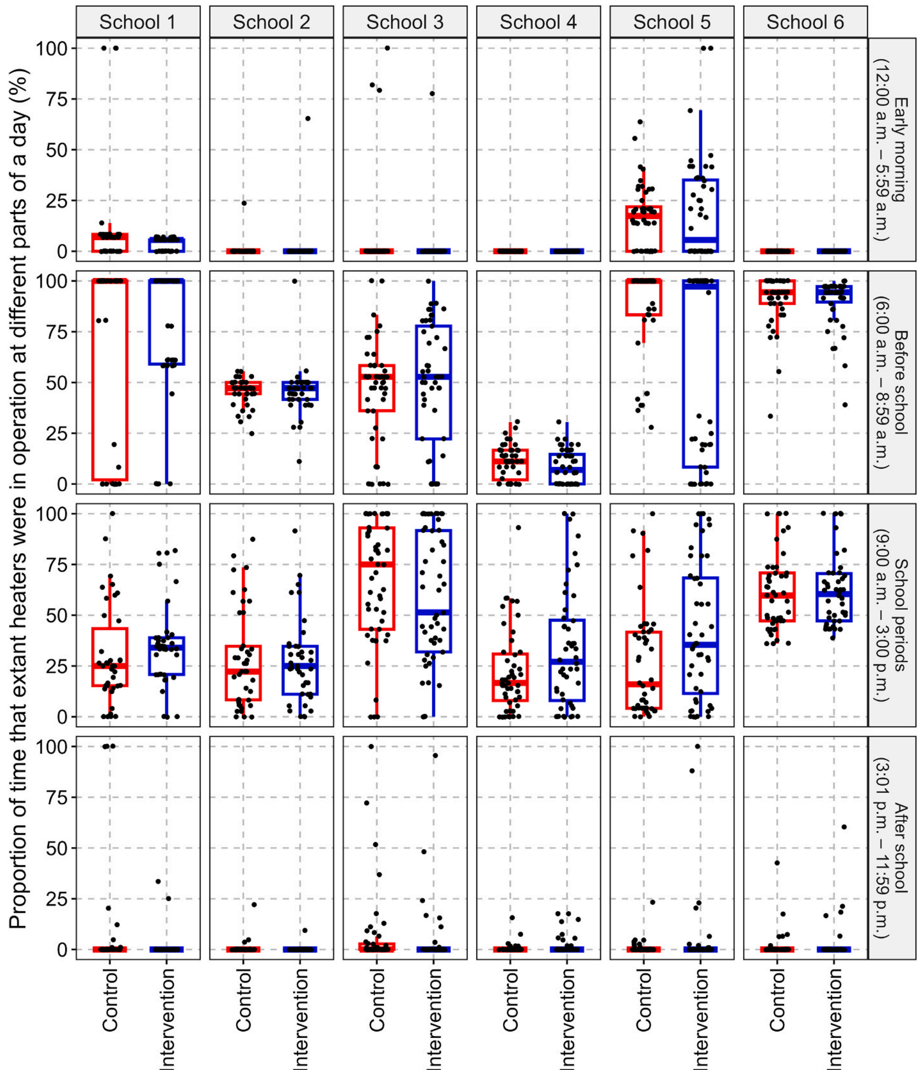

Fig. 6. Boxplot of proportion of time that extant heaters were in operation at different parts of a day.

classroom temperature, it was shown that one SAH panel could make a useful contribution to classroom air quality. In future, a temperature-compensated CO_2 set-point fan is recommended to avoid the overheating and overcome the inadequate ventilation in classrooms.

The limitations and strengths of this study are as follows. The main limitation is that the opening and closing of windows and doors were not monitored. It was assumed that windows and doors in the control and intervention classrooms from the same school had similar conditions. However, observational data during the study suggested this assumption may not be true for some schools. The analysis of CO_2 results would be beneficial if the conditions of windows and doors being open or closed, along with the airflow through these openings, had been monitored. Additionally, the heat loss of the classrooms were not measured.

Nevertheless, to our knowledge, this study is the first known investigation into the suitability of retrofitting SAHs in schools to increase ventilation using a randomised crossover design. While this study adopted an experimental intervention approach, it was not blinded. Though the classrooms users (teachers and students) were not told whether the classroom was the control classroom or the intervention classroom, it was impossible to ignore the operation of the SAH in the classroom when the warm air entered into the classroom through the ducts. However, the randomized crossover design would minimise this possible bias and the effects of other confounding factors might result in. Another strength of this study was the length of the real-time measurement. This study conducted five consecutive weeks of measurements in each intervention scenario, totaling 10 weeks, which was equal to the length of the winter school term. In comparison, some intervention studies lasted only several days or a couple of weeks. This study, conducted over 10 weeks in 12 classrooms across six schools, is more likely to provide more reliable results. Furthermore, this study demonstrates that retrofitting solar energy applications has the potential to improve the indoor environment and reduce energy consumption and is worthy of further exploration as a means to decarbonise buildings.

5. Conclusion

Most NZ schools rely on natural ventilation and are often inadequately ventilated in winter. This poses health and educational risks to occupants. This study presents the findings of a randomized crossover intervention study conducted to assess the effectiveness of retrofitting SAHs in schools and to identify potential improvements to improve air quality in classrooms. This study was conducted in 12 classrooms from six primary schools in the winter of 2014. The results showed that the mean (SD) SAH outlet air temperature was 29.2 (10.4) °C at a mean (SD) velocity of 0.7 (0.3) $m \cdot s^{-1}$. The mean volumetric flow rate of the SAH outlet air ranged between 25.6 $m^3 \cdot h^{-1}$ and 39.2 $m^3 \cdot h^{-1}$. During most school periods (64–99%) classrooms maintained temperatures in the 18–25 °C range and relative humidity in the 35–70% range

Table 9
Proportion of time extant heaters were in operation at different parts of a day.

Parts of a day	School	Control classrooms median (interquartile range)	Intervention classrooms, median (interquartile range)	p-value
Full day (12:00 a.m.–11:59 p.m.)	1	20.5 (17.8–24)	19.1 (16.8–22.8)	0.57
	2	11.5 (8.3–17.7)	12.2 (9–14.9)	0.84
	3	27.1 (19.4–36.8)	23.6 (13.9–31.9)	0.16
	4	5.9 (4.1–9.5)	9.2 (4.7–14.4)	**0.05**
	5	22.7 (17–31.9)	25.9 (14.9–42.1)	0.4
	6	26.2 (22.3–29.9)	26.2 (22.9–29.6)	0.83
Early morning (12:00 a.m.–5:59 a.m.)	1	6.9 (0–8.3)	5.6 (0–5.6)	**0**
	2	0 (0–0)	0 (0–0)	1
	3	0 (0–0)	0 (0–0)	0.3
	4	0 (0–0)	0 (0–0)	NA
	5	17.4 (0–21.9)	5.6 (0–35.1)	0.81
	6	0 (0–0)	0 (0–0)	NA
Before school (6:00 a.m.–8:59 a.m.)	1	100 (2.1–100)	100 (59–100)	1
	2	47.2 (44.4–50)	47.2 (41.7–50)	0.8
	3	52.8 (36.1–58.3)	52.8 (22.2–77.8)	0.49
	4	11.1 (2.1–16.7)	6.9 (0–14.6)	0.16
	5	100 (83.3–100)	97.2 (8.3–100)	**0**
	6	94.4 (88.9–100)	94.4 (89.6–97.2)	0.56
School periods (9:00 a.m.–3:00 p.m.)	1	25 (15.3–43.4)	34 (20.8–38.9)	0.07
	2	22.2 (8.3–34.7)	25 (11.1–34.7)	0.81
	3	75.0 (43.1–93.1)	51.4 (31.9–91.7)	0.18
	4	16.7 (8–30.9)	27.1 (8–47.6)	0.08
	5	16.0 (4.2–41.7)	35.4 (11.5–68.4)	**0.05**
	6	59.7 (47.2–70.8)	60.4 (47.2–70.5)	0.77
After school (3:01 p.m.–11:59 p.m.)	1	0 (0–0)	0 (0–0)	**0.05**
	2	0 (0–0)	0 (0–0)	0.32
	3	0 (0–2.8)	0 (0–0)	0.1
	4	0 (0–0)	0 (0–0)	0.23
	5	0 (0–0)	0 (0–0)	0.74
	6	0 (0–0)	0 (0–0)	0.83

simultaneously. The concurrent use of the extant heaters reduced, and CO_2 concentrations improved, lowering exposure for occupants. While this study demonstrated the potential of retrofitting SAHs to improve classroom air quality, it also highlighted areas where further improvements could be made.

This study is the first known investigation into the suitability of retrofitting SAHs in schools to increase ventilation with a randomised crossover design. The use of solar energy applications can assist in reducing the non-renewable energy consumption for heating and ventilating classrooms, thereby contributing to the reduction of greenhouse gas emissions. Future research needs to investigate the impact of operating a SAH on classrooms air quality, taking into account occupant behaviour. It is recommended to design custom-made SAHs for the school environment, prioritizing the maximization of volumetric flow rates while ensuring the management of thermal comfort in classrooms.

CRediT authorship contribution statement

Yu Wang: Visualization, Methodology, Investigation, Formal analysis, Conceptualization, Writing – original draft, Writing – review & editing. **Robyn Phipps:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Mikael Boulic:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Manfred Plagmann:** Writing – review & editing, Supervision. **Chris**

Table 10
Summary of the mean school period carbon dioxide concentration per day.

Variable	School	Control classrooms, median (interquartile range)	Intervention classrooms, median (interquartile range)	p-value
Mean carbon dioxide (CO_2) concentration during school periods per day (ppm)	1	1015 (777–1332)	1018 (913–1192)	0.94
	2	1115 (989–1286)	959 (819–1144)	**0.01**
	3	1921 (1663–2614)	1807 (1550–2103)	0.09
	4	1558 (1217–1999)	1457 (1194–1776)	0.12
	5	1813 (1580–2358)	1854 (1417–2307)	0.27
	6	1150 (923–1443)	1210 (941–1428)	0.58
% of school periods per day with CO_2 below 1250 ppm	1	74.4 (43.3–92.8)	75 (55.6–84.4)	0.95
	2	66.7 (48.9–77.8)	77.8 (56.7–92.8)	**0.01**
	3	6.7 (0–26.7)	13.9 (0.6–30)	0.29
	4	27.8 (10.4–55)	29.8 (15.4–58.5)	0.29
	5	17 (2.2–34.4)	18.9 (1.5–41)	0.86
	6	57.8 (38.9–81.3)	57.5 (32.7–79.7)	0.64
% of school periods per day with CO_2 above 1250 ppm	1	25.6 (7.2–56.7)	25 (15.6–44.4)	0.95
	2	33.3 (22.2–51.1)	22.2 (7.2–43.3)	**0.01**
	3	93.3 (73.3–100)	86.1 (70–99.4)	0.29
	4	72.2 (45–89.6)	70.2 (41.5–84.6)	0.29
	5	83.1 (65.6–97.8)	81.1 (59–98.4)	0.86
	6	42.2 (18.7–61.1)	42.5 (20.3–67.3)	0.64

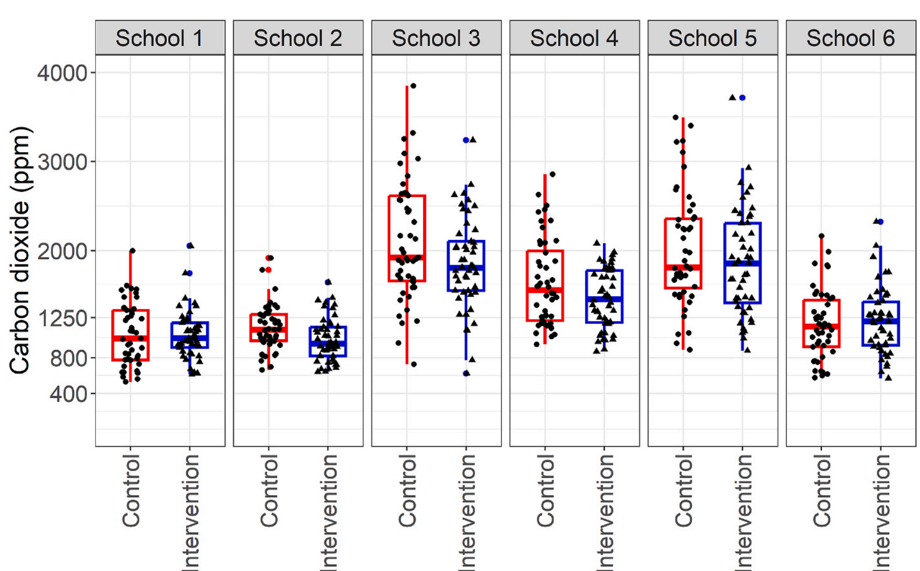

Fig. 7. Boxplot of the mean carbon dioxide concentration in classrooms during school periods per day.

Cunningham: Writing – review & editing. **Gaëlle Guyot:** Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111552.

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