

Indoor Environmental Quality of Social Housing Buildings in British Columbia



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Executive Summary

On behalf of BC Housing, RDH Building Science Inc. conducted a monitoring study to understand the indoor environmental quality (IEQ) of existing multi-unit social housing buildings in the Metro Vancouver area. The study identified trends in monitored temperature, humidity, and carbon dioxide (CO₂) concentrations as well as analyzed the IEQ impact of building retrofits and upgrades.

Twenty-five suites across five buildings were selected for this study. Indoor conditions were quantified with sensors that collected ambient air temperature, relative humidity (RH), and CO₂ concentrations at 15-minute intervals. Suite airtightness and airflow rates through the bathroom exhaust fans were also measured both before and after the retrofit periods.

The study revealed overheating to be a significant IEQ issue. On average, the suites experienced more than 700 hours with the indoor air temperature exceeding 26°C, with peaks in excess of 31°C. Four of five buildings were equipped with central heating systems with no suite-level control, and all buildings relied on passive measures (e.g., opening windows) for cooling. While the building with more window openings and suite-level control of thermostats experienced less overheating, it was a general finding that passive cooling was insufficient to ensure BC Housing's overheating guidelines were met.

CO₂ concentrations generally remained below 1,100 ppm, with elevated concentrations typically experienced overnight. Elevated CO₂ concentrations overnight suggests reduced ventilation (i.e., closing windows, turning off exhaust fans) and/or increased occupancy (i.e., returning from work).

All of the measured suites are ventilated with an exhaust only strategy, with the intent that make-up air is provided from the corridor and open windows. Prior to the building retrofits, the measured exhaust airflow rates were generally lower than those specified by the relevant codes and standards. While some of the building retrofit packages included replacement of the exhaust fans, improved exhaust fan performance had no significant impact on the monitored IEQ parameters. This is likely the result of a lack of use, which may be due to fan noise or other factors.

Pre- and post-retrofit airtightness measurements varied significantly across the suites. No significant trends were observed. This is likely a result of retrofits not being specifically focused on improving airtightness. However, buildings that underwent window replacements generally showed an improvement in airtightness of between 5% and 20%.

The building retrofit measures from this study were focused on building enclosure and mechanical upgrades. While retrofit measures such as window and exhaust fan replacements have an impact on IEQ, the reliance on open windows for ventilation and cooling likely reduced the potential impact of these upgrades and no change in the IEQ trends were observed post-retrofit. For future building retrofits seeking IEQ improvements, specific IEQ strategies including suite-level controls, active cooling, and suite compartmentalization should be considered.

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1 Introduction

This study evaluated the indoor environmental quality (IEQ) of social housing suites throughout the Metro Vancouver area. IEQ encompasses the conditions within a space that impact occupant health and comfort. Although IEQ includes many factors such as lighting, air quality, acoustics, and more, this study focused primarily on indoor air properties including air temperature, relative humidity, dew point temperature and CO₂ concentrations. The specific project objectives included:

- Analyzing the IEQ of units both before and after the buildings have undergone various retrofit upgrades,
- Characterizing the impact of building enclosure and ventilation system retrofit measures with respect to IEQ metrics, and
- Examining the impact of wildfire smoke ingress and COVID-19 on suite IEQ.

Other indoor air contaminants, such as particulate matter and volatile organic compounds were not measured as part of this study. The following subsections describe the measured variables from this study in further detail.

1.1 Air Temperature & Relative Humidity

Air temperature and relative humidity are basic properties used to characterize ambient conditions within a space and to predict thermal comfort. Ambient air temperature is affected by many factors including solar heat gain, mechanical heating and cooling, internal gains (e.g., occupants, lights, computers), air leakage, and more. Air temperatures between 20°C and 26°C are typically considered to be within an acceptable thermal comfort zone, although individual sensations of comfort vary significantly on clothing, activity, radiant temperature, air speed, and relative humidity.¹

Relative Humidity (RH) is a measure of the moisture in the air compared to the maximum amount of moisture air at that temperature can hold. HVAC systems serving residential occupancies in B.C. are typically designed to remove excess moisture through fresh air ventilation.

A thorough discussion of RH is provided by Lstiburek.² While ASHRAE and CSA provide limited guidance on appropriate levels of RH, there is no consensus on the appropriate RH within a building. Typically, the industry accepts RH values from 20% to 60%, with Health Canada recommending a narrower range between 30% and 55%. Note that lower condensation values are often required to avoid condensation in cold climates.

The human comfort range for RH again depends on the individual and other environmental factors but is generally considered to be between 30-55%.³ RH levels below this range can cause irritation and levels above may cause feelings of discomfort or deterioration of interior finishes. The World Health Organization identifies high levels of

¹ ASHRAE 2017, "ANSI/ASHRAE Standard 55-2017 – Thermal Environmental Conditions for Human Occupancy". American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

² RH – Research Report 0203. Building Science Corporation. <https://buildingscience.com/documents/reports/rr-0203-relative-humidity/view>.

³ ASHRAE, 2013. 2013 ASHRAE Handbook: Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 2013.

moisture as a hazard to human health. This is at least partially due to biological growth on interior surfaces (mould, bacteria, fungi, etc.)⁴ which has been correlated with increases in respiratory symptoms such as coughing and wheezing⁵ and infections.⁶

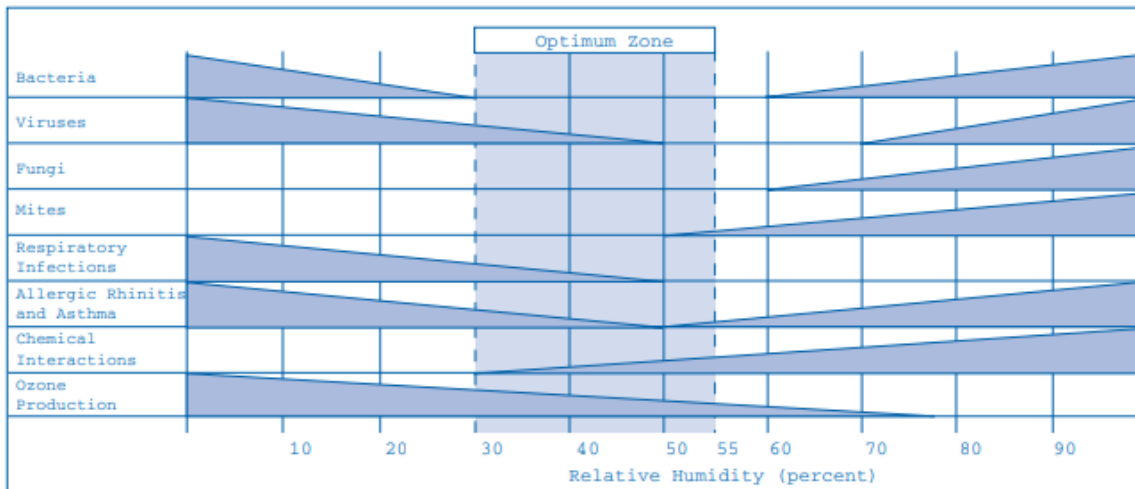


Figure 1.1 – Health range of indoor RH according to Health Canada.

1.2 Carbon Dioxide & Ventilation

Ventilation is provided to the indoor environment to control pollutant build-up and to contribute to satisfactory IEQ conditions. Ventilation can be provided to residential buildings through a variety of system types including corridor make-up air units, balanced in-suite ventilation, intermittent exhaust fans (washroom or kitchen), or natural ventilation designs. The ASHRAE standards for ventilation distinguish between low-rise residential (ASHRAE 62.2-2019) and other residential (mid- and high-rise) or commercial buildings (ASHRAE 62.1-2019).^{7,8} These standards have been adopted in numerous forms within North American building codes including the British Columbia (B.C.) Building Code, the International Mechanical Code, the Uniform Mechanical Code, and California Title 24, Part 6, among other codes.

ASHRAE Standards 62.1 and 62.2 provide a prescriptive *Ventilation Rate Procedure* used to size the ventilation equipment. The procedure aims to maintain indoor carbon dioxide (CO₂) levels below ~1,100 ppm (700 ppm above the outdoor air concentration of ~400 ppm) by specifying a per person ventilation rate for various occupancy types. This target is based on earlier research that linked CO₂ with perceived IEQ issues related to bioeffluents and odours. An additional floor area-based ventilation rate is included to

⁴ WHO, 2009, “WHO Guidelines for Indoor Air Quality: Dampness and Mould”. The WHO European Centre for Environmental Health, Bonn, Germany.

⁵ Fisk et al., 2007. “Meta-analyses of the associations of respiratory health effects with dampness and mold in homes”. *Indoor Air* 17: 284-296

⁶ Fisk et al., 2010. “Association of residential dampness and mold with respiratory tract infections and bronchitis: a meta-analysis”. *Environmental Health* 9: 72.

⁷ ASHRAE 2019a, “ANSI/ASHRAE Standard 62.1-2019 – Ventilation for Acceptable Indoor Air Quality”. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

⁸ ASHRAE 2019b, “ANSI/ASHRAE Standard 62.2-2019 – Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings”. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

control build-up of other indoor contaminants such as volatile organic compounds (VOCs) that impact IEQ.⁹

While there are numerous indoor pollutants that could be monitored to evaluate IEQ, the majority of the current indoor environmental design methodologies use CO₂ as a proxy for measuring IEQ and controlling ventilation. There are three advantages to using CO₂ as a proxy for IEQ:

- 1) CO₂ has a consistent indoor source (occupant respiration),
- 2) CO₂ can easily be measured, and
- 3) CO₂ has historically been considered benign at the low concentrations typically seen in buildings.

Numerous studies have linked exposure to poor IEQ to detrimental health impacts including: cognitive decline, fatigue, eye, nose, and throat irritation, headaches, dizziness, respiratory disease, heart disease, and cancer.¹⁰ As a result of these studies and potential health impacts, exposure limits have been set for a number of pollutants.¹¹ A 2012 study showed moderate declines in cognitive performance with exposure to CO₂ concentrations of 1,000 parts per million (ppm) and significant declines at concentrations of 2,500 ppm compared to baseline testing at 600 ppm.¹² A follow-up study controlling both CO₂ and VOC concentration in a simulated office environment similarly showed that increased CO₂ concentration reduced cognitive function.¹³ In addition, the study found that a 500 µg/m³ increase in Total VOC exposure was associated with a further 18% decline in cognitive function. Intervention studies of CO₂ reductions on student testing showed improved results for concentration changes from 1,300 ppm to 900 ppm.¹⁴ Exposure to elevated bedroom CO₂ concentrations have also been shown to result in decreased perceived and measured sleep quality and to cause reductions in next day performance using intervention studies in college dormitories.¹⁵ The research indicates that CO₂ levels in homes and workplaces can lead to productivity losses even at near to design concentration levels. Research also suggests that CO₂ is a potential indicator of health impacts from other pollutant sources.

While several studies have linked CO₂ concentrations to negative health outcomes, other studies have contradicted these findings.¹⁶ Recognizing the need for further study, research in the area of IEQ, ventilation, and work performance is identified as a goal in ASHRAE's current strategic research plan as well as their 2019–2024 Strategic Plan.

⁹ Persily, A. 2015, "Challenges in Developing Ventilation and Indoor Air Quality Standards: The Story of ASHRAE Standard 62", *Building and Environment* 91: 61-69.

¹⁰ WHO 2010, "WHO Guidelines for Indoor Air Quality", The WHO European Centre for Environmental Health, Bonn, Germany.

¹¹ Government of Canada 2015, "Residential Indoor Air Quality Guidelines" Available at: <http://healthycanadians.gc.ca/healthy-living-vie-saine/environnement-environnement/air/guidelines-lignes-directrices-eng.php>

¹² Satish et al. 2012, "Is CO₂ an Indoor Pollutant? Direct Effects of Low-to-Moderate CO₂ Concentrations on Human Decision-Making Performance", *Environmental Health Perspectives* 120(12): 1671-1677.

¹³ Allen, J.A. et al. 2015, "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments", *Environmental Health Perspectives*, DOI:10.1289/ehp.1510037

¹⁴ Wargocki, P. and Wyon, D.P. 2007, "The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257)", *HVAC&R Research* 13(2): 165-191.

¹⁵ Strom-Telsen, P et al. 2015, "The Effects of Bedroom Air Quality on Sleep and Next-Day Performance", *Indoor Air*, doi: 10.1111/ina.12254.

¹⁶ Fisk, Wargocki, and Zhang. 2019, "Do Indoor CO₂ Levels Directly Affect Perceived Air Quality, Health, or Work Performance?"

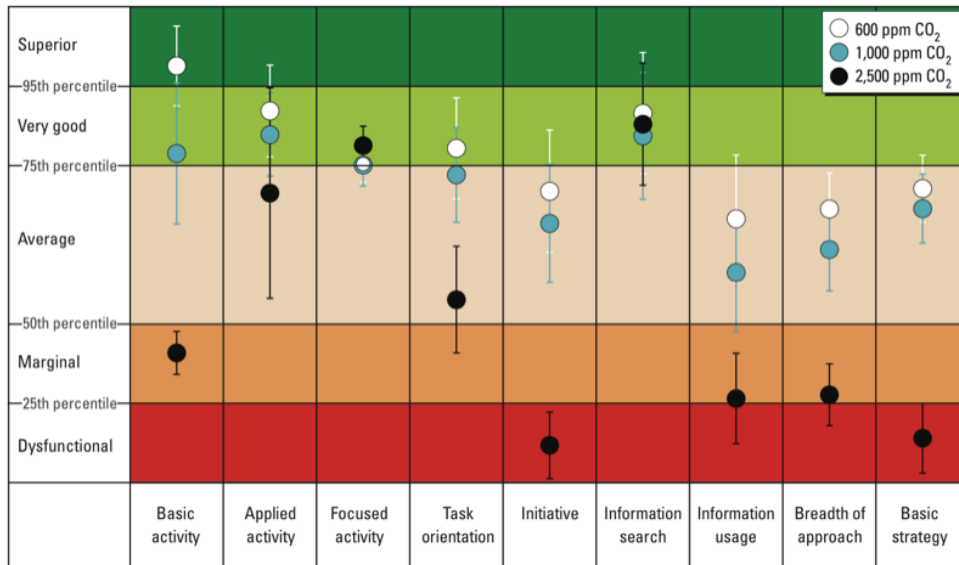


Figure 1.2 – Cognitive function test results for variations in CO₂ exposure (from Satish et al. 2012). Results show that increased levels of CO₂ can impact cognitive functions like information usage and basic strategy (dark black dots); however, findings are not consistent in all cases and vary significantly based on the wide range of whiskers of each dot.

Despite the observed relationships between CO₂ exposure and cognitive performance, the design and operation of many of our buildings expose occupants to elevated CO₂ levels. Numerous indoor CO₂ studies have documented concentrations in excess of 1,000 ppm in schools, daycares, offices, and homes with potentially significant impacts on human performance.^{17,18,19,20}

In addition to elevated CO₂ concentrations, a long-term monitoring study of a 13-storey multi-unit residential building (The Belmont) performed by RDH Building Science Inc. (RDH), and funded by an industry consortium including BC Hydro, BC Housing, FortisBC and others, showed that CO₂ concentrations in multi-unit residential buildings varied based on suite location within the building.²¹ Figure 1.3 shows the fraction of time the average concentration in suites on six different floors of a high-rise multi-unit residential building is above a specified threshold. CO₂ concentrations in suites on the upper floors were (top 25% of the building) generally below the design threshold of 1,100 ppm, whereas concentrations in suites on the lower floors (lower 25% of the building) were found to exceed this concentration more than 65% of the time. What this study and others have shown is that the in-service CO₂ concentration of a building, even one designed to ASHRAE standards, is generally unknown. IEQ and the importance of effective ventilation are garnering increased interest within the building industry and the public. This interest has identified a need for further monitoring studies aimed at establishing a baseline for the existing IEQ within our buildings and to subsequently measure the potential impacts

¹⁷ Bakó-Biró, Zs. et al. 2012, “Ventilation rates in schools and pupils’ performance”, Building and Environment 48: 215-223.

¹⁸ St-Jean, M. et al. 2012, “Indoor Air Quality in Montreal Area Day-Care Centres, Canada”, Environmental Research 118: 1-7.

¹⁹ Montgomery et al. 2015, “Comparison of the indoor air quality in an office operating with natural or mechanical ventilation using short-term intensive pollutant monitoring”, Indoor and Built Environment 24(6): 777-787.

²⁰ Eklund K. et al. 2015, “Pacific Northwest Residential Ventilation Effectiveness Study” Northwest Energy Efficiency Alliance Report #E15-015.

²¹ Montgomery, J. 2015, “Air Quality in Multi-unit residential buildings”, RDH Technical Bulletin No. 009.

of common retrofits strategies.

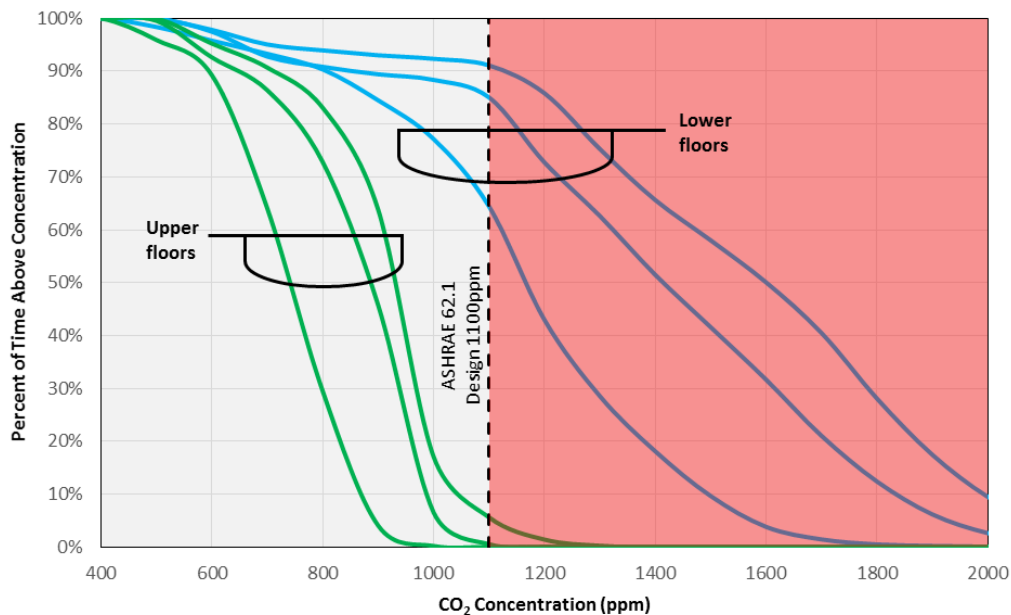


Figure 1.3 – Fraction of time the average suite CO₂ level is above a given concentration in The Belmont Building. Each line represents a separate floor in the building.

1.2.1 Ventilation Codes & Standards

The requirements for ventilation systems are outlined in the BC Building Code (BCBC) in Part 9.32 for self-contained dwelling units and Part 6.2.2 for ventilation in Part 3 Buildings. Ventilation system design requirements consist of both continuous general ventilation for the building as well as local exhaust ventilation requirements in kitchens and washrooms. A description of the compliance paths and the referenced standards are provided below along with a summary of the required ventilation rates in *Table 1.1*.

The ventilation requirements in Part 9 – *Housing and Small Buildings* of the building code differ depending on the type of system installed and are outlined in Subsection 9.32.3. Ventilation (i.e., outdoor air) is required to be provided to all living areas and all bedrooms within a dwelling unit. The code allows for compliance through prescriptive details in the subsection or alternately through CAN/CSA-F326-M.

CAN/CSA-F326-M91 *Residential Mechanical Ventilation Systems* “defines the requirements for performance, installation and application, and performance verification of mechanical ventilation systems”. It is specifically listed as a compliance path in the BCBC 9.32. The standard provides design guidelines for the ventilation system and specifies the minimum ventilation airflow requirements.

The ventilation requirements for Part 3 buildings are outlined in subsection 6.2.2 and indicate that compliance can be shown through adherence to the details in that part or through Subsection 9.32.3 for self-contained mechanical ventilation systems serving only one dwelling unit. The ventilation airflow rates for systems designed to conform with Part 6 reference ASHRAE 62-2001 (except Addendum n).

ASHRAE 62-2001 *Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2001) provides guidance on the minimum ventilation to be provided in commercial, institutional, and residential buildings. It is referenced in the existing BCBC 2018 Part 6 as the basis for the ventilation flow rates (6.3.1.1.2). The ventilation rate procedure described in Section 6.1 of ASHRAE 62-2001 indicates the amount of supply air required for residential facilities (Table 2.3 of ASHRAE 62-2001) as well as installed mechanical exhaust capacities.

In 2004, ASHRAE 62 was split into separate standards for low-rise residential buildings (62.2) and all other buildings (62.1). Standard 62.1 was responsible for multi-family residential buildings of four stories or more while 62.2 was responsible for other residential spaces. The revisions for the 2016 version of the standards removed residential occupancies from the scope of 62.1 and placed the responsibility of the dwelling units within 62.2 regardless of building height while maintaining the criteria for common areas (i.e., corridors) within 62.1. ASHRAE 62.1 and 62.2-2016 are not referenced in the building codes but are the latest iteration of this ventilation standard. A summary of the ventilation system design airflow rates is compared in *Table 1.1*. It is important to note that BC Housing ventilation rates are more stringent than code interpretations, especially for Part 3 buildings. BC Housing requirements and minimum ventilation rates can be found in Section 4 Division 23 00 00 of the Design Guidelines and Construction Standards.²²

TABLE 1.1 COMPARISON OF VENTILATION AIR REQUIREMENTS FOR DIFFERENT DESIGN STANDARDS (L/S). (MULTIPLY L/S BY 2.12 TO DETERMINE CFM.)				
Code	Note	Continuous	Kitchen (Intermittent/continuous)	Washroom (Intermittent/continuous)
BCBC 9.32	Based on the number of bedrooms and floor area.	14 - 78	47 / n.a.	23 / 9
	<u>Example:</u> 1 bdrm, <140m ²	14		
	<u>Example:</u> >7 bdrms, >700m ²	78		
CSA-F326	Based on the number of rooms of each type	5 - 10 per room	50 / 30	25 / 10
	<u>Example:</u> 1 bdrm, 1 bath, living room, kitchen	25		
BCBC 6.2.2	ASHRAE 62-2001 except addendum n referenced for airflow rates.			
ASHRAE 62-2001	Ventilation rate of 0.35 ACH required. Typically satisfied by natural ventilation. <u>Example:</u> 140 m ² apartment with 8 ft ceilings	33	50 / 12	25 / 10
ASHRAE 62.2-2016	Ventilation based on occupants (3.5 L/s/pp) and floor area (0.15 L/s/m ²) <u>Example:</u> 1 bdrm, 140m ²	28	50 / 5 ACH kitchen volume	25 / 10

²² <https://www.bchousing.org/sites/default/files/media/documents/BCH-Design-Guidelines-Construction-Standards.pdf>

2 Methodology

2.1 Building & Suite Selection

The buildings included in this study were selected by BC Housing from their building stock in the Metro Vancouver area. Buildings were limited to those scheduled for a retrofit some time after the initial monitoring period. Retrofits of interest included envelope upgrades, weatherization, make-up air unit replacements, roof replacements, and upgrades to in-suite exhaust fans.

Attempts were made to select suites within each building to provide a representation of the different types (single room occupancy, 1 bedroom, 2 bedroom, etc.) and suite locations. The general selection criteria, if applicable, were to monitor at least two suites per floor on three floors in each building to cover a representative selection of suite locations and to capture differences in occupant behaviour. The actual suites included in the study were influenced by vacancies and willingness of occupants to participate.

Generally, monitoring was limited to six suites in each building. Sensors were installed in the main bedroom and in the common area (kitchen or living room) of each suite with one or more bedrooms. Studio or single room occupancy (SRO) units were equipped with a single sensor.

2.2 Data Collection & Processing

The methodology used in this work consisted of pre/post-retrofit monitoring of IEQ metrics within individual suites of each of the five buildings. The following subsections present the collected data and describe how the data was processed prior to analysis.

2.2.1 Suite Airtightness

Airtightness tests were performed pre- and post-retrofit to identify potential changes in the air leakage rates and to compare against other ventilation rates. The methodology chosen for the blower door test is outlined in the Residential Energy Services Network (RESNET) Section 802 Procedures for Building Enclosure Airtightness Testing with modifications to treat the individual suites as dwelling units.²³ The suites were tested in an operational state with the windows closed, the kitchen/bathroom exhaust ventilation off, and the mechanical penetrations un-taped. Calculations were performed in accordance with ASTM E779-10. This information will be used to characterize the relative change in air leakage caused by the retrofits.

²³ RESNET Mortgage Industry National Home Energy Rating Systems Standard.
http://www.resnet.us/standards/RESNET_Mortgage_Industry_National_HERS_Standards.pdf

2.2.2 Indoor Environmental Quality

Monitoring equipment was installed to monitor environmental conditions within each suite. The sensors used were Onset's HOBO MX1102 sensors.²⁴ These sensors collect measurements of the ambient air temperature, the RH and the CO₂ concentrations at a 15-minute interval. The sensor is shown in *Figure 2.1*. Outdoor weather data from a local weather station was used for analytical purposes. To avoid skewing the results, sensor locations were carefully chosen to minimize impact of localized variations in the suite, such as proximity to local heat sources or direct exposure to solar radiation.

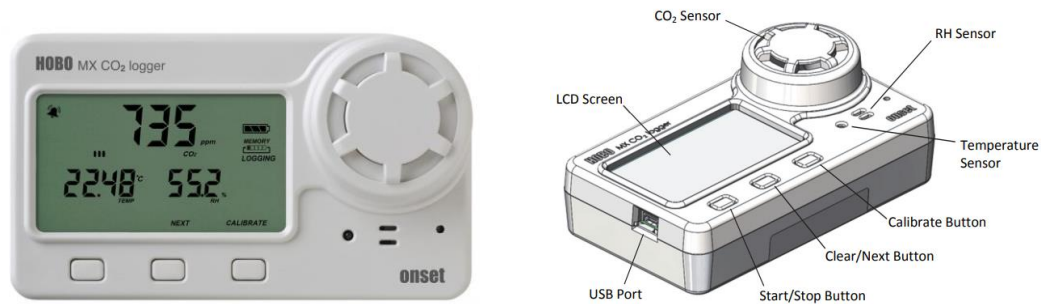


Figure 2.1 – HOBO MX1102 sensors for measuring ambient air temperature, RH and CO₂.

Data Processing

The raw data collected from the sensors was processed prior to analysis. The processing included removal of outliers and blank data, standardized the time zone, calibrating the CO₂ results, and calculation of additional outputs.

Figure 2.2 summarizes the data processing procedure.

2.2.3 Other Characteristics

In addition to the monitoring data, information regarding the building characteristics and typical operation was gathered including:

- Building enclosure design characteristics
- HVAC system design, controls and operation information for common areas and suite specifics
- Airflow and pressure measurements
- Exhaust fan flow rates pre/post-retrofit
- Description of suite operation (including frequency of window opening) and typical schedules from tenants
- Notes on any moisture damage, condensation, or fungal growth concerns

²⁴ Carbon dioxide measurement accuracy is ± 50 ppm $\pm 5\%$ of reading at 25°C (77°F), less than 70% RH and 1,013 mbar. Temperature measurement accuracy is ± 0.21 °C from 0° to 50°C (± 0.38 °F from 32° to 122°F). RH reading accuracy is $\pm 2.5\%$ from 10% to 90% RH (typical), to a maximum of $\pm 3.5\%$.

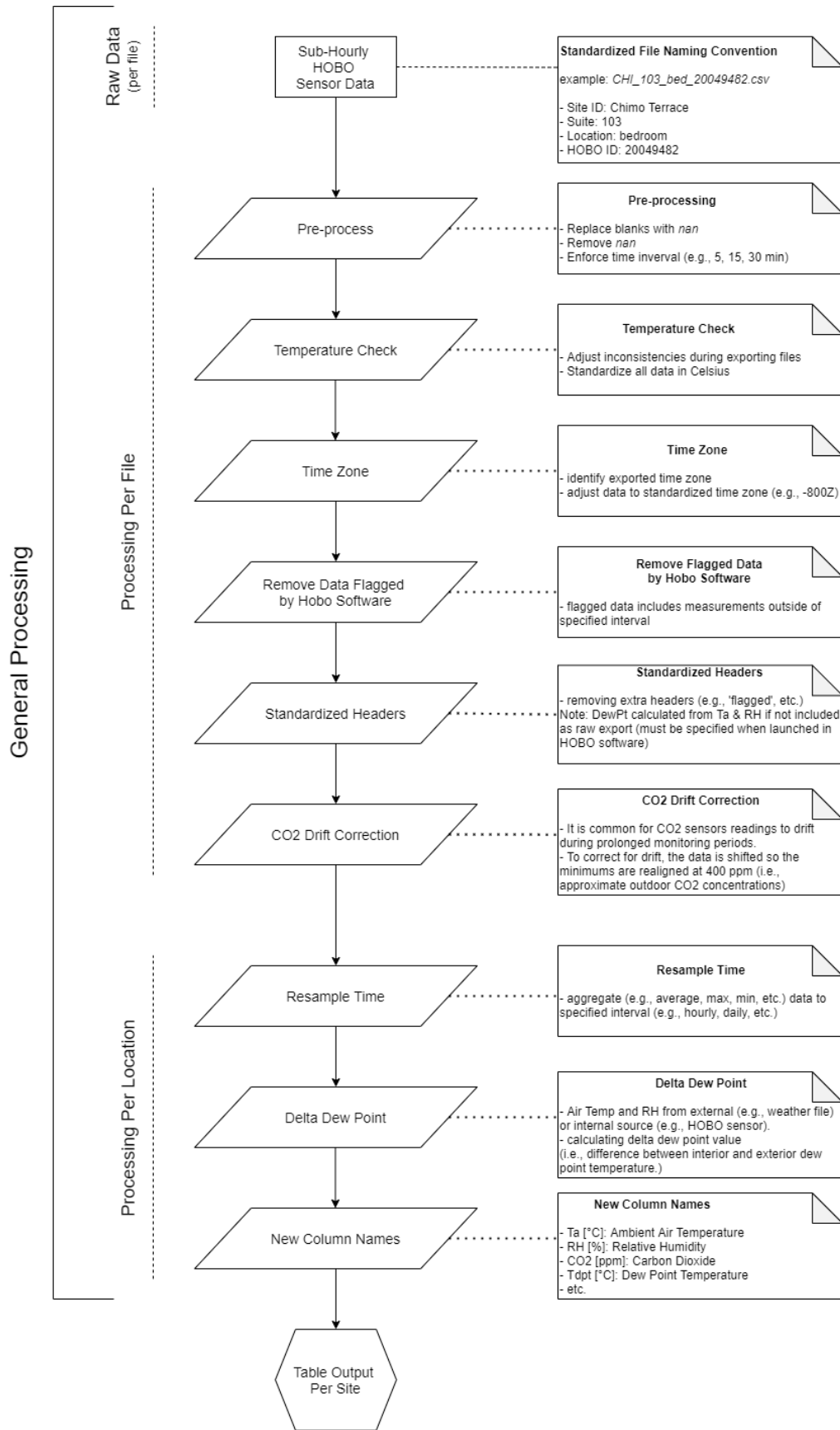


Figure 2.2 – General data processing flow chart

3 Building Information

To quantify IEQ, sensors were installed within 25 individual suites across five social housing buildings planned for various retrofit measures. A summary of the building information is provided in the *Table 3.1*.

Location	Building A	Building B	Building C	Building D	Building E
Building Type	Multi-Unit Residential	Multi-Unit Residential	Multi-Unit Residential	Townhouse	Multi-Unit Residential
Storeys	3	3	8	2	4
Total # Suites	14	43	103	65	146
# Suites Monitored	5	6	6	2	6
# of Sensors	8	12	10	6	6
Sensor Installation Date	Feb. 15, 2017	May 11, 2017	Apr. 13, 2017	Feb. 16, 2017	Dec. 21, 2016
Retrofit Period	Jun 2017 – July 2018	Sep 2018 – Aug 2019	Jun 2017 – Nov 2018	Sep 2017 – Sep 2018	Feb 2017 – Jul 2017
Retrofit Description	<ul style="list-style-type: none"> · window and exterior door replacement · targeted washroom fan upgrade 	<ul style="list-style-type: none"> · window and exterior door replacement · suite washroom fan replacements + motion sensors · new building CO₂ heat pumps (6) 	<ul style="list-style-type: none"> · roof replacement · Seismic upgrade to brick cladding (including humidity control upgrade) 	<ul style="list-style-type: none"> · window and exterior door replacement · roof shingle replacement · suite washroom fan replacement · attic insulation and air sealing 	<ul style="list-style-type: none"> · window and exterior door replacement · low slope and metal roof replacement · suite washroom fan replacement · exterior bricks cleaned and sealed · building heating and ventilation system automation

3.1 Building A

Building A consists of a mixture of low-rise apartment and townhouse buildings. The building included in this study is a three-storey, wood-frame low rise apartment building with 14 suites that open to an exterior corridor on each level. All suites in the building are one-bedroom apartments with a living room, kitchen area, bedroom, and a washroom. Suite ventilation is provided by intermittent exhaust fans located in the kitchens and washrooms. The building renewal included replacement of the windows and sliding doors, and upgrades to some washroom exhaust fans.

Five suites of the original proposed six had CO₂ sensors installed during the site visit. The sixth suite did not wish to participate in the study. Additionally, two other suites indicated that they did not want sensors installed in bedrooms. The final sensor locations are shown in *Figure 3.1*. The suites layout is identical on all floors of the building.

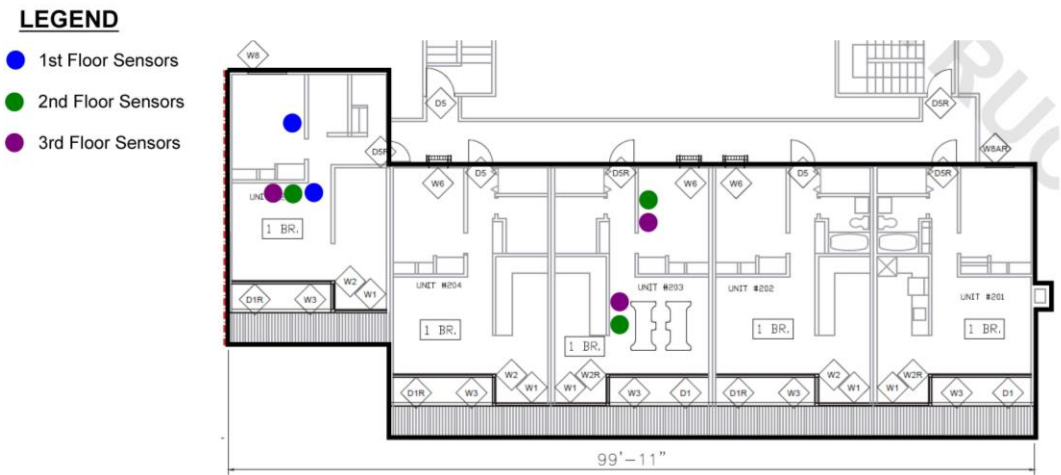


Figure 3.1 – Location of sensor installations at Building A

3.2 Building B

Building B consists of two three-storey wood-frame low-rise apartments. Only one of the two buildings was included in the study. The building consists of a mixture of one-bedroom and two-bedroom units with an interior corridor. Corridor ventilation is provided by dedicated fans in the stairwells at each end of the corridor on each floor to pressurize the common area. Suite ventilation is provided by intermittent exhaust fans located in the kitchen and washrooms. The building renewal included replacement of the windows and sliding doors.

Two suites on each floor of the building had sensors installed. Two CO₂ sensors were installed in the participating suites. The sensor locations within the building are shown on the floor plan in Figure 3.2. The suites layout is identical on floors one through three.

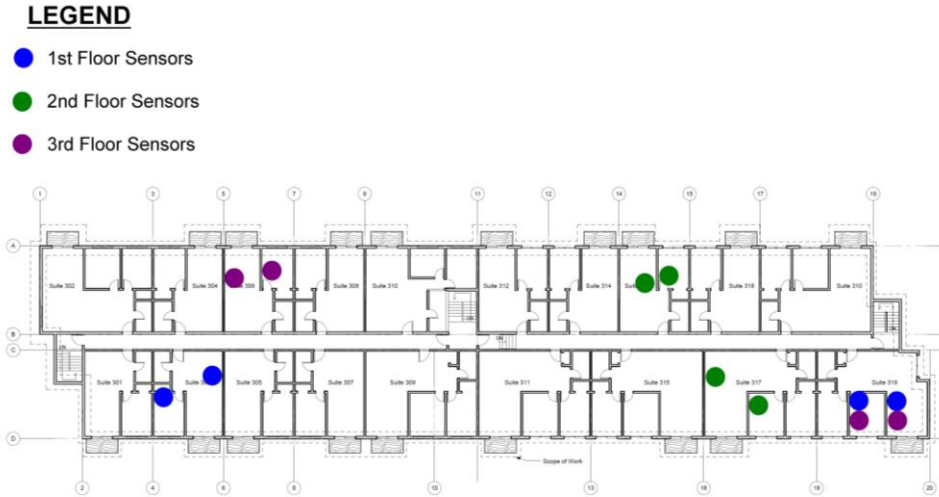


Figure 3.2 – Location of sensor installations at Building B

3.3 Building C

Building C consists of a high-rise apartment building and several townhouses. The building included in this study is an eight-storey, concrete high-rise apartment building with 149 suites with a mixture of SRO and one-bedroom designs. The building ventilation is provided by a make-up air unit located in the first-floor mechanical room that supplies to the corridor in the center of each floor. The suites do not have direct ventilation but are equipped with intermittent exhaust fans in the washroom and kitchen. The enclosure related building renewal included roof replacement and seismic upgrade of the brick cladding, and bathroom exhaust fan replacement including humidity controls.

Six suites, one SRO and a one-bedroom unit on each of levels 3, 5, and 7, agreed to participate in the study. One CO₂ sensor was installed in each of the three SRO units and two sensors in each of the one-bedroom units along with an additional sensor in the 5th floor corridor to capture common air background conditions. The sensor locations within the building are shown on the floor plan in *Figure 3.3*. The suites layout is identical on level 3 to level 7.

LEGEND

- 3rd Floor Sensors
- 5th Floor Sensors
- 7th Floor Sensors



Figure 3.3 – Location of sensor installations at Building C

3.4 Building D

Building D is a townhouse development consisting of a total of 65 units in nine clusters. The buildings are wood frame construction with two to four bedrooms over two storeys. Building D is the only building where occupants have control of the heating, whereas the others rely on centralized heating systems. Ventilation is provided by intermittent exhaust fans located in the kitchen and washrooms. The floor plan for participating units at Building D is shown in *Figure 3.4*. The building renewal included replacement of the windows and sliding doors, new washrooms exhaust fans, improved attic ventilation and air sealing.

LEGEND

- 1st Floor Sensors
- 2nd Floor Sensors

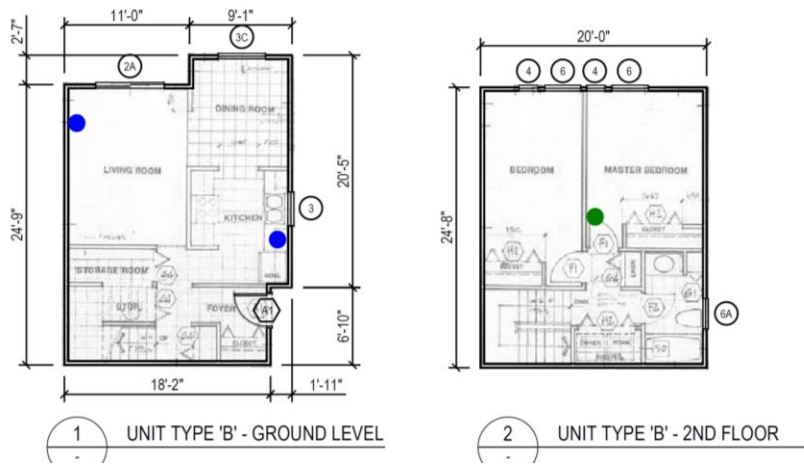


Figure 3.4 – Location of sensor installations at the Building D

Two units in the townhouse complex agreed to participate in the study. The townhouses were significantly larger than the suites at the other locations in the study and therefore warranted additional sensor coverage to determine a proper distribution. Three CO₂ sensors were installed in each of the suites to capture conditions in the living room, the bedroom and the kitchen. Locations of the sensors are indicated in Figure 3.4.

3.5 Building E

Building E is a four-storey concrete low-rise apartment. The building consists of two wings (West and East) off a central corridor (North). All suites in the building are SRO containing a living/sleeping area and a washroom. The building ventilation is provided by a rooftop make-up air unit that supplies in to the North and East wings and exhausts from the West wing. The suites do not have direct ventilation but are equipped with intermittent exhaust fans in the washroom. The building renewal included replacement of the windows in suites and common areas, replacement of exterior doors, sealing of bricks and a partial cladding replacement. One CO₂ sensor was installed in each of the six suites. The sensor locations within the building are shown on the floor plan in Figure 3.5.

LEGEND

- 2nd Floor Sensors
- 3rd Floor Sensors
- 4th Floor Sensors



Figure 3.5 – Location of sensor installations at Building E

4 Analysis & Discussion

This section provides an analysis and discussion of the measured parameters of this study, including suite airtightness, corridor pressurization, exhaust fan flow rates and IEQ. *Figure 4.1* is a Gantt chart of the study timeline including important dates and days monitored. Monitoring data was lost in the period of June to August 2019 as a result of suite access issues and the sensors losing power.

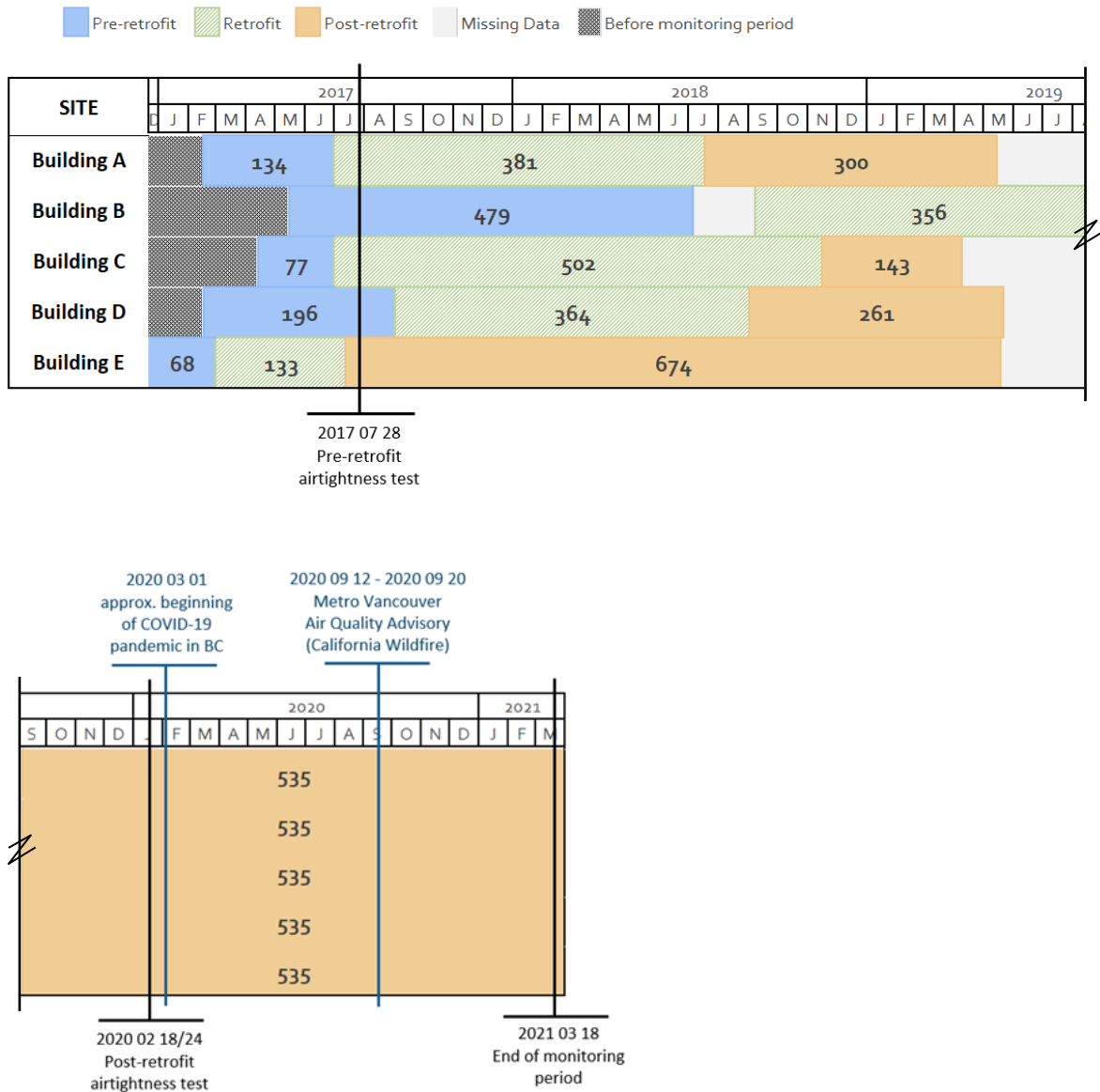


Figure 4.1 – Gantt chart of study timeline, important dates and number of days monitored

4.1 Suite Airtightness

A blower door test was performed on each unit within the study sample to allow for comparison of air leakage before and after the retrofit measures. Air leakage testing was performed with windows closed, but with all other openings including the bathroom and kitchen exhaust fans unsealed to represent the typical in-service conditions.

The suite level airtightness results, expressed as an air change rate at 50 Pa (ACH50) are presented for pre-retrofit and post-retrofit blower door testing, respectively in *Figure 4.2* and *Figure 4.3*.

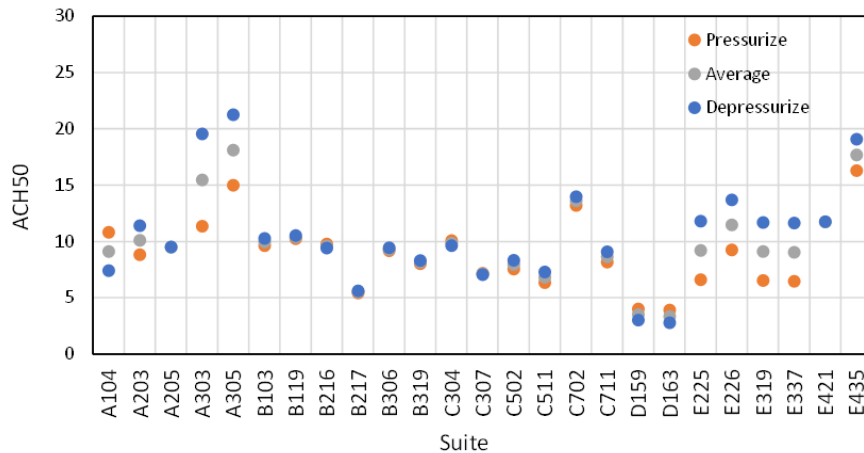


Figure 4.2 – Summary of suite air change rates at 50 Pa (ACH50) from pre-retrofit blower door testing

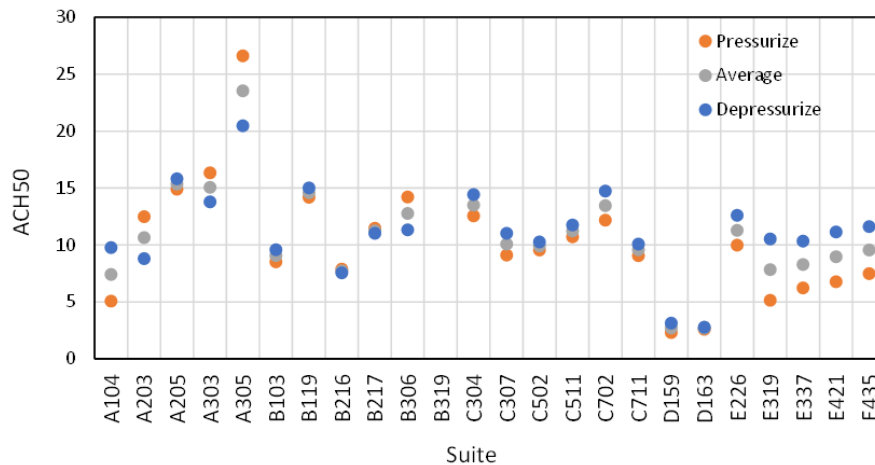


Figure 4.3 – Summary of suite air change rates at 50 Pa (ACH50) from post-retrofit blower door testing

Pre-retrofit, the ACH50 measurements across all of the buildings varied by an order of magnitude, ranging from 2.8 to 21.3 ACH50. This observed variability remained post-retrofit with airtightness values between 2.8 to 20.5 ACH50.

Figure 4.4 displays the average pre- and post-retrofit airtightness and percent difference for each suite. The measurements show that post-retrofit airtightness slightly improved for some suites and significantly worsened for others. For the units that became more airtight, the difference in pre- and post-airtightness was generally between 5% and 20%.

For the units that became less airtight, the values varied significantly between 5% and 60%, with one suite measuring over 100%. The inconsistency in airtightness differences before and after the retrofits may be the result of a lack of attention to airtightness and air sealing during the implementation of the retrofit measures. For example, if new windows are installed to replace older 'leakier' windows, the overall air leakage measurement taken after the window replacement can still be greater if the site-installed air seal between the window frame and the wall rough opening is not continuous.

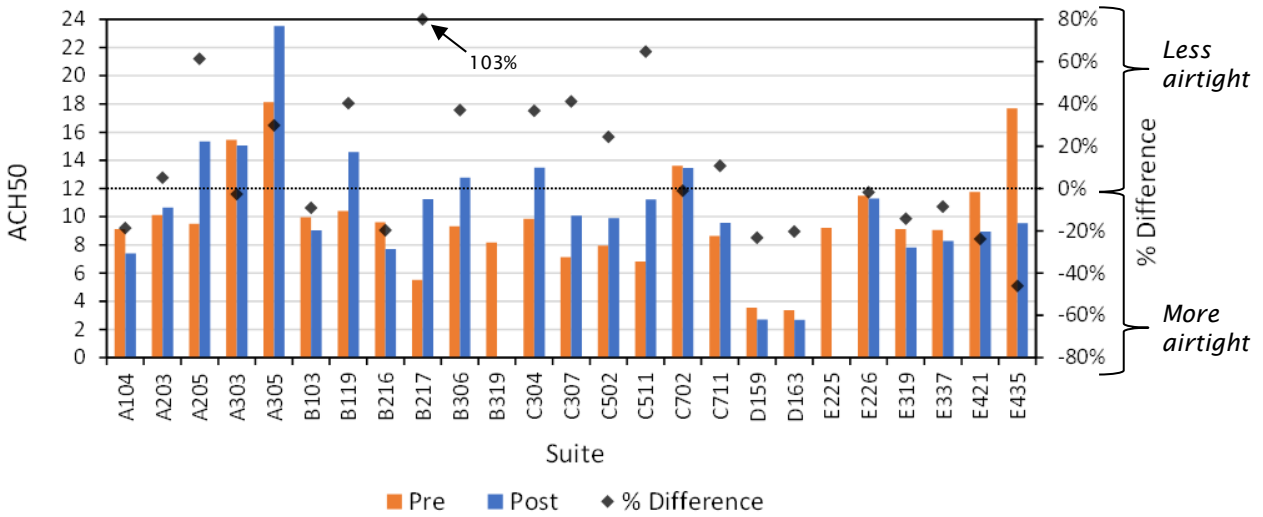


Figure 4.4 – Pre- and post-retrofit average airtightness test (ACH50) and percent difference.

4.2 Mechanical Ventilation

4.2.1 Corridor & Suite Pressurization

The intent of pressurized corridor ventilation is to deliver fresh air to suites by supplying fresh air into corridors and creating a positive pressure difference relative to the suites. The positive pressure drives the supply air into the suites through undercuts in the suite entrance doors. Three of the sites relied on pressurized corridor ventilation, requiring the in-service suite pressurization to be measure in each suite to understand the potential for fresh air to be deliver to the suites. The two other sites opened directly to the exterior instead of a corridor. However, these sites also lacked direct outdoor air ventilation and instead relied on exhaust only ventilation to draw fresh air into the suite. The performance of pressurized corridor ventilation systems has been extensively monitored,²⁵ with the result being a shift away from their use. In B.C., exhaust only ventilation has been unacceptable in Part 9 construction since 2014 and the B.C. Energy Step Code currently requires outdoor air to be supplied directly to each suite by mechanical ventilation.

Pressure measurements along with conditions during the test are shown in *Table 4.1*. The measurements were taken between the corridor and the suite. In the case of Building D and Building A, where there is no interior corridor, the pressure measurement was taken between the exterior and the suite (denoted with an asterisk).

²⁵ Ricketts, L., & Straube, J. (2014). Corridor Pressurization System Performance in Multi-Unit Residential Buildings.

TABLE 4.1 IN-SERVICE CONDITIONS DURING PRE-RETROFIT BLOWER DOOR TEST

<u>Label</u>	<u>Date</u>	<u>Suite Temp. (°C)</u>	<u>Corridor/ Outdoor Temp. (°C)</u>	<u>Δ Temp. (°C)</u>	<u>Suite RH (%)</u>	<u>ΔP Corridor to Suite (Pa)†</u>
A104	15-Feb-17	21	-/8	13	53	-1.5*
A203	15-Feb-17	23	-/8	15	43	-0.7*
A205	15-Feb-17	22	-/8	14	47	-0.9*
A303	15-Feb-17	21	-/8	13	43	0*
A305	15-Feb-17	22	-/8	14	49	1.2*
B103	15-May-17	25	24/-	1	38	0.9
B119	15-May-17	25	23/-	1	41	0.1
B216	15-May-17	24	26/-	-2	37	-0.4
B217	15-May-17	27	26/-	1	38	-0.1
B306	15-May-17	26	26/-	0	35	0.8
B319	15-May-17	24	26/-	-2	41	0.4
C304	13-Apr-17	21	20/-	1	46	-0.4
C307	13-Apr-17	22	20/-	2	46	0.3
C502	13-Apr-17	22	20/-	2	45	0.4
C511	13-Apr-17	22	20/-	2	45	1.7
C702	13-Apr-17	23	20/-	3	42	1.5
C711	13-Apr-17	19	20/-	-1	50	2.4
D159	15-Feb-17	21	-/10	11	44	0.8*
D163	15-Feb-17	22	-/10	12	50	0.5*
E225	21-Dec-16	25	25/-	0	36	0.4
E226	21-Dec-16	25	25/-	0	38	0
E319	21-Dec-16	24	23/-	1	34	0.5
E337	21-Dec-16	23	22/-	1	40	0.2
E421	21-Dec-16	23	22/-	1	35	0
E435	21-Dec-16	25	22/-	3	32	0.4

† positive values indicate that the corridor pressure is greater than the suite

* Suites without corridors (i.e., pressure difference is relative to outdoor environment)

The pressure measurements show that there is a very small pressure difference between the suites and corridors, less than 3 Pa.

The small pressure differences are likely the result of several factors including: open windows and non-operating exhaust fans along with wind and stack effect pressures competing against the mechanical system. While the pressure difference was measured at a single point in time, it is worth noting that the measured pressures would be insufficient to deliver fresh air to those suites.

4.2.2 Bathroom Exhaust

Rather than direct supply of outdoor air for ventilation, the suites in this study relied on either a combination of natural air infiltration through operable windows and/or the use of intermittent exhaust fans within the space, with make-up air coming from the corridor or other openings in the suite. The airflow rate provided by the intermittent washroom exhaust fans was measured and compared with code minimum values for each unit pre- (Figure 4.5) and post-retrofit (Figure 4.6). The measurements show that prior to the retrofits, most of the washroom exhaust fans provided airflow rates lower than the rates specified in the relevant codes and standards. Flow rates improved for many suites after the retrofits; however, around half of the measured units are still below code minimum rates. Note that four of five buildings underwent fan replacements or upgrades (Buildings A, B, D and E). Interestingly, Building A's exhaust fan flow rates did not improve significantly overall whereas Building C exhaust fan flow rates improved despite no note of fan retrofits.

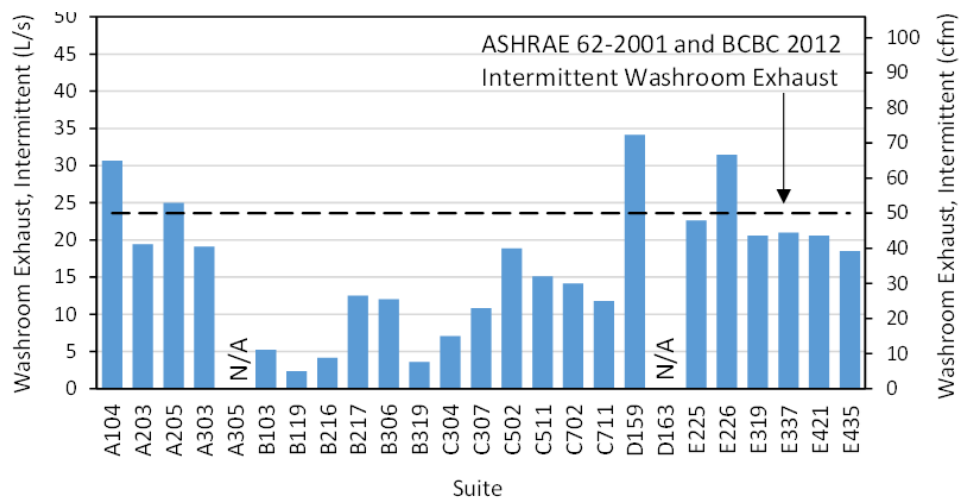


Figure 4.5 – Pre-retrofit washroom exhaust airflow rates (N/A indicates that no flow measurement was taken)

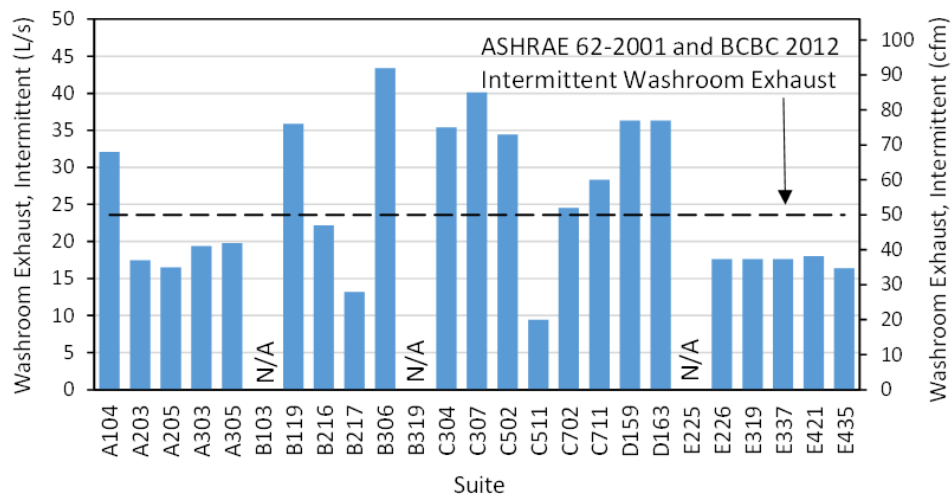


Figure 4.6 – Post-retrofit washroom exhaust airflow rates (N/A indicates that no flow measurement was taken)

In-service flow rates from exhaust fans can be reduced relative to their nominal rated performance value due to long ductwork, extensive duct fittings, wind pressures exerted on a building, insufficient fan power, blocked vents and/or debris build-up within the ducts. Regular cleaning can help to maintain the flow rate of exhaust fans.

In addition, occupants at many of the sites that exhibited low fan flow rates expressed concerns that the fans did not function properly (unable to remove moisture or smells) and were too noisy. These concerns from tenants can result in infrequent fan use, further reducing the effective suite ventilation.

4.3 Indoor Environmental Quality

This section is an analysis and discussion of the measured IEQ and is divided into four sub-sections: air temperature, RH, dew point temperature and CO₂ concentrations.

4.3.1 Air Temperature

Pre-retrofit, four of the five sites were equipped with central hydronic heating systems. The one exception, Building D, provided heat using electric baseboard heaters with dedicated thermostats in each room. Building C and Building A had in-suite thermostats to control the temperature. Building B and Building E relied on central controls and did not have in-suite thermostats to control the temperature. None of the suites included air-conditioning, so cooling was only possible through the use of open windows or portable fans and air conditioners.

To provide an overview of the measurements, *Table 4.2* provides a heat map of the average monthly indoor temperature recorded in each suite during the pre- and post-retrofit monitoring periods. The data is coloured based on intensity, where residents are more likely to experience thermal discomfort as values become a darker red or darker blue. Note that, due to retrofit scheduling, some of the pre- and post-retrofit data do not align amongst all of the buildings. A heat map including the actual values and monthly average exterior air temperature is included in *Appendix D*. As the heat map shows, there were no observable trends in the average suite temperatures.

Of the five sites, only Building A (semi-detached homes) exhibited comfortable (according to ASHRAE Standard 55) average temperatures year-round. This trend is also apparent in *Figure 4.7* which shows the average monthly temperature for each building. The cooler temperatures measured in Building A are likely a result of greater control via the multiple thermostats and an increase in the number of operable windows allowing for improved cross-ventilation.

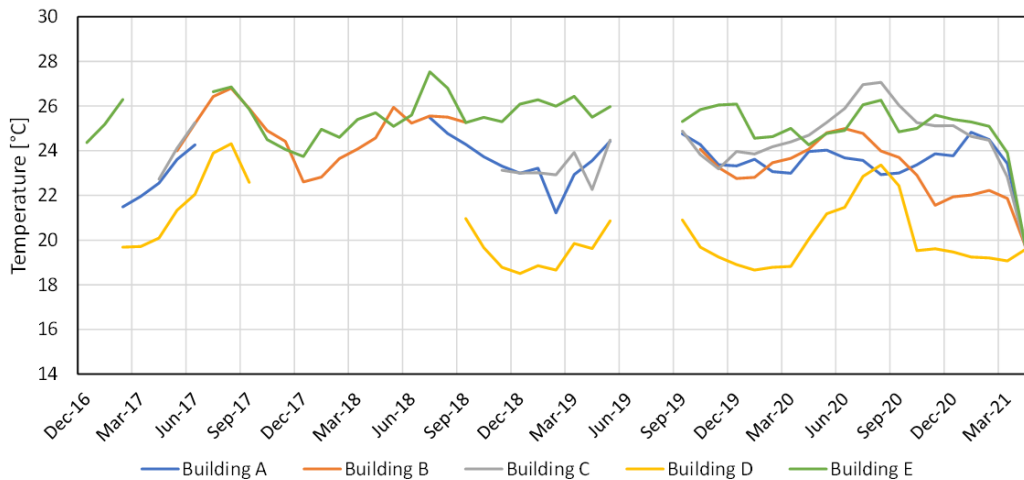


Figure 4.7 - Monthly average air temperature for each building. Gaps in data are either retrofit periods or missing data.

To understand if the air temperature may have been impacted by the retrofits, *Figure 4.8* compares the air temperature frequency distribution pre- and post-retrofit. The graph suggests that the ambient air temperature in the suites was not significantly affected by the retrofits. This finding is unsurprising as the retrofits did not add cooling or improve suite level control of the temperature.

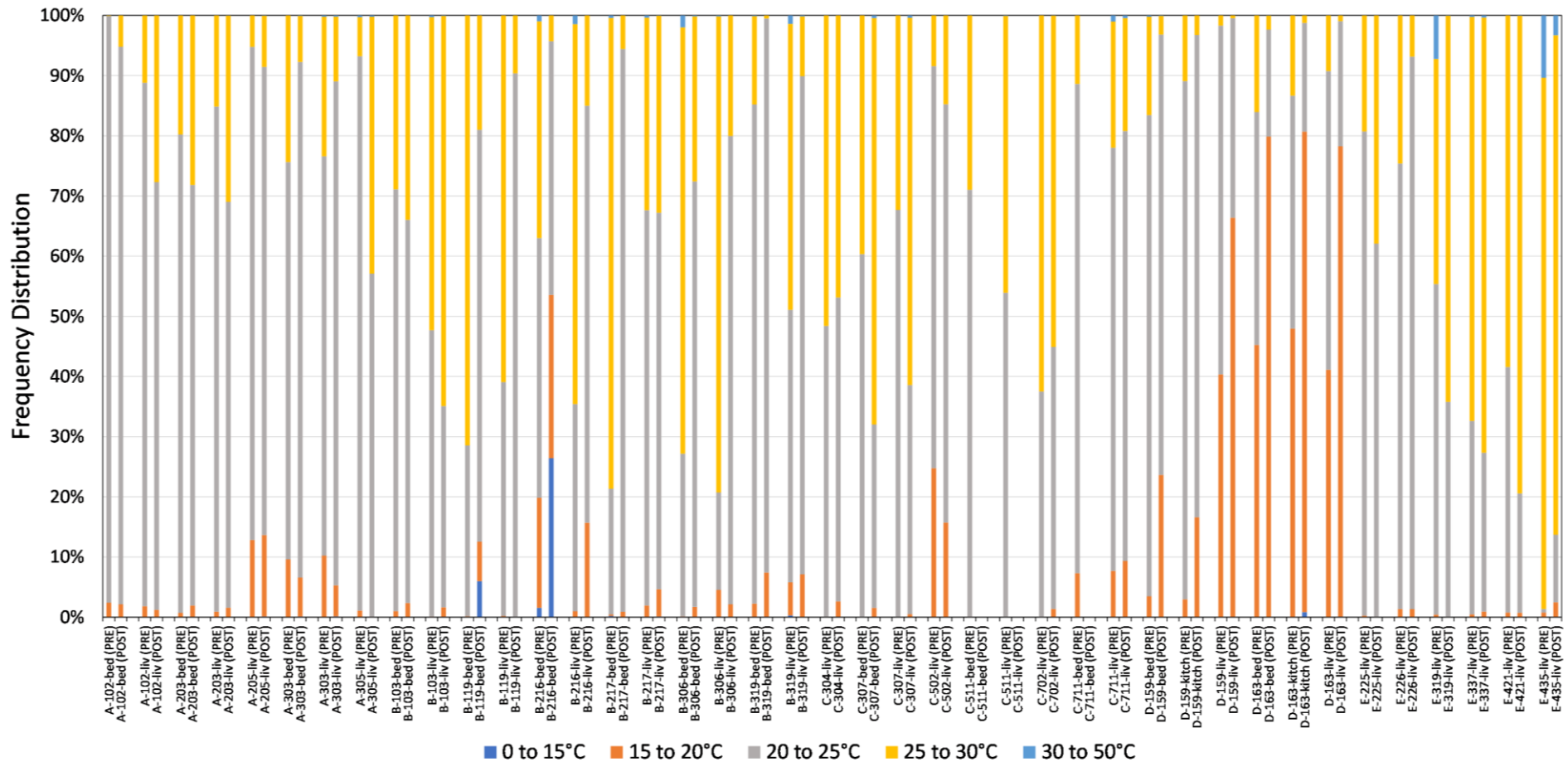


Figure 4.8 – Frequency distribution of air temperature (pre- vs. post-retrofit). Blank columns are the result of no measurements taken during the defined analysis period

To put the temperatures results into context, BC Housing requires new buildings to be designed to limit the number of hours with overheating. The requirements are based on the City of Vancouver's Energy Modelling Guidelines, which in turn reference ASHRAE Standard 55-2010 Section 5.3 as an acceptability limit for naturally cooled spaces. The City of Vancouver Energy Modelling Guideline requirement is:

“For buildings that do not incorporate mechanical cooling, it must be demonstrated that interior dry bulb temperatures of occupied spaces do not exceed the 80% acceptability limits for naturally conditioned spaces, as outlined in ASHRAE 55-2010 Section 5.3, for more than 200 hours per year [or 5.5%] for any zone.

For buildings or spaces with vulnerable groups (for example, seniors housing, shelter and supportive housing, daycares, schools, healthcare facilities, etc.), [...] it is recommended that projects target a more stringent threshold of not exceeding the 80% acceptability limits for more than 20 hours per year.”

Note that the BC Housing Design Guidelines and Construction Standards are stricter than the City of Vancouver limits, targeting a maximum of 20 overheating hours for any zone.

The measured indoor temperatures during summer 2020 for all suites was compared against the overheating limit defined by BC Housing Design Guideline (COV Energy Modelling Guideline – Table 4). *Figure 4.9* and *Figure 4.10* are two examples of this comparison for Building C and Building D, respectively. See *Appendix C* for all overheating analysis plots. The plots show that the interior air temperatures in Building C exceed the overheating limit for a significant portion of the defined summer period. The suites in Building D, by comparison, exceeded the overheating limit far less. *TABLE 4.3* lists all the measured suites and the number of overheating hours. Results suggest that overall, the suites across all buildings exceeded the overheating limit roughly 21% of the summer in 2020.

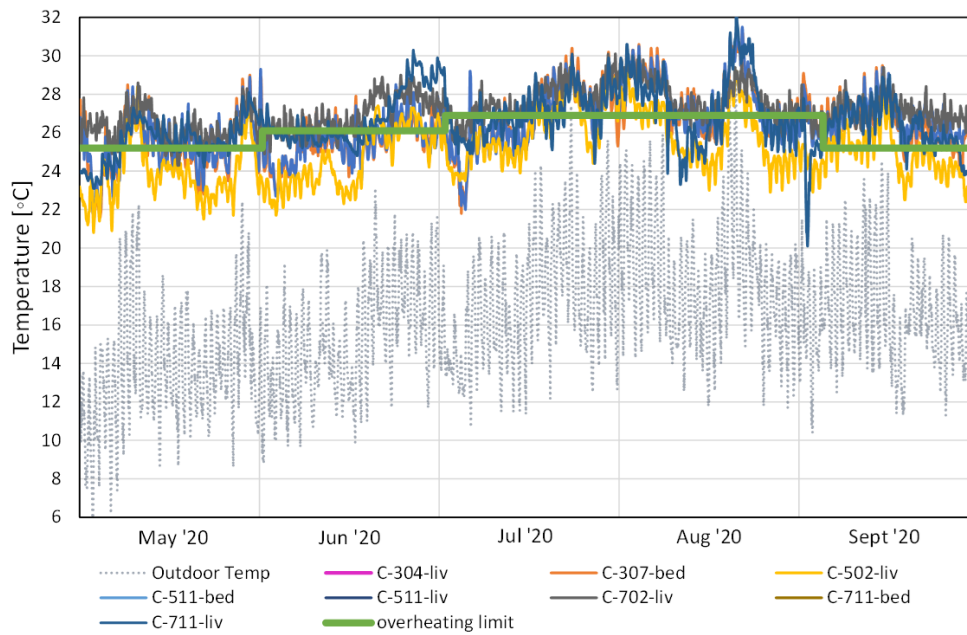


Figure 4.9 – Suite interior air temperature for Building C (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines. Note that the acceptability limit varies by month.

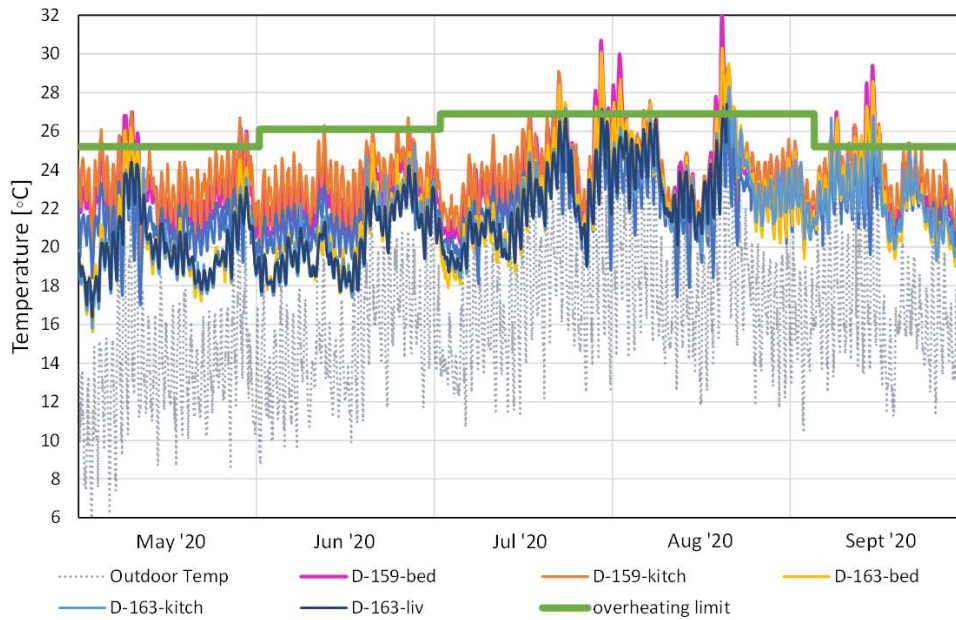


Figure 4.10 – Suite interior air temperature for Building D (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines. Note that the acceptability limit varies by month.

TABLE 4.3 OVERHEATING HOURS IN 2020 DEFINED BY BC HOUSING GUIDELINES			
Location	Hours Measured between May 1 – Sept 30	Total hours above limit	Percentage of time above limit between May 1 – Sept 30
A-102-bed	3672	169	5%
A-102-liv	3672	497	14%
A-203-bed	3672	160	4%
A-203-liv	3672	208	6%
A-205-liv	3663	157	4%
A-303-bed	1370	75	5%
A-303-liv	632	68	11%
A-305-liv	0	0	N/A
B-103-bed	3672	1114	30%
B-103-liv	3672	1787	49%
B-119-bed	3672	20	1%
B-119-liv	3658	54	1%
B-216-bed	3672	241	7%
B-216-liv	3672	701	19%
B-217-bed	1908	133	7%
B-217-liv	15	4	27%
B-306-bed	2661	135	5%
B-306-liv	3672	611	17%
B-319-bed	14	0	0%
B-319-liv	14	3	21%
C-304-liv	12	12	100%
C-307-bed	3672	1972	54%
C-307-liv	3660	2073	57%
C-502-liv	3660	929	25%
C-511-bed	0	0	N/A
C-511-liv	0	0	N/A
C-702-liv	3672	3108	85%
C-711-bed	0	0	N/A
C-711-liv	3672	2076	57%
D-159-bed	3672	280	8%
D-159-kitch	3672	207	6%
D-159-liv	3672	15	0%
D-163-bed	3672	206	6%
D-163-kitch	3672	34	1%
D-163-liv	2615	4	0%
E-225-liv	0	0	N/A
E-226-liv	3672	59	2%
E-319-liv	3672	782	21%
E-337-liv	16	2	13%
E-421-liv	3672	1142	31%
E-435-liv	3188	2434	76%
		Average	21%

Generally, an average monthly temperature of around 24°C within suites is considered comfortable based on the ASHRAE Standard 55 comfort range for occupants with typical indoor metabolic rates and clothing levels. However, thermal comfort is not only a function of air temperature and humidity. Other environmental factors such as draughts and direct solar radiation can affect how an occupant feels within a space. Personal factors can also influence thermal comfort, such as metabolic rate (activity level) and the type/amount of clothing they are wearing. It is also important to note that occupants, when exposed to a thermal environment for a prolonged period of time, can adapt to conditions that may initially be perceived as uncomfortable.

To provide a clearer understanding of the air temperature and RH conditions measured during the study, data was plotted on a psychrometric chart that includes an ASHRAE Standard 55 thermal comfort range. The comfort range assumes a typical occupant seated and relaxed (metabolic rate of 1 MET) and includes two clothing insulation levels: someone wearing pants and a long-sleeve shirt (0.6 clo) and someone wearing pants and a long-sleeve sweater (1 clo). Note that the following are sample plots for illustrative purposes. Additional plots are included in *Appendix B*.

Figure 4.11 and *Figure 4.12* plot the air temperature and RH measured in two suites in Building A during summer and winter 2020, respectively. Results show that the conditions in both suites are similar and lie primarily within the ASHRAE comfort range. *Figure 4.13* and *Figure 4.14* plot two sample suites in Building E during summer and winter 2020, respectively. In summer, the bulk of the data lies on the edge of the upper limits of the comfort range, suggesting that the suites are too warm. In winter, suite 421 lies within the upper limit of the comfort range, whereas suite 435 is consistently outside the comfort range. Solar and internal heat gains are likely responsible for the upper points on the plots, whereas open windows in the winter are likely responsible for the lower points. It is important to note that people may in fact be comfortable in these environments despite the conditions laying outside of the ASHRAE Standard 55 comfort range either due to adaptation or changing clothing and activity levels. For this reason, thermal comfort surveys should be considered as a means of verifying these findings.

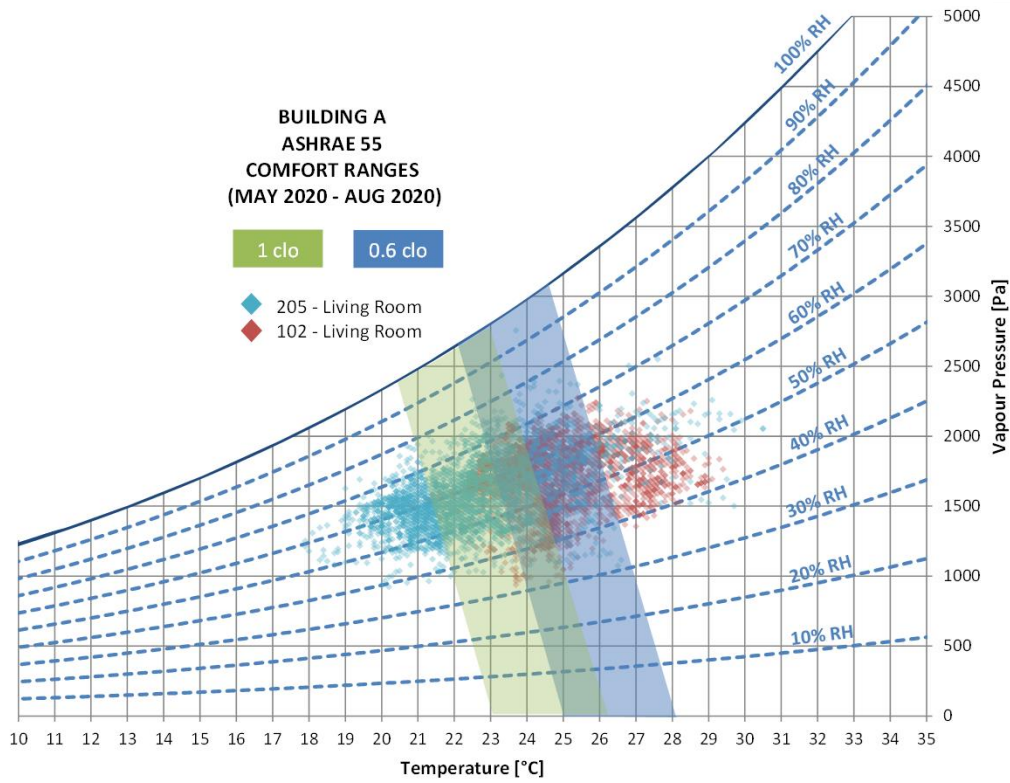


Figure 4.11 - Hourly air temperature measurements of two samples suites from Building A plotted on psychrometric chart (summer)

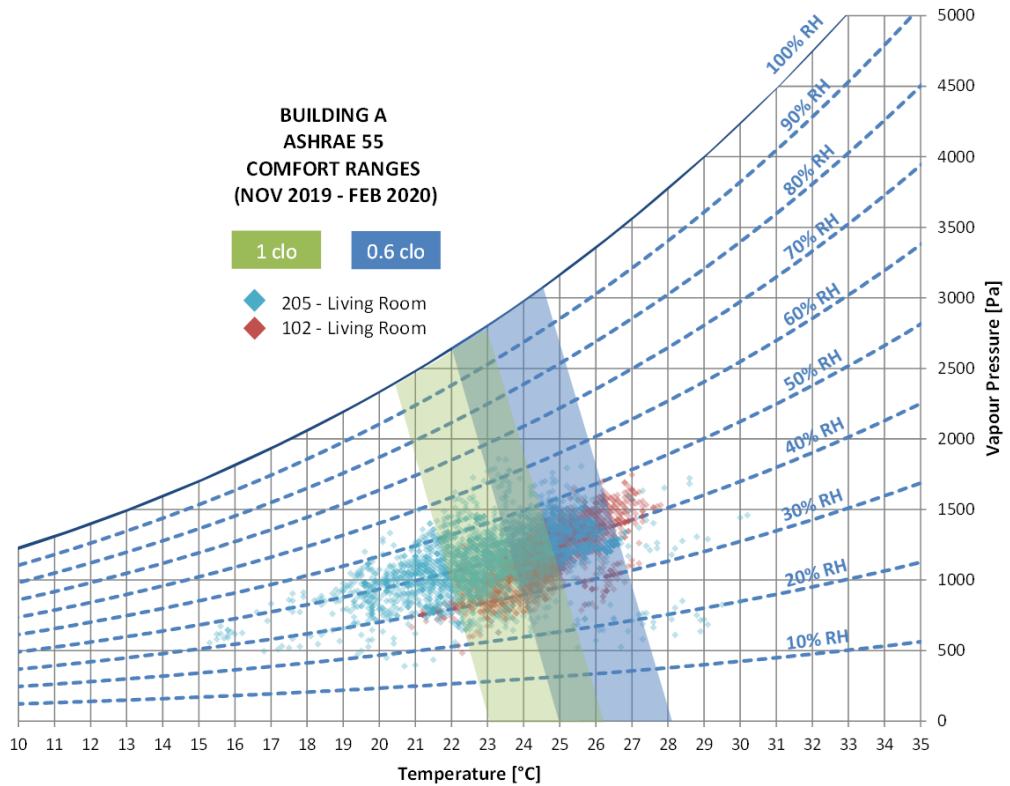


Figure 4.12 - Hourly air temperature measurements of two samples suites from Building A plotted on psychrometric chart (winter)

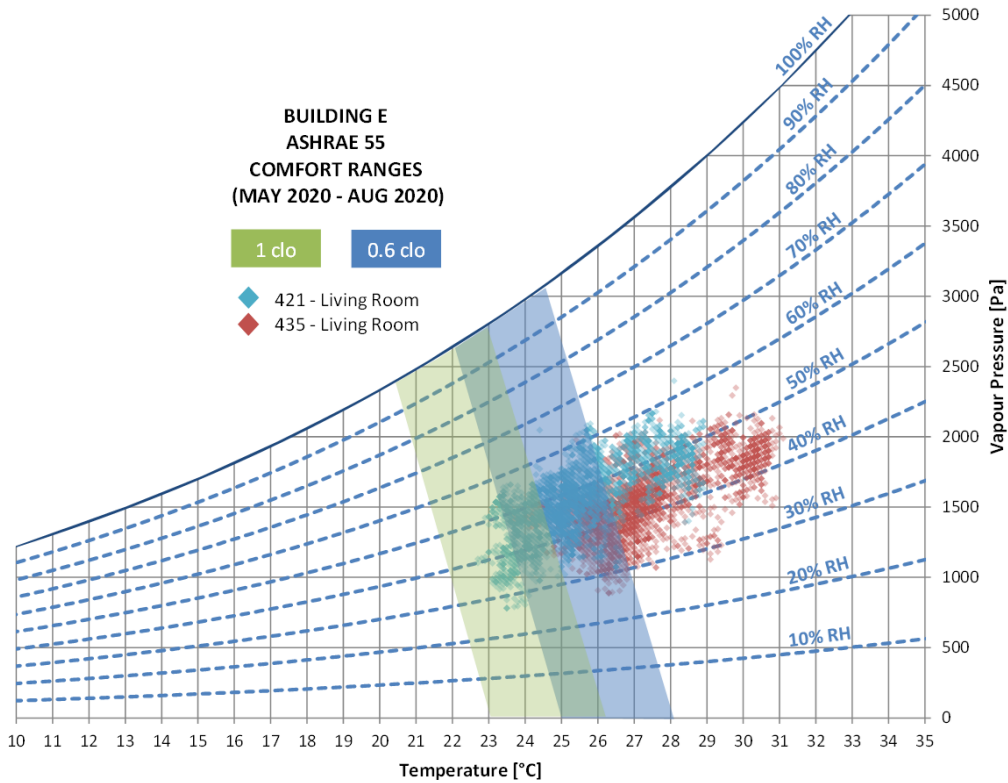


Figure 4.13 – Hourly air temperature measurements of two samples suites Building E plotted on psychrometric chart (summer)

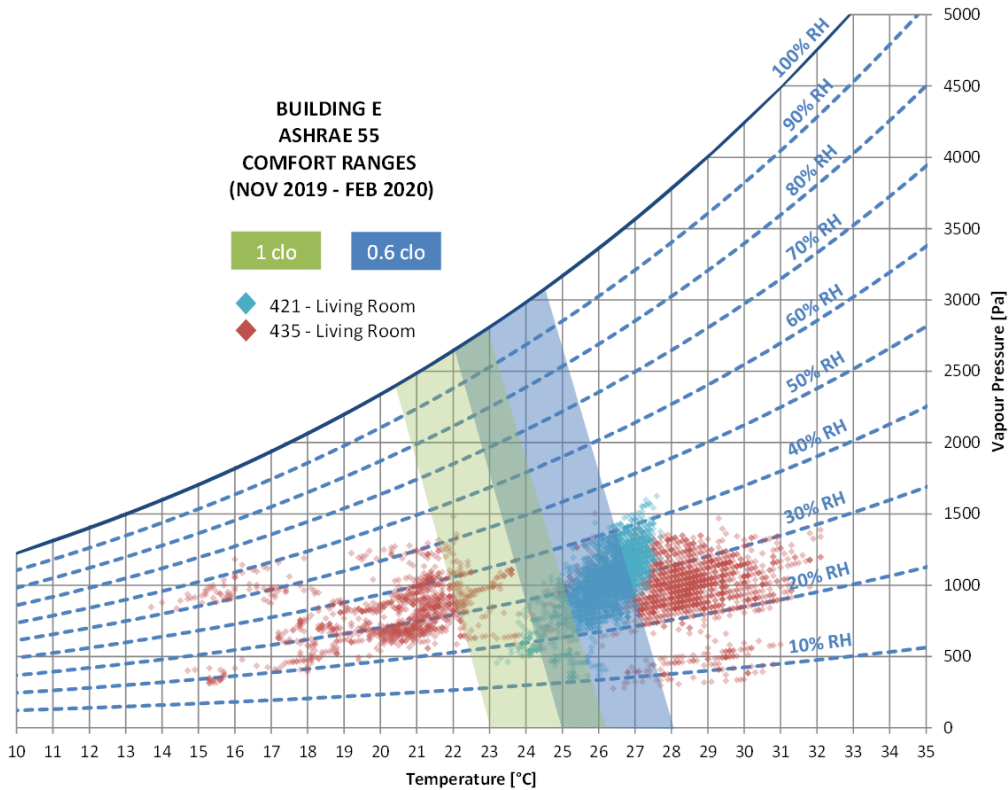


Figure 4.14 – Hourly air temperature measurements of two samples suites from Building E plotted on psychrometric chart (winter)

4.3.2 Relative Humidity

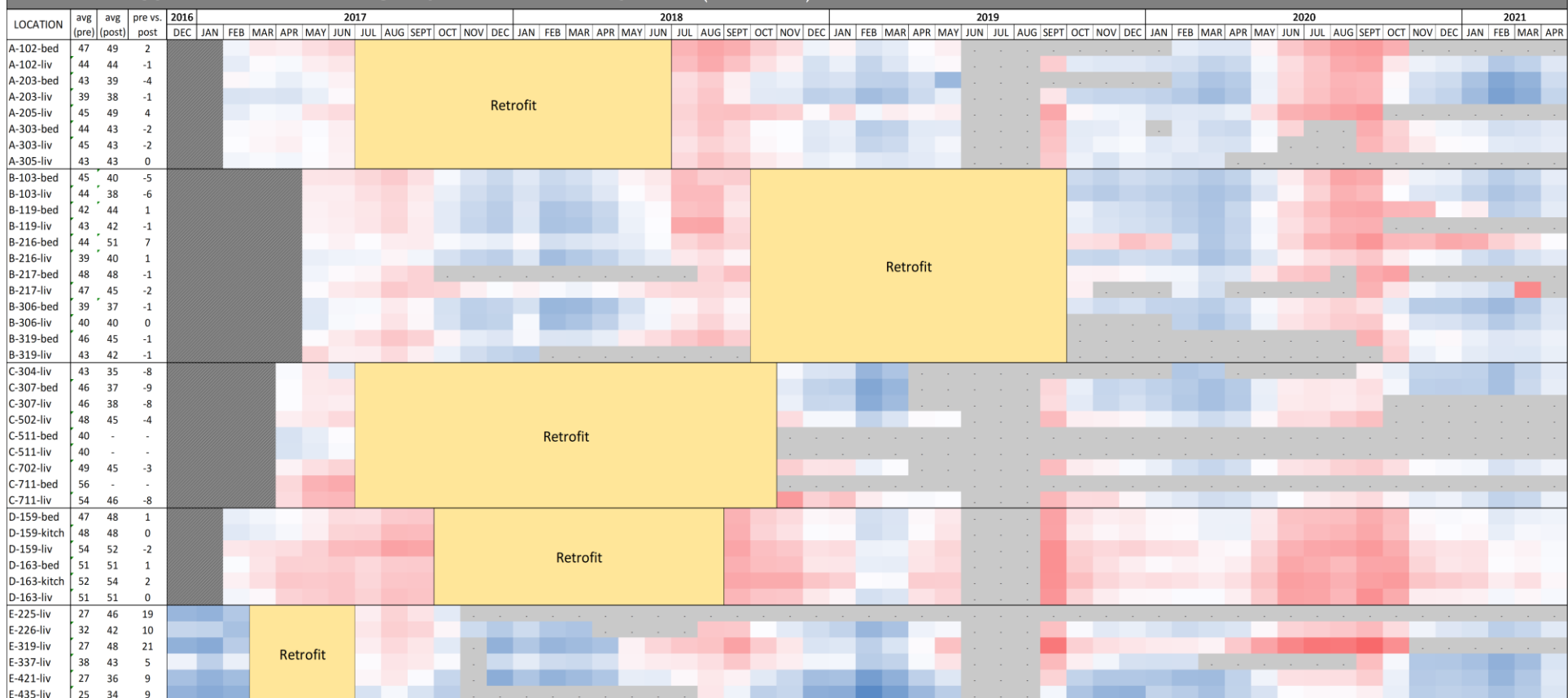
Figure 4.15 shows the average monthly RH for each building. Results show that RH is generally consistent for all buildings, with the exception of Building D, which experienced higher RH levels for the majority of the monitoring period. The monthly average RH readings are typically within the 30% to 60% design range for comfort. Generally, the reported monthly average RH levels did not reach above 60% (with the exception of a few cases), which indicates that the spaces do not typically experience excessive humidity. However, some of the spaces do show levels that are at the high end of the typical design scale and may be a concern. High RH is a concern in the winter due to potential condensation and is a concern in the summer because of the associated impacts on indoor comfort.

To provide a clearer overview of the measurements, the monthly RH recorded in each suite during the pre- and post-retrofit monitoring periods are shown as a heat map in Table 4.4. The monthly summary table also shows that the Building D suites tend to have generally higher RH. This is a result of the suites being relatively cooler than the other measured buildings in this study. In the following section, the dew point temperature was calculated and analyzed to assess the amount of moisture in the suites, which unlikely RH is independent of the ambient air temperature.



Figure 4.15 - Monthly average RH for each building. Gaps in data are either retrofit periods or missing data.

TABLE 4.4 SUMMARY TABLE: AVERAGE MONTHLY RELATIVE HUMIDITY (HEAT MAP)



Relative Humidity [%]



4.3.3 Dew Point Temperature

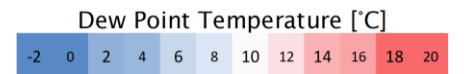
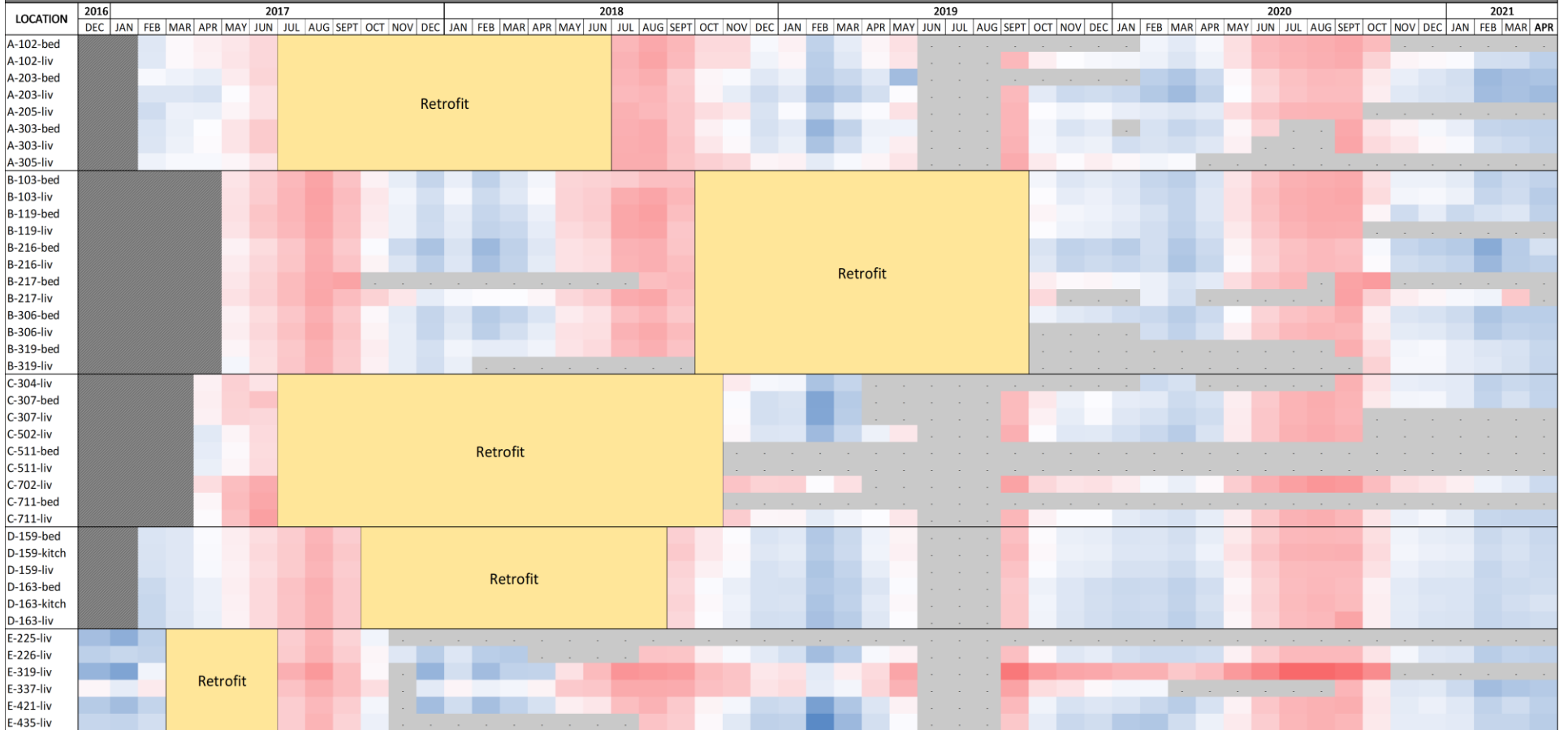
Dew point temperature is the temperature at which air must be cooled to become saturated with water vapour. It can be used as an indicator of the potential for condensation and mold growth within a suite. Previous work by RDH has indicated that a wintertime dew point temperature of greater than 10°C results in an elevated risk of window condensation in Vancouver's climate.²⁶ Wintertime dew point temperatures in the range of 5 to 10°C represent a potential risk.

To provide an overview of the measurements, the monthly average dew point temperatures recorded in each suite during the pre- and post-retrofit monitoring periods are shown as a heat map in *Table 4.5*. Results show that dew point temperature measurements above 10°C are generally found in summer and therefore pose less of a risk, say, compared to colder winter months when window frames which could go below the dew point temperature.

One particular suite to note is Building E 337 which had frequent readings with dew point temperature above 10°C throughout much of the monitoring period. This suite was also noted to have condensation on the windows during the site visit. All of the other buildings for which winter data was recorded show significant frequency of measurements above 10°C and most above 5°C. This data indicates that most of the suites in the study have a risk of condensation during winter months.

²⁶ RDH Technical Bulletin #9. <http://rdh.com/wp-content/uploads/2015/09/TB-9-Air-Quality-in-MURBs-Technical-Bulletin-2015-08-25.pdf>

TABLE 4.5 SUMMARY TABLE: AVERAGE MONTHLY DEW POINT TEMPERATURE (HEAT MAP)



The average monthly dew point temperature of buildings in the study are shown in *Figure 4.16*. The dew point temperatures show sharp increases and decreases in the summer and winter months, respectively. Higher dew point temperature in the summer months is expected and are generally less of a concern in heating dominated climates.

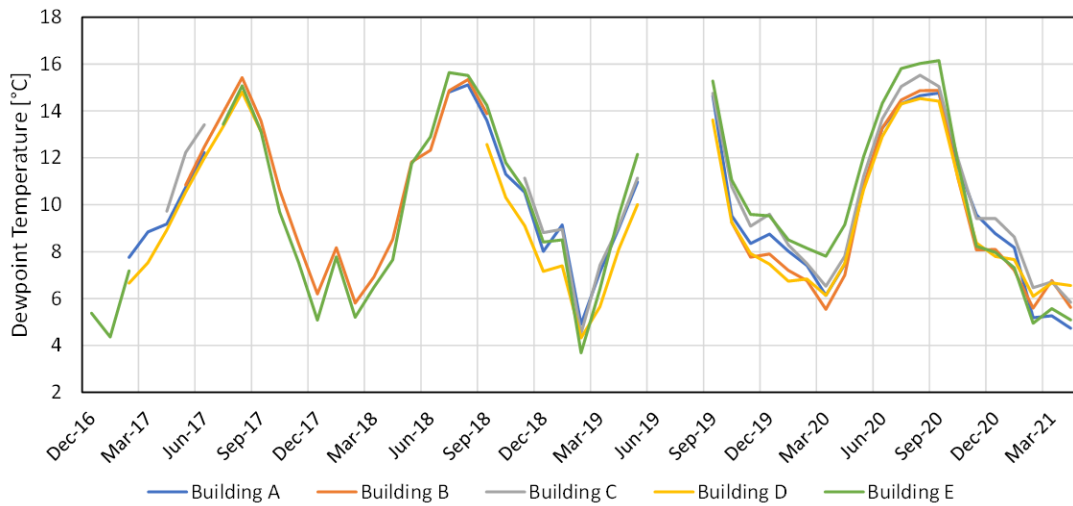


Figure 4.16 – Monthly average dew point temperature for each building. Gaps in data are either retrofit periods or missing data.

The distribution of dew point temperatures when condensation risk is greater (between October and March) is shown in *Figure 4.17*. The plot illustrates that the dew point temperature in the suites during cool outdoor conditions did not change significantly, other than a few cases such as Building E 319 living room and Building A 305 living room which show relatively greater distribution of dew point temperatures above 10°C compared to before the retrofits. These changes suggest that moisture build up in these suites is greater after the retrofits, perhaps a result of decreased ventilation or change in occupant behaviour.

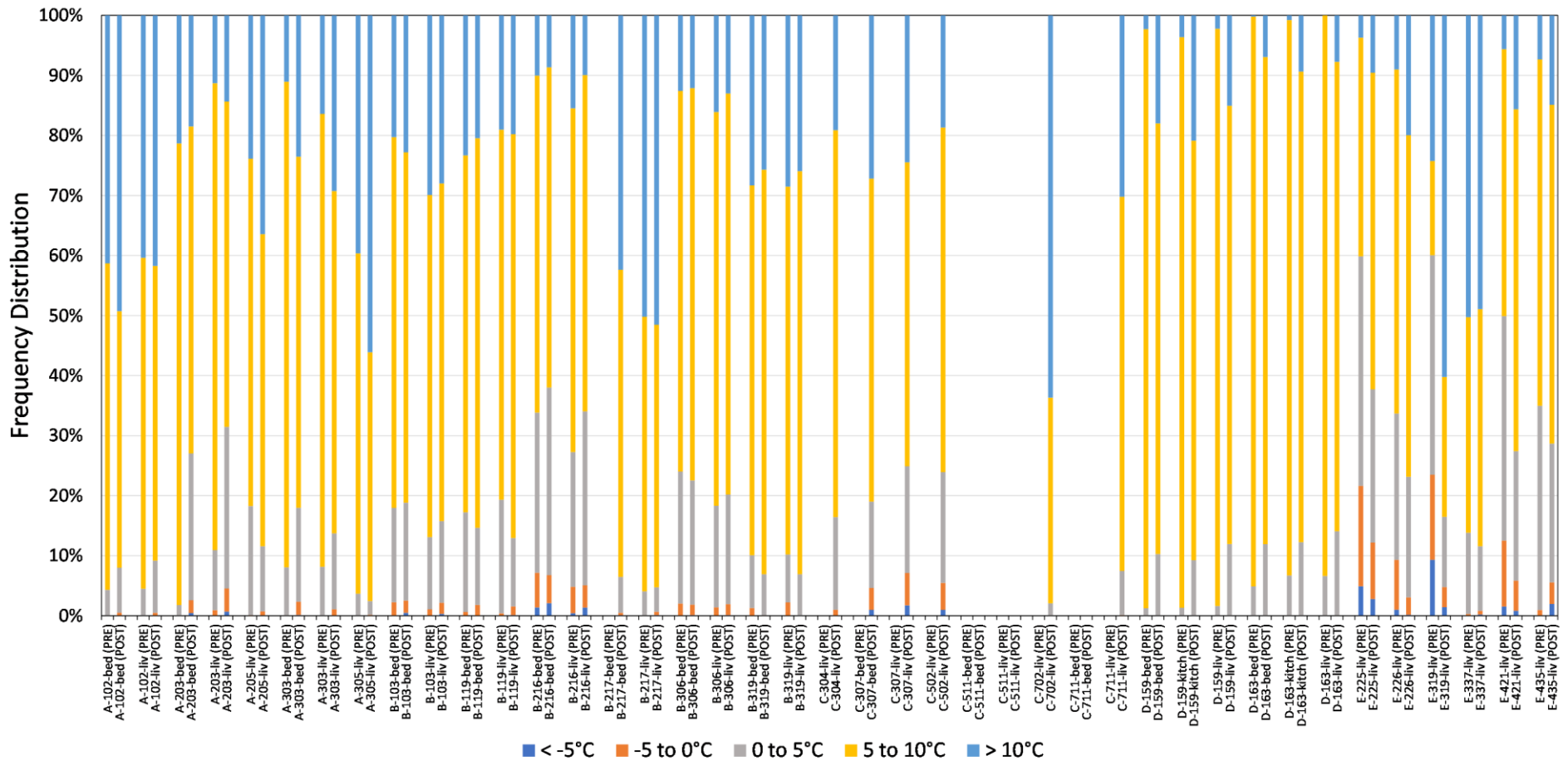


Figure 4.17 – Frequency distribution of dew point temperature between October and March (pre- vs. post-retrofit). Blank columns are the result of no measurements during the defined analysis period.

The delta dew point (or dew point rise) temperature metric is an indicator of the interior moisture generation and indoor ventilation effectiveness. This is the calculated difference in dew point temperature between the outdoor and indoor air. The delta dew point shows the relative increase in interior ambient moisture compared to the outdoors due to human activity (respiration, showering, etc.). A building that is perfectly ventilated will see a small difference in the interior and exterior dew points, as the indoor and outdoor are approaching the same moisture conditions. However, a building with relatively poor ventilation will experience a build-up of moisture related to indoor moisture sources such as occupant activity (breathing, cooking, etc.), plants, pets, etc. Although perfect ventilation is not generally possible, one of the objectives of an effective ventilation system is to reduce the buildup of indoor moisture, from both a building durability and IEQ perspective.

The average monthly delta dew point temperature of buildings in the study are shown in *Figure 4.18*. Results show that build-up of moisture relative to outdoor conditions is greatest during cooler months. This is likely due to the relatively drier winter air and more frequent closing of windows which would reduce ventilation.

The monthly average dew point temperatures recorded in each suite during the pre- and post-retrofit monitoring periods are shown as a heat map in *Table 4.6*. The table shows similar results from *Figure 4.18*, though shows a significant build up of moisture for suite Building E 337 during winter of 2019/2020. Also, significant increase in moisture is noted in nearly all measured suites during February of 2019.

The distribution of delta dew point temperatures when condensation risk is greater (between October and March) is shown in *Figure 4.19*. The plot illustrates that the delta dew point temperature in the suites during cool outdoor conditions did not change significantly, with the exception of Building E 319 living room.

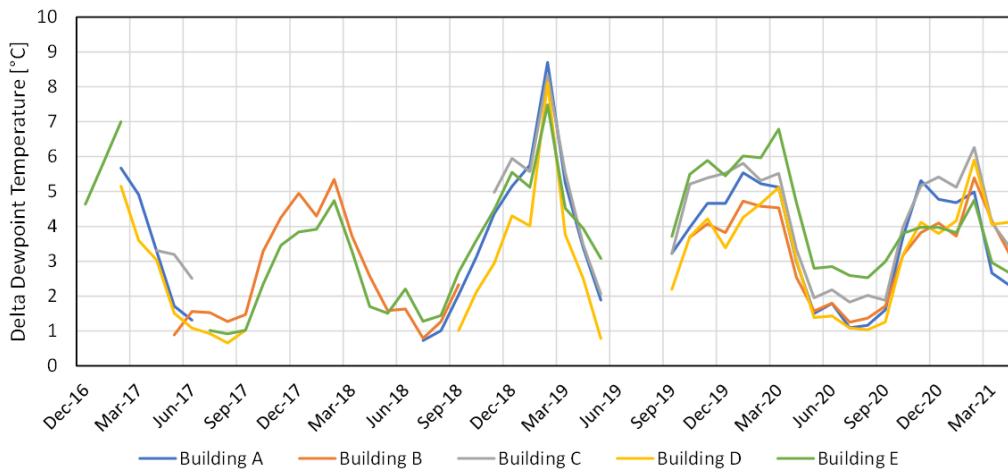


Figure 4.18 – Monthly average delta dew point temperature for each building. Gaps in data are either retrofit periods or missing data.

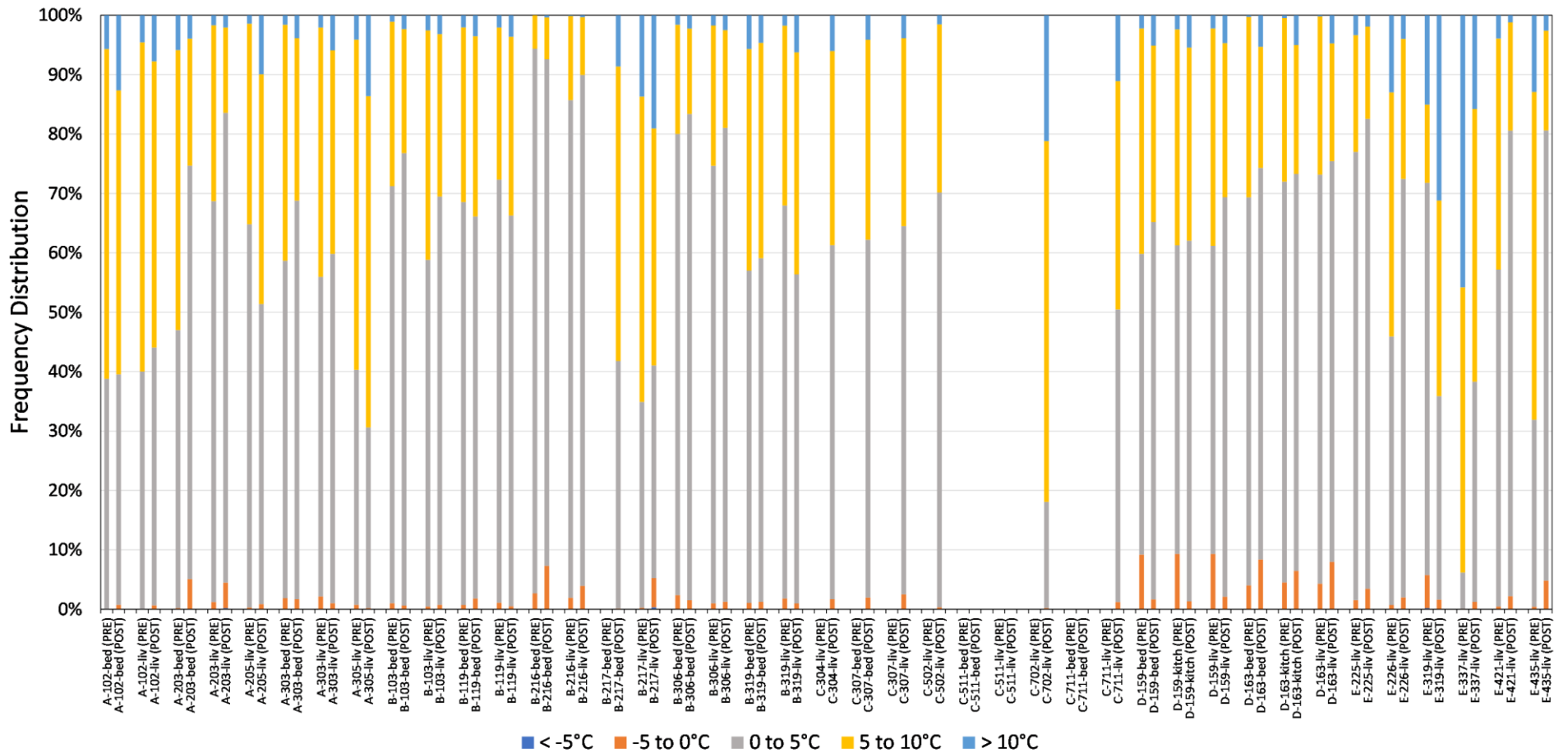


Figure 4.19 – Frequency distribution of delta dew point temperature between October and March (pre- vs. post-retrofit). Blank columns are the result of no measurements taken during the defined period.

4.3.4 Carbon Dioxide Concentrations

As described in Section 1.1, several studies have linked high CO₂ concentrations and negative health outcomes such as fatigue, headaches, dizziness, cognitive decline, etc. and the importance of proper ventilation in order to avoid the buildup of CO₂ concentrations. To provide an overview of the measurements, the monthly average CO₂ concentrations recorded in each suite during the pre- and post-retrofit monitoring periods are shown as a heat map in *Table 4.7*.

The average indoor CO₂ concentration during the pre-retrofit period varied significantly, between roughly 400 ppm and 4,800 ppm. As the heat map shows, there are no distinct trends in the overall average suite CO₂ concentrations other than suite 217 from Building B having significantly higher concentrations of CO₂ after the retrofit period. Interestingly, the blower door test results for this suite showed an increase in the air leakage rate (5.5 to 11.2 ACH50), therefore it is unlikely that the retrofit measures are responsible for the high concentrations of CO₂.

Figure 4.20 shows that the average CO₂ concentration in most suites was in the range of 500 to 1300 ppm, which is generally within normal design conditions. However, most monitored suites experienced CO₂ concentrations in excess of 1,100 ppm for more than 20% of the monitoring period. Examining the hourly data in a sample of the suites showed that the CO₂ concentrations typically increased in the evening and overnight with a decrease the following morning. This finding is generally consistent with standard occupancy patterns, where CO₂ steadily rises when occupants are present in the evening and sleep.

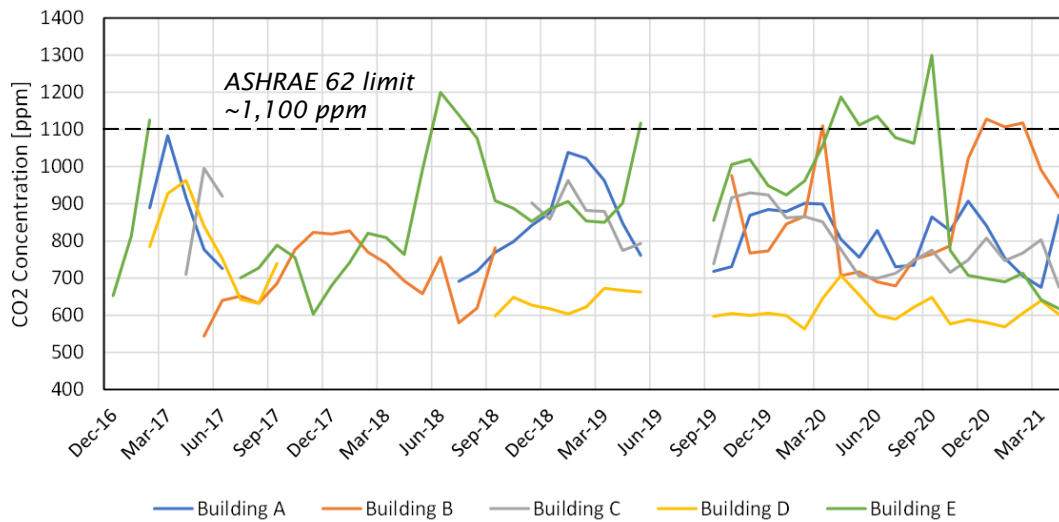
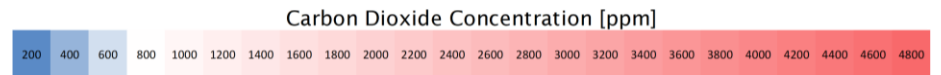
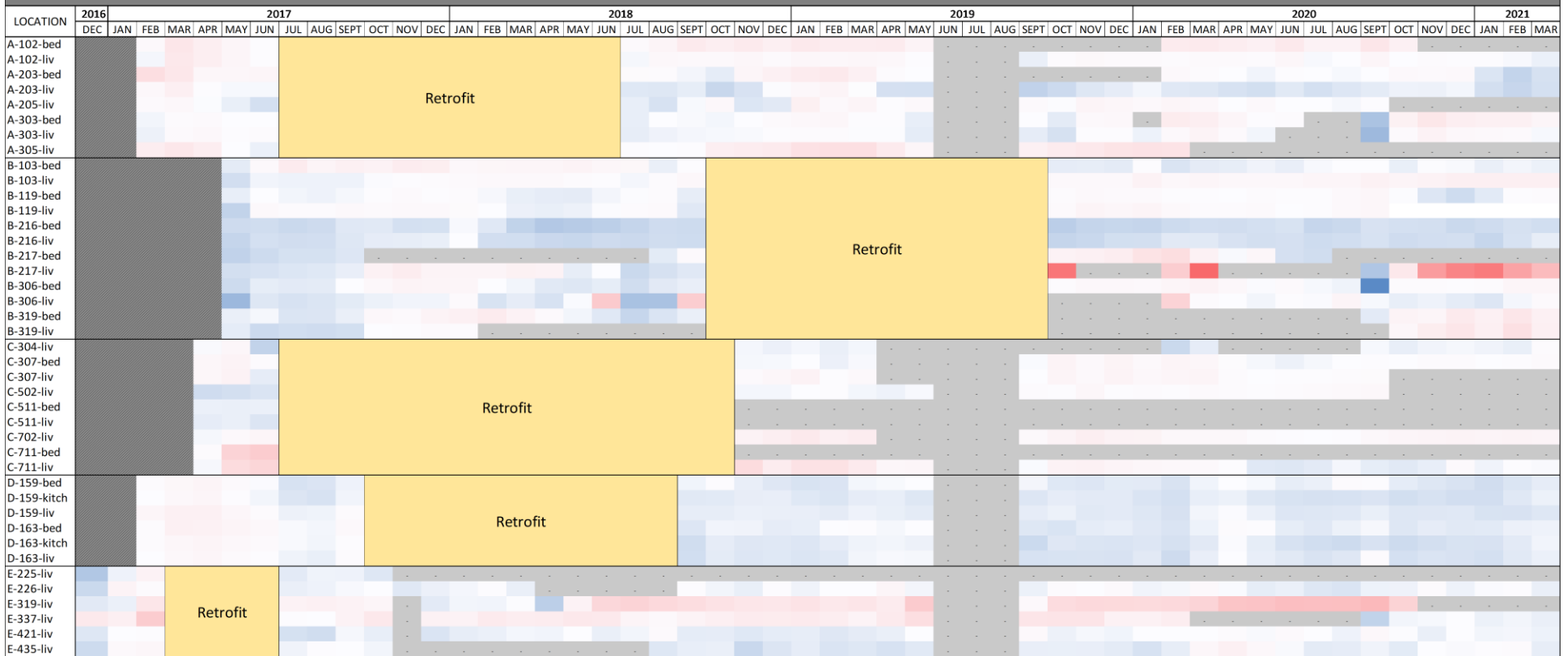


Figure 4.20 – Monthly average carbon dioxide concentrations for each building. Gaps in data are either retrofit periods or missing data

TABLE 4.7 SUMMARY TABLE: AVERAGE MONTHLY CARBON DIOXIDE CONCENTRATIONS (HEAT MAP)



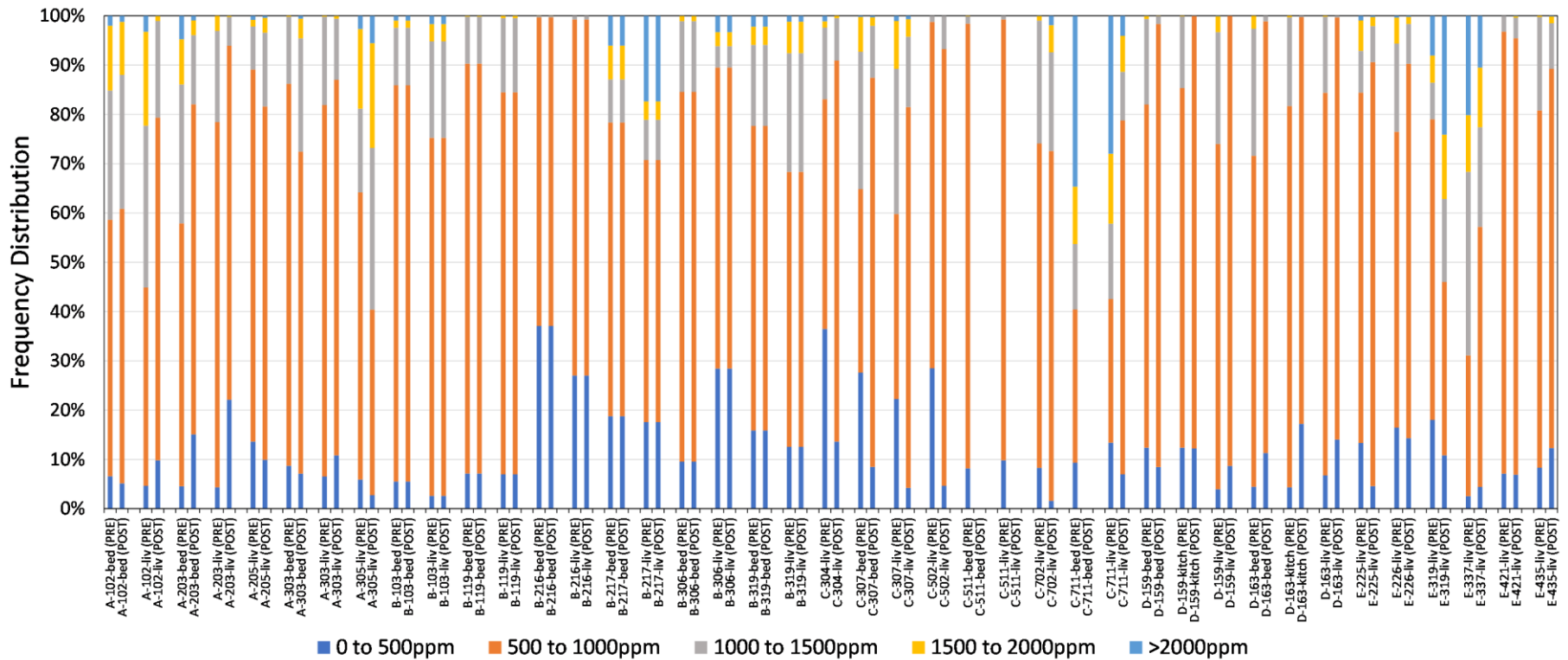


Figure 4.21 – Frequency distribution of CO₂ concentrations (pre- vs. post-retrofit). Blank columns are the result of no measurements taken during the defined analysis period.

4.4 Special Events

During the monitoring period, two notable special events occurred including a City of Vancouver Air Quality Advisory due to wildfires in the interior along with the beginning of the COVID-19 lockdown. This section specifically looks at possible trends during these events.

4.4.1 COVID-19

The Province of British Columbia declared a public health emergency related to the COVID-19 pandemic on March 17, 2020, with the closure of restaurants, personal service establishments, and physical distancing requirements starting shortly thereafter. These public health measures were anticipated to result in increased occupancy of the suites due to people remaining indoors. Similar increases in cooking and other indoor activities were expected.

Figure 4.22 and *Figure 4.23* are samples of the air temperature and CO₂ concentrations for the entire monitoring period for Building B and Building A, respectively. For similar plots of other measured buildings, see *Appendix A*. Based on an analysis of the data immediately before and after the Provincial lock-down orders, there were no significant changes in the measured IEQ parameters due to COVID-19 policies.

The lack of observable trends pre- and post-lockdown is likely the result of the elevated pre-lockdown trends in temperatures, CO₂, and interior moisture along with the 15-min monitoring interval being too long to capture short-term events less than 30-min in duration.

4.4.2 Wildfire Season

Wildfires are increasingly resulting in air quality advisories in the Lower Mainland due to elevated concentrations of outdoor particulate matter. During air quality advisories, public health guidance is to remain sheltered indoors with windows closed. As operable windows were often the main source of fresh air ventilation and cooling in the suites, the wildfires were expected to result in a measurable increase in the indoor air temperature, RH, and CO₂ concentrations.

Figure 4.24 and *Figure 4.25* plot the air temperature and CO₂ concentrations during the September 2020 Metro Vancouver Air Quality Advisory for Building B and Building A, respectively. The plots include data from one week before and one week after the advisory for comparative purposes. The results show that the temperature in Building B did not significantly change as a result of the advisory; however, the CO₂ concentrations in Building A appear to have increased suddenly at the beginning of that period. This agrees with the public health recommendations to stay indoors with windows and doors closed. For similar plots of other measured buildings, see *Appendix A* and *Appendix F*.

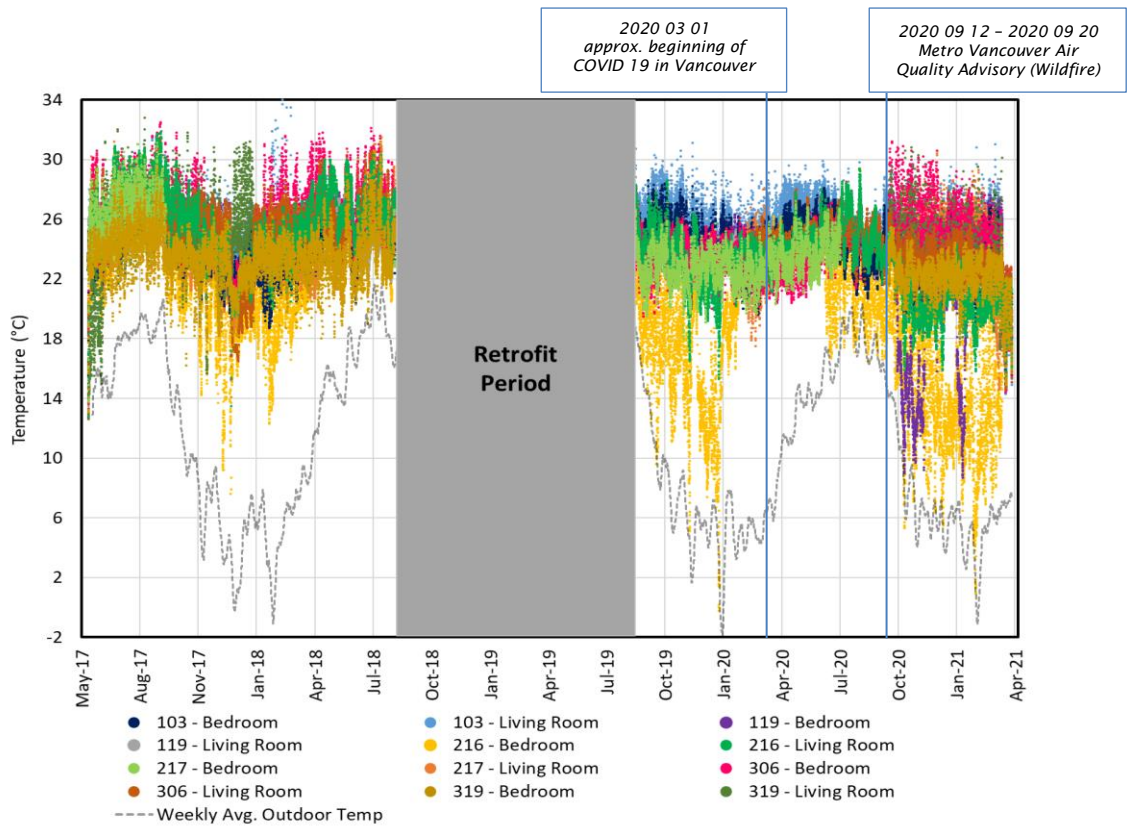


Figure 4.22 – Air temperature measurements throughout monitoring period (Building B)

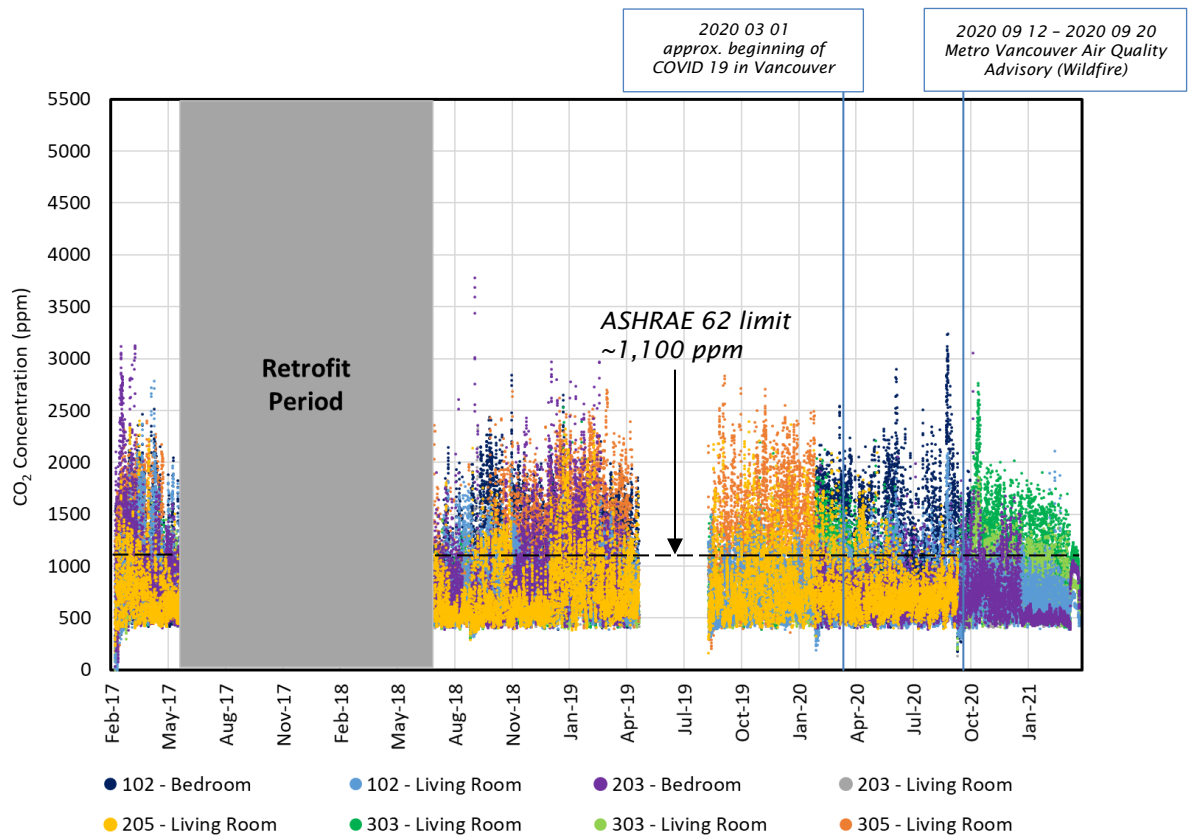


Figure 4.23 – CO₂ concentration measurements throughout monitoring period (Building A)

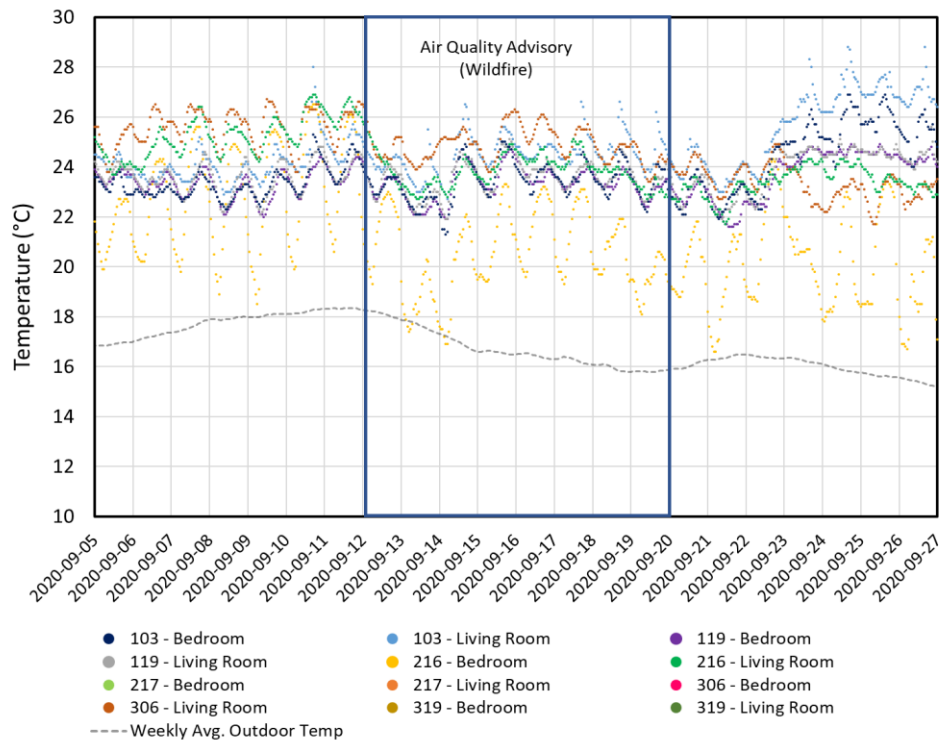


Figure 4.24 – Air temperature measurements during the Metro Vancouver Air Quality Advisory (Building B)

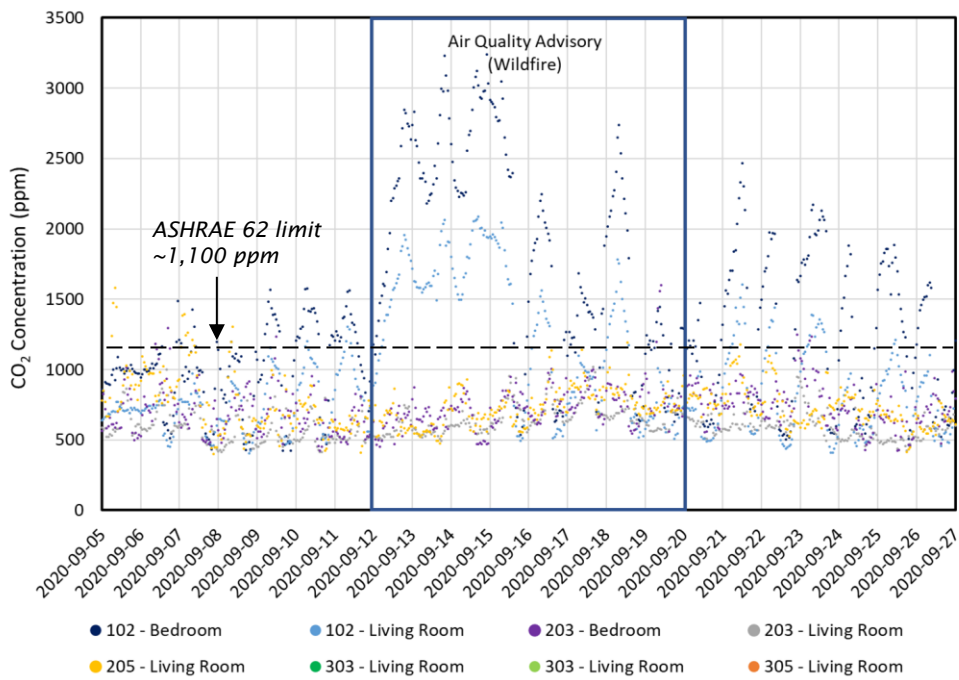


Figure 4.25 – CO₂ concentration measurements during the Metro Vancouver Air Quality Advisory (Building A)

4.5 Other Considerations

Some IEQ variables beyond the those measured in this study were noted during site visits. As previously stated, IEQ includes a broader assessment of the indoor conditions (e.g., lighting, acoustics, ergonomics, smells, etc.). The following general observations were noted as additional considerations and/or concerns with the suite-level IEQ:

Tobacco Smoke & Odours

The smell of tobacco smoke was heavy in public spaces, corridors, and the suites of tenants who reported being non-smokers. Efforts to open windows, use exhaust fans, and close/seal around doors was ineffective at preventing odours entering the suites.

Use of the exhaust fans pulled smoke from the corridors into the suite, and opening windows provided another path for smoke and odours to pass between the suites.

In the absence of a no-smoking policy for indoor spaces, effective control of tobacco smoke and other air contaminants would require:

1. Exhaust ventilation in spaces where smoking is permitted, with the exhaust air discharging away from nearby fresh air intakes (e.g., adjacent open windows)
2. Suite-level compartmentalization to provide an air barrier between suites
3. Continuous fresh air ventilation

Bugs & Pests

Anecdotally, insects (e.g., bed bugs, cockroaches, etc.) were a significant problem reported by the tenants. In one case, a tenant had blocked their exhaust fan as they claimed bugs were entering their suite through the duct work. During the sensor take-down at the end of the study, three sensors were damaged by the excessive accumulation of insects inside the hardware.

While the buildings had on-going pest control plans, it is worth noting that suite-level compartmentalization would have an added benefit of reducing the spread of pests between suites.

Mould & Mildew

Mould and mildew were noted in several suites, particularly in bathrooms where exhaust fans were observed to be performing poorly or non-functional.

5 Key Findings

The intended outcomes of this study were to understand the indoor environmental quality in existing multi-unit social housing buildings in B.C. These objectives were met through long-term monitoring of several IEQ parameters. Additionally, the potential impacts of building enclosure and mechanical system upgrades were assessed through pre- and post-retrofit monitoring. The measured IEQ parameters included ambient air temperature, RH, dew point temperature, and CO₂ concentrations. The key findings and discussion are summarized below.

- Four of the five monitored buildings experienced significant periods of overheating. On average, across all buildings, the suites experienced more than 700 hours with the indoor air temperature exceeding 26°C. The peak indoor air temperature was in excess of 31°C.
 - Suite-level control of the heating system was inconsistent and likely contributed to overheating in the shoulder seasons
 - Cooling is only provided through natural ventilation of the open windows, and the findings show that this is insufficient to meet BC Housing's overheating guidelines
 - Relying on open windows will reduce the effectiveness of possible future IEQ or energy upgrades
- With a few exceptions, the RH remained within 30% - 60%, with the elevated humidity periods experienced in the summer months. This observation is consistent with open windows.
- CO₂ concentrations generally remained below 1,100 ppm with elevated concentrations overnight. This trend is consistent with reduced ventilation (i.e., closed windows) and/or sustained occupancy overnight.
- No significant trends were observed in the monitored IEQ parameters pre- and post-retrofit. Continued reliance on open windows for ventilation and the lack of IEQ specific upgrades likely contributed to this finding. Refer to Part 6 *Recommendations* for additional discussion.
- In general, the pre-retrofit airflow rates through the exhaust fans were lower than the rates specified in the relevant codes and standards. Post-retrofit measurements of the airflow rates were higher than the pre-retrofit measurements but remained below specified rates in nearly half the suites. Building upgrades included new exhaust fans in some, but not all units.
- Improved exhaust fan performance had no significant impact on the monitored IEQ parameters. This is likely the result of lack of use, which may be due to fan noise or other factors.
- Pre- and post-retrofit airtightness measurements of the suites in buildings that underwent a window replacement generally showed an improved airtightness between 5% to 20%. The air leakage testing did not control for air leakage between suites due to lack of adjacent suite access. Building C, which did not undergo a window replacement, saw a consistent increase in the air leakage post-retrofit.

6 Recommendations

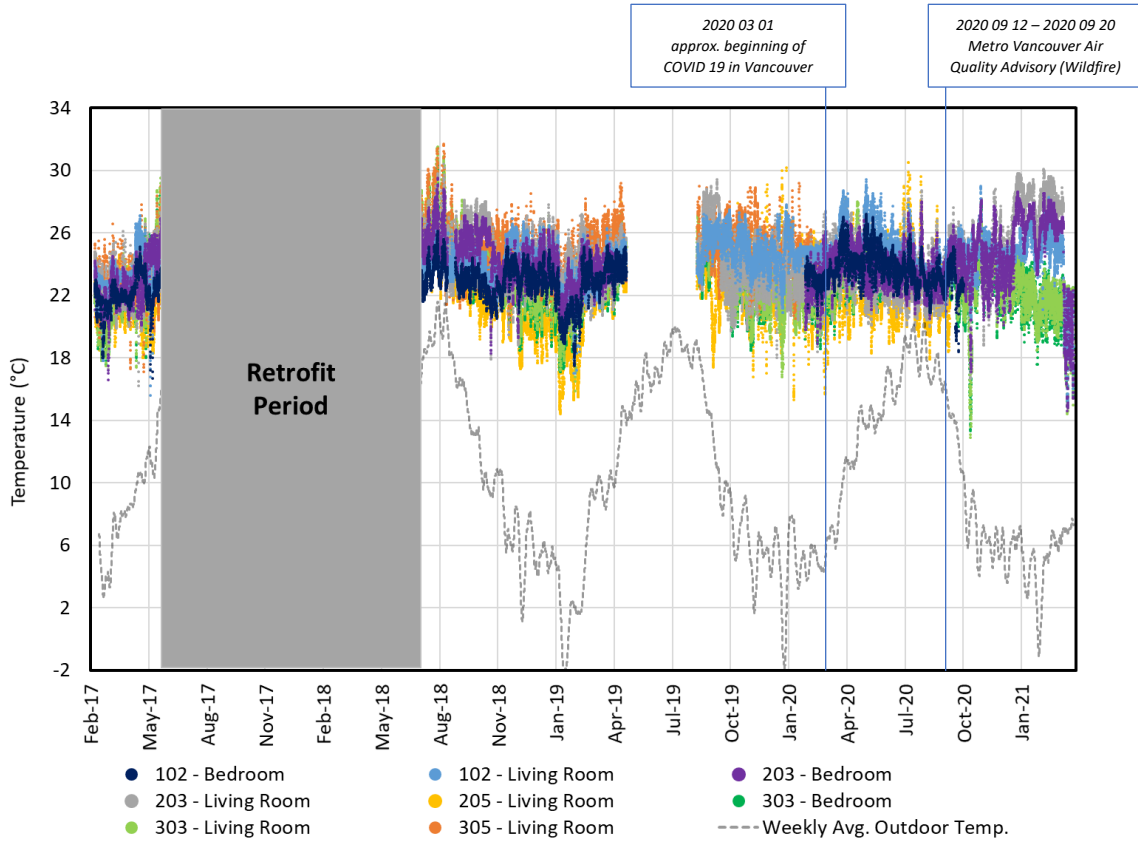
The key finding of this study was significant periods of overheating. Relying on open windows was generally ineffective as a cooling strategy for the monitored suites and led to negative IEQ consequences such as transfer of odours and exposure to outdoor contaminants (e.g., wildfires). The building retrofit measures from this study were largely focused on building enclosure and mechanical upgrades. While for example, window replacements and repairs to damaged equipment could have an impact on IEQ, no impacts were observed in this study. For future building retrofits, we recommend that specific strategies be considered for improving IEQ. These strategies could include:

- Addition of suite-level ventilation to provide consistent supply of fresh air to suites instead of relying on exhaust only ventilation and windows (e.g., heat-recovery ventilators)
- Addition of suite-level control of space heating equipment
- Suite compartmentalization to improve air sealing between suites and to reduce contaminant transfer (e.g., odours, pests, etc.)
- Addition of active cooling (e.g., centralized air-source or ductless mini-split heat pumps)
- Installation of windows with low solar heat gain coefficients (SHGC) or exterior shading to reduce incoming solar radiation
- Upgrade to high performance mechanical ventilation filters (e.g., MERV 13 or higher) during air quality advisories

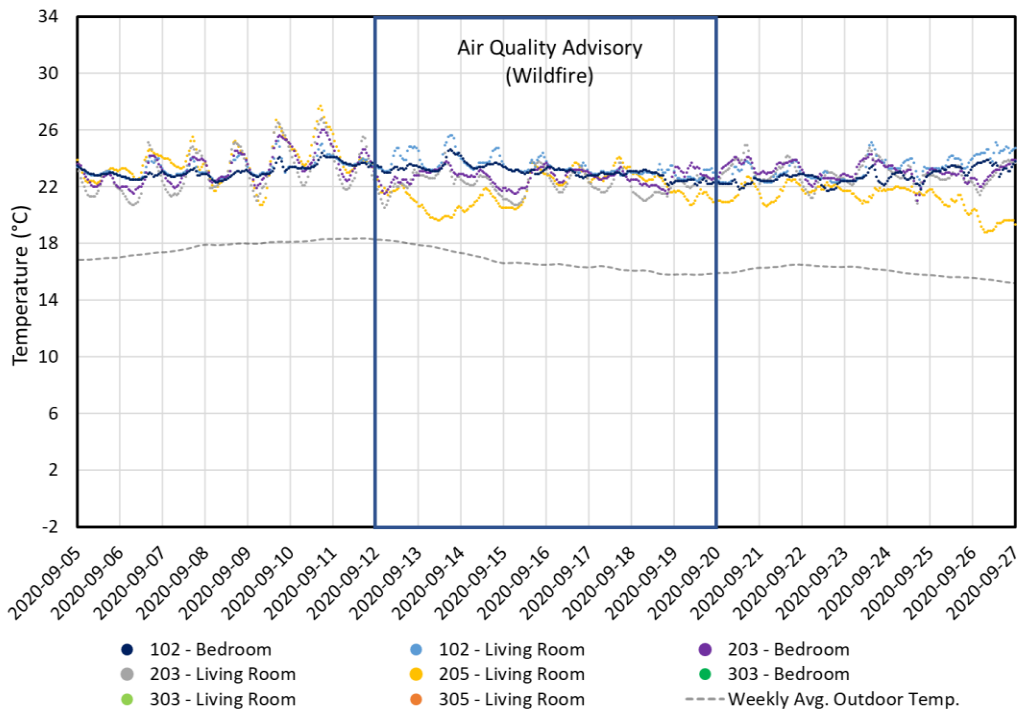
When these upgrades are considered in conjunction with more conventional building enclosure upgrades focused on thermal efficiency of walls and windows, reductions in unwanted solar gains, and improved airtightness, it is possible to meaningfully improve IEQ. Providing an airtight enclosure with adequate ventilation can also improve resilience to extreme events, such as those experienced during this study. IEQ retrofits will be an important aspect of adapting to a changing climate.

Appendix A

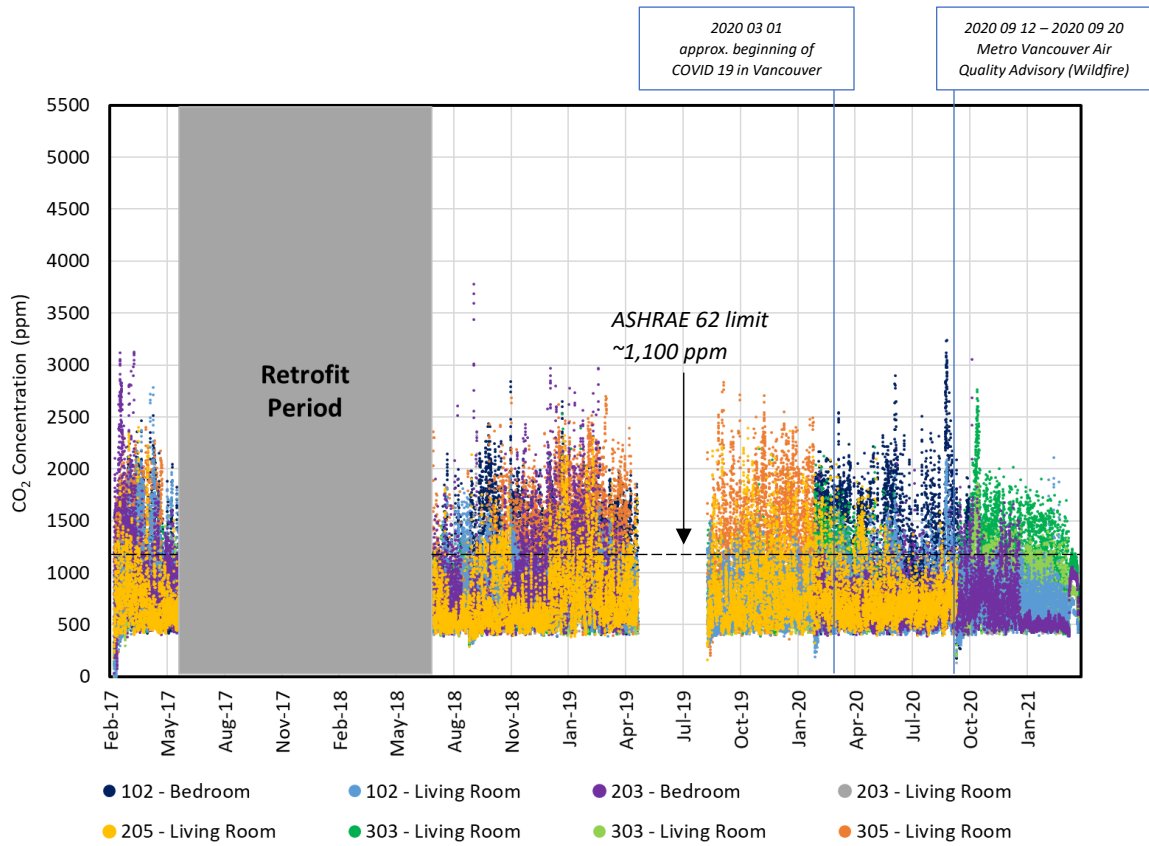
Air Temperature & Carbon Dioxide Scatter Plots



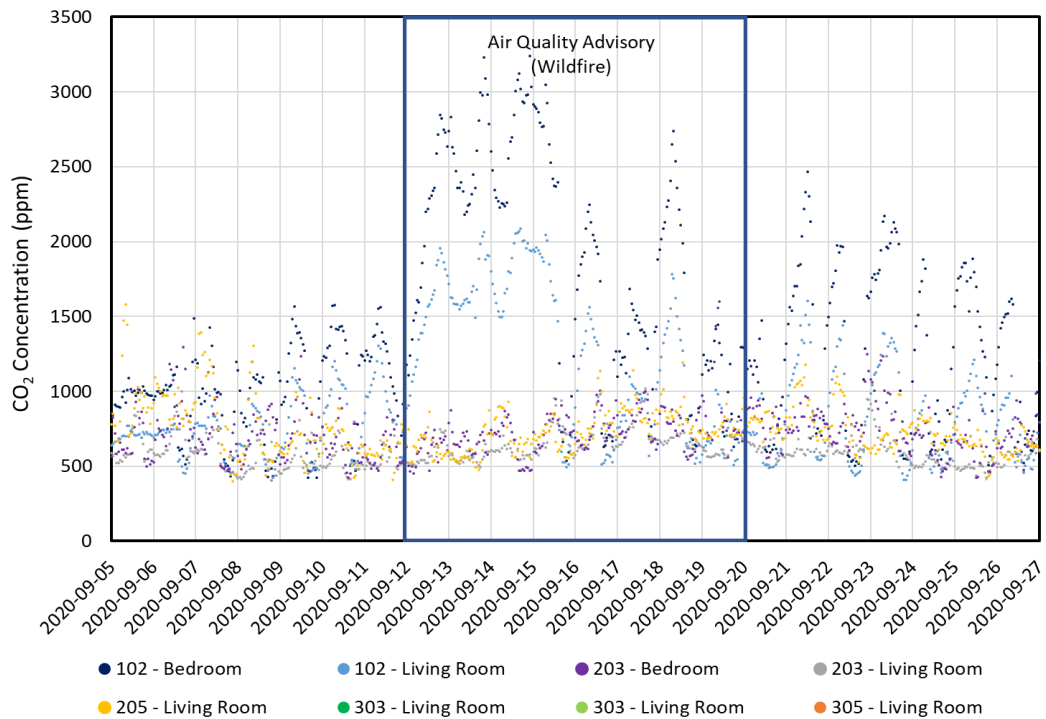
Appendix A.1 – Air temperature measurements throughout monitoring period (Building A)



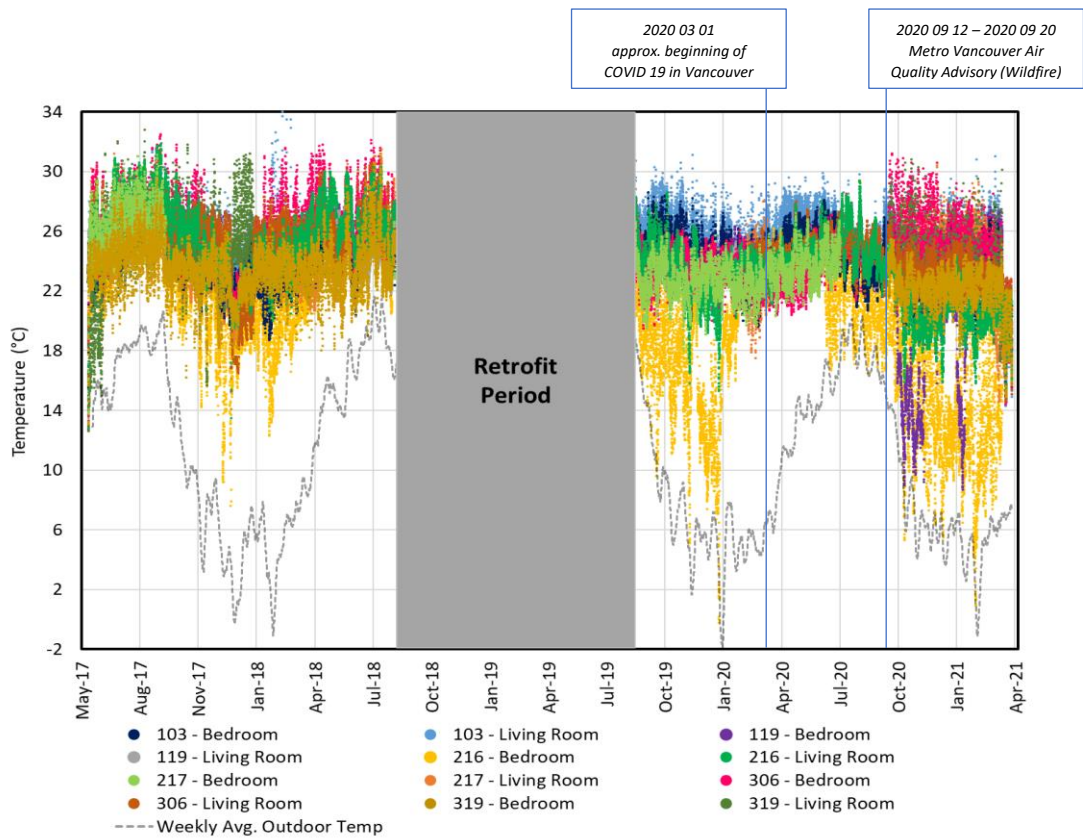
Appendix A.2 – Air temperature one week before, during and after the 2020 wildfire air quality advisory (Building A)



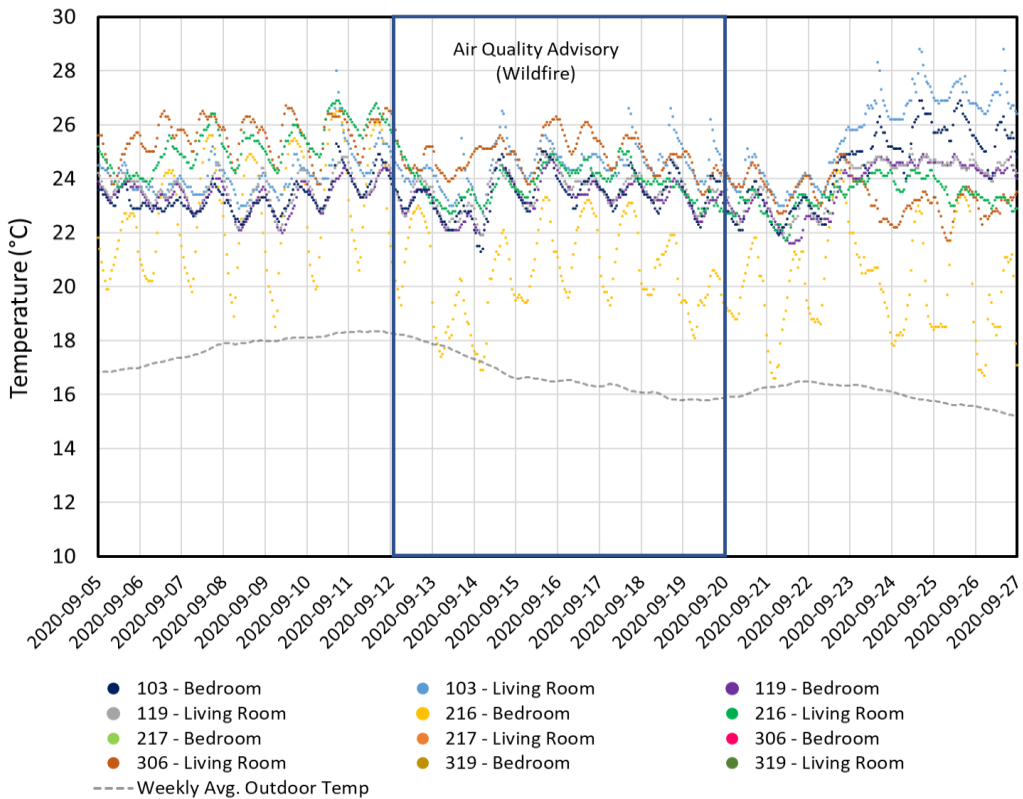
Appendix A.3 – CO₂ concentration measurements throughout monitoring period (Building A)



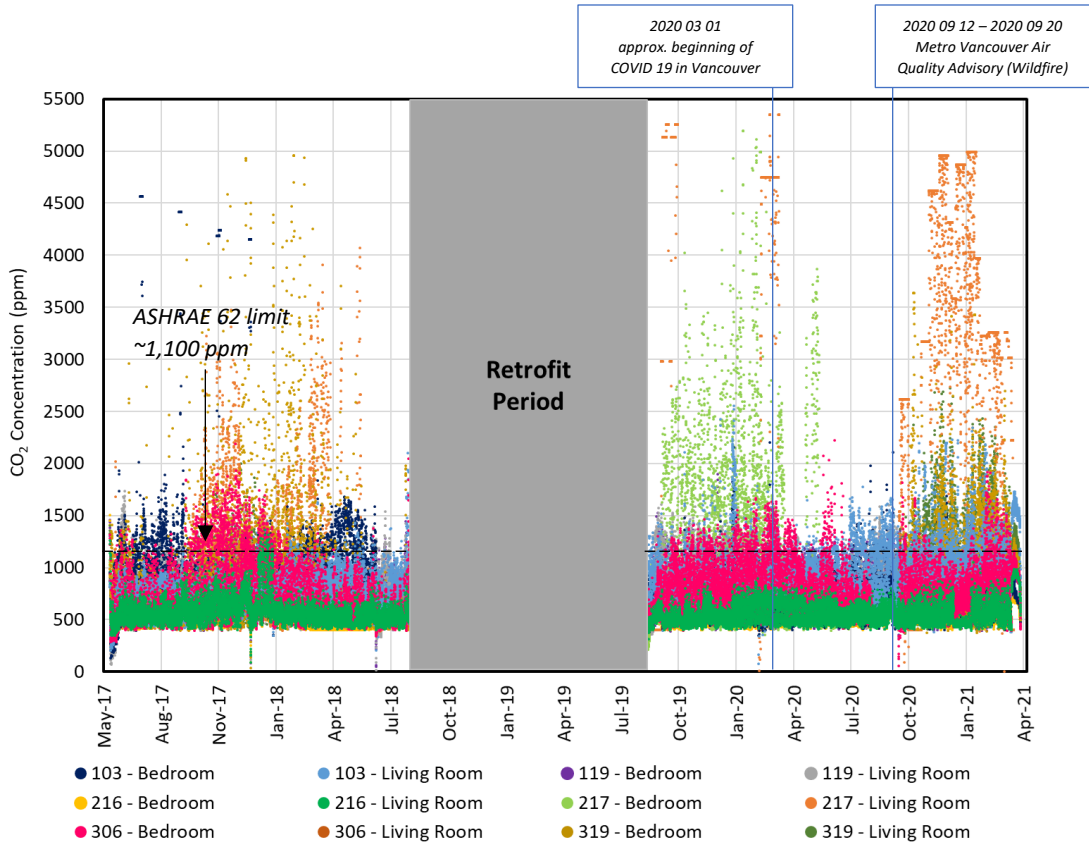
Appendix A.4 – CO₂ concentration one week before, during and after the 2020 wildfire air quality advisory (Building A)



Appendix A.5 – Air temperature measurements throughout monitoring period (Building B)



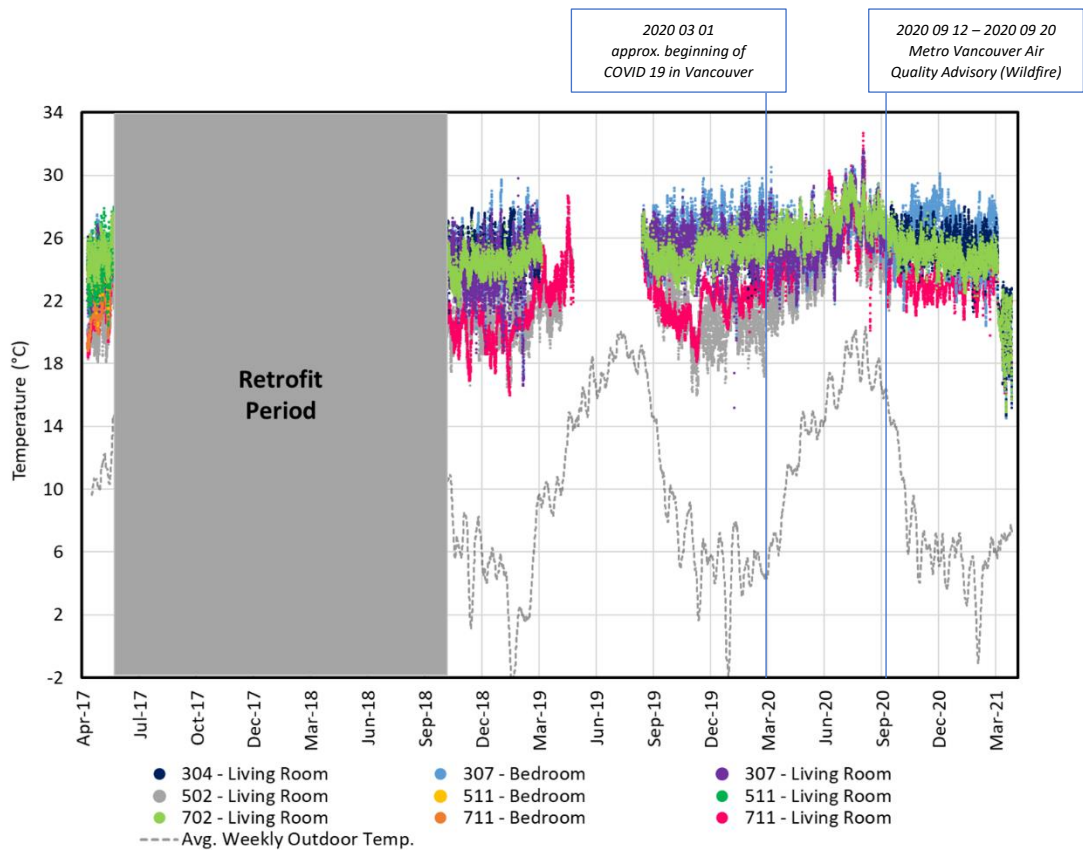
Appendix A.6 – Air temperature one week before, during and after the 2020 wildfire air quality advisory (Building B)



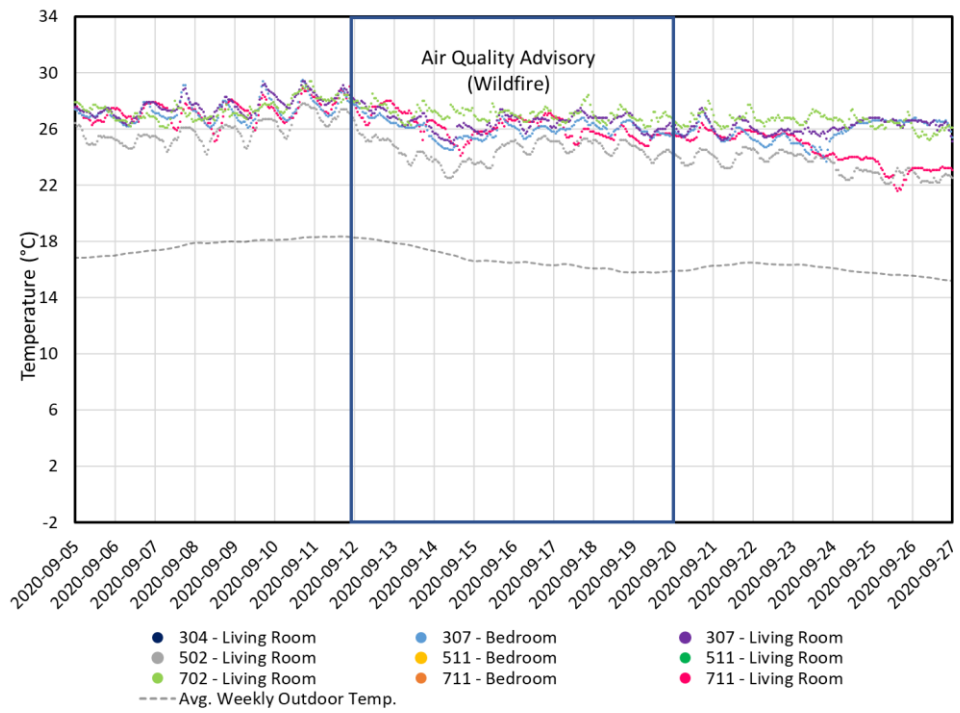
Appendix A.7 – CO₂ concentration measurements throughout monitoring period (Building B)



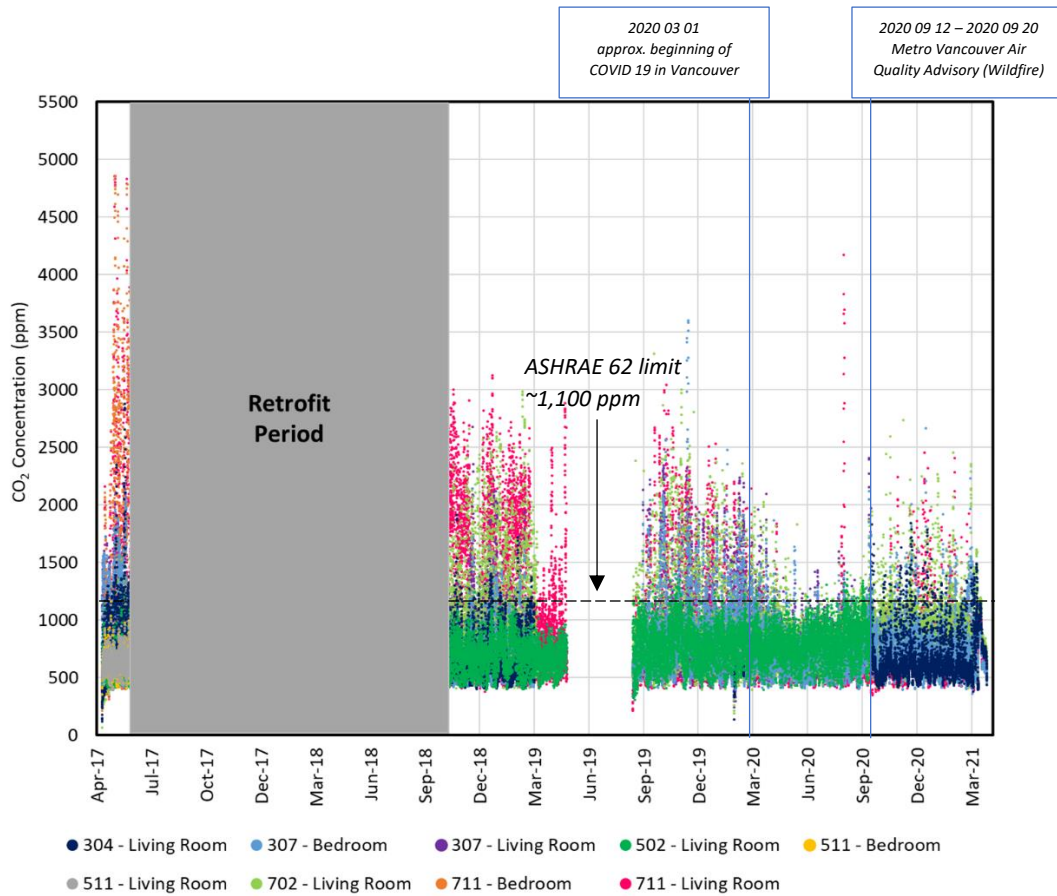
Appendix A.8 – CO₂ concentration one week before, during and after the 2020 wildfire air quality advisory (Building B)



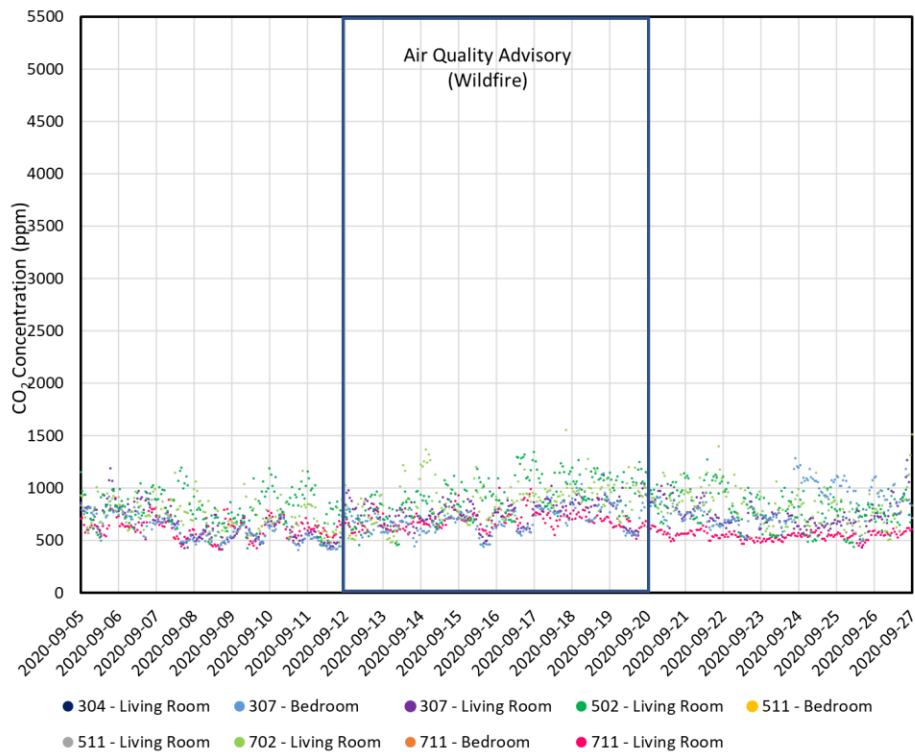
Appendix A.9 – Air temperature measurements throughout monitoring period (Building C)



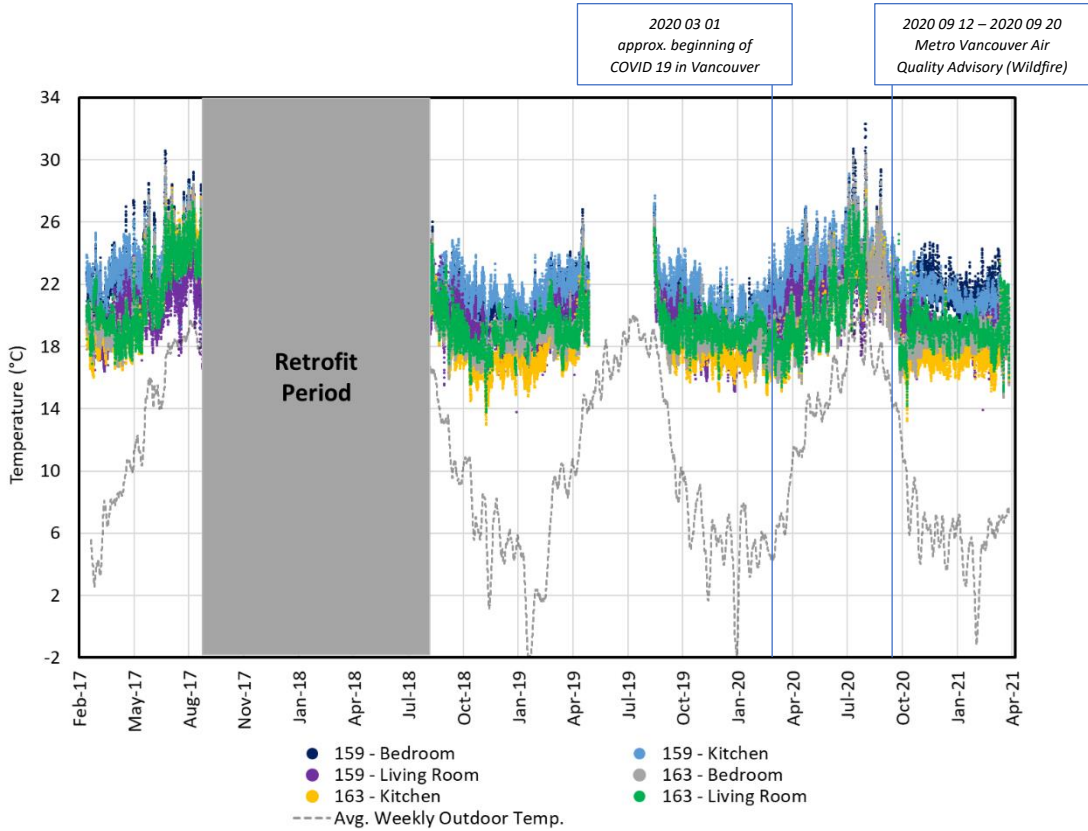
Appendix A.10 – Air temperature one week before, during and after the 2020 wildfire air quality advisory (Building C)



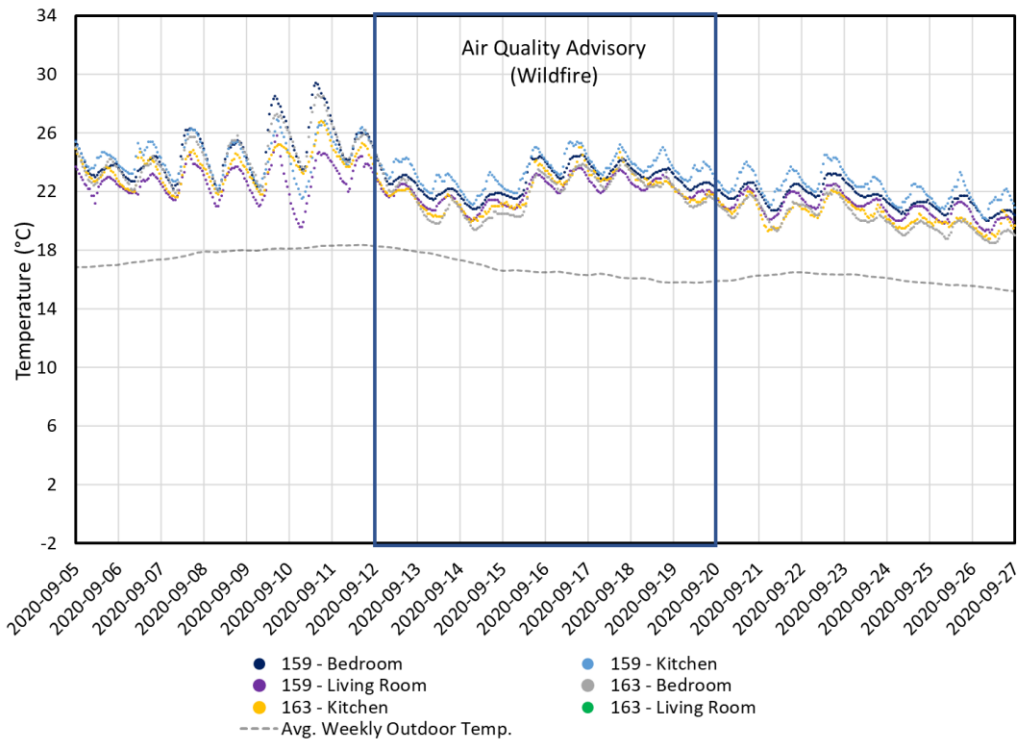
Appendix A.11 – CO₂ concentration measurements throughout monitoring period (Building C)



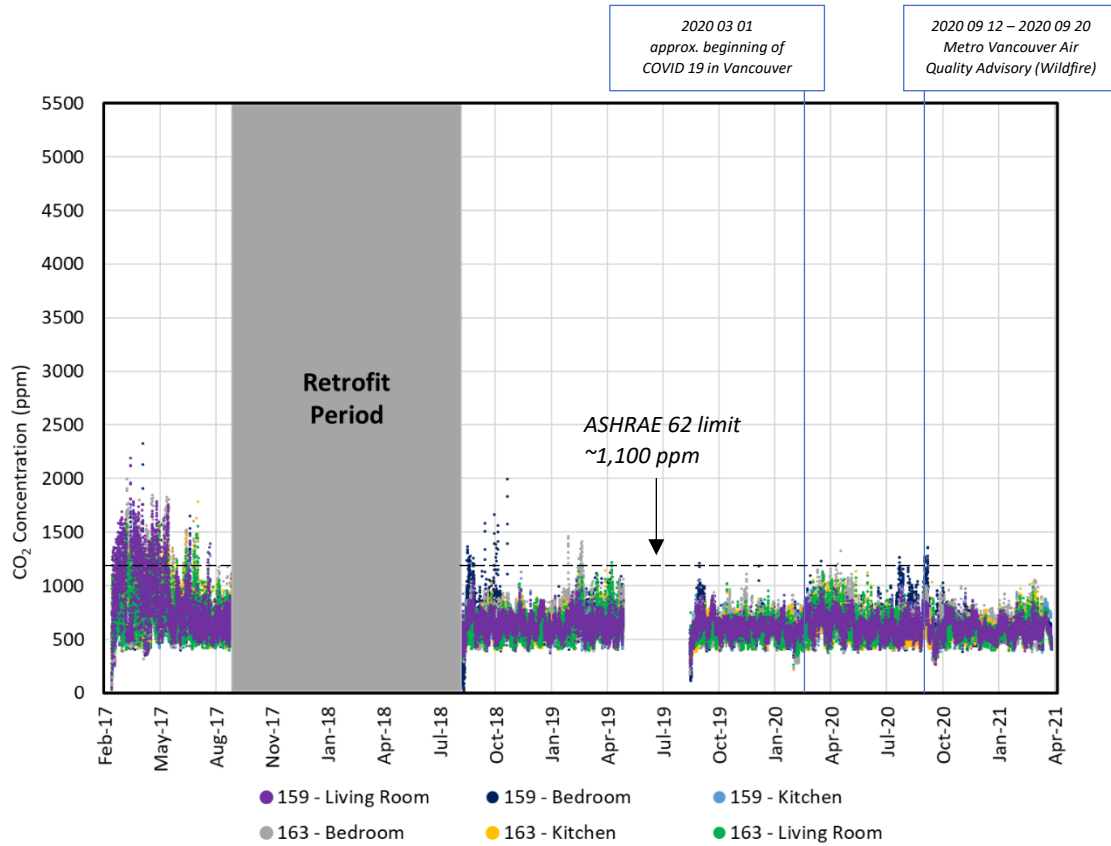
Appendix A.12 – CO₂ concentration one week before, during and after the 2020 wildfire air quality advisory (Building C)



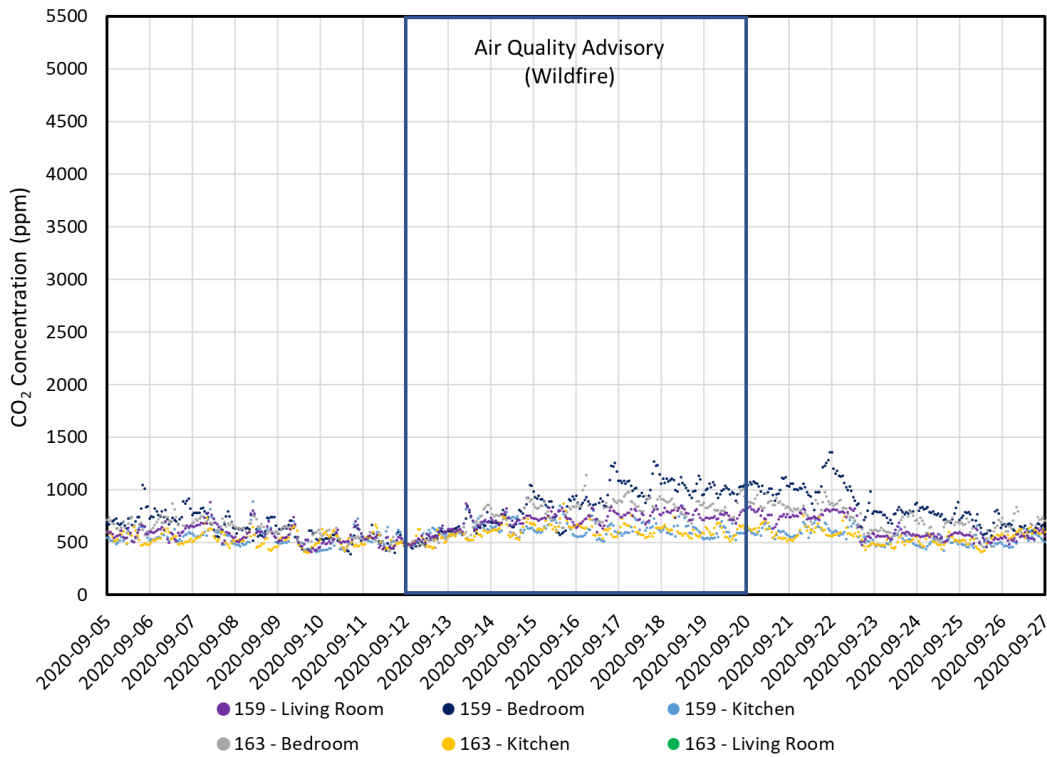
Appendix A.13 – Air temperature measurements throughout monitoring period (Building D)



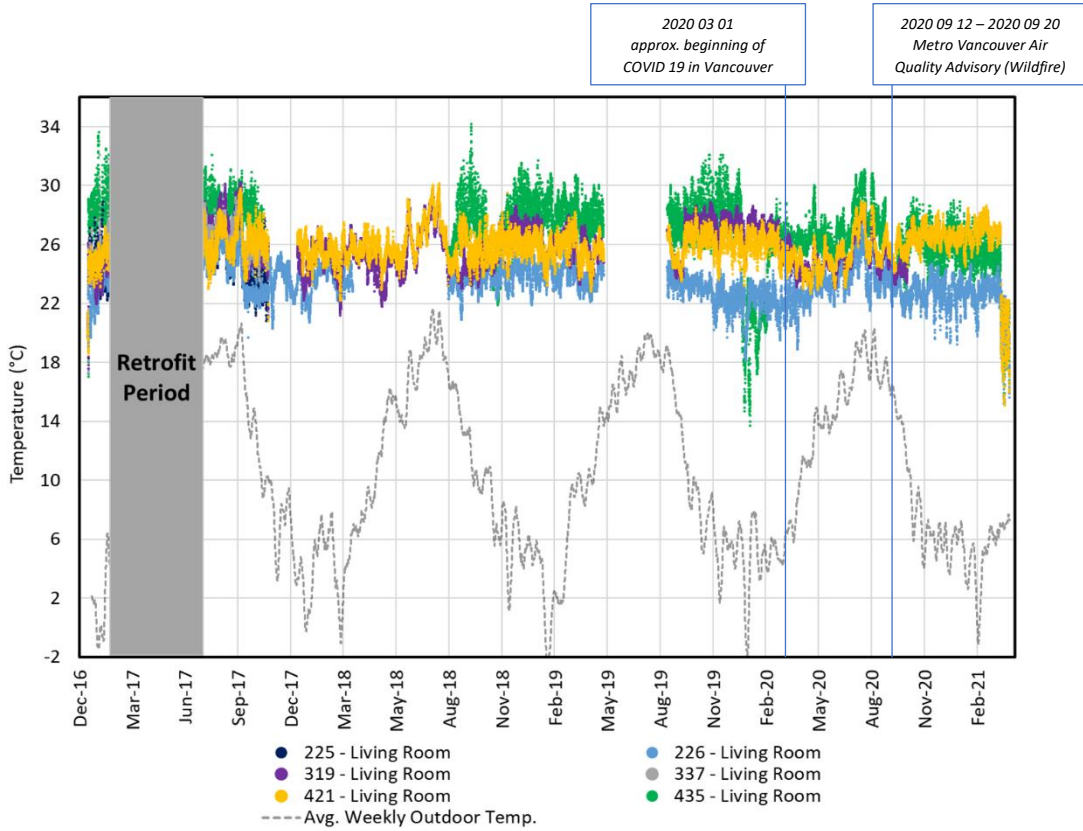
Appendix A.14 – Air temperature one week before, during and after the 2020 wildfire air quality advisory (Building D)



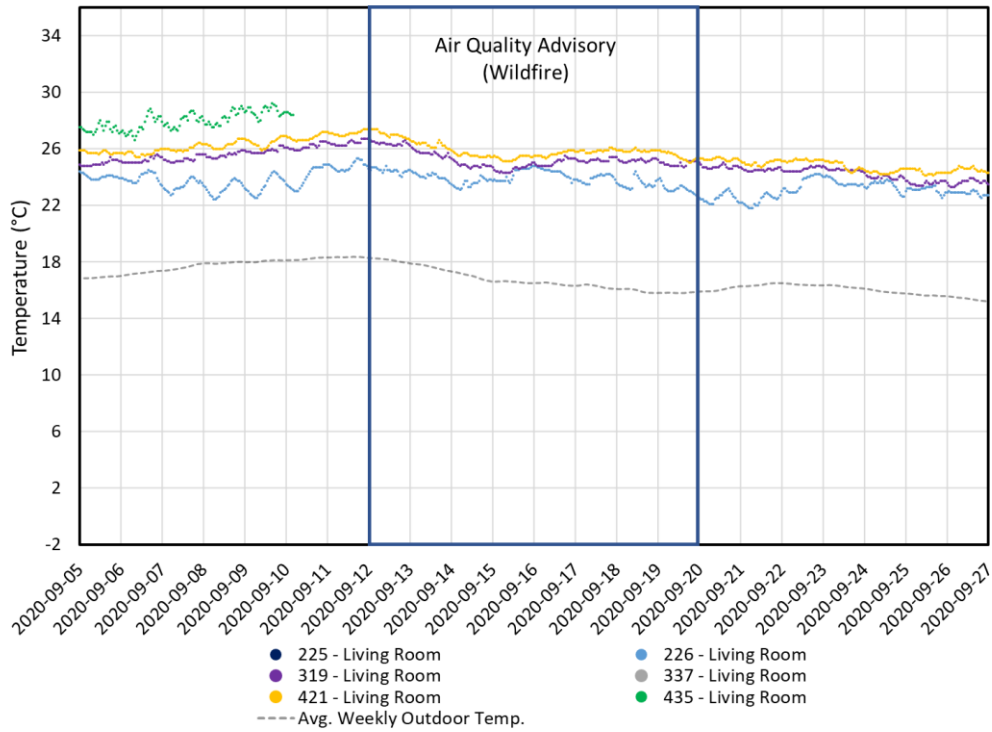
Appendix A.15 – CO₂ concentration measurements throughout monitoring period (Building D)



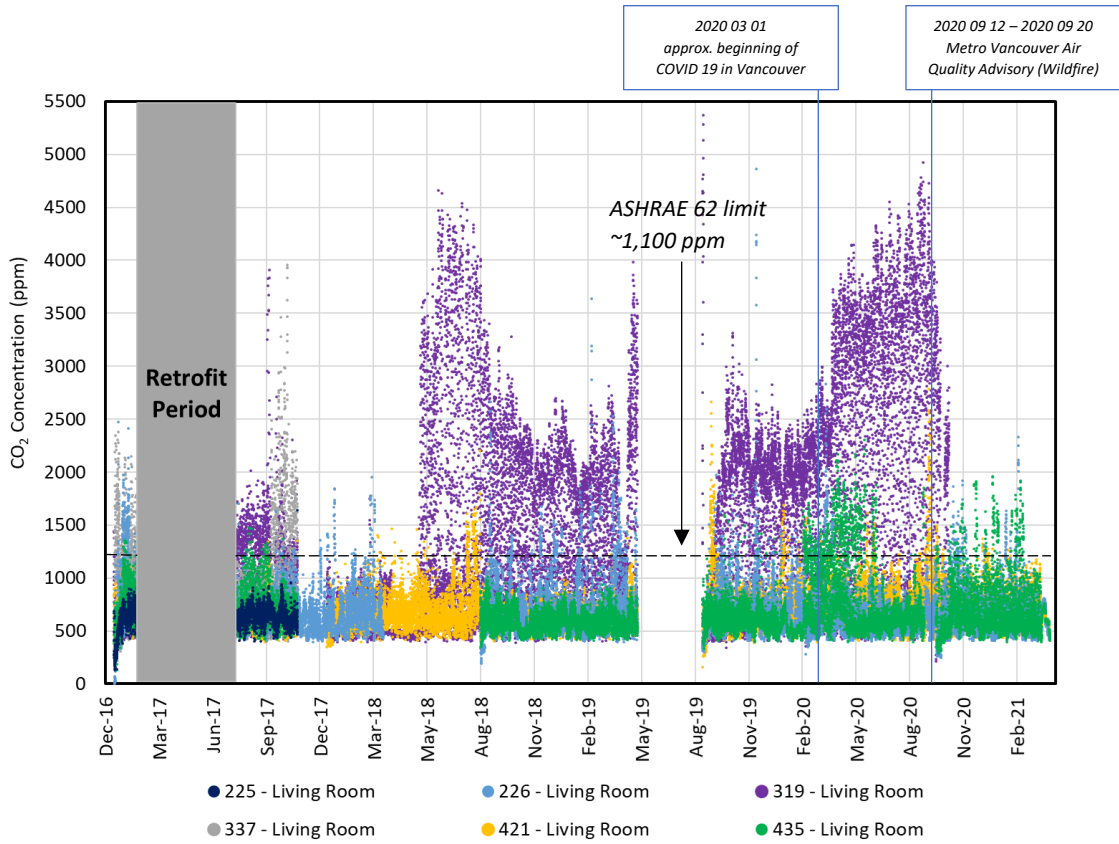
Appendix A.16 – CO₂ concentration one week before, during and after the 2020 wildfire air quality advisory (Building D)



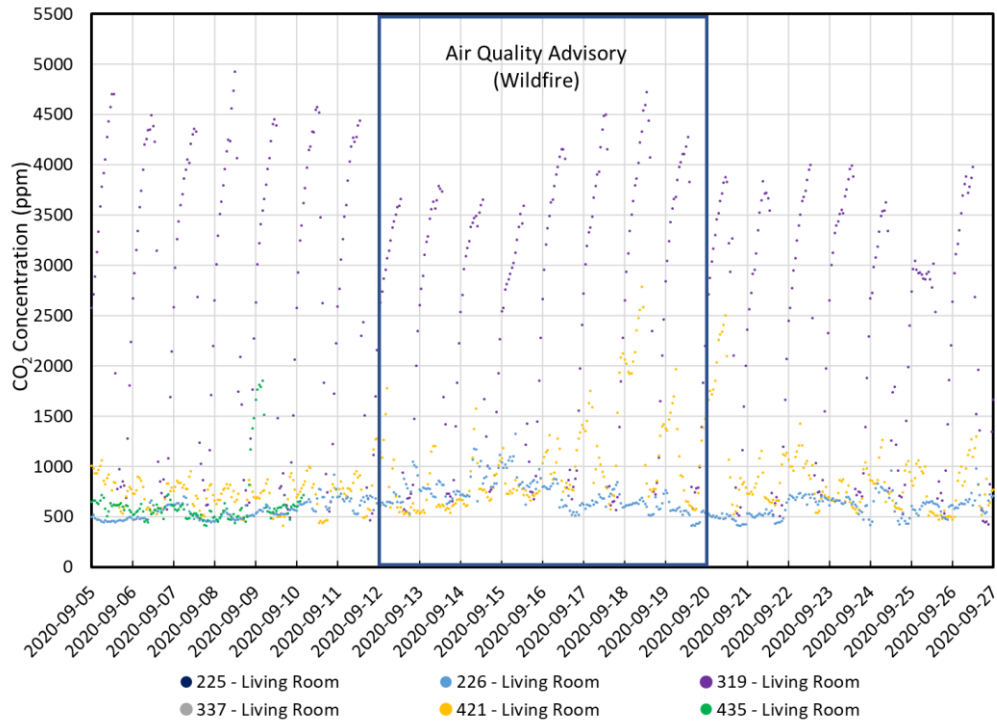
Appendix A.17 – Air temperature measurements throughout monitoring period (Building E)



Appendix A.18 – Air temperature one week before, during and after the 2020 wildfire air quality advisory (Building E)



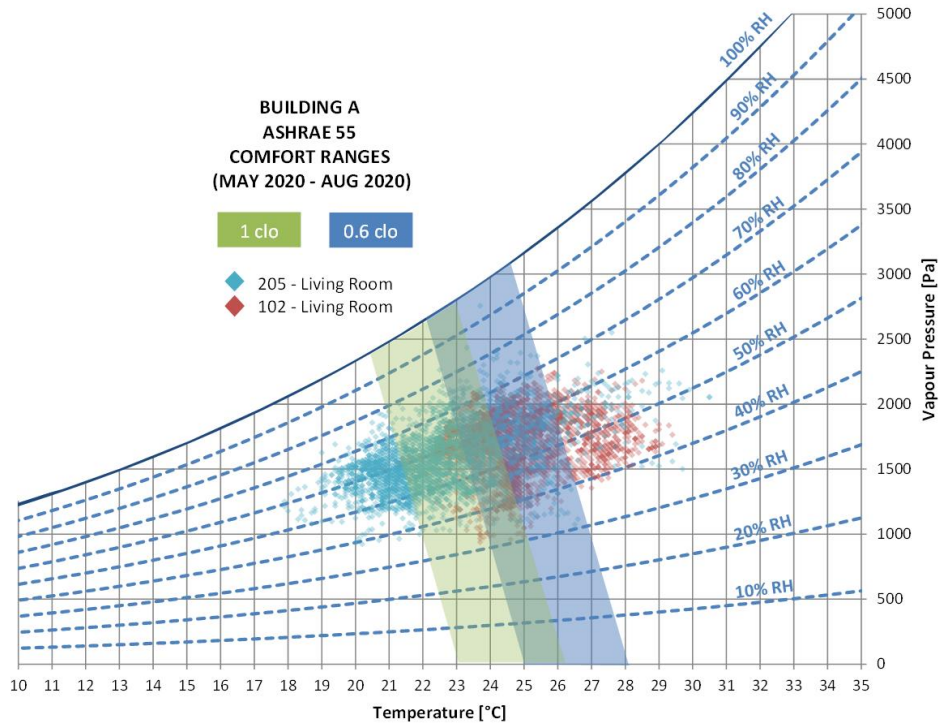
Appendix A.19 – CO₂ concentration measurements throughout monitoring period (Building E)



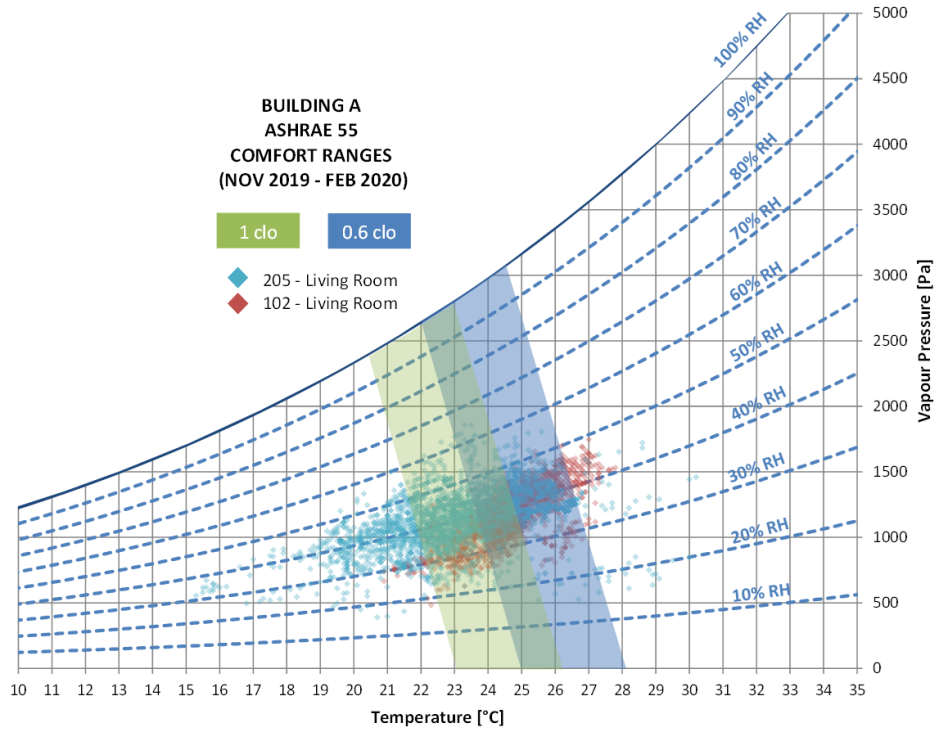
Appendix A.20 – CO₂ concentration one week before, during and after the 2020 wildfire air quality advisory (Building E)

Appendix B

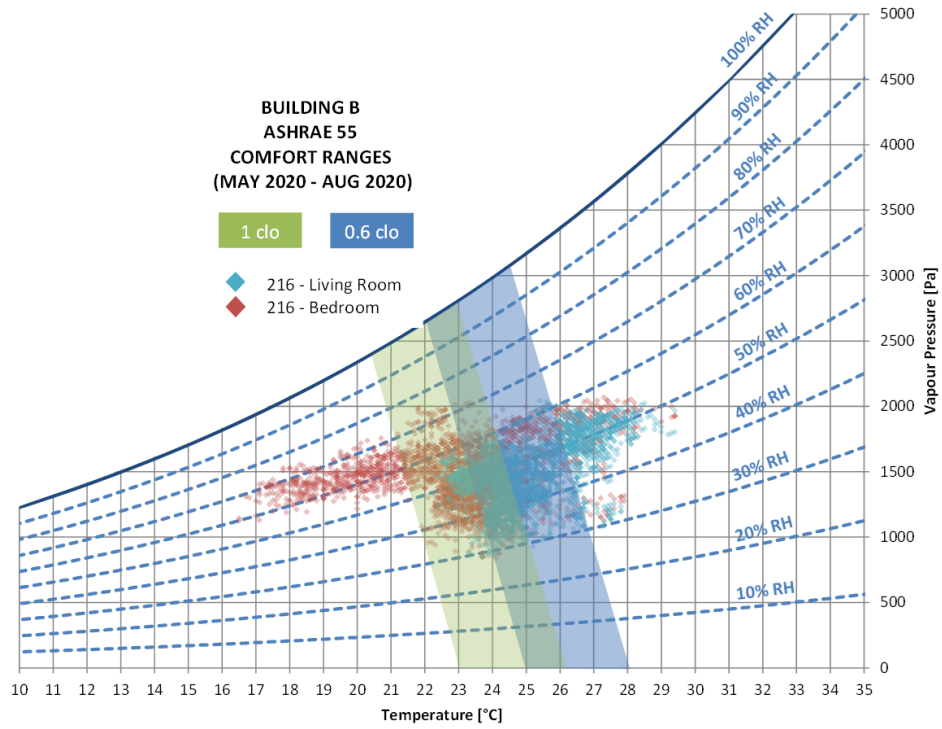
ASHRAE 55 - Psychrometric Chart Analysis



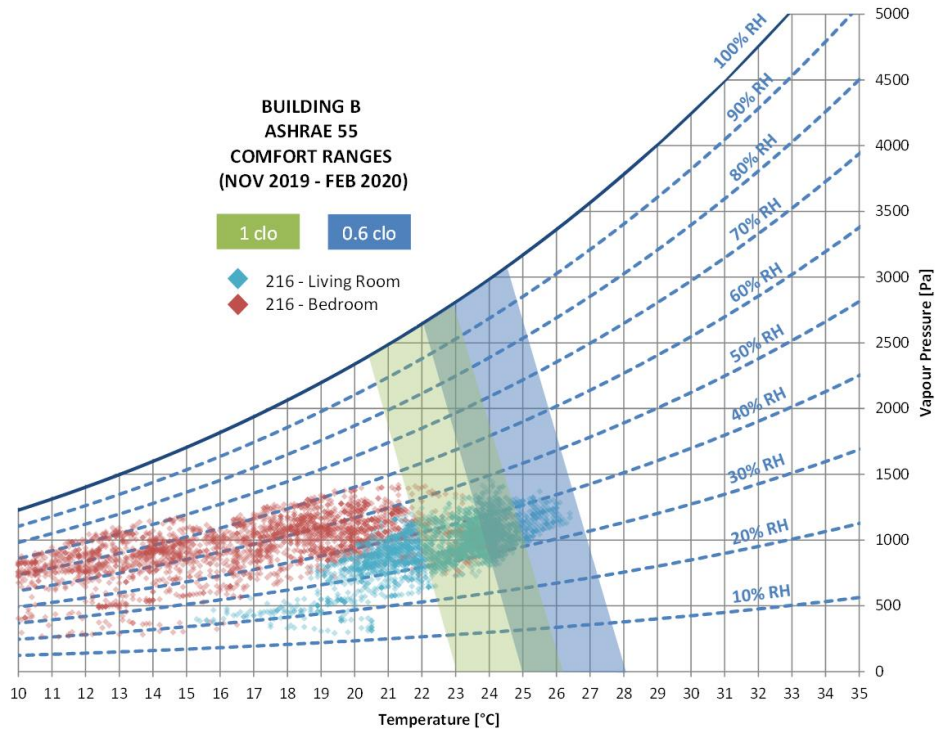
Appendix B.1 – Hourly air temperature measurements of two samples suites from Building A plotted on psychrometric chart (summer)



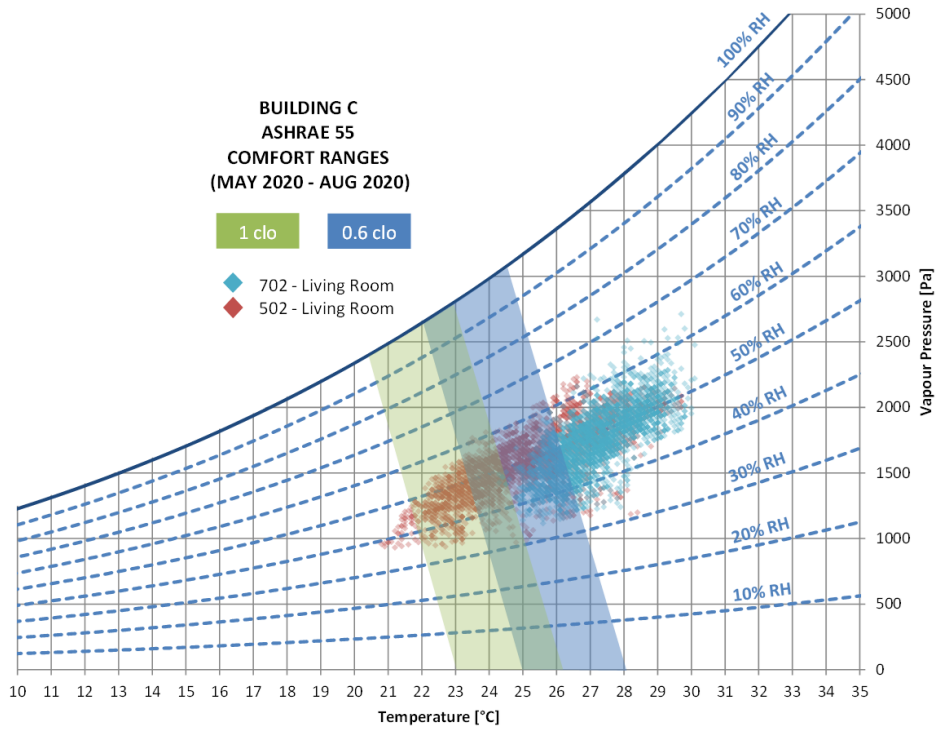
Appendix B.2 – Hourly air temperature measurements of two samples suites from Building A plotted on psychrometric chart (winter)



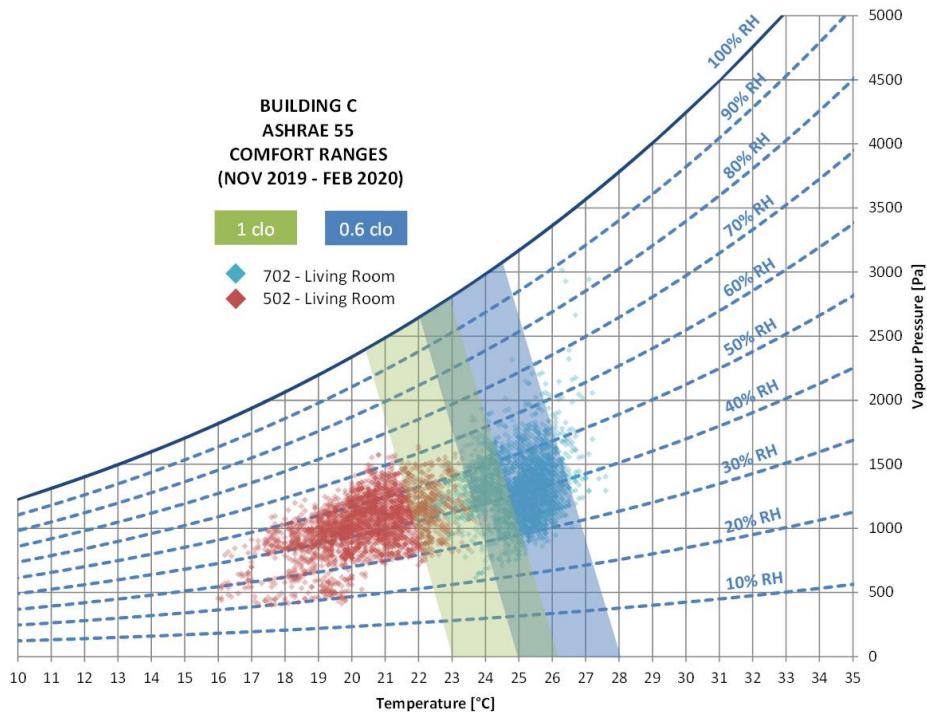
Appendix B.3 – Hourly air temperature measurements of two samples suites from Building B plotted on psychrometric chart (summer)



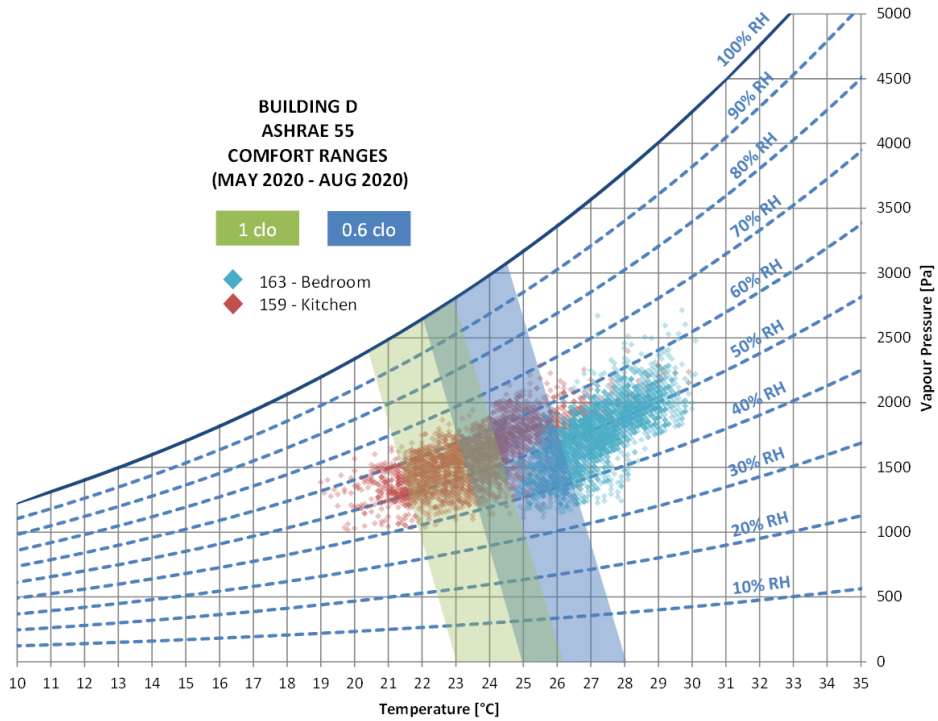
Appendix B.4 – Hourly air temperature measurements of two samples suites from Building B plotted on psychrometric chart (winter)



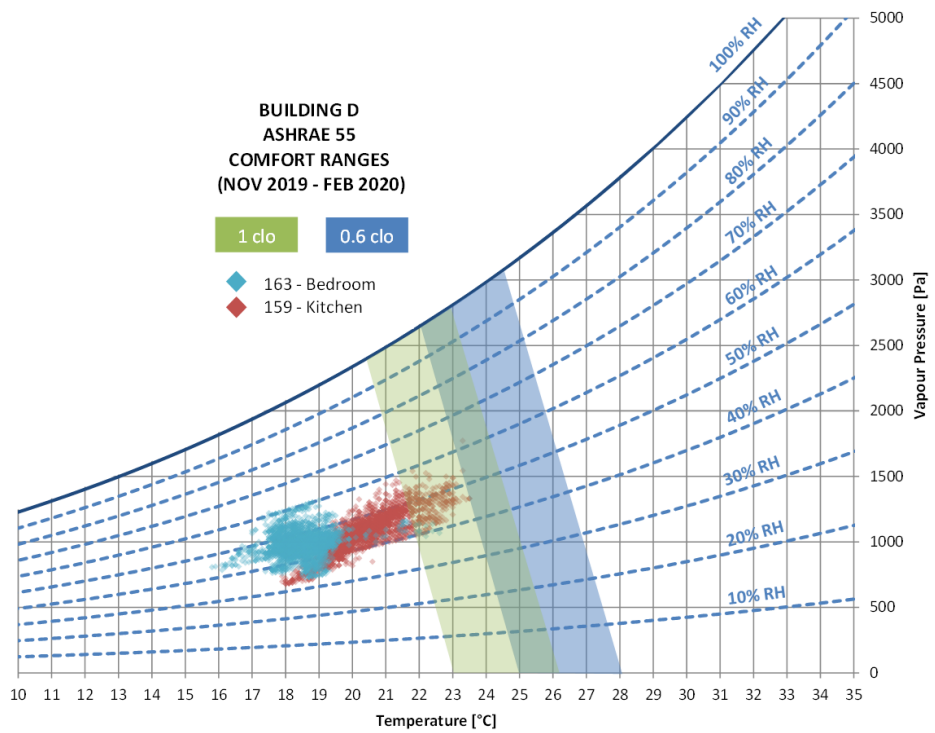
Appendix B.5 – Hourly air temperature measurements of two samples suites Building C plotted on psychrometric chart (summer)



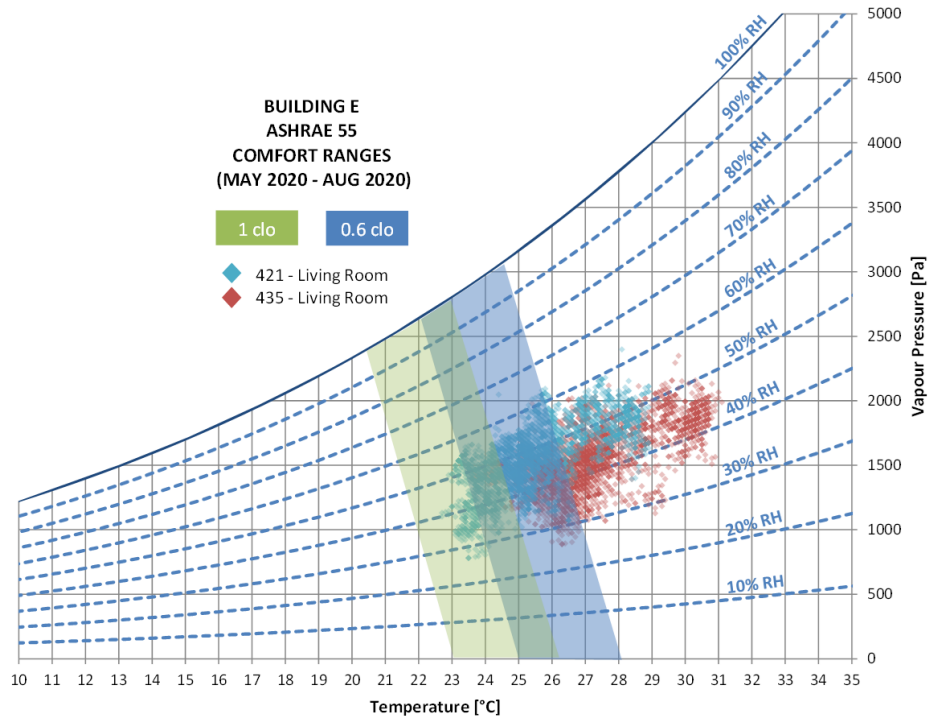
Appendix B.6 – Hourly air temperature measurements of two samples suites from Building C plotted on psychrometric chart (winter)



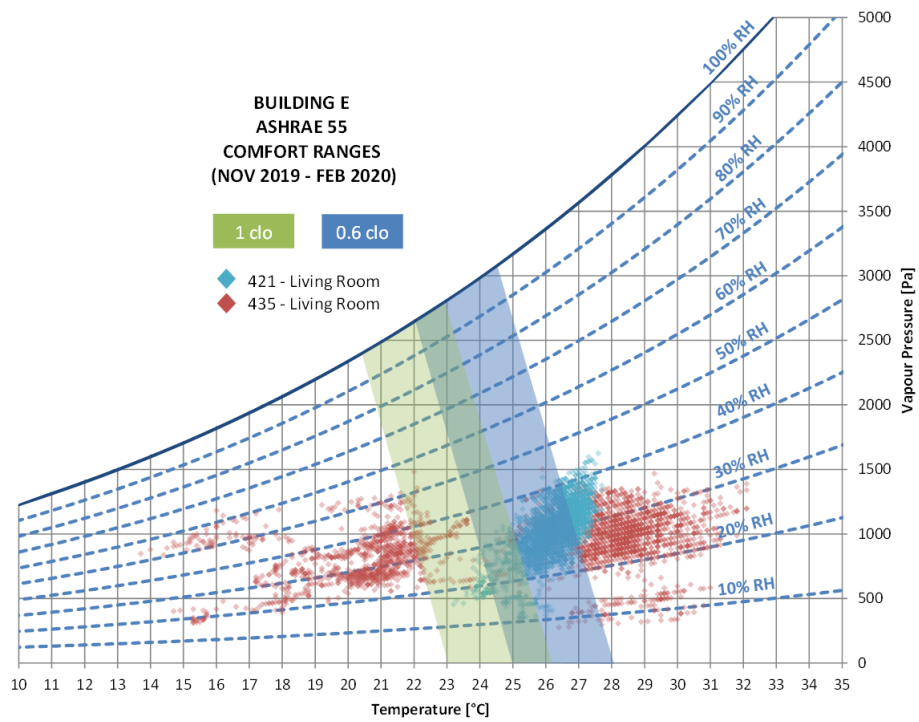
Appendix B.5 – Hourly air temperature measurements of two samples suites Building D plotted on psychrometric chart (summer)



Appendix B.6 – Hourly air temperature measurements of two samples suites from Building D plotted on psychrometric chart (winter)



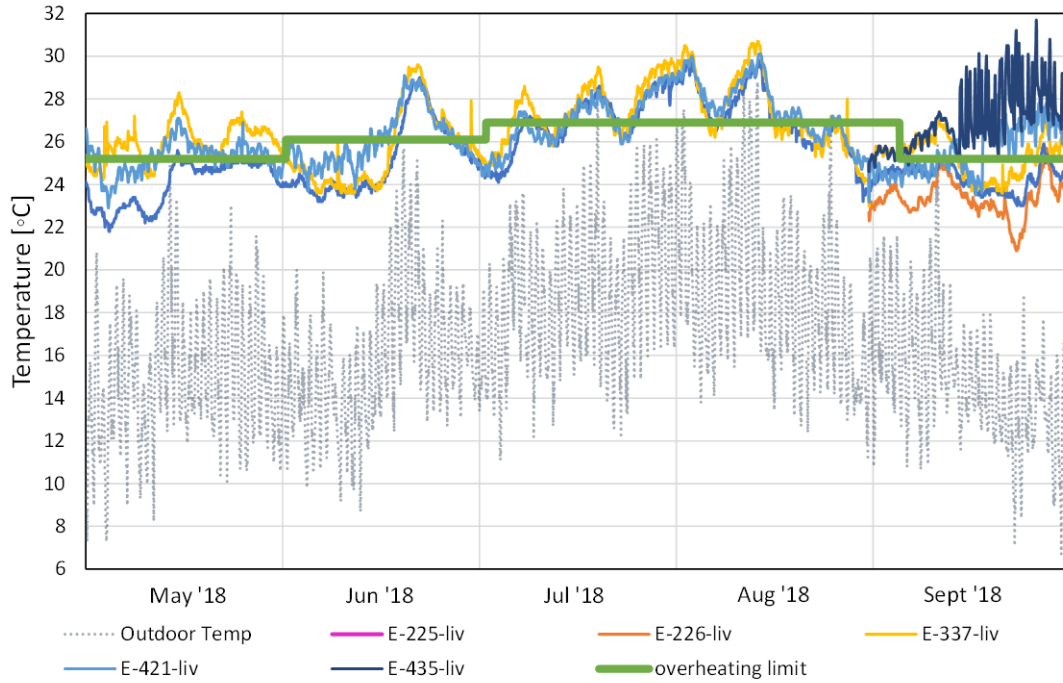
Appendix B.5 – Hourly air temperature measurements of two samples suites Building E plotted on psychrometric chart (summer)



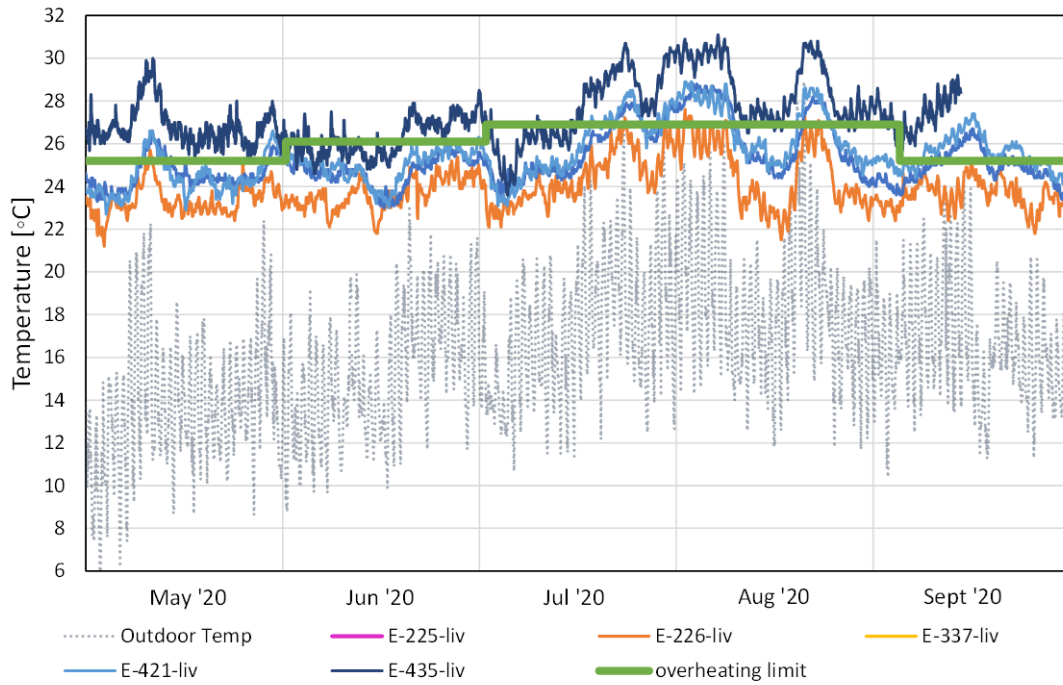
Appendix A.B – Hourly air temperature measurements of two samples suites from Building E plotted on psychrometric chart (winter)

Appendix C

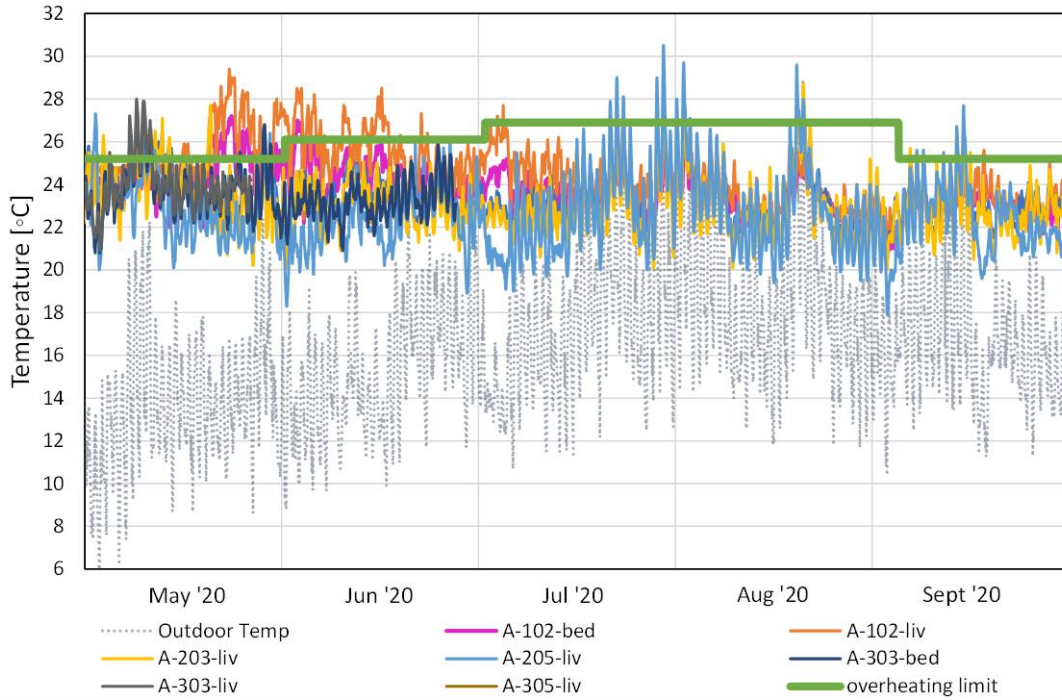
Suite Overheating Analysis



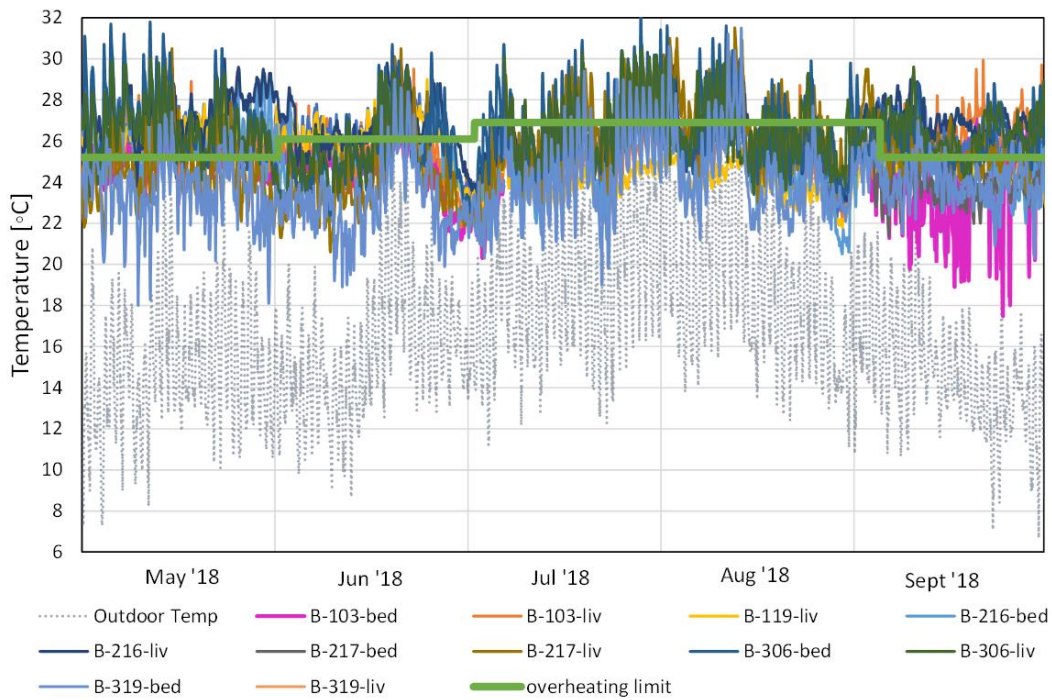
Appendix C.1 – Suite interior air temperature for Building E (2018, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



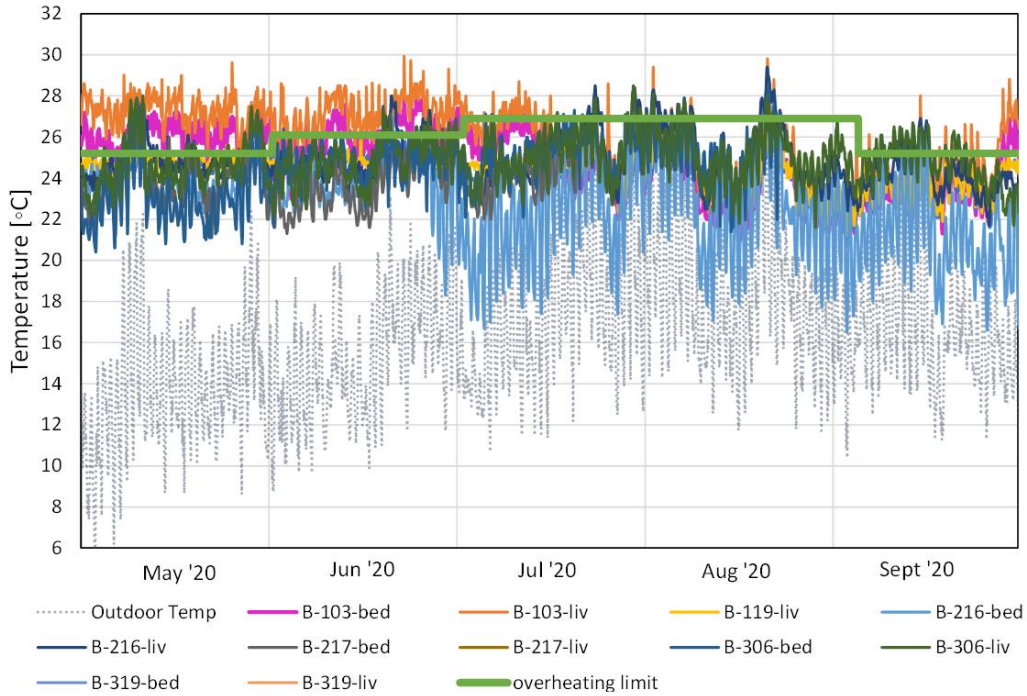
Appendix C.2 – Suite interior air temperature for Building E (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



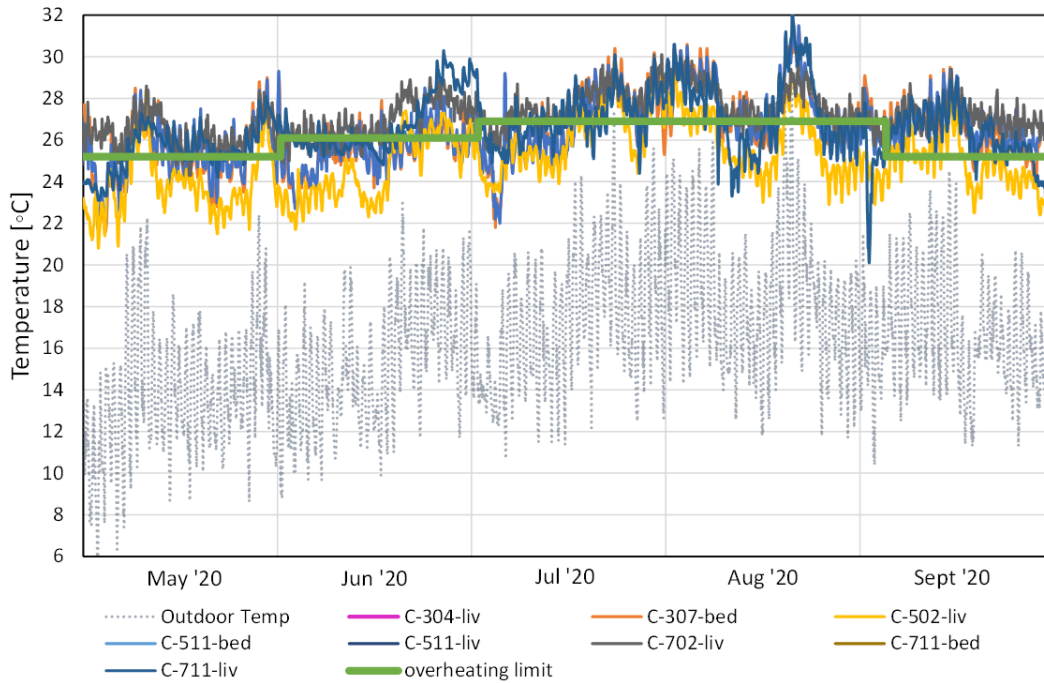
Appendix C.3 – Suite interior air temperature for Building A (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



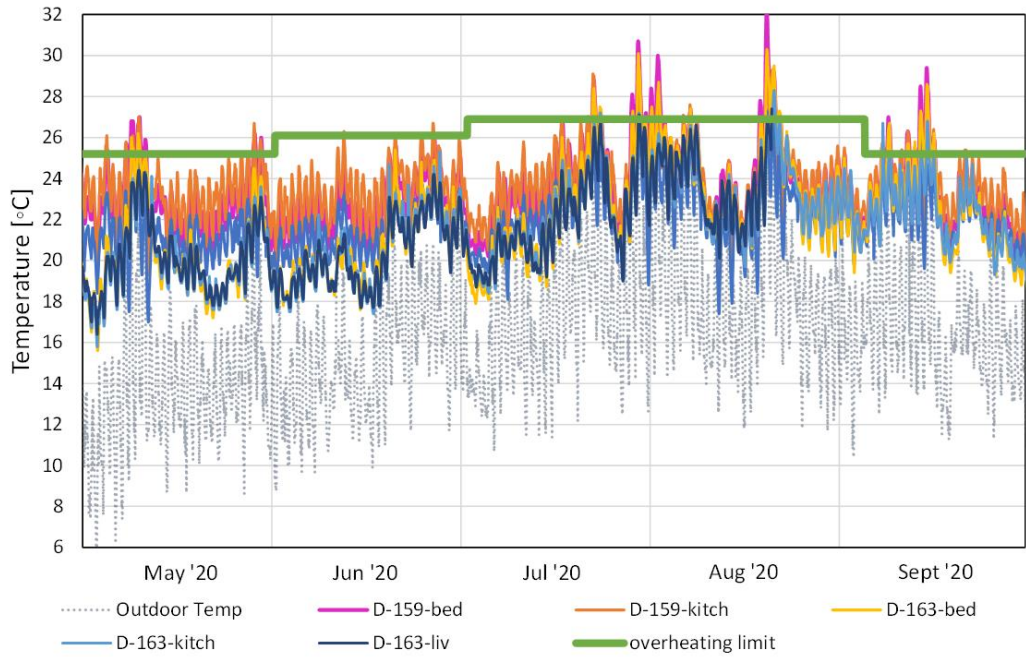
Appendix C.4 – Suite interior air temperature for Building B (2018, pre-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



Appendix C.5 – Suite interior air temperature for Building B (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



Appendix C.6 – Suite interior air temperature for Building C (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.



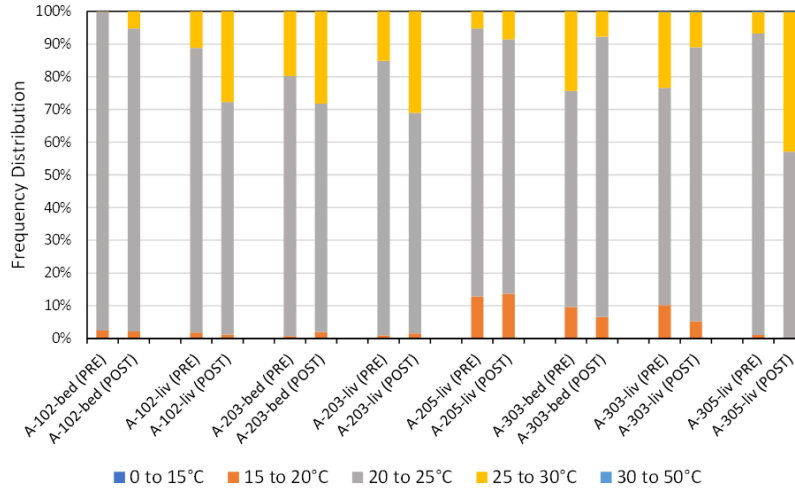
Appendix C.7 – Suite interior air temperature for Building D (2020, post-retrofit) against the summer overheating limit defined by BC Housing Design Guideline and City of Vancouver Energy Modelling Guidelines.

Appendix D

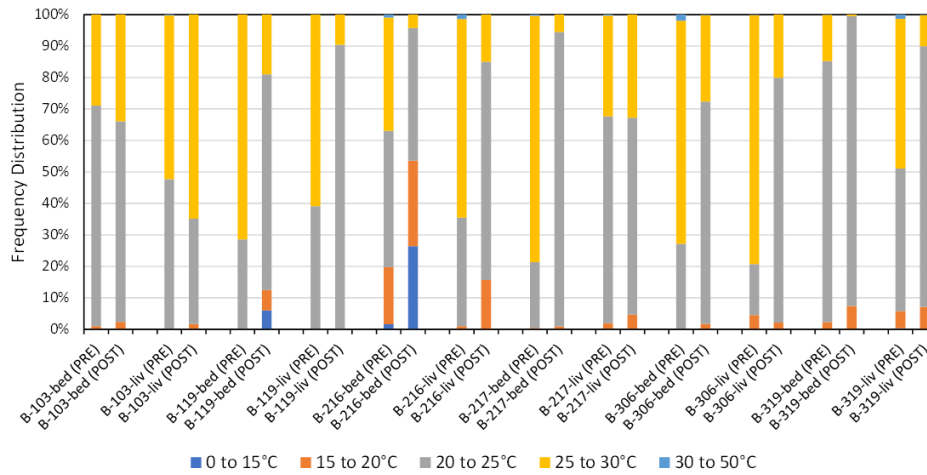
Summary Tables with Values

Appendix E

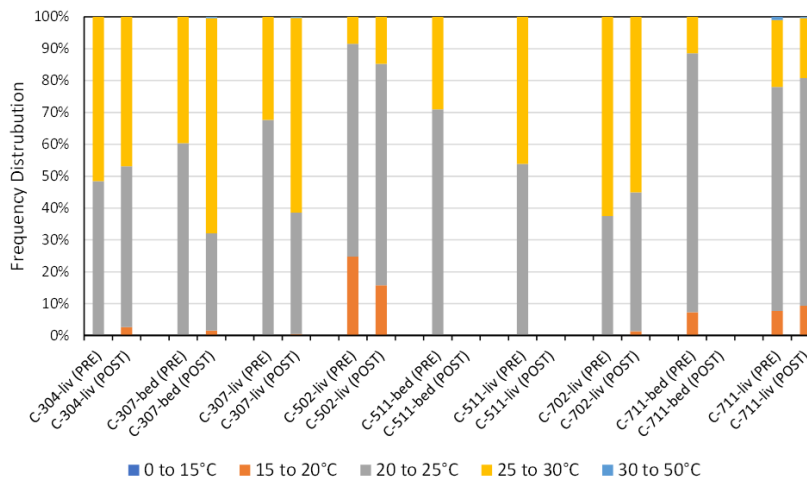
Frequency Distribution Bar Charts



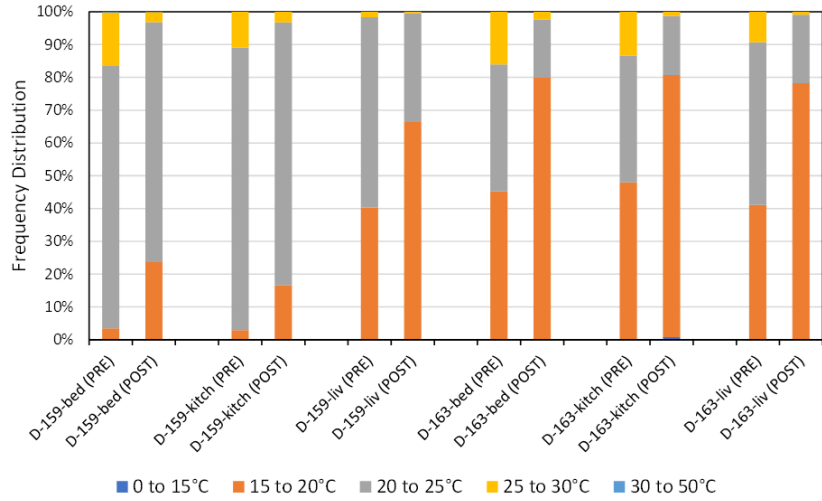
Appendix E.1 – Pre/post-retrofit air temperature frequency distribution for Building A



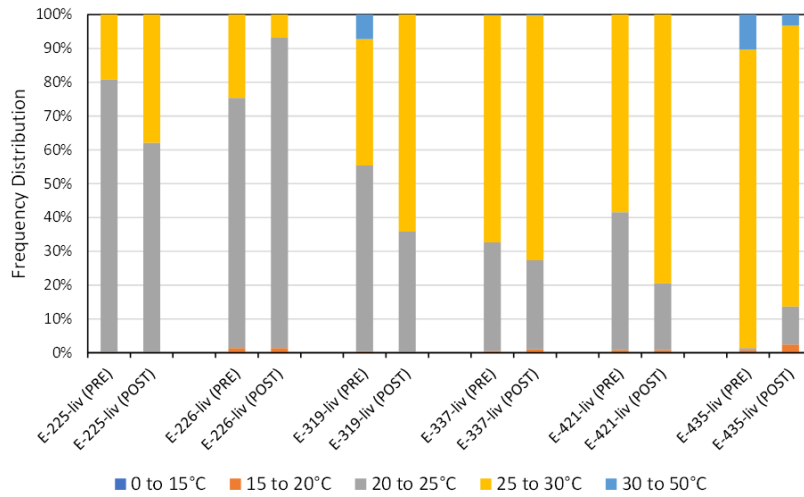
Appendix E.2 – Pre/post-retrofit air temperature frequency distribution for Building B



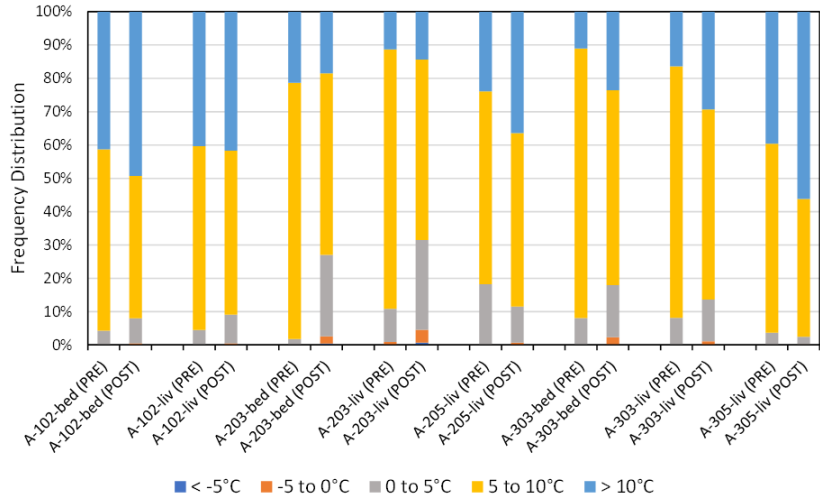
Appendix E.3 – Pre/post-retrofit air temperature frequency distribution for Building C



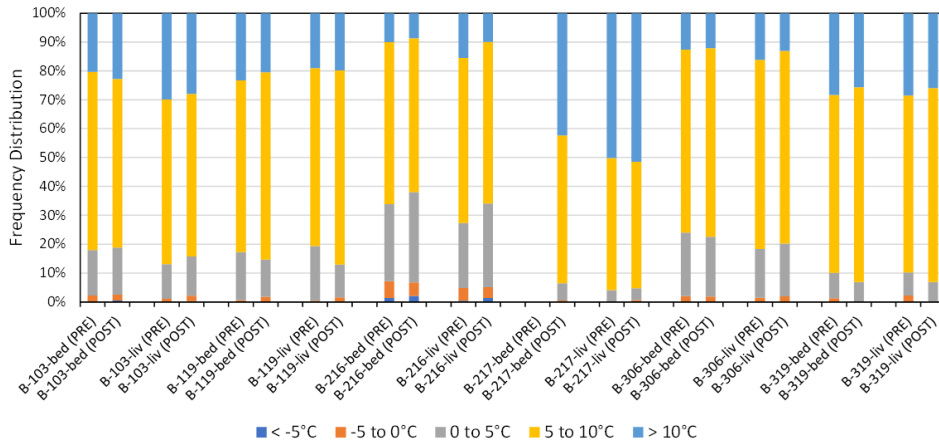
Appendix E.4 – Pre/post-retrofit air temperature frequency distribution for Building D



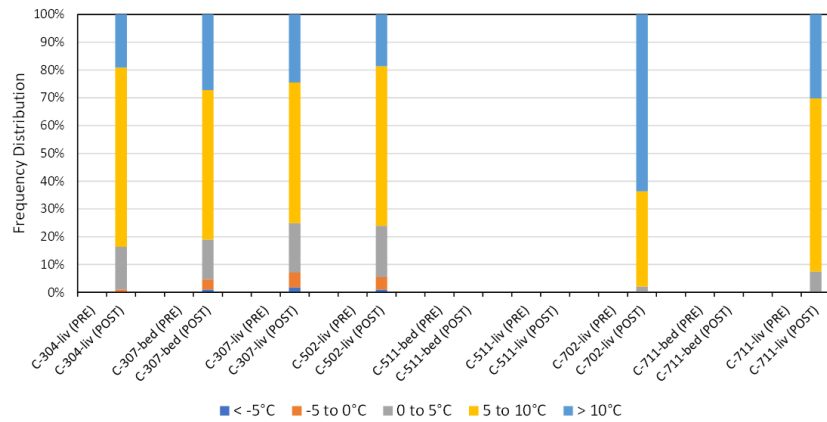
Appendix E.5 – Pre/post-retrofit air temperature frequency distribution for Building E



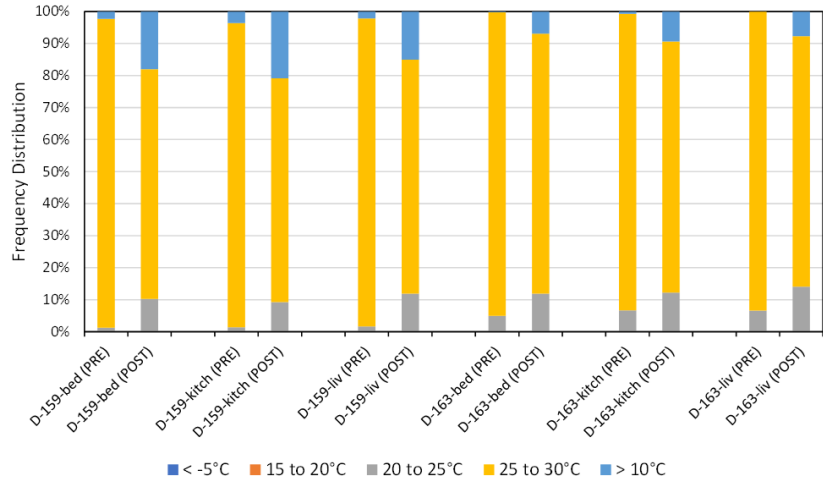
Appendix E.6 – Pre/post-retrofit dew point temperature frequency distribution for Building A between Oct-Mar



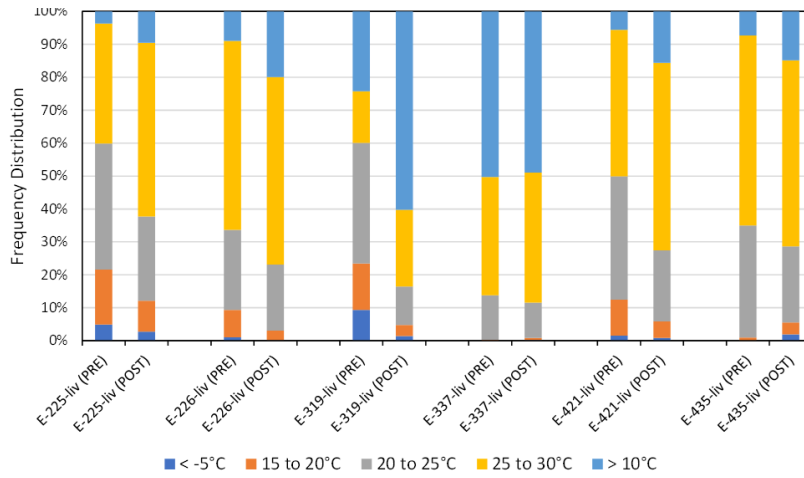
Appendix E.7 – Pre/post-retrofit dew point temperature frequency distribution for Building B between Oct-Mar



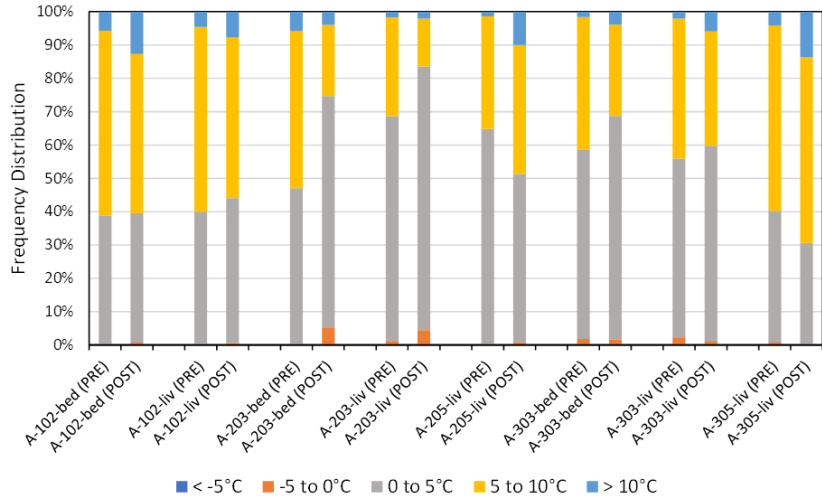
Appendix E.8 – Pre/post-retrofit dew point temperature frequency distribution for Building C between Oct-Mar



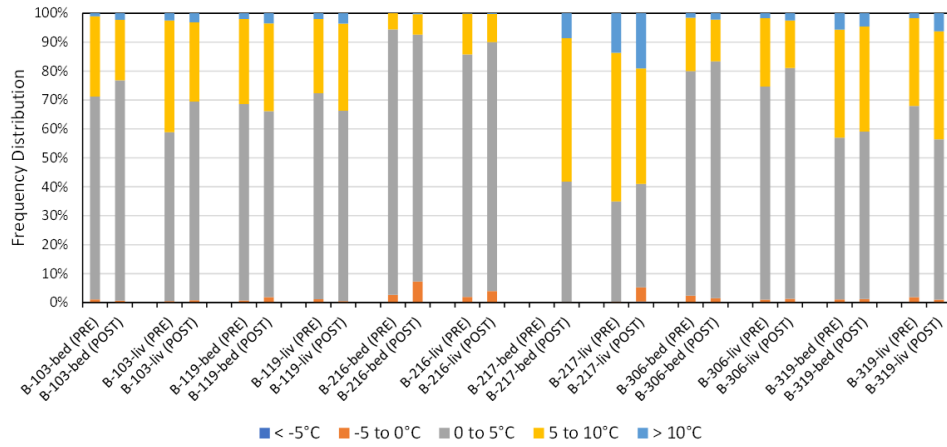
Appendix E.9 – Pre/post-retrofit dew point temperature frequency distribution for Building D between Oct-Mar



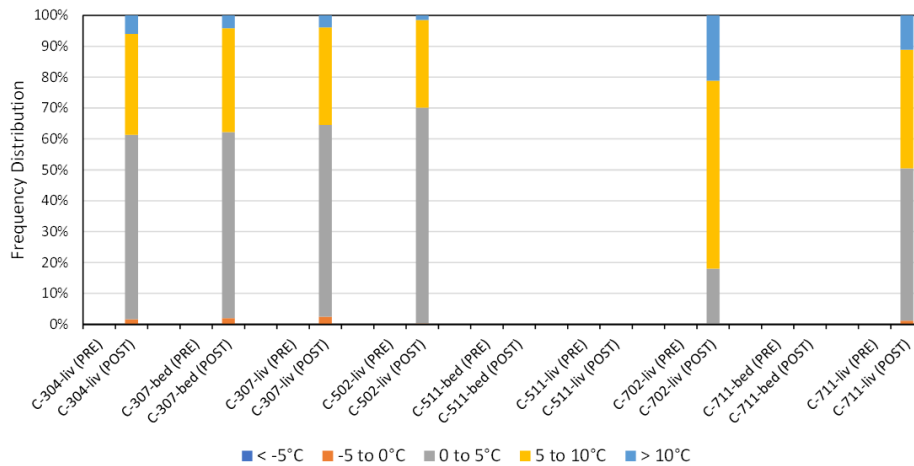
Appendix E.10 – Pre/post-retrofit dew point temperature frequency distribution for Building E between Oct-Mar



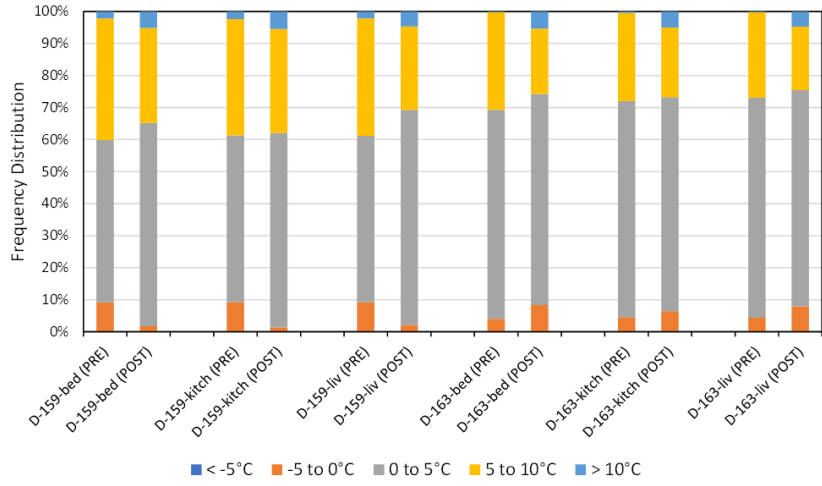
Appendix E.11 – Pre/post-retrofit delta dew point temperature frequency distribution for Building A between Oct-Mar



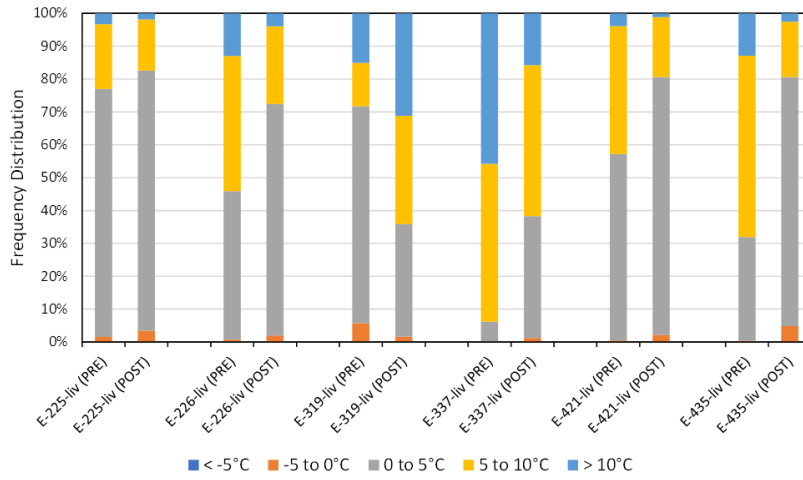
Appendix E.12 – Pre/post-retrofit delta dew point temperature frequency distribution for Building B between Oct-Mar



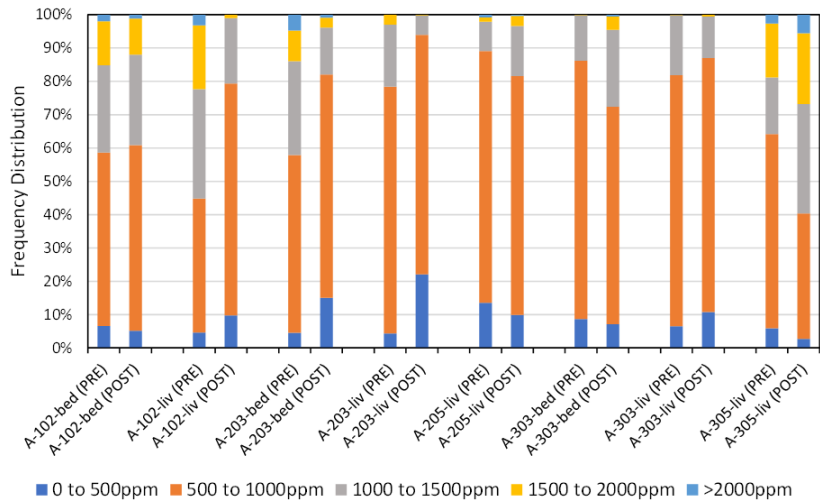
Appendix E.13 – Pre/post-retrofit delta dew point temperature frequency distribution for Building C between Oct-Mar



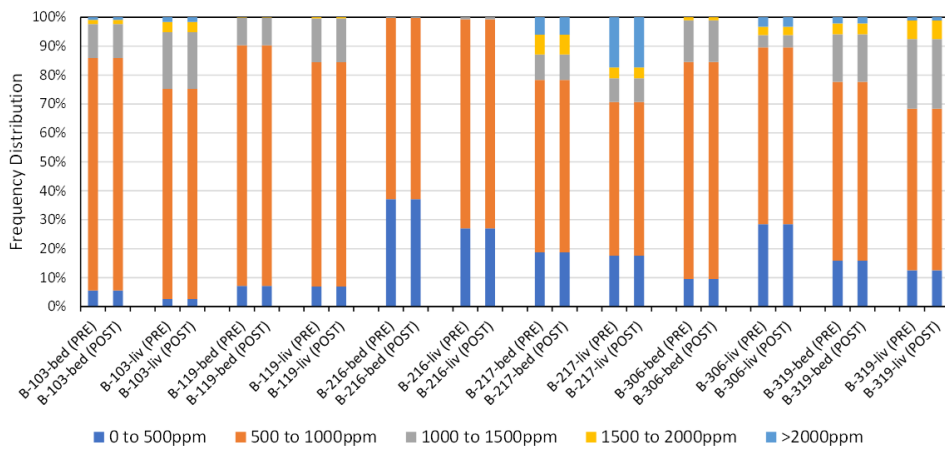
Appendix E.14 – Pre/post-retrofit delta dew point temperature frequency distribution for Building D between Oct-Mar



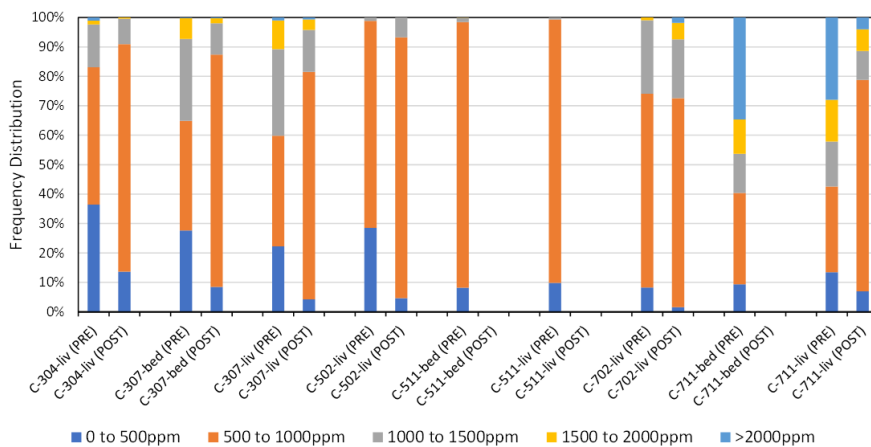
Appendix E.15 – Pre/post-retrofit delta dew point temperature frequency distribution for Building E between Oct-Mar



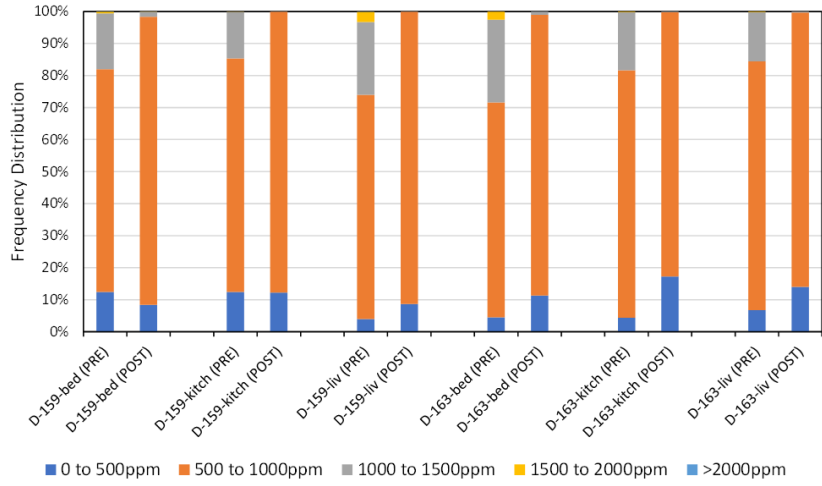
Appendix E.16 – Pre/post-retrofit carbon dioxide concentration frequency distribution for Building A



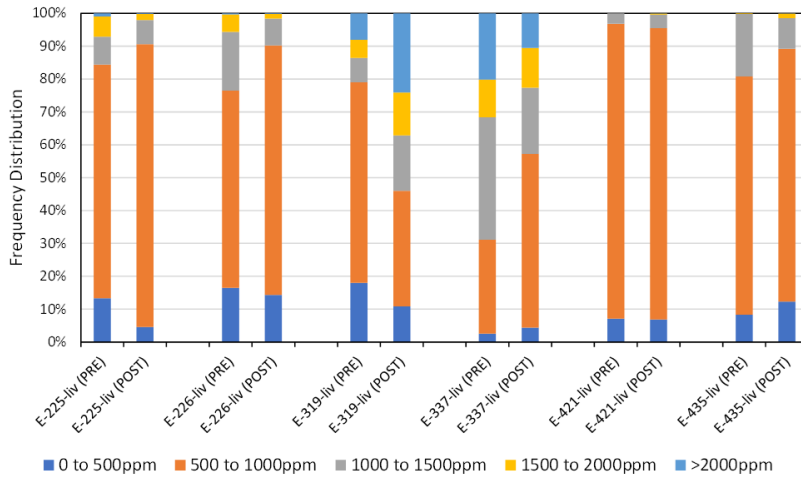
Appendix E.17 – Pre/post-retrofit carbon dioxide concentration frequency distribution for Building B



Appendix E.18 – Pre/post-retrofit carbon dioxide concentration frequency distribution for Building C



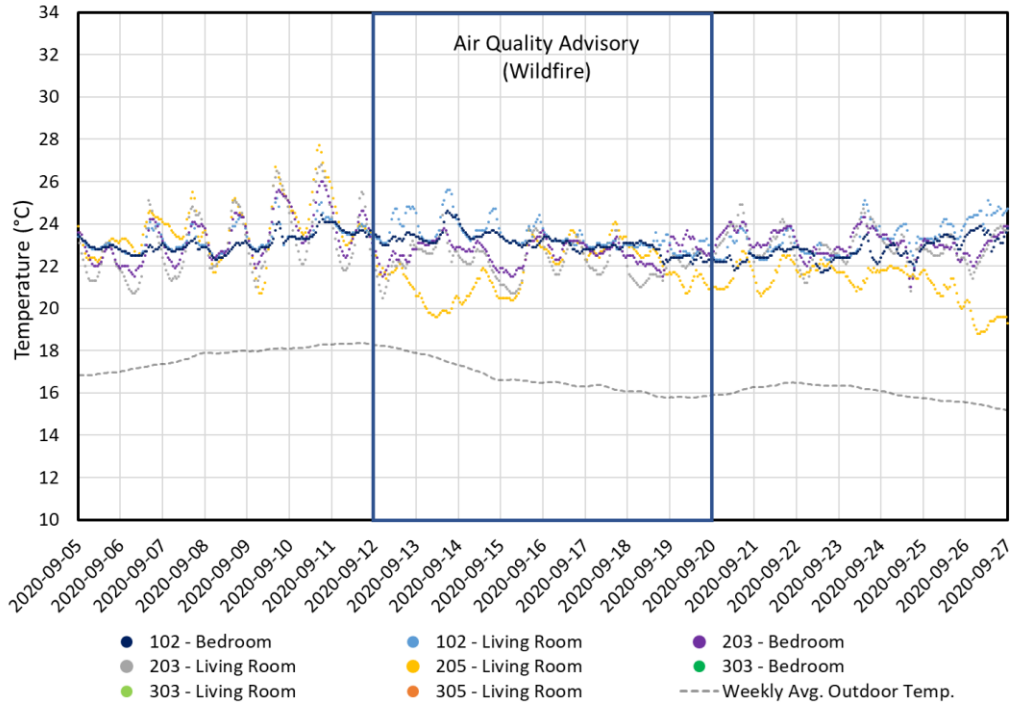
Appendix E.19 – Pre/post-retrofit carbon dioxide concentration frequency distribution for Building D



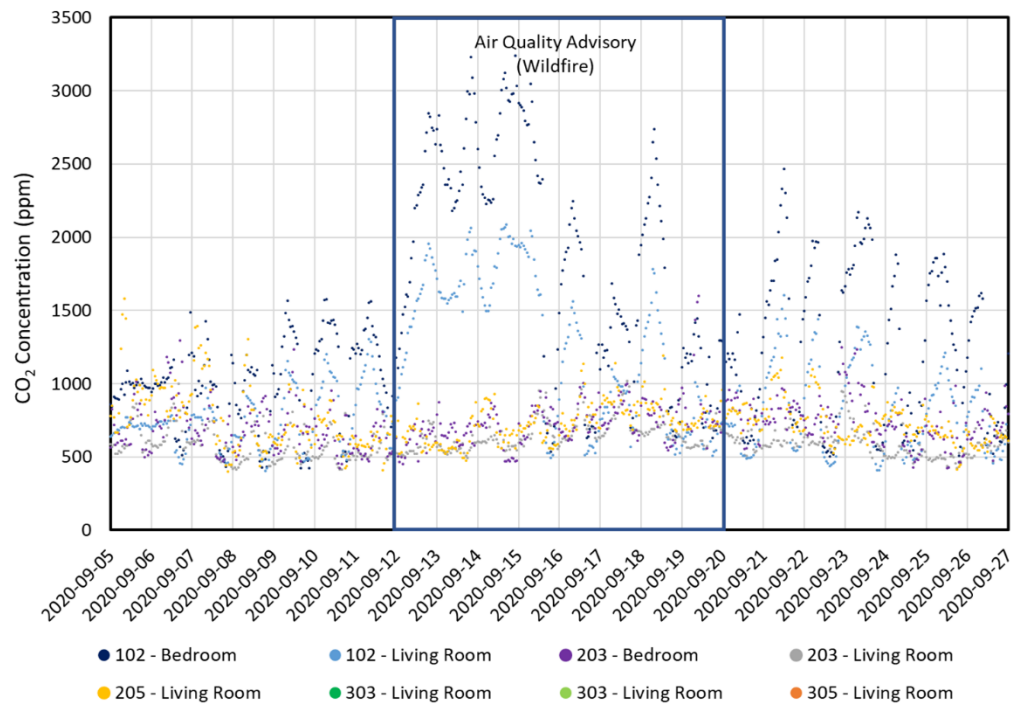
Appendix E.20 – Pre/post-retrofit carbon dioxide concentration frequency distribution for Building E

Appendix F

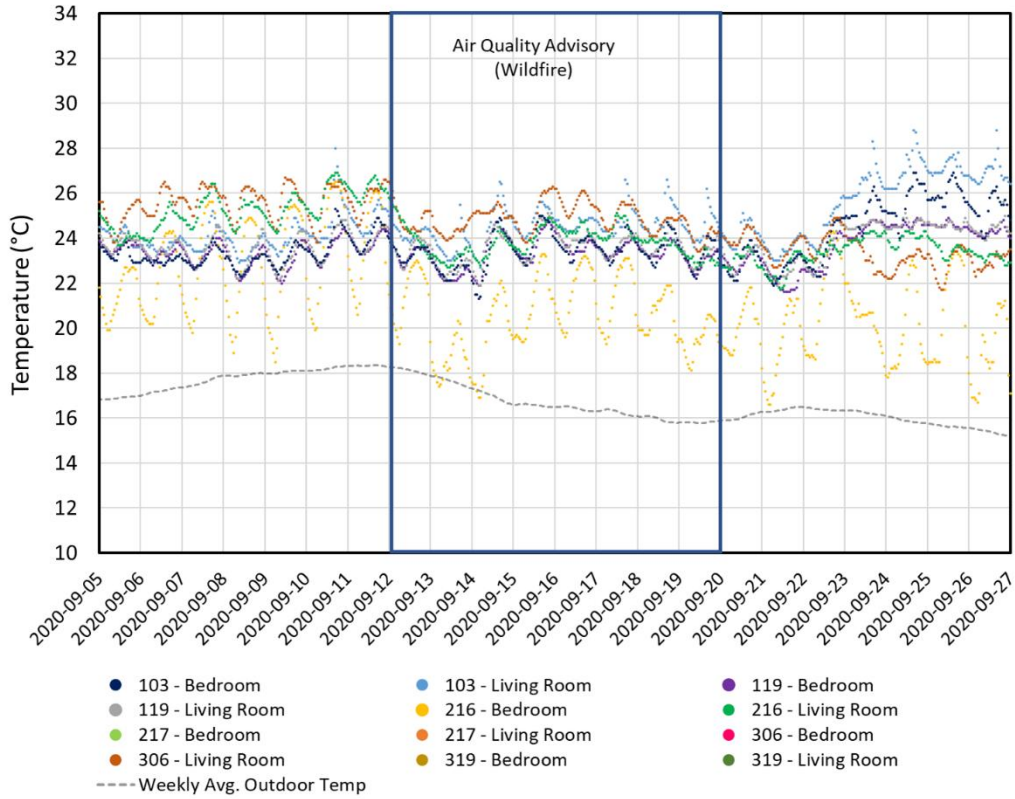
Air Quality Advisory (Wildfire) Analysis



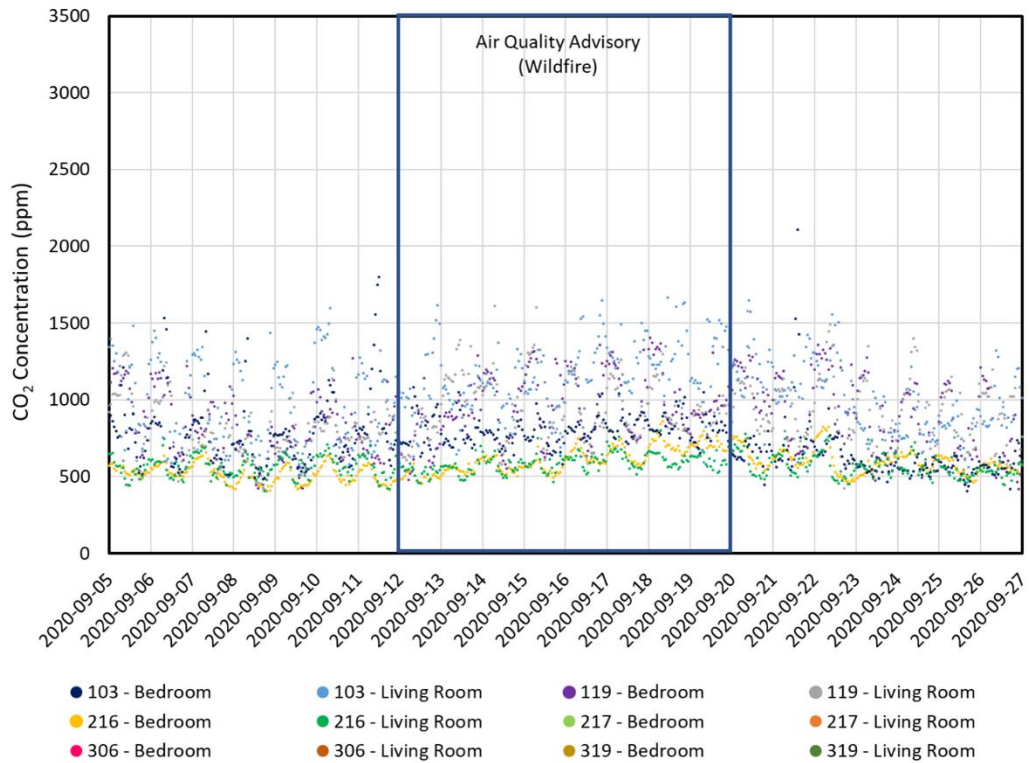
Appendix F.1 – Air temperature for three-week period during Air Quality Advisory (Wildfire) for Building A



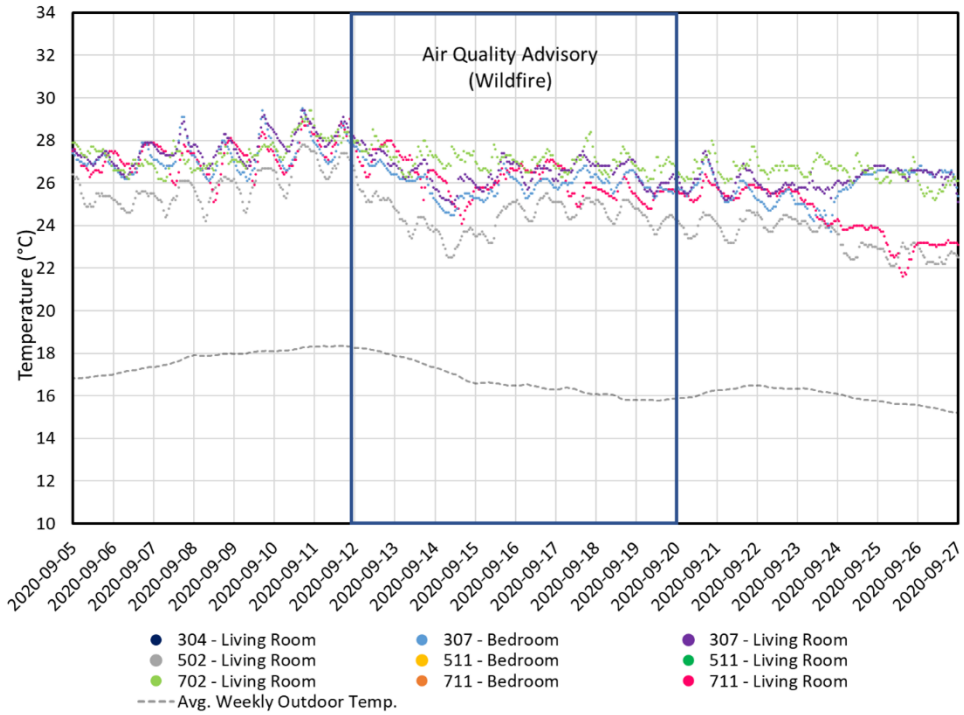
Appendix F.2 – Carbon Dioxide concentrations for three-week period during Air Quality Advisory (Wildfire) for Building A



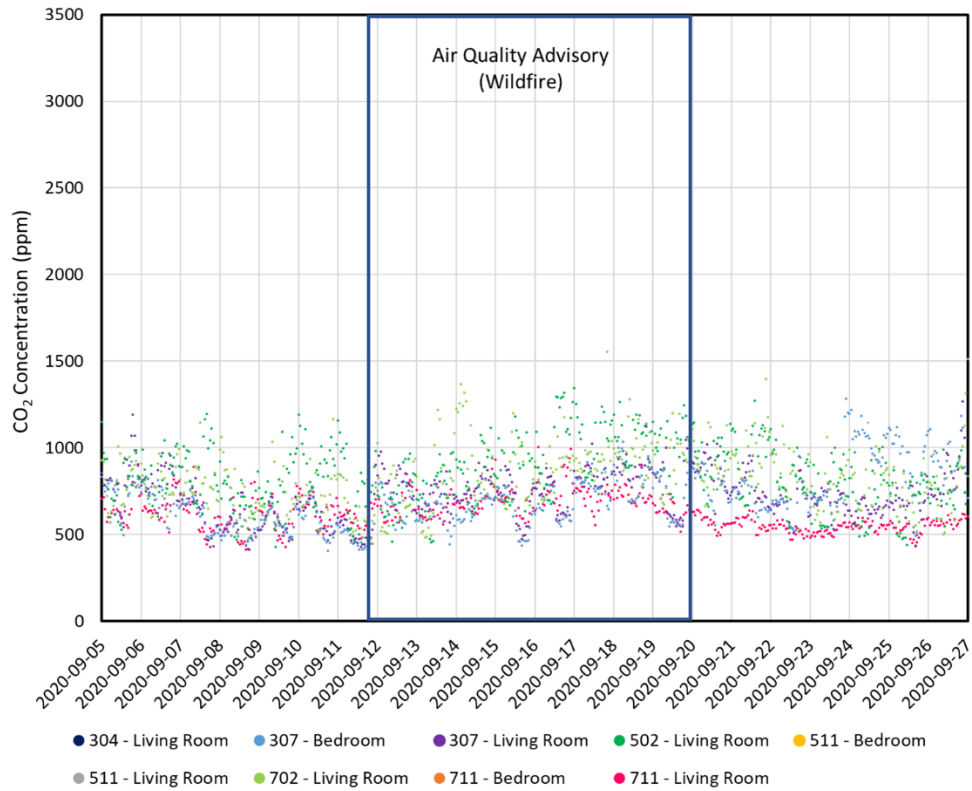
Appendix F.3 – Air temperature for three-week period during Air Quality Advisory (Wildfire) for Building B



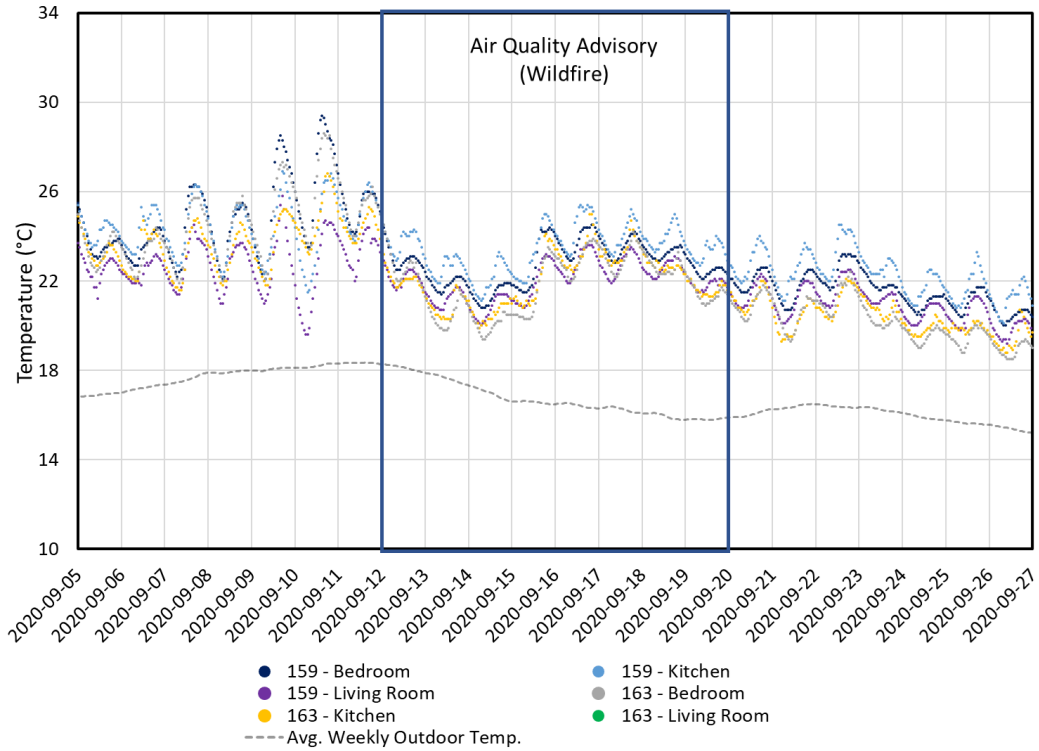
Appendix F.4 – Carbon Dioxide concentrations for three-week period during Air Quality Advisory (Wildfire) for Building B



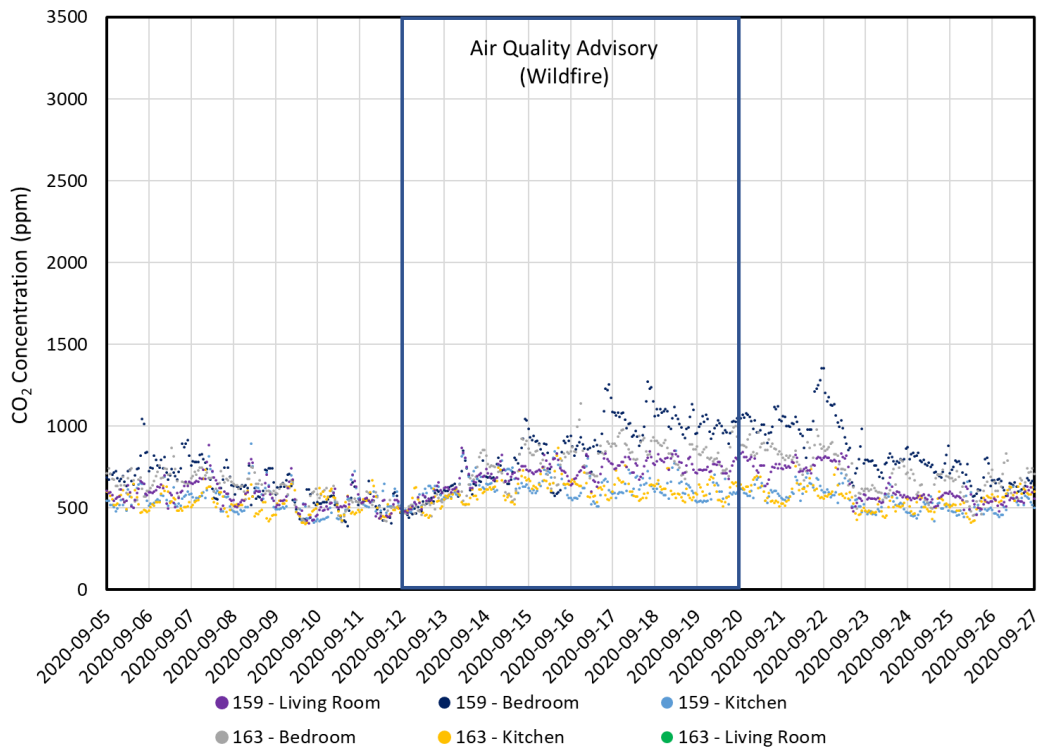
Appendix F.5 – Air temperature for three-week period during Air Quality Advisory (Wildfire) for Building C



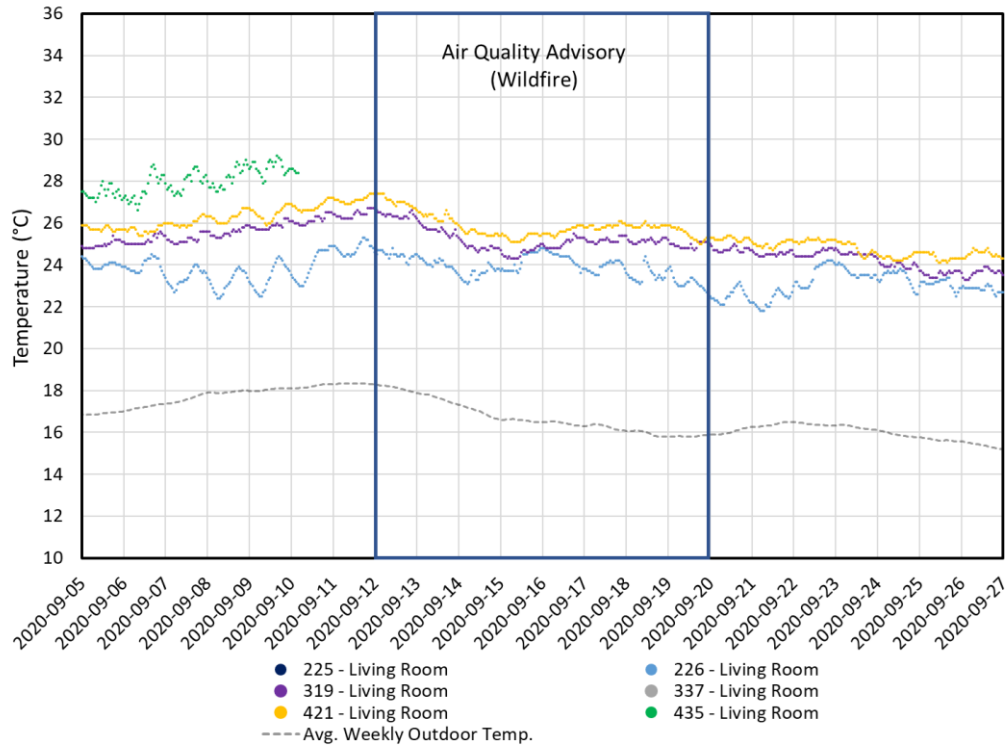
Appendix F.6 – Carbon Dioxide concentrations for three-week period during Air Quality Advisory (Wildfire) for Building C



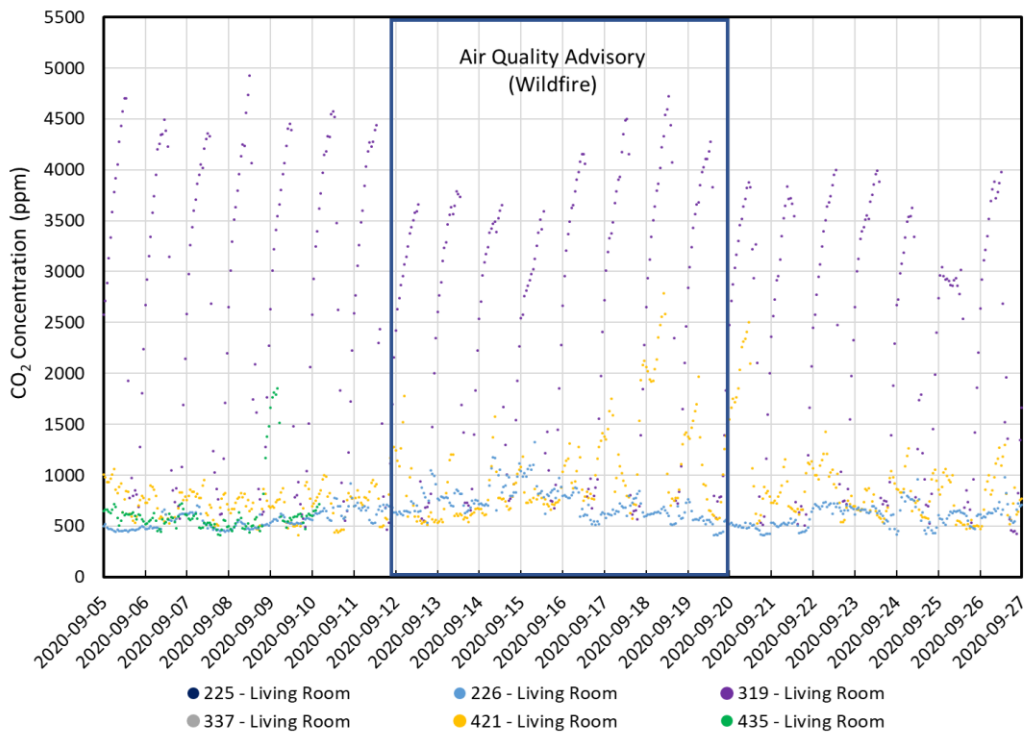
Appendix F.7 – Air temperature for three-week period during Air Quality Advisory (Wildfire) for Building D



Appendix F.8 – Carbon Dioxide concentrations for three-week period during Air Quality Advisory (Wildfire) for Building D



Appendix F.9 – Air temperature for three-week period during Air Quality Advisory (Wildfire) for Building E.



Appendix F.10 – Carbon Dioxide concentrations for three-week period during Air Quality Advisory (Wildfire) for Building E. Note the scale for this graph is significantly higher than the other buildings (3500 vs. 5000 ppm).

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