Thermostat control strategies for thermal comfort and energy-efficient operation

Jian Li

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Signed by the final Examining Committee:

______________________________ Chair

Dr. Joonhee Lee, Concordia University

______________________________ Examiner

Dr. Joonhee Lee, Concordia University

______________________________ Examiner

Dr. Jong Won Ma, Concordia University

______________________________ Supervisor

Dr. Bruno Lee, Concordia University

Approved by ____

Chair of Department or Graduate Program Director

____________ 2024 ____

Dean of Faculty

Abstract

Thermostat control strategies for thermal comfort and energy-efficient operation

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Thermal comfort standards, such as ASHRAE Standard 55, prescribe a thermal comfort zone based on operative temperature, which includes both dry-bulb temperature and mean radiant temperature in the calculation. However, the built environment, regulated by a dry-bulb temperature based thermostat, will quite often maintain a space outside of its thermal comfort zone. The problem is more pronounced in a space open to a large window surface when the influence of the mean radiant temperature is not considered. The objective of the research is to develop control strategies that can maintain the space within the thermal comfort zone and offer energy savings.

The work is based on energy modeling and simulation of the five thermal zones (core, south, east, north, and west) of a prototypical small office building for four different climate zones (represented by Miami, San Diego, New York, and Montreal) under the influence of various window sizes (ranging from window-to-wall ratios of 10% to 80%). EnergyPlus software is used to simulate indoor environmental conditions and calculate the energy demand to maintain such conditions. Fanger's Predicted Mean Vote (PMV) model is used to estimate occupants' thermal sensations in the space operated under the control of conventional dry-bulb thermostats. A performance indicator is developed to facilitate the calculation of new thermostat setpoints (and subsequent development of control strategies) that could ensure the space is maintained within the thermal comfort zone and operated with some energy savings for all occupied hours.

Simulation results reveal a monotonic correlation between window size and the number of hours outside of the thermal comfort zone. The proposed control strategies are not only able to maintain the space within the thermal comfort zone and offer energy savings but also can be implemented with no modification to existing HVAC equipment or building fabric.

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Section 1. Introduction

The indoor environment exerts crucial influences on human activities, given that individuals spend more than 85% of their time within such settings. This percentage further rises to over 90% for specific occupations and age groups [1]. As employees working at office, they spend more than half of daytime to stay in indoor environment. Despite HVAC systems can effectively manage indoor environment within specified conditions, values exhibit deviations between thermostat measurements in dry-bulb temperature and the requirements of standards in operative temperature to meet occupants thermal comfort needs. And the discuss of thermal comfort and approach to eliminate or mitigate this deviation will be discussed in following content.

The steady-state model is commonly used to describe thermal perception close to stationary occupants [2-5], and in the late 1960s, Fanger developed it and created PMV model which is applicable to individuals for all kinds of building to estimate human thermal sensations, regardless of the climate zone. PMV model concerns six primary factors, including (1) air temperature, (2) mean radiant temperature, (3) humidity ratio, (4) air velocity, (5) clothing insulation values, and (6) metabolic rate to predict human thermal dissatisfaction [3]. In the following decades, a plethora of inquiries has been conducted pertaining to thermal comfort, encompassing investigations in authentic environmental settings as well as controlled enclosures, these studies have contributed substantive insights grounded in the principles of the PMV model [6]. In addition, extra critical factors are applied in other various thermal comfort models to develop their methods in accurately estimating human's thermal sensations [7]. For instance, feedback from testers of different genders and ages reflects various thermal sensations to a same indoor environment. However, if the clothing insulation values and anthropometric characteristics of individuals have been regulated, any variations in thermal comfort between different test groups become nullified [8]. In general, over twenty variables utilization of thermal comfort measurements still aligns with the primary factors employed by the PMV model [9]. To describe human thermal sensations among these models, ASHRAE develops a scale from many studies to qualify. It is divided into seven levels from -3 (cold) to +3 (hot), and 0 (neutral) means the person feels neither cold nor hot in this current condition. A range between -0.5 to +0.5 is considered as acceptable thermal comfort by ASHRAE. Furthermore, operators can control HVAC system to maintain indoor thermal comfort environment with the help of this index.

In the pursuit of establishing a thermally comfortable indoor environment, the implementation of HVAC systems stands as a viable method within building structures. Furthermore, the optimization of thermostat setpoints exhibits substantial potential for achieving energy conservation. A research demonstrated that occupants have the adaption to higher room temperature than current setpoints in commercial buildings, but temperature regulation should be carefully adjusted to avoid thermal discomfort feedback from occupants [10]. In fact, typical commercial buildings should maintain indoor air temperature in a certain range to agree with lease requirement, however, a higher setpoint in summer can still establishes a cognitively efficient work environment without posing a significant threat to the thermal comfort of office workers [11]. In Malaysia (tropical regions), the PMV index frequently overestimates the thermal sensation of occupants, resulting in a tendency for excessive cooling, as a result, setting a higher thermostat setpoint appearances potential to energy saving, since [12]. If regions characterized by a prevailing cold climate (Canada), office buildings could potentially face a significant risk of overheating, and extending the setpoints range may lead to a significant proportion of time falls beyond the ±0.5 threshold in PMV model. Hence, extended setpoint range could reduce energy demand, but it may also sacrifice the time in thermal comfort with improper setpoints setting, and overheating problem can be detected even if in a dominant cold climate [13]. Besides, a reduction of variable air volume flow rate is another approach to achieve energy savings, since the minimum volume flow rates are still excessive in some cases [14]. Hence, there are several useful approaches to adjust HVAC system to maintain a certain indoor environment in thermal comfort conditions.

In the aspect of building enclosure, window is one of vital parameter to design process, which greatly affect building performance. Assessing the impact of window glazing properties on energy consumption, the ASHRAE offers terms, including but not limited to thermal conductance (U-value), the solar heat gain coefficient (SHGC), and visual transmittance (VT), to compute the energy transfer through window assemblies [15]. U-factor and SHGC of window glazing can significantly affect Human's thermal comfort if they stay close to windows [16]. In addition, WWR plays a crucial role in influencing the demand for cooling and lighting, whereas its impact on heating is not substantial [17], and the increasing window size requires more cooling demand with less interior lighting [18]. The ideal WWR is narrowed between 30% and 45 %, if considering minimum energy use of cooling, heating, and lighting in mid-latitude region of European [19]. An office building with large windows can not only enhance the employees' efficiency but also reduce the amount of work, when WWR reaches to 60%, results show the highest efficiency and lowest workloads [20]. As the increasing of window size, overheating problem begins to occur, even if rooms can receive more natural daylighting [21]. Besides, the office building with large proportions of window area was observed to be associated with heightened environmental impacts (CO_2, SO_2, O_3, etc.), increased occupant thermal dissatisfaction, and a rise in life cycle costs [22]. In general, overall performance of a building with various window sizes involves carefully balancing factors such as thermal comfort, cooling and heating demand, lighting, environmental impacts, costs, etc.

The thermostats in buildings cannot fulfil requirement of standards based on PMV model. A survey, supported by the Office of Energy Efficiency and Renewable Energy, etc., concludes the room temperature sensor in different measuring methods [23]. These temperature sensors are widely used in thermostats of buildings, which are dry-bulb temperature based. However, basing on Fanger's PMV model, ASHRAE and ISO [2, 3] require operative temperature as one of factors to evaluate thermal comfort. Furthermore, if contemplating structures featuring expansive window dimensions, the absorption of solar radiation induces a rise in the temperature of the indoor enclosure surfaces, thereby accentuating the distinction between the dry-bulb temperature and the operative temperature. Even if HVAC systems can align with a predetermined set temperature, the measurement of thermostats in buildings has deviations when compared to the requirements by standards. This bias hinders the effective regulation of HVAC systems that only considering room dry-bulb temperature is not enough to ensure indoor thermal comfort conditions [24]. The HVAC system will intensify thermal dissatisfaction if setpoints are set inappropriately or over-regulation adjustment via end users [25]. Therefore, the motivation of this paper is exploring the possibility to maintain indoor thermal comfort with existing thermostats in buildings.

In general, the identified issues of overheating and inadequately adjusted setpoints are observed across various building types and climates. These experiences significantly influence both thermal comfort and energy demand within the built environment. Furthermore, a disparity is evident between thermostat measurements based on dry-bulb temperature and the operational temperature stipulated by the prescribed standards. This paper aims to examine the influence on thermal comfort to prototype small office buildings located in four different climates with various

WWRs. It also endeavours to propose an approach to eliminate or mitigate the deviation between thermostat measurement and requirements of standards to thermal comfort based on PMV model.

Section 2. Case study: prototype small office building type model

In this research, prototype small office model is selected, Figure 1 shows thermal zones. This model is supported by U.S. Department of Energy (DOE), which covers most of commercial building floor area across all U.S. climate zones. In addition, it fulfills recent editions of ASHRAE Standard 90.1, the parameters of buildings are revised depending on different locations [26], such as U-factor of walls, floors, and windows; SHGC, visible transmittance of window glazing, etc. The partial parameters of building enclosure are in Table 1. In this research, all four orientations of walls have an equivalent window fraction. WWR will change from 10% to 80% and increase by 5% each step. HVAC system is ideal loads air system to satisfy heating or cooling load, and other requirement, which means this setting has infinite capacity to meet its load [28]. The air velocity follows the recommendation of ASHRAE Standard 55-2017, which keeps under 0.2 m/s. In addition, energy demand for heating or cooling will be calculated in the simulation process by EnergyPlus software. To eliminate the impact of certain dates or holidays, this research counts the total occupied hours for the year amount to 3285 hours, encompassing the period from 9 a.m. to 5 p.m. The daily-occupied hours represent the standard working hours, which the building is regularly utilized [26].

Four locations are picked out for prototype buildings in this research, including: Miami (1A very hot humid), San Diego (3B warm marine), New York (4A mixed humid), and Montreal (6A cold humid) [27]. These cities locate from very hot to cold climate, temperature and humidity ratio can also spread in wide ranges. The selection of these locations aims to investigate the impact to thermal comfort and energy demand in different climate zones.

Figure 1 Thermal zones

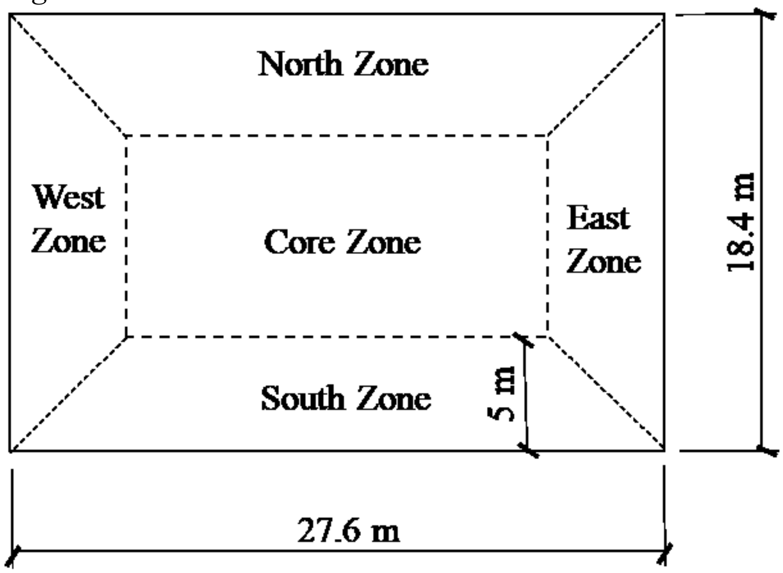


Table 1 Partial parameters of building enclosure in different locations

Location (climate zone)	exterior wall U-factor (W/m²·K)	floor U-factor (W/m²·K)	Attic roof (W/m²·K)	window glass U-factor (W/m²·K)	Window glass SHGC	Window glass visible transmittance
Miami (1A)	2.38	2.19	5.01	5.84	0.25	0.11
San Diego (3B)	0.51	3.08	2.86	2.39	0.25	0.28
New York (4A)	0.36	3.08	2.86	2.05	0.36	0.40
Montreal (6A)	0.27	0.67	0.15	1.90	0.39	0.40

Section 3. Thermal comfort zones and performance indicator

Thermal comfort zones will be determined based on PMV model, which intends to fit office activities. And the introduced performance indicator quantifies the proportion of occupied time, which helps to compare the impact to thermal comfort with different conditions.

3.1 Decision of thermal comfort zones

In this research, Fanger's PMV model is used to predict human thermal sensations. ASHRAE implies analytical comfort zone method based on his model [29], and it removes humidity limit for thermal comfort, since previous graphical comfort zone method has an upper limit at 0.012 kg $_{H_2O}$/ kg $_{dry\ air}$ in humidity ratio. The main process of evaluate human thermal comfort calculates heat stored in a human body multiply by thermal sensation transfer coefficient, which is utilised by ASHRAE with permission from Annex D of ISO 7730 [3], show in Equations (1.1) & (1.2).

PMV= (Thermal sensation transfer coefficient) · (Heat production in human body – Heat loss through skin – Heat loss by sweating – Heat loss by latent respiration – Heat loss by dry respiration – Heat loss by radiation – Heat loss by convection)

Equation (1.1)

$$PMV = (0.303 \cdot e^{-0.036 \cdot M} + 0.028) \cdot \{(M - W) - 3.5 \times 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - P_a] - 0.42 \cdot (M - W - 58.15) - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - T_a) - 3.96 \times 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}$$

Equation (1.2)

$$I_{cl} = 0.155 \cdot Clo$$

Equation (2)

M, metabolic rate, W/m^2

W, external work, W/m^2

P_a, water vapour pressure, Pa

t_a, air Temperature, °C

f_{cl}, clothing area factor, unitless

t_{cl}, surface temperature of the clothing, °C

t_r, mean radiant temperature, °C

h_c, convection heat transfer coefficient, W/(m^2·K)

I_{cl}, thermal insulation of the clothing, (m^2·K)/W

Clo, clothing insulation, clo

This method is suitable for thermal perception close to stationary occupants and it gives accuracy estimation for occupants in low values of metabolic rates. For the tasks in office buildings, reading and writing activities are close to stationary, and other rest tasks are at low values comparing other working condition. Table 2 lists some metabolic rates for different tasks. The unit "met" is defined by ASHRAE as the rate of energy generation per unit skin surface area of an average person. In seated resting condition, metabolic rate is 1.0 met, and equals 58.1 W/m² (average skin area of a person is 1.8 m^2 [15]). Since this research investigates thermal comfort in prototype office buildings, 1.2 met (M= 70 W/m^2) will be selected as an average value to simulate common activities of employees in office.

Table 2 Metabolic rates for different activities [3]

Activity	Met units	W/m²
Office activities		
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filing, seated	1.2	70
Filing, standing	1.4	80
Walking about	1.7	100
Resting		
Sleeping	0.7	40
Seated, quiet	1.0	60
Other activities		
Cooling	1.6 - 2.0	95 - 115
House cleaning	2.0 - 3.4	115 - 200
Dancing, social	2.4 - 4.4	140 - 255
Basketball	5.0 - 7.6	290 - 440

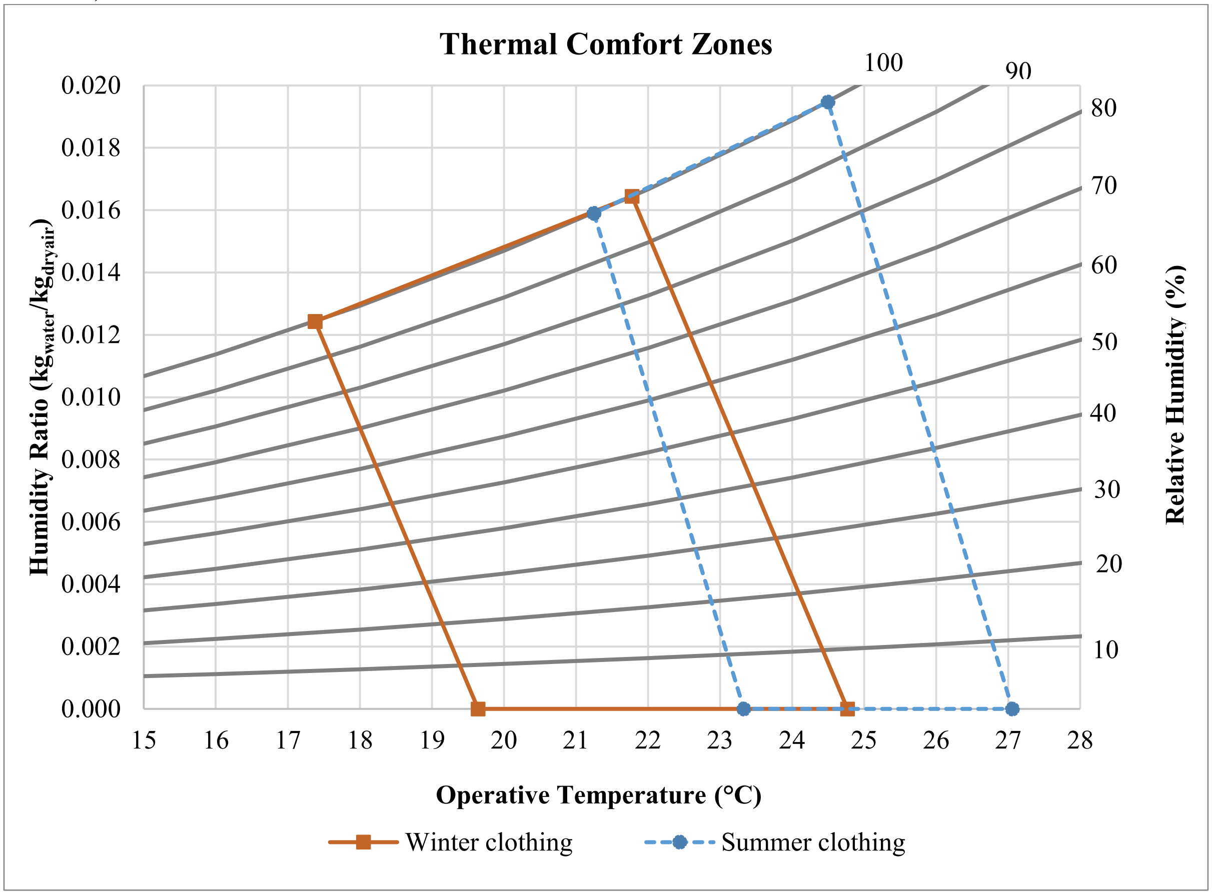
In Fanger's PMV model, clothing insulation is one of six primary factors to affect thermal sensations. Change different clothing is also an efficient way to maintain thermal comfort [30]. The unit "clo" is utilized to denote the insulation value of clothing, where 1.0 clo is equivalent to 0.155 (m²·K)/W, Equation (2). ASHRAE handbook describes that 0.5 clo for summer and 1.0 clo for winter are typical individual clothing for indoor environment, Table 3. On the other hand, clothing insulation prediction can be a challenge if consider many external factors. A study demonstrates that the average value of clothing insulation in summer is 0.59 clo, and this value has obvious difference in winter comparing ASHRAE handbook [31]. Their clothing insulation model is based on outdoor dry-bulb temperature and indoor operative temperature, which gives a dynamic prediction. This research will follow the values in ASHRAE handbook. Furthermore, in pursuit of simulating office conditions, this study deliberately selects two insulation values tailored to office activities across all seasons, which are adjusted to 0.6 clo in summer and 1.1 clo in winter respectively, with accounting for the inclusion of a standard office chair (equivalent +0.1 clo) [3].

Table 3 Summer and winter clothing insulation based on ASHRAE 55-2013

	Clothing (including: shoes, socks, and underwear; standard office chair)	Clothing insulation (clo)
Summer	Trousers, short-sleeve shirt	0.6
	/Knee-length skirt, short-sleeve shirt	0.6
Winter	Trousers, long-sleeve sweater, T-shirt	1.1
	/Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.1

When indoor air velocity, metabolic rate, and clothing insulation are decided to simulate office environment and activities, thermal comfort zones will be determined via the suggestion of ASHRAE Handbook, Figure 2. It shows thermal comfort zones ($-0.5 < PMV < +0.5$) with revised clothing insulation in selected office activity (met= 1.2). Two areas distinguish summer and winter clothing with dotted and solid lines. An overlapping area shows that occupants are in thermal comfort condition no matter with summer or winter clothing. In addition, this research assumes that occupants can adjust their clothing themselves, but the selection of clothing insulation cannot exceed the range of summer or winter clothing insulation.

Figure 2 Thermal comfort zones based on the common office activity and clothes (0.6 to 1.1 clo, 1.2 met)



3.2 Performance indicator: percentage of time not met thermal comfort

The introduced performance indicator in this research quantifies the proportion of time in thermal discomfort conditions to indoor environment, denoted by Equation (3). Its range is between 0% and 100%, also, a bigger value describes a longer time in thermal discomfort for indoor environment.

$$\text{percentage of time not met thermal comfort} = \frac{\text{occupied hours not met thermal comfort}}{\text{occupied hours}} \times 100\%$$

Equation (3)

Conclude Section 3, the thermal comfort zones and performance indicator will help to estimate indoor environment in thermal comfort. In addition, they will guide to adjust setpoints to fulfill both thermal comfort and energy saving.

Section 4. Results and discussion

For prototype small office building model, thermostat setpoints are 21 °C for heating and 24 °C for cooling as default setting, which means room air temperature will maintain a range between 21 °C and 24 °C during occupied time in a whole year. This same default setting will be applied in prototype small office with various WWRs in four locations (Miami, San Diego, New York, and Montreal).

4.1 Thermal discomfort occurrence in prototype small office building

Thermal discomfort happens in buildings with different WWRs and locations. With the help of EnergyPlus, each simulation data point contains two values with both operative temperature and humidity ratio, which locates a position in coordinate system (shows in Figure 2). In detail, if a data point drops inside any of these two areas, it will be determined as occupants are in thermal comfort condition. As a result, initial thermal discomfort occurs in buildings with various window sizes will list in Table 4, and details in following section.

Table 4 Thermal discomfort starts to occur in specific WWRs
("-" means thermal discomfort does not occur when WWR is between 10% and 80%)

	Thermal zoning				
Locations (climate zone)	South zone	East zone	North zone	West zone	core zone
Miami (1A)	35%	40%	-	35%	-
San Diego (3B)	65%	-	-	60%	-
New York (4A)	50%	55%	-	45%	-
Montreal (6A)	30%	25%	20%	20%	-

4.1.1 Various WWRs effects on thermal comfort in Miami

In Miami, with default thermostat setpoints in the prototype small office building, increasing window sizes lead to thermal discomfort issues in south, east, and west zones.

In the south zone, thermal discomfort starts to occur when WWR is 35%, thermal discomfort problem is apparently observed as WWR reaches to 80%. In detail, percentage of time not met thermal comfort is 0.1%, Figure 3.1. Consequently, occupants are anticipated to experience a total of 2 hours of thermal discomfort throughout the entire year. Even if the value is very small, the distribution of data points shows the big effect of adding mean radiant temperature. Most of data points locate the right side of 24 °C, which 94% data points (3103 hours) exceed the default cooling setpoint. On the other hand, only one of data points is lower than default heating setpoint, which still can provide a thermal comfort condition to people in the office. As WWR increases to 80%, these data points have the trend to spread around that a few data points of shift to upward, however, window size impacts operative temperature very much, which leads to overheat problem. More data points are out of control range of room temperature, 3123 data points exceed the default cooling setpoint, Figure 3.2. In addition, 13.1% of data points are out of thermal comfort zones that employees experience 431 hours of slightly warm thermal discomfort sensation during occupied time. Therefore, it is imperative to note that thermal discomfort is expected to be observed in the south zone, particularly with larger window sizes.

Figure 3.1 Data points distribution in Miami (south zone,35% WWR)

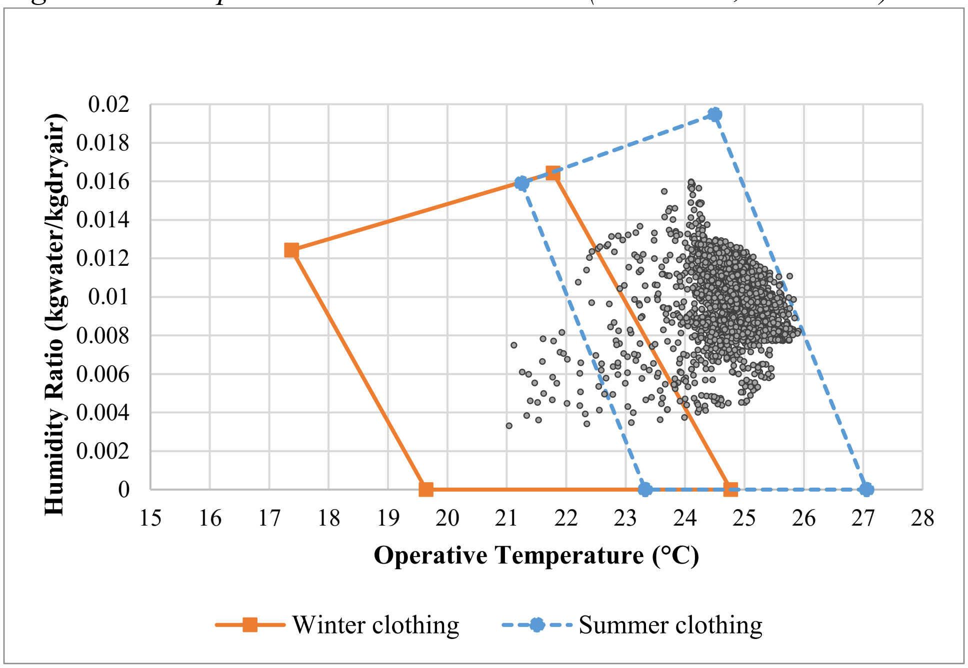
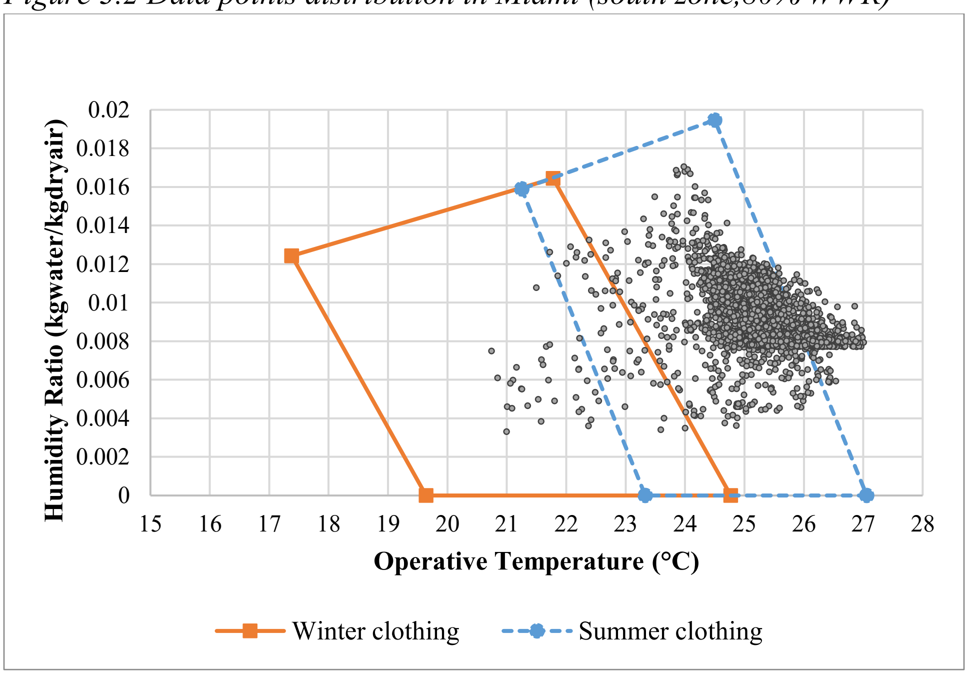


Figure 3.2 Data points distribution in Miami (south zone,80% WWR)



The east and west zone are also in thermal discomfort condition with large window sizes, which is detected at 40% WWR and 35% WWR separately. In the east zone, Figure 4.1, 4.2, and west zone, Figure 5.1, 5.2, data points shows the same trend as the south one that they move to both left and right sides (mostly to the right side) as window size increases. Furthermore, thermal discomfort could be a problem when WWR is 80%, since 14.5% and 16.0% of occupied time is outside of thermal comfort zones in east and west zone separately.

In general, south, east, and west zones will face thermal discomfort problem as window sizes increase with default setpoints in prototype small office building. On the other hand, the core and north zones have less effect to the change of window sizes in thermal comfort than other perimeter zones, which can maintain thermal comfort conditions.

Figure 4.1 Data points distribution in Miami (east zone, 40% WWR)

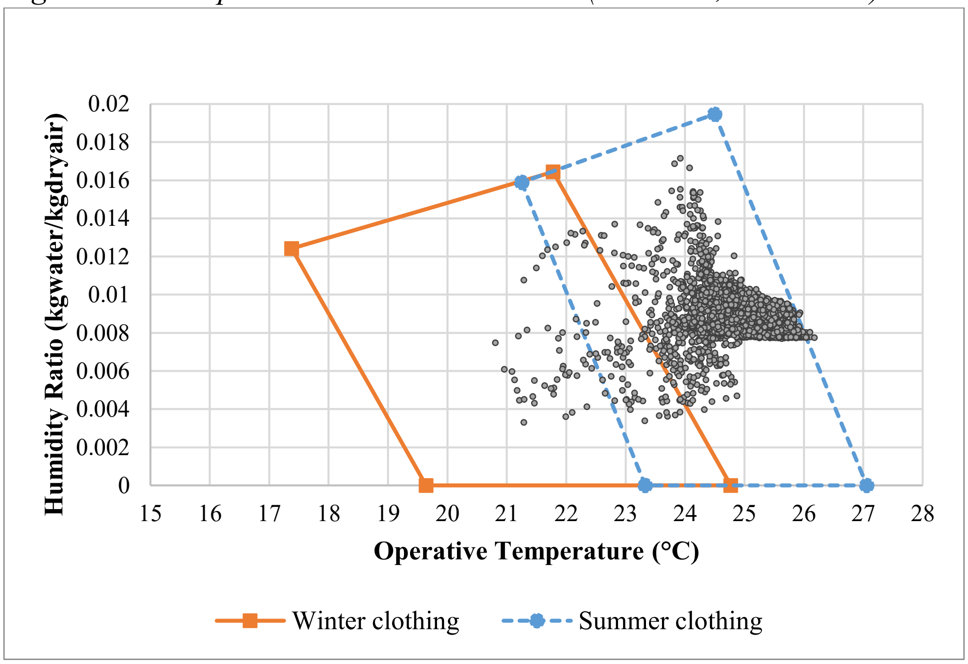


Figure 4.2 Data points distribution in Miami (east zone, 80% WWR)

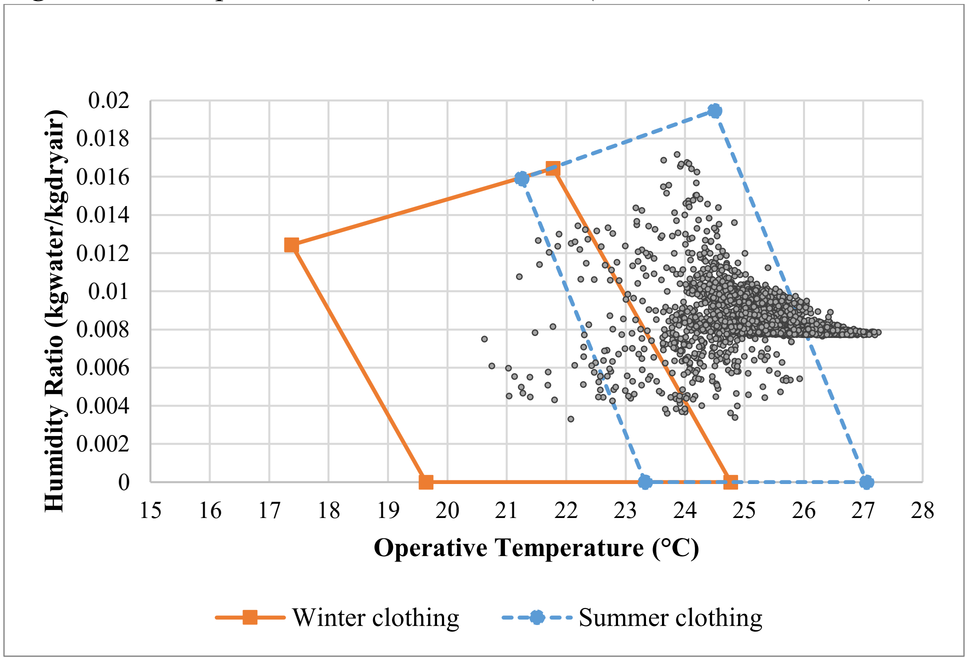


Figure 5.1 Data points distribution in Miami (west zone, 35% WWR)

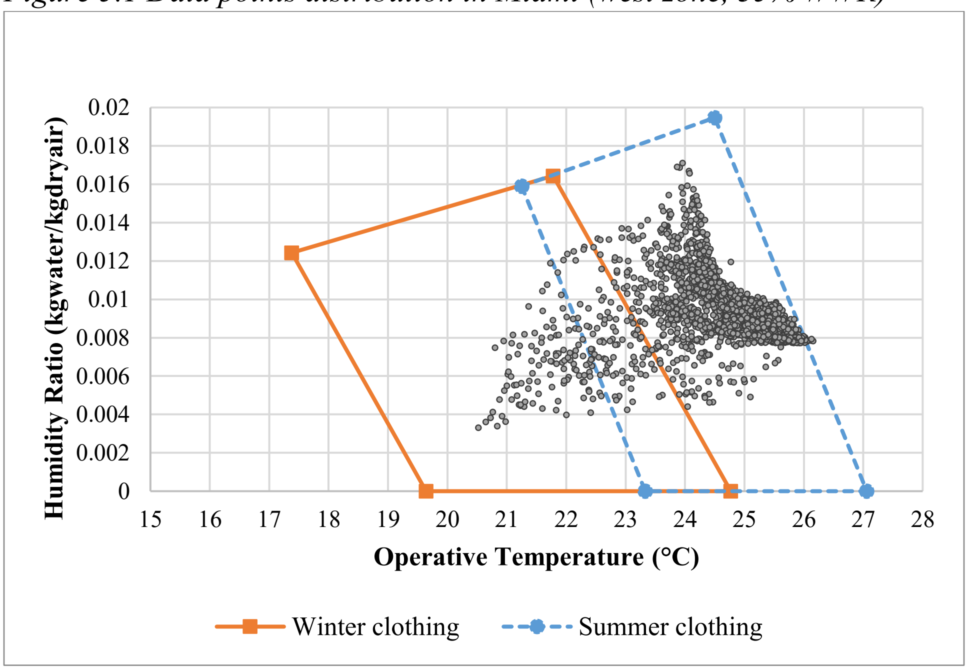
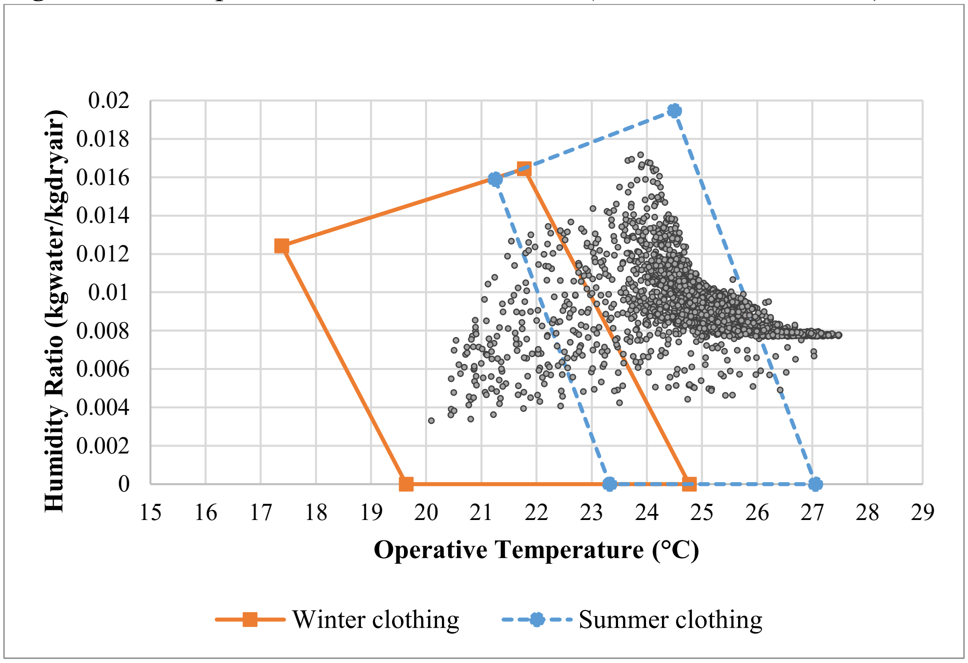


Figure 5.2 Data points distribution in Miami (west zone, 80% WWR)



4.1.2 Various WWRs effects on thermal comfort in San Diego

In San Diego, only the south and west zone face thermal discomfort problem in buildings with large window sizes, which the problem is not obvious. However, the discrepancy between operative temperature and dry-bulb temperature is still noticeable in small buildings.

In the south zone, thermal discomfort is not obvious in buildings with various window sizes. It is first observed when the WWR reaches 65%. The percentage of time not met thermal comfort is 0.2%, which 5 hours of occupied time is in thermal discomfort conditions, Figure 6.1. However, the effect of mean radiant temperature cause bias in controlling indoor environment, since more than half of data points (62.7%) are over 24 °C in operative temperature. In addition, 1.0% (34 hours) of data points lower than default heating setpoint and they distribute the thermal comfort zone. Thermal discomfort is still not obvious when WWR increases to 80%, Figure 6.2. Employee will experience 0.6% (19 hours) of occupied time thermal discomfort, which is not considered as a big problem. On the other hand, more data points (66.7%) distribute over 24°C in operative temperature that they have the trend to shift to right side. Hence, the discrepancy between operative temperature and room air temperature still exist, even if thermal discomfort is not a big problem in the south zone.

Figure 6.1 Data points distribution in San Diego (south zone,65% WWR)

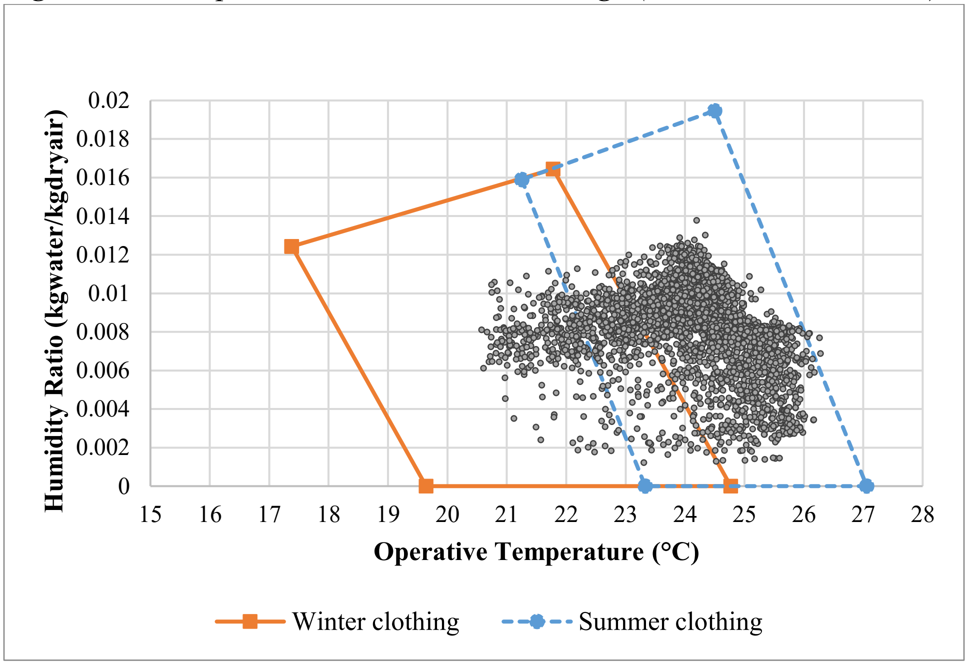
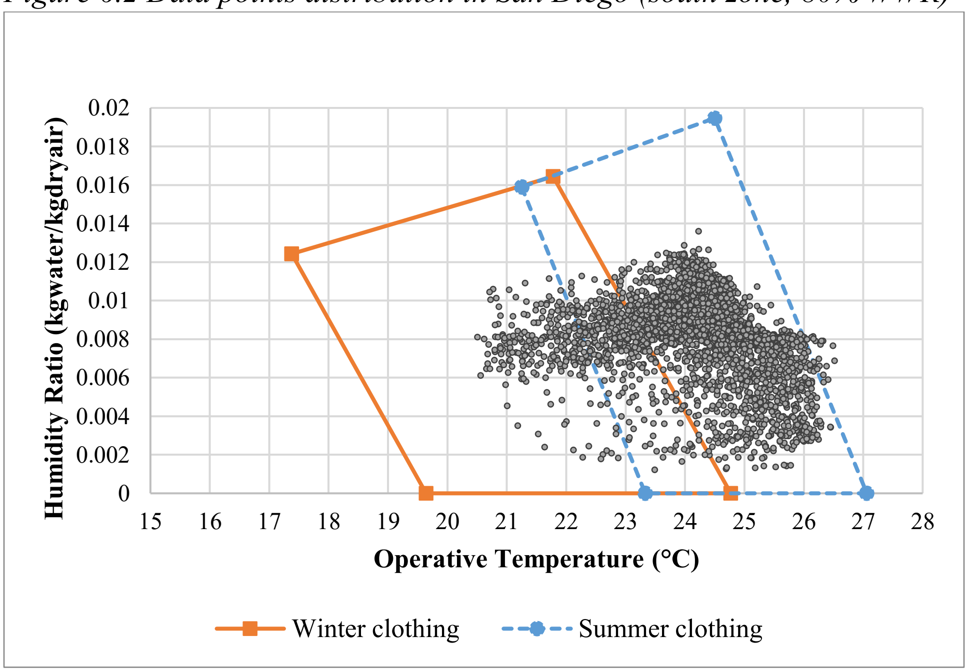


Figure 6.2 Data points distribution in San Diego (south zone, 80% WWR)



Furthermore, thermal discomfort can be observed in the west zone with medium or large window sizes. The percentage of time not met thermal comfort is 0.1% (2 hours) and 2.2% (73 hours) when WWR is 60% and 80% separately, Figure 7.1, 7.2. In the west zone, the data points show similar trend as the south zone that some of them shift to right side and go across boundary of thermal comfort zone. In addition, the trend to shifting to left is not obvious if comparing window size from 60% to 80%.

In general, thermal discomfort problem is not obvious in small office building located in San Diego. The south and west zone can be detected slight warm thermal sensation as WWR increases. on the other hand, if WWR is under 80%, the core, east, and north zone won't face thermal discomfort problem with default setpoints.

Figure 7.1 Data points distribution in San Diego (west zone, 60% WWR)

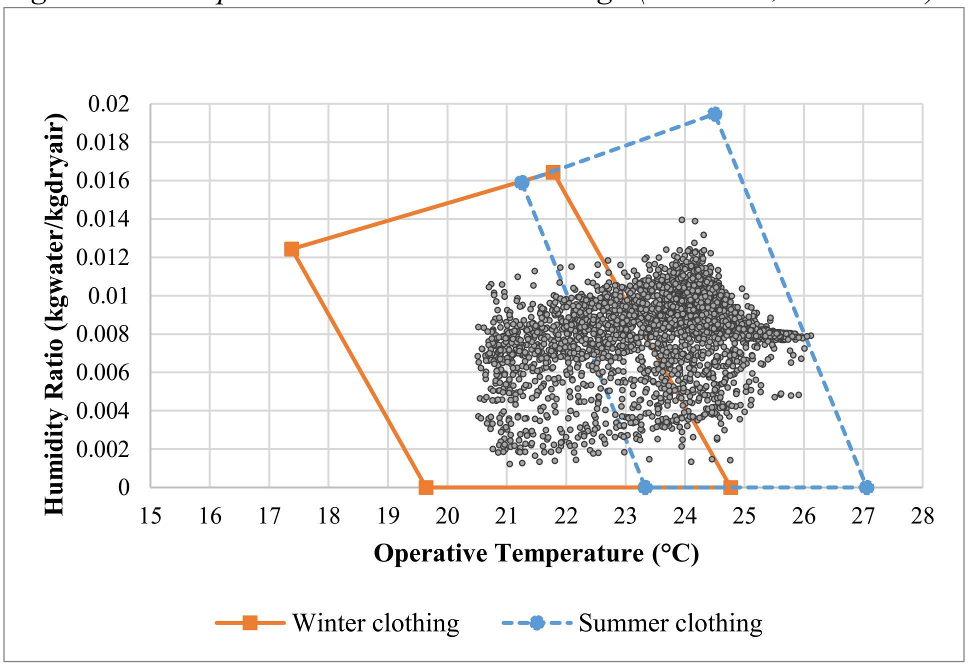
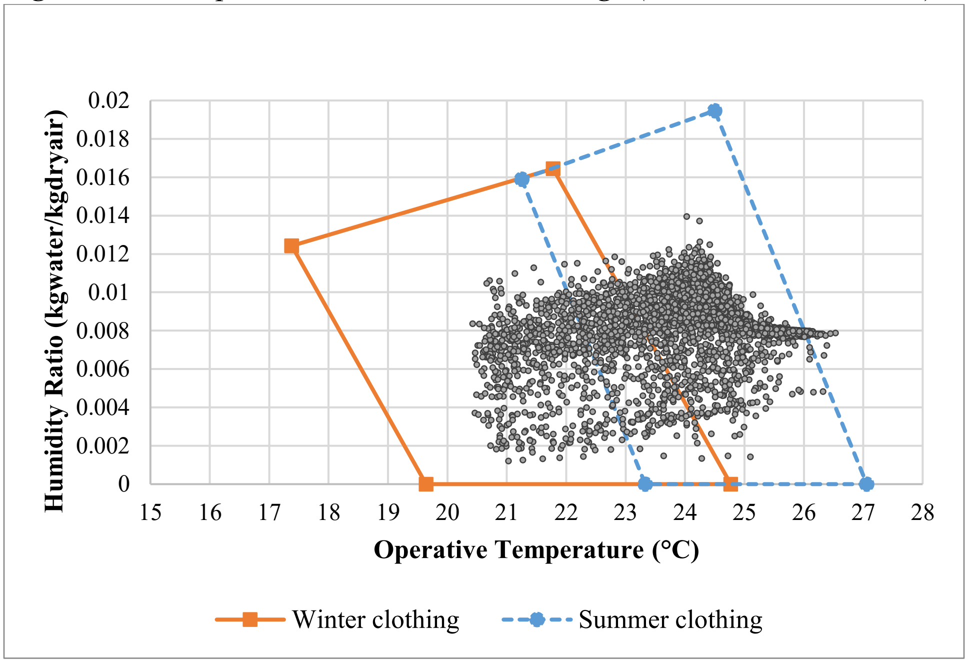


Figure 7.2 Data points distribution in San Diego (west zone, 80% WWR)



4.1.3 Various WWRs effects on thermal comfort in New York

In New York, thermal discomfort occurs in the south, east, and west zones, and it is not obvious until buildings install big window glazing. Also, both slight cool and warm thermal discomfort can be detected in the worst case.

In the south zone, thermal discomfort is first detected when WWR is 50%, and it behaves 2 hours of slightly warm discomfort during occupied time, Figure 8.1. The operative temperature has 63.6% of data points distribute out of the range between 21°C and 24°C. Furthermore, data points with large window size distribute in a large area, and percentage of time not met thermal comfort is 1.6% of occupied time when WWR reaches to 80%, Figure 8.2, which is not a big problem in thermal discomfort. Furthermore, data points have the trend to move right side as window area increase, since 16.6% of data points are lower than 21°C, 55.4% of data points are bigger than 24°C. Hence, as increasing window size, the proper adjustment of setpoints is necessary to maintain thermal comfort in the south zone, which is caused by the deviation between dry-bulb temperature and operative temperature.

Figure 8.1 Data points distribution in New York (south zone, 50% WWR)

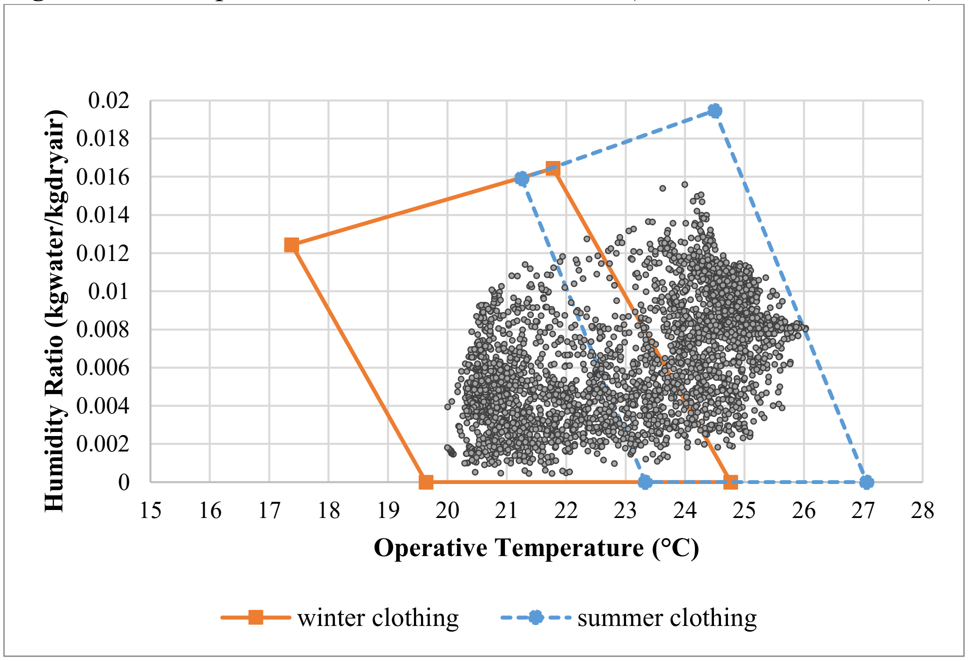
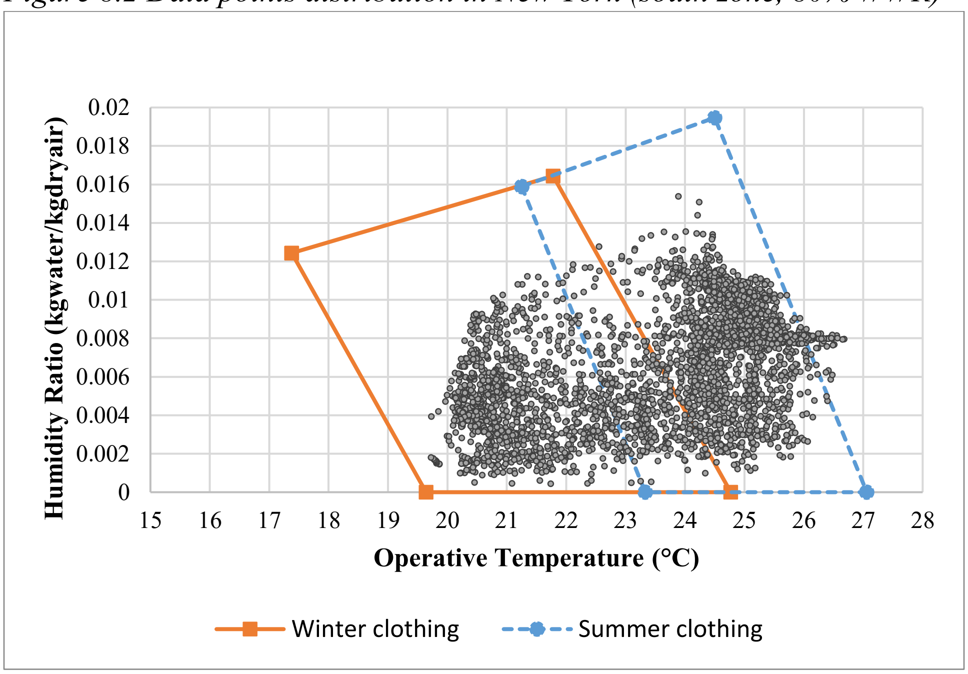


Figure 8.2 Data points distribution in New York (south zone, 80% WWR)



Thermal discomfort can also be detected in the east and west zones. It happens when WWR is over 55% in east zone, Figure 9.1, and 45% in west zone, Figure 10.1. Furthermore, data points in operative temperature distribute away from the room air temperature range as window area increases. When WWR is 80%, Figure 9.2, 10.2, over one hundred data points out of the range between 21℃ and 24 ℃ comparing the distribution of previous two cases. The worse case happens in the west zone, Figure 10.2. The enlarged distribution of data points goes across both left and right boundaries of thermal comfort zones during occupied time, which means employees will experiences both slight cool discomfort during winter and slight warm discomfort during summer even if they wear proper indoor clothing. Also, occupants will experience 155 hours of thermal discomfort in a year.

In general, cases in New York, the north and core zones can maintain thermal comfort conditions with various window sizes, and both slight cool and warm thermal discomfort happens in the worst case.

Figure 9.1 Data points distribution in New York (east zone, 55% WWR)

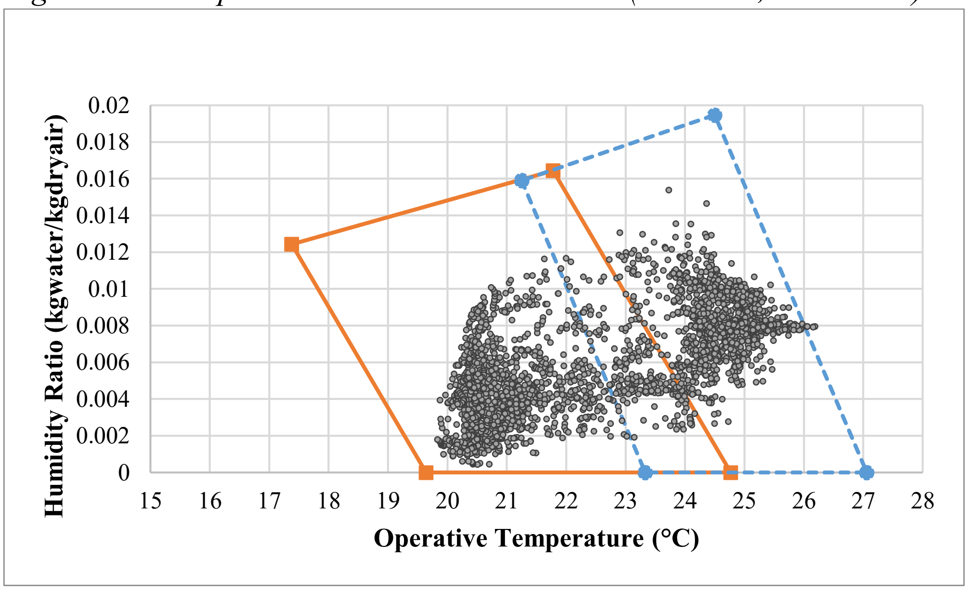


Figure 9.2 Data points distribution in New York (east zone, 80% WWR)

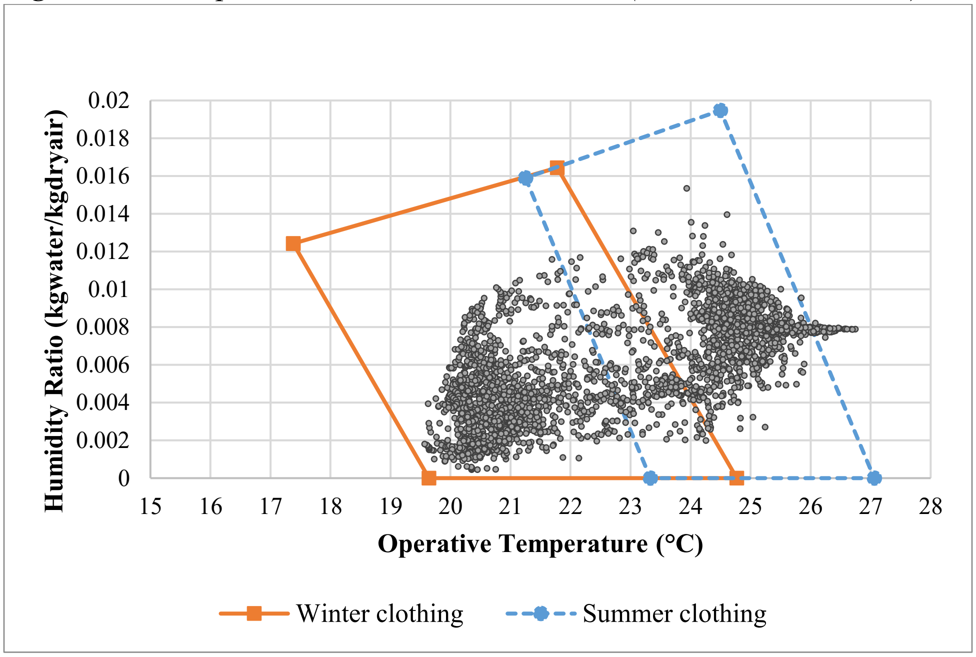


Figure 10.1 Data points distribution in New York (west zone, 45% WWR)

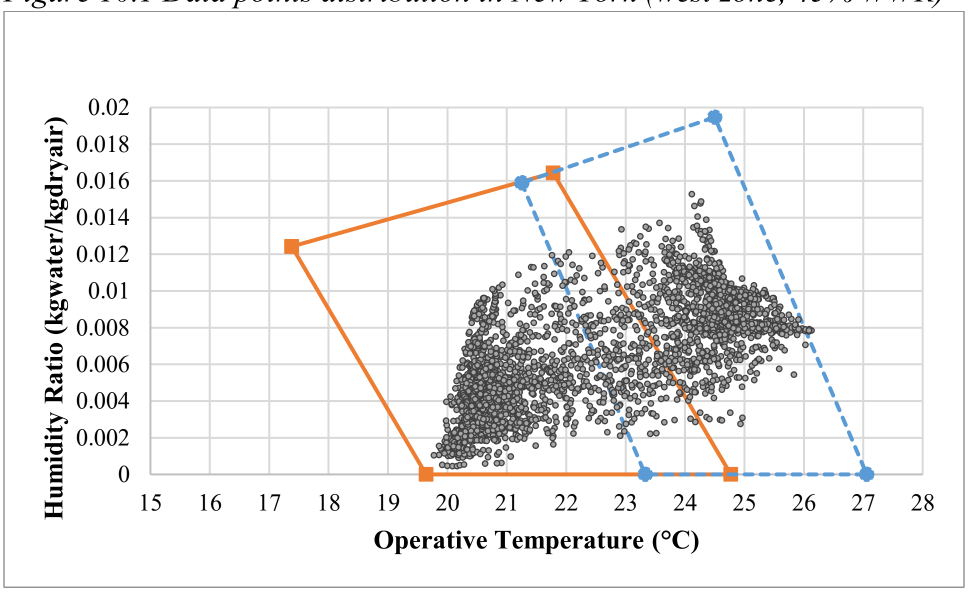
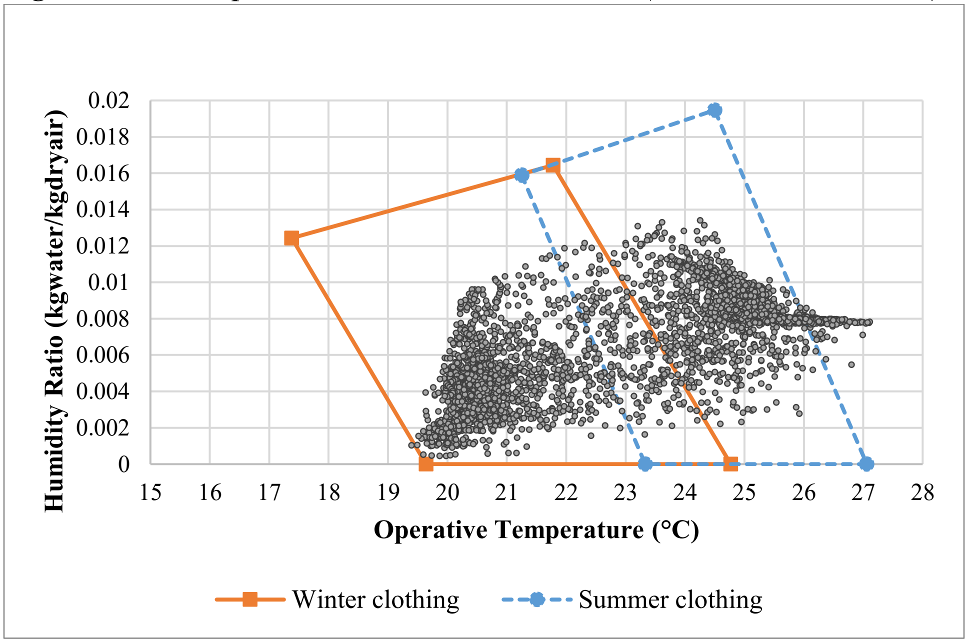


Figure 10.2 Data points distribution in New York (west zone, 80% WWR)



4.1.4 Various WWRs effects on thermal comfort in Montreal

In Montreal, thermal discomfort is observed in all perimeter (south, east, north, and west) zones in small office building with small window sizes, and the distribution of data point shows that both slight cool and warm thermal discomfort frequently happens in buildings with big window sizes.

In the south zone, employees start to feel thermal discomfort when WWR is 30%. Unlike previous 3 locations mentioned, show in Figure 11.1, some data points go across left boundary of thermal comfort zone during winter, which means employees will experience slight cool sensation. Also, overheating problem do not show in buildings with small window size, since none of data points go across the right boundary of thermal comfort zone during summer. On the other hand, thermal discomfort is obviously detected when WWR increases to 80%, Figure 11.2, percentage of time not met thermal comfort is 2.7% (88 hours). Among these thermal discomfort hours, employees experience 38 hours of slight cool sensation and 50 hours of slight warm sensation during occupied time. In addition, operative temperature is greatly affected by large window size in Montreal. The distribution of data points is more diffuse if changing WWR from 30% to 80%. Over two of third of data points (2352 data points) distribute out of the range in operative temperature. Hence, the south zone will face

Figure 11.1 Data points distribution in Montreal (south zone, 30%WWR)

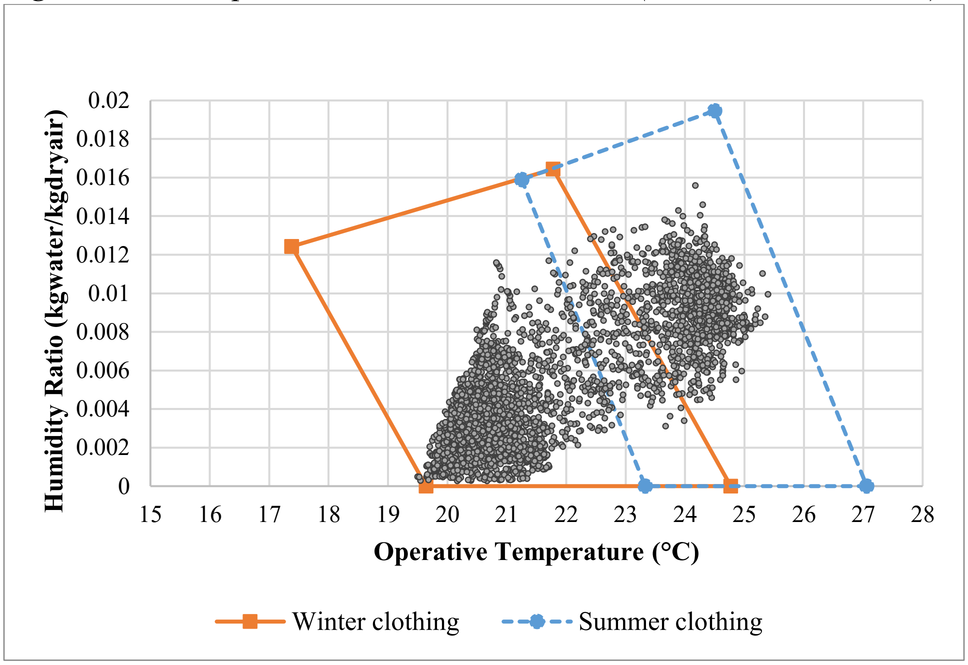
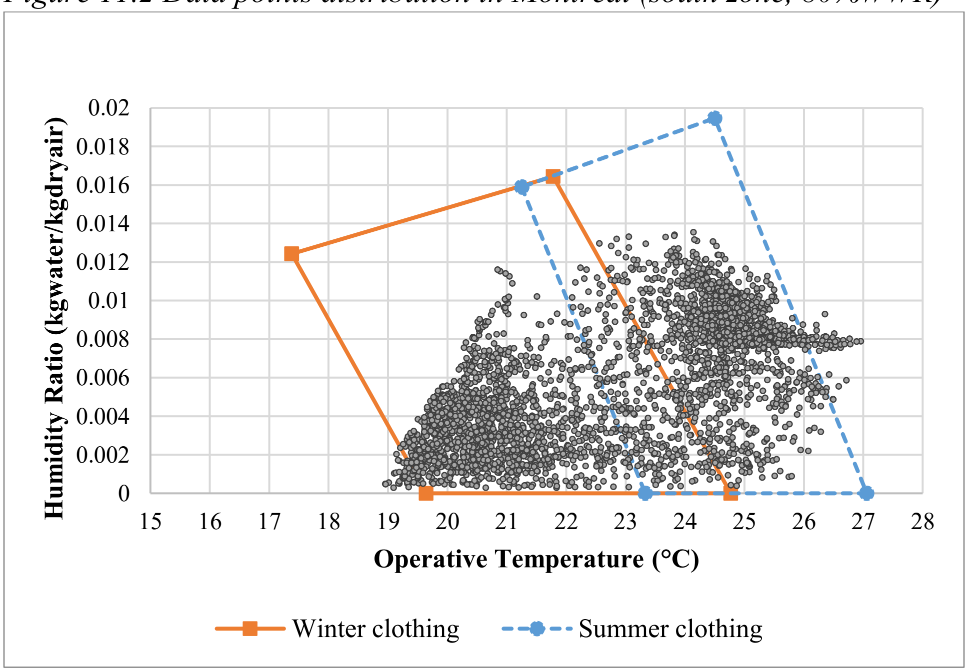


Figure 11.2 Data points distribution in Montreal (south zone, 80%WWR)



In the east, north, and west zones, thermal discomfort starts to occur in small window size, which is 25%, 20%, and 20% separately, Figure 12.1, 13.1, 14.1. they all provide a slight cool environment with small window sizes. Especially in north zone, Figure 13.2, only slightly cool thermal discomfort occurs regardless window size changes from 20% to 80%. In east and west zones, Figure 12.2, 14.2, both slight cool and slight warm sensations can be detected when WWR reaches to 80%. Hence, window sizes of perimeter zones show similar impacts to thermal comfort in Montreal.

As a result, in buildings with large window size located in Montreal, both slightly cool and warm thermal discomfort occurs in perimeter zones except the north one. Only the core zone can maintain thermal comfort conditions with default setpoints regardless of various WWRs.

Figure 12.1 Data points distribution in Montreal (east zone, 25% WWR)

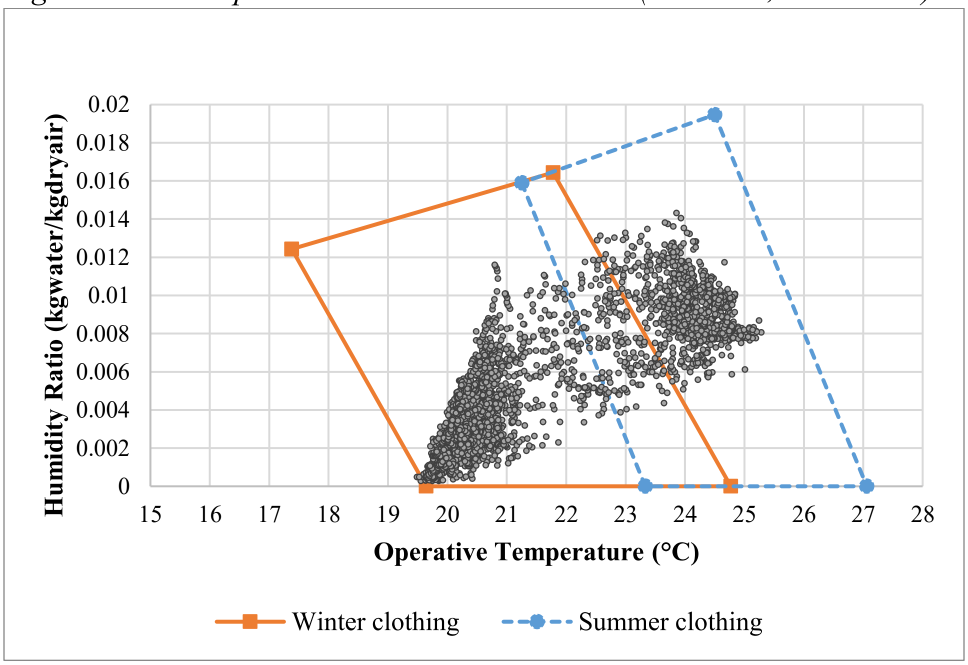


Figure 12.2 Data points distribution in Montreal (east zone, 80% WWR)

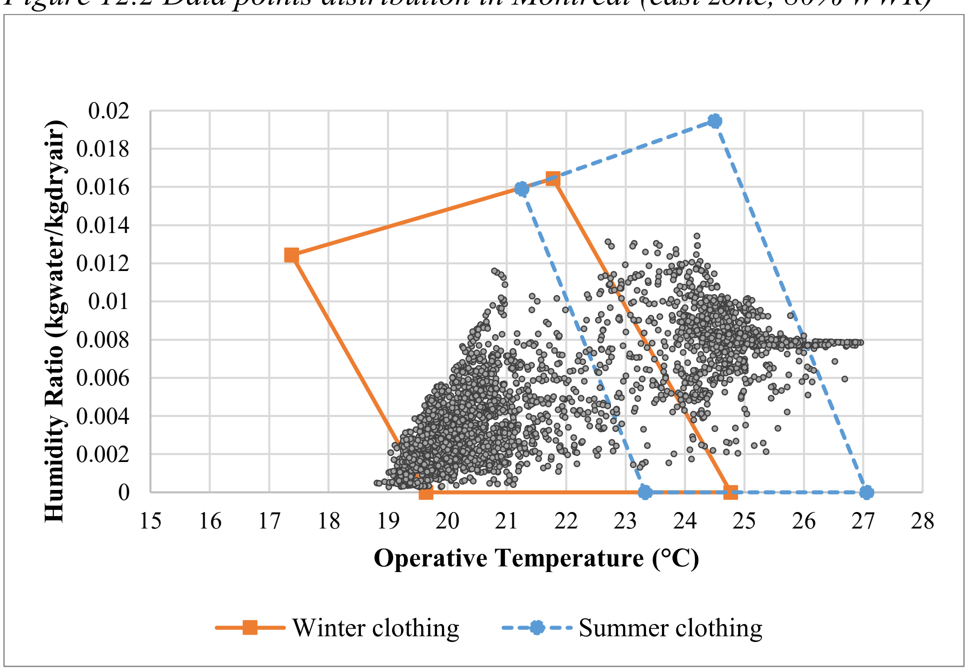


Figure 13.1 Data points distribution in Montreal (north zone, 20% WWR)

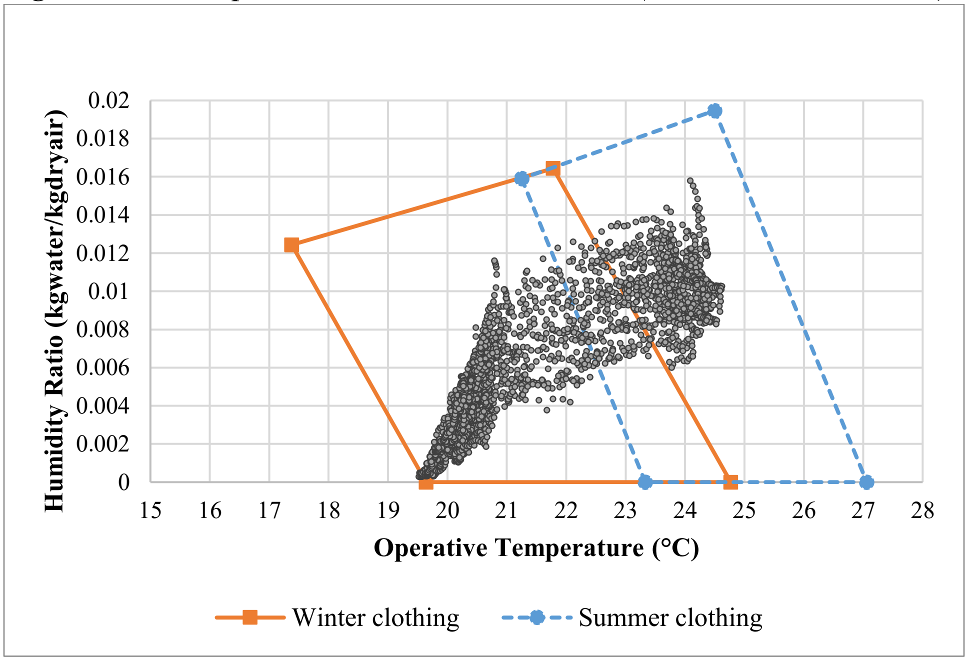


Figure 13.2 Data points distribution in Montreal (north zone, 80% WWR)

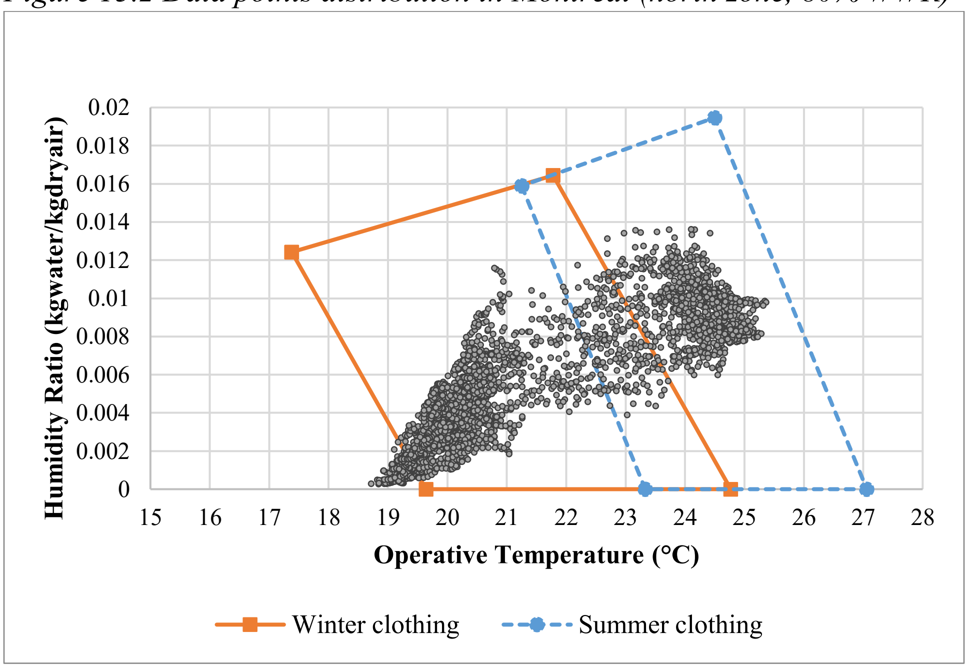


Figure 14.1 Data points distribution in Montreal (west zone, 20% WWR)

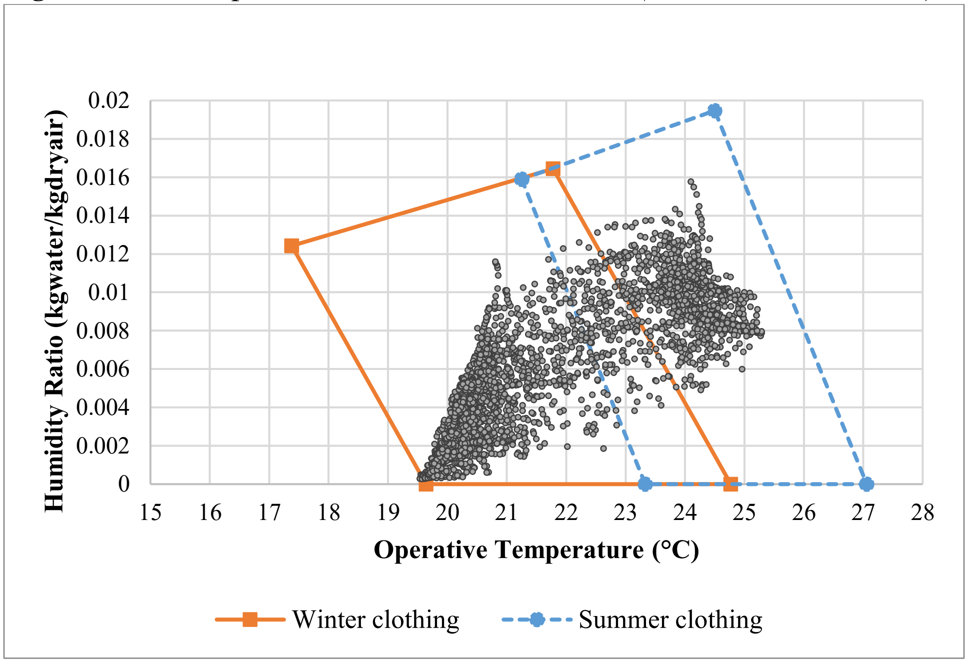
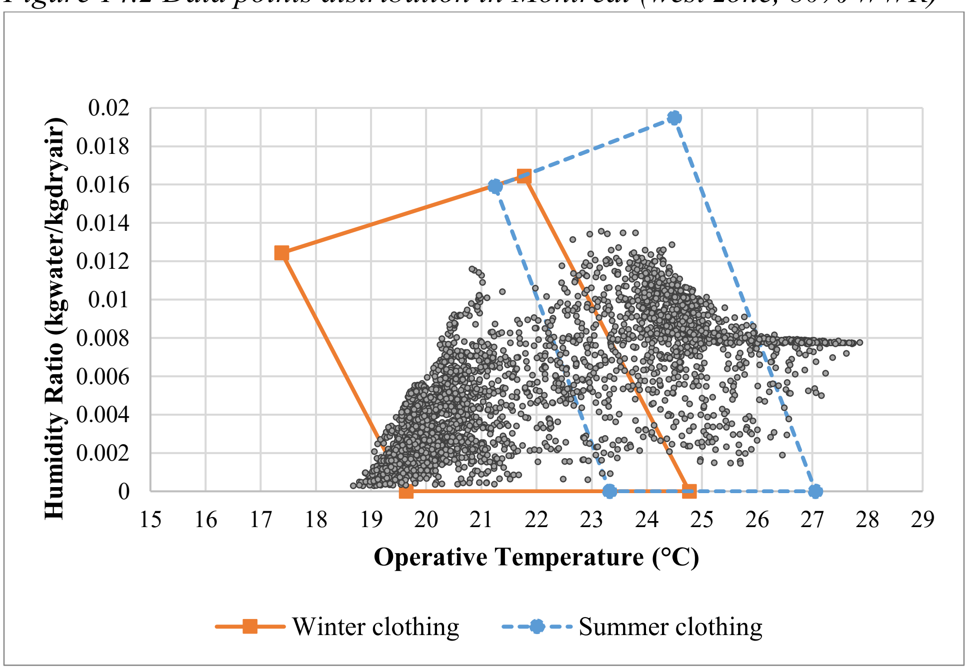


Figure 14.2 Data points distribution in Montreal (west zone, 80% WWR)



4.2 Setpoints adjustment to fulfil thermal comfort and minimum energy demand

Two goals, thermal comfort and minimum energy demand, are considered to guild adjust setpoints in this research. Even if HVAC system maintains room air temperature between 21℃ and 24℃, distribution of data points will expand to a wider area as WWR increases. The operative temperature will easily out of the range because of adding mean radiant temperature in room air temperature, which leads to thermal discomfort problem in some cases. Hence, the adjustment of setpoints focuses on room air temperature to affect operative temperature, and then, a reverse calculation to adjust setpoints is applied to make sure all data points distributing in thermal comfort zones. In three steps setpoint adjustment process: (1) change values based on default setpoints, as a higher heating setpoint will drag room operative temperature to bigger values, or a lower cooling setpoint will drag room operative temperature to smaller values; (2) the interval of each step to adjust setpoints is 0.1 °C considering the resolution of mechanical or digital thermostats; (3) final setpoints is picked out if all data points locate in thermal comfort zones(performance indicator equals zero) and barely reach to its boundary, which requires minimum energy demand. As a result, the appropriate adjustment will fulfill these two goals no matter clothing values during occupied time.

4.2.1 Setpoints adjustment in Miami

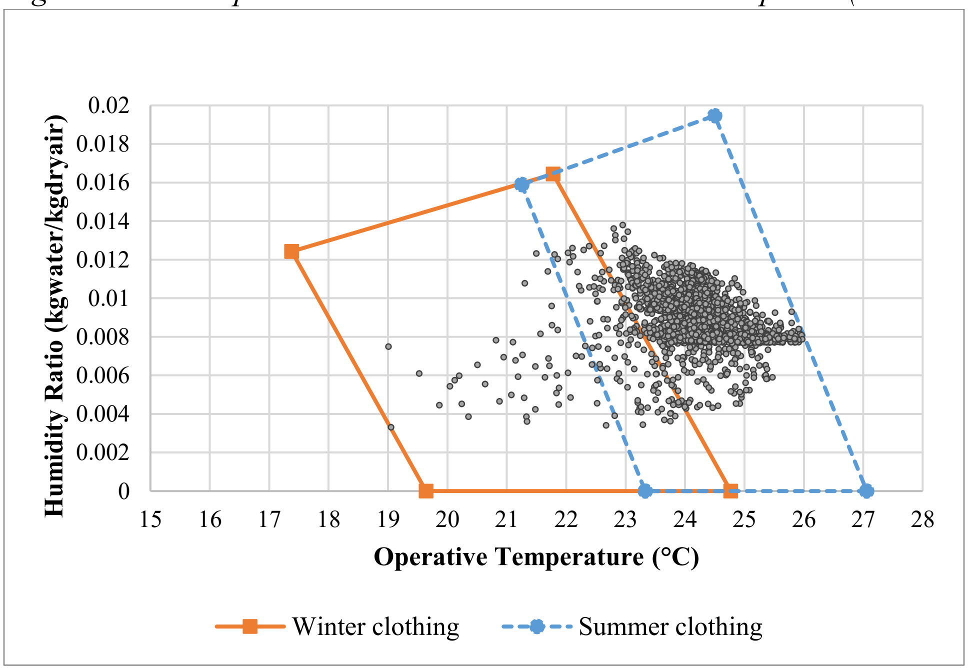
To fulfilling both thermal comfort and minimum energy demand in Miami, a list of new setpoints in all five controlled thermal zones is shown in Table 5. In prototype small office building with default setpoints, distribution of data points still has some space to the left of thermal comfort boundary when people wear winter clothing, on the other hand, some data points already go across right boundary of thermal comfort zones with summer clothing which means they will experience slightly warm thermal discomfort sensation. The strategy is turning down heating setpoint, and turning up cooling setpoint. As a result, the room air temperature range is controlled from 18.0°C to 22.7°C when WWR is 80%. The adjustment of setpoints changes the values of operative temperature and the distribution of data points, which make all data points stay in thermal comfort zone regardless winter or summer clothing, Figure 15.1.

Table 5 New setpoint adjustment in Miami
(“-” means no need to adjust heating setpoint or turn heater on)

	Core zone		South zone		East zone		North zone		West zone	
WWRs	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)
10%	-	24.6	-	24.4	-	24.5	18.8	24.7	18.5	24.6
15%	-	24.6	-	24.4	-	24.4	18.9	24.7	18.7	24.4
20%	-	24.6	-	24.2	-	24.4	19.0	24.7	18.8	24.3
25%	-	24.6	-	24.1	-	24.2	19.1	24.7	18.9	24.2
30%	-	24.6	-	23.9	-	24.1	19.1	24.7	19.0	24.0

35%	-	24.6	-	23.7	-	24.0	19.2	24.7	19.1	23.8
40%	-	24.6	-	23.6	-	23.8	19.3	24.6	19.2	23.6
45%	-	24.6	-	23.5	-	23.6	19.3	24.6	19.3	23.4
50%	-	24.6	17.5	23.3	-	23.4	19.4	24.5	19.4	23.2
55%	-	24.6	17.6	23.2	-	23.2	19.4	24.5	19.5	23.0
60%	-	24.6	17.7	23.1	-	23.0	19.4	24.4	19.5	22.8
65%	-	24.6	17.8	23.0	-	22.8	19.5	24.4	19.6	22.6
70%	-	24.6	17.8	22.9	-	22.7	19.6	24.3	19.7	22.4
75%	-	24.6	17.9	22.8	-	22.6	19.7	24.3	19.7	22.3
80%	-	24.6	18.0	22.7	-	22.4	19.7	24.2	19.8	22.2

Figure 15.1 Data points distribution in Miami with new setpoints (south zone, 80% WWR)



Especially east zone with 80% WWR, distribution of data points with new setpoints is shown in Figure 15.2. On one hand, there is no need to turn on heater since indoor operative temperature can stay in high values that all data points can distribute the right side of thermal comfort boundary with winter clothing. On the other hand, Miami has a very hot climate that cooling setpoint should be set at 22.4°C, which make sure data points do not go across the right boundary of thermal comfort zone with summer clothing. Similarly, in core zone, Figure 15.3, heating is not necessary as well, and the selected cooling setpoint is 24.6°C. Even if all data points stay in thermal comfort zone with the selected setpoints, some data points can reach to very high humidity ratio during summer, which may lead to other problems. In general, new setpoints reduce the room air temperature range as window size increases.

Figure 15.2 Data points distribution in Miami with new setpoints (east zone, 80% WWR)

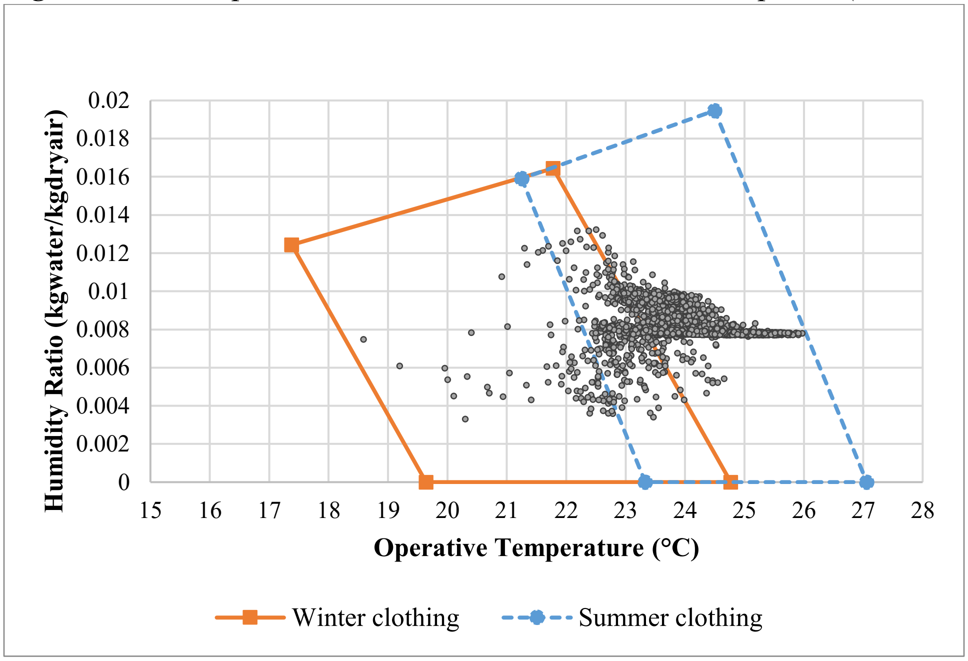
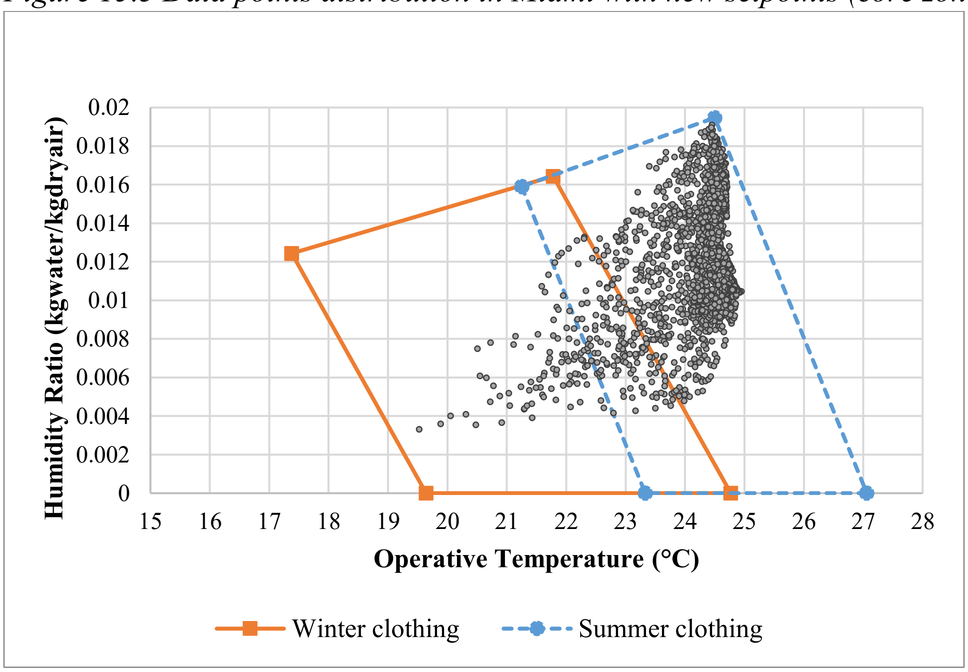


Figure 15.3 Data points distribution in Miami with new setpoints (core zone, 80% WWR)



4.2.2 Setpoints adjustment in San Diego and New York

The shortened range of room air temperature is also detected in San Diego or New York as increasing window size. In Table 6, south zone, HVAC system maintians room air temperature between 18.8°C and 25.0°C, 18.4°C and 23.4°C that maintain indoor environment in thermal comfort conditions in buildings with 10% and 80% WWR separately. Hence, the room air temperature range shortens from 6.2°C to 5.0°C as WWR increases. Furthermore, a list of setpoint adjustment to New York, Table 7, shows the similar phenomena in shortened setpoint range. The new distributions of data points in San Diego and New York, Figure 16, 17, illustrate that even if data points can reach both left and right boundaries, they can be controlled inside thermal comfort zones. Hence, the adjustment in this research still can be used in San Diego and New York.

Table 6 New setpoint adjustment in San Diego

	Core zone		South zone		East zone		North zone		West zone	
WWRs	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)
10%	18.7	25.2	18.8	25.0	19.0	25.2	19.4	25.3	19.3	25.1
15%	18.7	25.2	18.7	25.0	18.9	25.2	19.4	25.3	19.3	25.0
20%	18.7	25.2	18.6	24.9	18.7	25.1	19.4	25.3	19.3	24.9
25%	18.6	25.2	18.5	24.8	18.5	25.0	19.4	25.3	19.3	24.8
30%	18.6	25.2	18.4	24.7	18.5	24.9	19.5	25.3	19.3	24.7
35%	18.5	25.2	18.3	24.6	18.5	24.8	19.5	25.2	19.3	24.5
40%	18.5	25.2	18.1	24.4	18.5	24.7	19.5	25.2	19.3	24.4
45%	18.5	25.2	18.1	24.3	18.5	24.6	19.5	25.2	19.3	24.2
50%	18.5	25.2	18.1	24.1	18.4	24.6	19.5	25.2	19.3	24.1
55%	18.5	25.2	18.1	24.0	18.3	24.5	19.5	25.2	19.3	23.9
60%	18.5	25.2	18.2	23.8	18.3	24.4	19.5	25.1	19.3	23.8
65%	18.5	25.2	18.2	23.7	18.3	24.3	19.6	25.1	19.3	23.6
70%	18.4	25.2	18.2	23.6	18.3	24.2	19.6	25.1	19.3	23.5
75%	18.4	25.2	18.3	23.5	18.3	24.1	19.6	25.1	19.3	23.4
80%	18.4	25.2	18.4	23.4	18.4	24.1	19.6	25.1	19.3	23.3

Figure 16 Data points distribution in San Diego with new setpoints (south zone, 80% WWR)

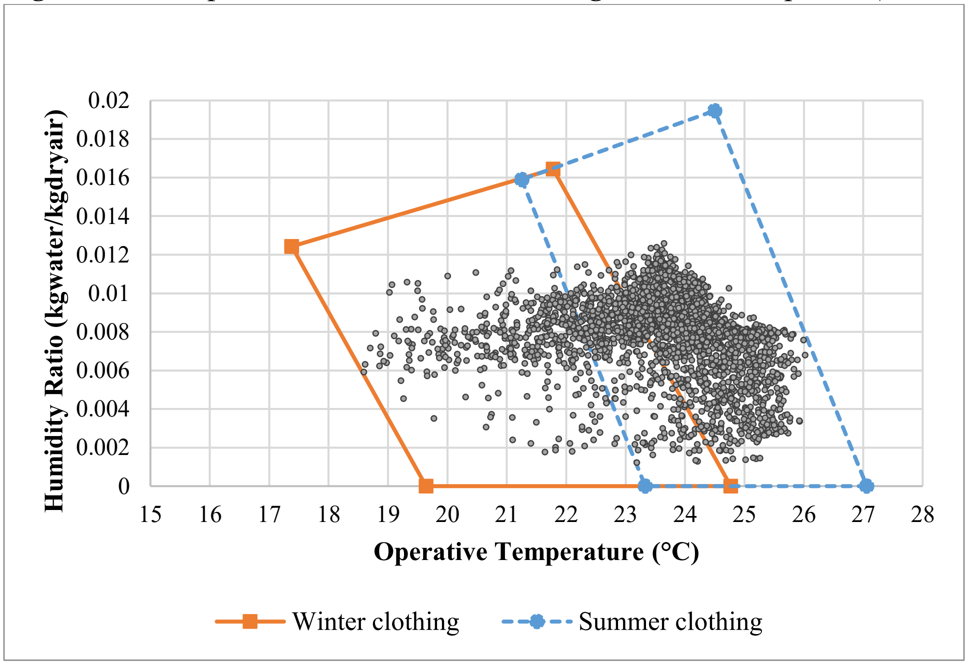
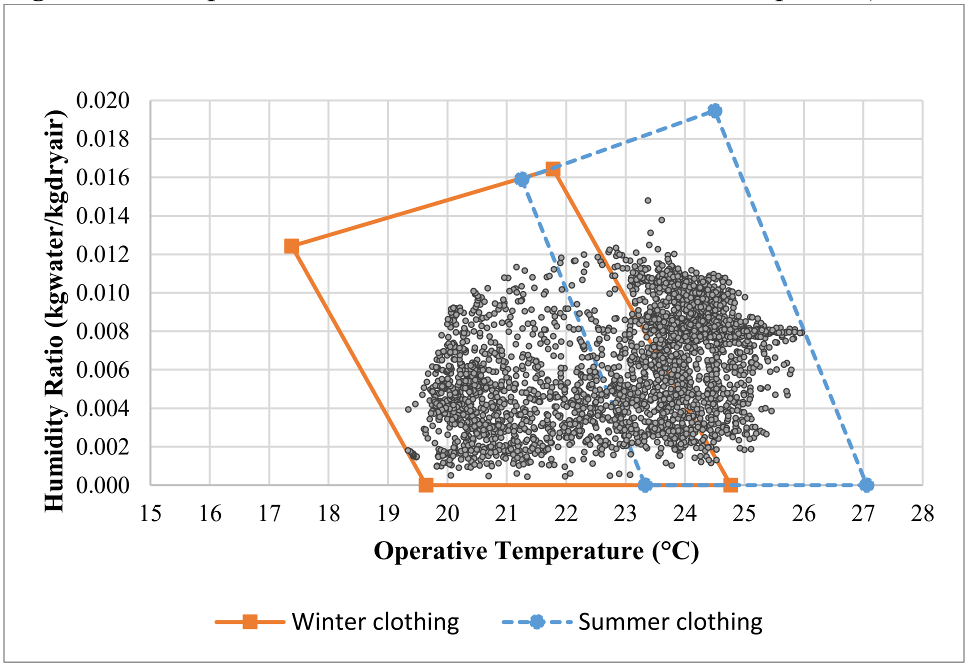


Table 7 New setpoints adjustment in New York

WWRs	Core zone Heating setpoint (°C)	Core zone Cooling setpoint (°C)	South zone Heating setpoint (°C)	South zone Cooling setpoint (°C)	East zone Heating setpoint (°C)	East zone Cooling setpoint (°C)	North zone Heating setpoint (°C)	North zone Cooling setpoint (°C)	West zone Heating setpoint (°C)	West zone Cooling setpoint (°C)
10%	19.8	24.7	20.2	24.7	20.2	24.7	20.4	24.7	20.4	24.7
15%	19.8	24.7	20.2	24.7	20.2	24.7	20.5	24.7	20.4	24.7
20%	19.8	24.7	20.2	24.6	20.3	24.7	20.5	24.7	20.5	24.6
25%	19.8	24.7	20.2	24.5	20.3	24.5	20.5	24.7	20.5	24.4
30%	19.8	24.7	20.2	24.4	20.4	24.4	20.6	24.7	20.6	24.3
35%	19.8	24.7	20.2	24.3	20.4	24.3	20.6	24.7	20.6	24.2
40%	19.8	24.7	20.2	24.2	20.4	24.2	20.7	24.7	20.7	24.0
45%	19.8	24.7	20.3	24.1	20.5	24.0	20.7	24.7	20.8	23.8
50%	19.8	24.7	20.3	23.9	20.5	23.9	20.8	24.7	20.8	23.6
55%	19.7	24.7	20.4	23.7	20.6	23.7	20.9	24.7	20.9	23.4
60%	19.7	24.7	20.4	23.6	20.6	23.6	20.9	24.7	20.9	23.3
65%	19.7	24.7	20.5	23.5	20.7	23.4	21.0	24.6	21.0	23.1
70%	19.7	24.7	20.5	23.4	20.7	23.3	21.0	24.6	21.0	23.0
75%	19.7	24.7	20.6	23.3	20.7	23.2	21.1	24.5	21.1	22.8
80%	19.7	24.7	20.6	23.2	20.8	23.1	21.1	24.5	21.2	22.7

Figure 17 Data points distribution in New York with new setpoints (south zone, 80% WWR)



4.2.3 Setpoints adjustment in Montreal

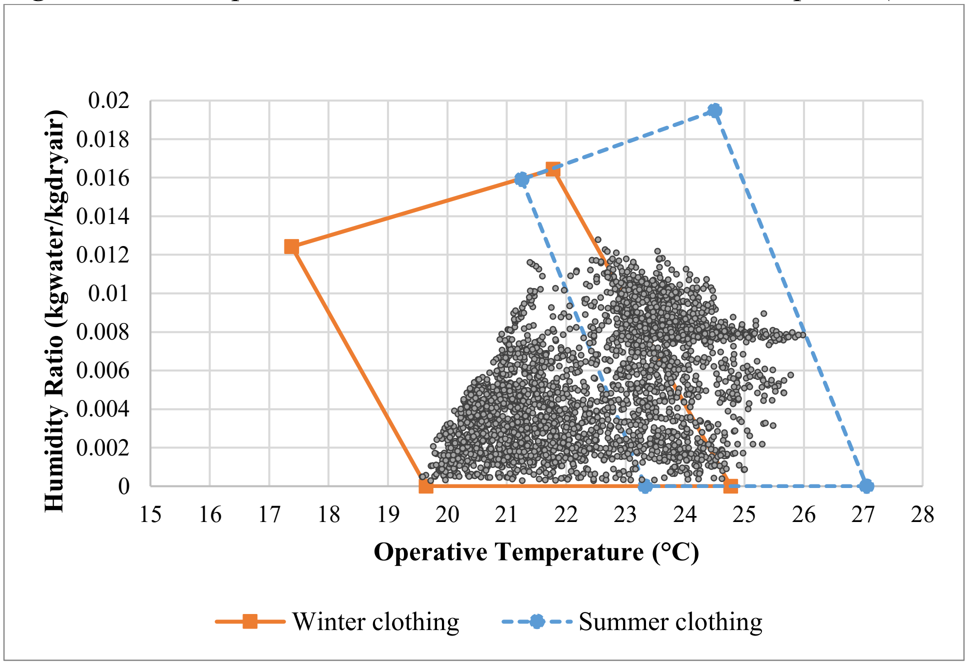
For cold humid climate in Montreal, new adjustment of setpoints shrinks the distribution of data points in operative temperature as well, however, the shortened room air temperature range will turn to a specific number in some extreme cases. Table 8 shows new setpoints values of five thermal zones. For example, the heating setpoint should be at 21.7°C and cooling setpoint at 22.8°C in the south to maintain thermal comfort and consumes minimal energy demand at the same time, data points distribution in Figure 18.1.

Table 8 New setpoints adjustment in Montreal

	Core zone		South zone		East zone		North zone		West zone	
WWRs	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)	Heating setpoint (°C)	Cooling setpoint (°C)
10%	20.7	24.7	20.9	24.8	20.9	24.8	21.0	24.8	21.0	24.8
15%	20.7	24.7	21.0	24.7	21.0	24.8	21.1	24.8	21.1	24.8
20%	20.7	24.7	21.0	24.6	21.1	24.7	21.1	24.8	21.1	24.6
25%	20.7	24.7	21.1	24.4	21.1	24.6	21.2	24.8	21.2	24.4
30%	20.7	24.7	21.1	24.2	21.2	24.5	21.3	24.8	21.3	24.2
35%	20.7	24.7	21.1	24.1	21.3	24.3	21.4	24.8	21.4	23.9
40%	20.7	24.7	21.2	24.0	21.3	24.1	21.4	24.8	21.5	23.6
45%	20.7	24.7	21.3	23.9	21.4	23.9	21.5	24.8	21.5	23.4
50%	20.7	24.7	21.4	23.8	21.5	23.7	21.6	24.8	21.6	23.1

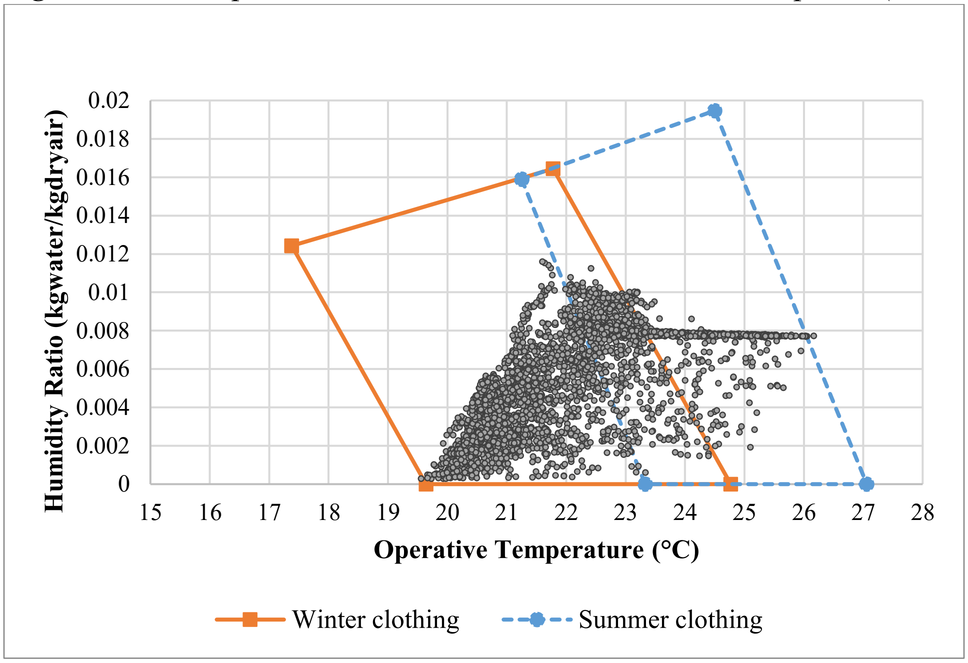
55%	20.7	24.7	21.4	23.7	21.5	23.5	21.7	24.7	21.7	22.9
60%	20.7	24.7	21.5	23.5	21.6	23.3	21.7	24.7	21.8	22.6
65%	20.7	24.7	21.5	23.2	21.7	23.2	21.8	24.6	21.8	22.4
70%	20.7	24.7	21.6	23.1	21.7	23.1	21.9	24.6	21.9	22.2
75%	20.7	24.7	21.7	22.9	21.8	23.0	22.0	24.5	22.0	22.0
80%	20.7	24.7	21.7	22.8	21.9	22.9	22.0	24.5	22.0	22.0

Figure 18.1 Data points distribution in Montreal with new setpoints (south zone, 80% WWR)



However, if the distribution of data points spread a wider range in operative temperature axle, the higher heating setpoint and lower cooling setpoint are necessary to drag data points within thermal comfort zones, which narrows room air temperature range as a number. In an extreme case, the heating setpoint has the same value as cooling setpoint, and the room air temperature range becomes a zero value. This will happen in the west zone with 75%WWR and 80%WWR. In Figure 18.2, when heating and cooling setpoints are the same at 22.0°C to fulfill most time in thermal comfort condition, there still some data points out of thermal comfort zones. A narrow range of room air temperature will cause HVAC system switches between cooling and heating modes frequently, which may lead to mechanical problems. Hence, the method that only adjusting cooling and heating setpoints in a year does not cover two goals of thermal comfort and energy saving in some extreme cases.

Figure 18.2 Data points distribution in Montreal with new setpoints (west zone, 80% WWR)



4.3 Energy demand influences in four locations

The adjustment of setpoints will also lead to influences in energy demand. In fact, new adjustment of setpoints shows that a lower value in heating setpoint will both consume less energy and maintain thermal comfort or a higher value in cooling setpoint can perform these two goals as well, details in following section.

4.3.1 Impact to energy demand in Miami

In Miami, the adjustment of setpoints shows energy saving potential in buildings with small window sizes. Especially energy saving reflects in cooling demand to maintain thermal comfort conditions with certain adjustment of setpoints. In Table 9, if WWRs are between 10% and 40%, there is a reduction in total energy demand from 10.2% to 1.5%. Once the WWR goes over the threshold at 45%, more energy demand is necessary to maintain indoor thermal comfort with selected setpoints comparing default prototype building setpoints. Even if 9.2% of more energy demand is required than default setpoints setting, occupants still experience thermal comfort during occupied time when WWR increases to 80%. Hence, new setpoints adjustment can be applied in the balance between energy saving and thermal comfort depending on window sizes.

Table 9 Energy demand comparation in Miami

WWRs	Energy demand with default setpoints (heating setpoint: 21°C, cooling setpoint: 24°C)			Energy demand with new setpoints (values in Table 5)			Total energy demand change
	Heating demand (kWh/m²)	**Cooling demand (kWh/m²)**	**Total energy demand (kWh/m²)**	**Heating demand (kWh/m²)**	**Cooling demand (kWh/m²)**	**Total energy demand (kWh/m²)**	
10%	0.05	82.89	82.94	0.00	74.47	74.47	-10.2%
15%	0.05	85.91	85.96	0.00	78.00	78.01	-9.3%
20%	0.05	88.85	88.90	0.00	81.87	81.87	-7.9%
25%	0.05	91.76	91.81	0.00	85.74	85.74	-6.6%
30%	0.05	94.63	94.68	0.01	90.04	90.05	-4.9%
35%	0.05	97.46	97.51	0.01	94.34	94.35	-3.3%
40%	0.05	100.24	100.30	0.01	98.80	98.81	-1.5%
45%	0.06	102.96	103.02	0.01	102.88	102.89	-0.1%
50%	0.06	105.63	105.69	0.01	107.73	107.74	1.9%
55%	0.06	108.22	108.29	0.01	111.73	111.74	3.2%
60%	0.07	110.72	110.79	0.01	116.05	116.06	4.8%
65%	0.07	113.17	113.24	0.01	119.95	119.96	5.9%
70%	0.08	115.41	115.48	0.02	123.80	123.82	7.2%
75%	0.08	117.55	117.63	0.02	126.95	126.97	7.9%
80%	0.09	119.61	119.69	0.02	130.67	130.70	9.2%

4.3.2 Impact to energy demand in San Diego

In San Diego, the method of setpoints adjustment shows the big potential in energy saving in buildings with various window sizes. Both heating and cooling demand decreases using new setpoints adjustment. Cooling demand is much bigger than heating demand, and values with selected setpoints are all smaller than those in buildings with default setpoints, Table 10. When WWR is 10%, 45.2% less heating and cooling demand than prototype building. If WWR increases to 80%, it still shows energy saving in heating and cooling, and 9.8% less energy demand than prototype buildings. The results illustrate that window size affects less in heating demand, and much in cooling demand, also, values of cooling demand are much bigger than heating one.

Table 10 Energy demand comparation in San Diego

	Energy demand with default setpoints (heating setpoint: 21°C, cooling setpoint: 24°C)	Energy demand with new setpoints (values in Table 6)	

WWRs	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Total energy demand change
10%	0.56	14.73	15.29	0.12	8.25	8.37	-45.2%
15%	0.53	15.90	16.43	0.11	9.09	9.20	-44.0%
20%	0.50	17.16	17.67	0.10	10.23	10.33	-41.5%
25%	0.48	18.50	18.98	0.10	11.51	11.61	-38.8%
30%	0.47	19.88	20.35	0.10	12.92	13.02	-36.0%
35%	0.46	21.29	21.74	0.10	14.56	14.66	-32.6%
40%	0.45	22.71	23.15	0.10	16.31	16.40	-29.2%
45%	0.44	24.13	24.56	0.10	18.02	18.12	-26.2%
50%	0.43	25.53	25.96	0.10	19.83	19.93	-23.2%
55%	0.43	26.89	27.32	0.10	21.59	21.69	-20.6%
60%	0.43	28.20	28.63	0.10	23.60	23.70	-17.2%
65%	0.43	29.45	29.87	0.11	25.34	25.45	-14.8%
70%	0.43	30.57	31.00	0.11	26.87	26.98	-13.0%
75%	0.44	31.53	31.97	0.12	28.27	28.38	-11.2%
80%	0.45	32.39	32.84	0.12	29.49	29.61	-9.8%

4.3.3 Impact to energy demand in New York

In New York, new setpoints adjustment, Table 11, shows the potential to energy saving, since total energy demand of HVAC system with new selected setpoints is less than default values of setpoints. Even if heating and cooling demand increase as increasing of window size to buildings with both default and new select setpoints, the adjustment of setpoints will require less heating demand to various window sizes. In addition, if WWR is under 60%, buildings with new selected setpoints show slight usages in cooling demand, otherwise, HVAC system consumes more energy to maintain thermal comfort when WWR is over 65%. Since cooling demand is much larger than heating demand in prototype small office buildings with various window sizes, a threshold of WWR is 65% that buildings perform both thermal comfort and energy saving under this threshold, and require 3.0% more energy demand to maintain thermal comfort for a mixed humid climate in New York. In general, this method illustrates energy saving potential in buildings with small and medium window sizes.

Table 11 Energy demand comparation in New York

	Energy demand with default setpoints (heating setpoint: 21°C, cooling setpoint: 24°C)	**Energy demand with new setpoints (values in Table 7)**	

WWRs	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Total energy demand change
10%	9.44	19.37	28.81	8.40	17.13	25.53	-11.4%
15%	9.48	20.69	30.17	8.48	18.38	26.85	-11.0%
20%	9.51	22.10	31.62	8.56	19.83	28.40	-10.2%
25%	9.57	23.53	33.10	8.61	21.42	30.03	-9.3%
30%	9.62	24.98	34.60	8.77	22.98	31.75	-8.2%
35%	9.69	26.44	36.13	8.84	24.55	33.39	-7.6%
40%	9.78	27.88	37.66	9.01	26.18	35.19	-6.6%
45%	9.88	29.31	39.19	9.19	27.89	37.08	-5.4%
50%	9.98	30.71	40.69	9.37	29.64	39.01	-4.1%
55%	10.11	32.08	42.19	9.64	31.51	41.15	-2.5%
60%	10.25	33.43	43.68	9.78	33.12	42.90	-1.8%
65%	10.40	34.71	45.11	10.10	34.95	45.06	-0.1%
70%	10.58	35.91	46.48	10.29	36.46	46.75	0.6%
75%	10.78	37.02	47.80	10.65	38.14	48.78	2.1%
80%	11.03	38.03	49.06	10.97	39.53	50.51	3.0%

4.3.4 Impact to energy demand in Montreal

For the cold humid climate in Montreal, the fact of energy saving is not obvious in most cases and extra more energy demand is required in buildings with large window sizes. In Table 12, heating demand is much greater than cooling demand and energy demand increases as WWR increases. Both heating and cooling demand increase as WWR increases, and cooling demand is more sensitive than heating demand in Montreal. If compare default setpoints adjustment, total energy demand with new selected setpoints require less until WWR is under 40%. When WWR is over 45%, to provide a thermal comfort indoor environment, more heating and cooling demand are necessary. And 11.7% more total energy demand is needed as WWR increases to 80%. Furthermore, window size affects cooling demand obviously than heating demand, but the amount of heating demand is much larger than cooling demand in a cold climate location. In general, energy saving is not obvious in buildings with small and medium window size.

Table 12 Energy demand comparation in Montreal

	Energy demand with default setpoints (heating setpoint: 21°C, cooling setpoint: 24°C)			**Energy demand with new setpoints (values in Table 8)**			

WWRs	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Heating demand (kWh/m²)	Cooling demand (kWh/m²)	Total energy demand (kWh/m²)	Total energy demand change
10%	39.65	8.75	48.41	39.16	6.44	45.60	-5.8%
15%	39.63	9.75	49.38	39.46	7.36	46.82	-5.2%
20%	39.59	10.85	50.45	39.49	8.54	48.02	-4.8%
25%	39.56	12.02	51.58	39.73	9.94	49.67	-3.7%
30%	39.54	13.24	52.77	39.94	11.46	51.40	-2.6%
35%	39.54	14.48	54.02	40.29	13.08	53.37	-1.2%
40%	39.58	15.75	55.33	40.41	14.77	55.18	-0.3%
45%	39.65	17.02	56.67	40.78	16.47	57.24	1.0%
50%	39.75	18.29	58.04	41.26	18.30	59.56	2.6%
55%	39.90	19.54	59.44	41.62	20.17	61.79	4.0%
60%	40.10	20.76	60.85	42.09	22.25	64.35	5.7%
65%	40.33	21.93	62.26	42.59	24.43	67.02	7.6%
70%	40.63	23.05	63.67	43.23	26.20	69.43	9.0%
75%	40.99	24.10	65.09	44.05	28.27	72.32	11.1%
80%	41.44	25.08	66.52	44.62	29.69	74.31	11.7%

Section 5. Conclusions

This research employs ASHRAE thermal comfort zone to develop an approach to determine a set of thermostat set points that can maintain the space within thermal comfort zone and yet potentially reduce cooling and heating energy demand. The research is implemented in EnergyPlus, applied to four climate zones, and investigated for a small office building with window to wall ratio ranging from 10% to 80%. The results indicated that thermal comfort can be maintained without changes to existing HVAC equipment or replacing current dry-bulb temperature based thermostats.

These are the major findings: (1) Under current dry-bulb temperature-based thermostat operation, the operative temperature of many hours falls out of the thermal comfort zone; (2) Increasing window size further exaggerate the problem in perimeter zones; (3) Both heating and cooling demand increase as window size increases, cooling demand is more sensitive than heating demand with respect to window sizes; (4) For small and medium window sizes, new set points show potential in energy saving. For larger window sizes, more energy demand is required to maintain thermal comfort.

The key contribution of this research is to offer an approach that can maintain thermal comfort that is specified in terms of operative temperature without any change to exiting dry-bulb temperature-based thermostat operation. In practice, facility managers can simply apply the recommended new set points to maintain thermal comfort without the need for additional equipment or operational modifications.

As the investigation involved only one building type (small office building) and limited to only four climate zones, further studies are needed to extend the investigation to other building types, indoor end-uses, and climates.

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