Outdoor Thermal Comfort Analysis in a Cold Continental Climate:

The Case of a Pedestrian-Only Street in Downtown Toronto

by

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Outdoor Thermal Comfort Analysis in a Cold Continental Climate:
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Abstract

Increased interest in urban thermal comfort has emerged in recent years with unpredictable weather patterns and unprecedented temperature extremes around the world. Urban modelling computer software can help with understanding interactions between built environment and microclimates. However, results of simulations can be difficult to interpret if acceptable thermal conditions for a location are unknown. Using a compound approach of field investigation and microclimate modelling for a pedestrian-only street in Toronto, Canada, this study investigates urban outdoor thermal comfort (OTC) in a cold continental climate. Four thermal indices were used to analyze field data and the results were compared with OTC research conducted in other climates. In this study, the Physiological Equivalent Temperature (PET) provided the strongest annual correlation with the pedestrian thermal sensation votes. A PET comfort range between 9°C and 24°C was found. Survey results were then used to interpret the simulated effect of urban vegetation within the case study microclimate during a summer scenario.

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List of Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATSV	Actual Thermal Sensation Vote
CFD	Computational Fluid Dynamics
MEMI	Munich Energy Balance Model
MRT	Mean Radiant Temperature
MTSV	Mean Thermal Sensation Vote
PET	Physiological Equivalent Temperature
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
RANS	Reynolds-Average Navier-Stokes
RH	Relative Humidity
SET	Standard Effective Temperature
SVF	Sky View Factor
UHI	Urban Heat Island
UTCI	Universal Thermal Climate Index

1 Introduction

Increased interest in pedestrian thermal comfort has emerged in recent years with higher frequencies of unpredictable weather patterns and unprecedented temperature extremes around the world. Severe environmental conditions can cause discomfort for pedestrians, therefore, it is important for cities to understand outdoor thermal comfort and how to design cities to mitigate discomfort within the urban environment. One method for understanding microclimate and built environment interactions is by using computer simulation software. Recent new tools can help in informing designers to ensure that they create comfortable and safe outdoor urban spaces. However, the results of these simulations can be difficult to interpret, especially if the thermal conditions acceptable for a specific region are largely unknown. Outdoor Thermal Comfort (OTC) studies have begun to emerge in various climates in attempts to better understand the physiological thermal sensations of pedestrians in different climatic regions. Varying results among OTC studies indicate that physiological sensation and comfort can differ depending on location and climate. OTC as a discipline is still relatively new, therefore few studies have been conducted in cold climates thus far. Therefore, using a compound approach of field investigation and microclimate modelling of a pedestrian-only street in Toronto, Canada, this study investigates OTC and how urban vegetation can affect the physiological sensation of pedestrians in a cold climate. This introduction will provide readers with background information including the thermodynamic concept of human heat balance, what thermal indices are and how they can help in understanding physiological sensation and how to simulate OTC in urban microclimates using advanced computer software.

1.1 The Human Heat Balance

The second law of thermodynamics establishes the natural direction of heat transfer in a constant direction from higher to lower temperatures. The human body is not exempt from this law and is in a continuous state of heat exchange with the environment, especially when exposed to complex outdoor conditions. While naturally maintaining an internal temperature of roughly

35°C to 37°C, many natural and human factors influence the heat loss or gain of a human body. The six basic parameters for assessing human thermal environments described by Fanger (1970) are air temperature, relative humidity, wind speed, mean radiant temperature, metabolic rate (MET), and clothing insulation levels (clo). An example of the impact of personal parameters and how the Fanger model is applicable in all climates is to conceptualize a person skiing down a hill in winter with their child on their back. When they reach the bottom of the hill, the internal heat production of the skier is enough to compensate for the convective heat loss experienced from the activity of travelling down the hill, whereas the child will have lost heat to the cold environment and will be much colder (Erell et al., 2011).

The heat inputs and outputs are calculated from a combination of heat transfer equations combined into a single heat balance equation. The underlying concepts of a human heat balance equation involve heat generation in the body, heat transfer and heat storage, and can be expressed as:

$$\mathrm{M} + \mathrm{W} + \mathrm{R} + \mathrm{C} + E_D + E_{Re} + E_{Sw} + S = 0$$

where M represents the internal energy production or metabolic rate, W is the physical work output, R the net-radiation of the body, C the convective heat flow, E_D the latent heat flow to evaporate water diffusion from the skin, E_{Re} the sum of heat flows for heating and humidifying the inspired air, E_{Sw} the heat flow due to evaporation of sweat, and S the storage heat flow for heating or cooling the body mass (Höppe, 1999). If the heat balance net result is zero, then the heat inputs are equal to the heat outputs (Figure 1). If the net result is positive, the heat inputs are greater than the outputs and some measure may need to be taken to increase the output of heat and restore the balance. It is important to note that there is not a steady state balance that occurs due to the continuous fluctuation of the human body and its surrounding environment, though for a roughly constant internal temperature there will be a dynamic balance (Parsons, 2002).

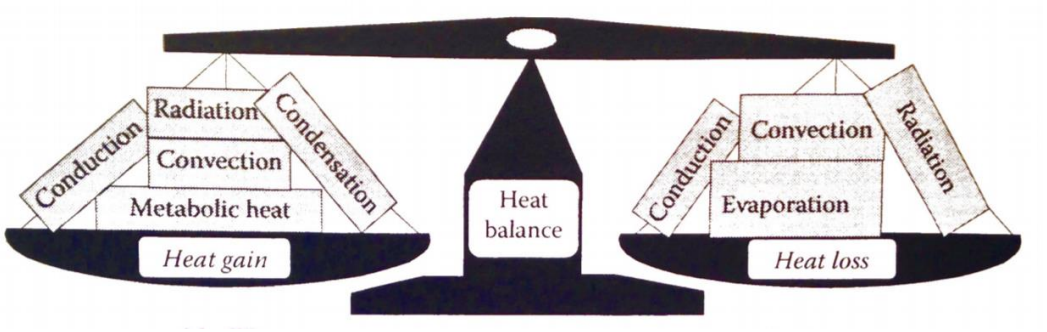


Figure 1. The heat balance concept (source: Parsons, 2002).

The two main methods prompting thermal discomfort are the absorption or emission of energy in the form of radiation and the absorption or dissipation of heat by convection (Erell et al., 2011). Short-wave radiation delivered by direct sunlight is the primary source of radiation that reaches the Earth. Long-wave (or thermal) radiation however is emitted largely by the atmosphere and by both natural and human-made surfaces. A human body's exposure to heat gains and losses can be influenced by the characteristics of an urban area. Figure 2 displays the many methods of heat transfer found in the built environment. A common way of establishing specific levels of radiation in an area is by knowing the mean radiant temperature (MRT). MRT is defined as the temperature of a hypothetical enclosure in which radiant energy exchange with the body equals the radiant exchange in the actual non-uniform enclosure (ASHRAE 55, 2017).

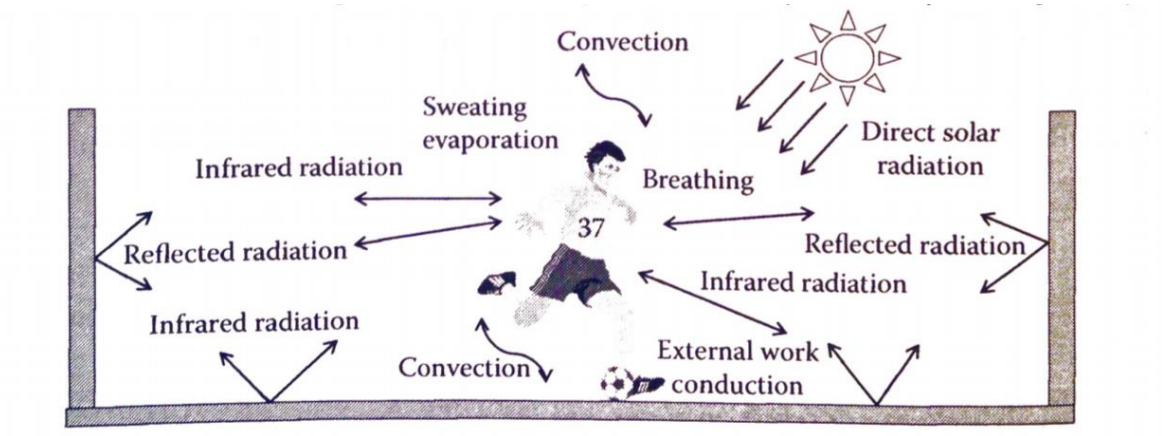


Figure 2. Heat transfer modes for a personal in an outdoor thermal environment (source: Parsons, 2002).

In 1975, a meta-analysis of published thermal comfort research found that indoor thermal comfort within actual buildings can be achieved within a wider band of indoor conditions that

what is determined by Fanger's PMV/PPD model (Humphreys, 1975). Adaptive comfort theory, proposed by de Dear and Brager (1998) suggest that people can form physiological, behavioral and psychological adaptations for thermal comfort, largely with respect to acclimatization, expectations towards indoors and outdoor conditions, or with the amount of control over the environment. The wider thermal comfort ranges in adaptive models can also have consequent energy conservation implications by reducing the energy intensity of mechanical systems to achieve the smaller and more conservative PMV/PPD range. ASHRAE 55:2004 was the first comfort standard to adopt an adaptive comfort model. Figure 3 is a chronological map demonstrating the eventual adoption of adaptive comfort for many comfort standards around the world.

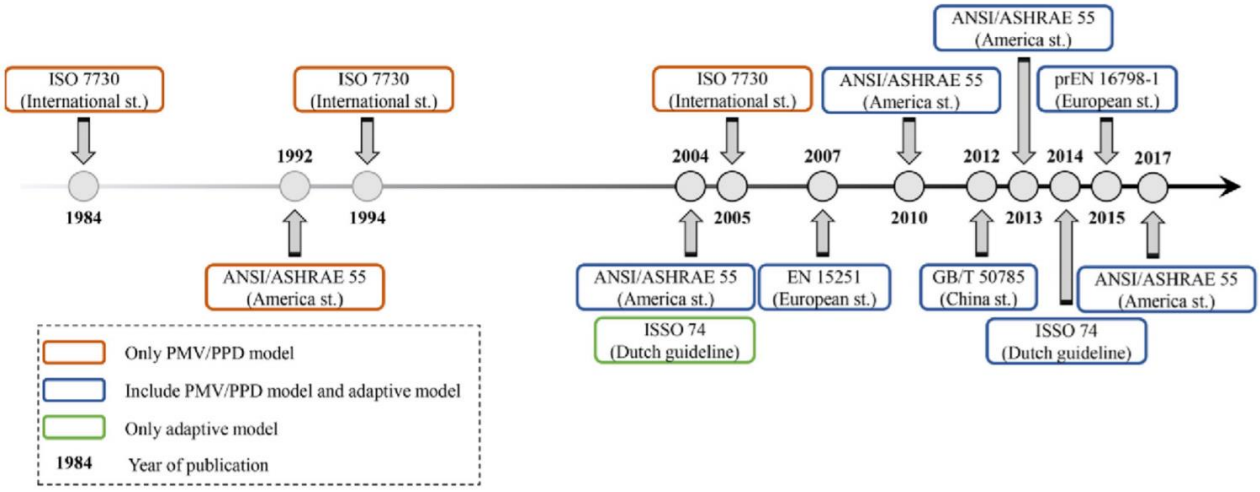


Figure 3. Chronology of the integration and refinement of thermal comfort models in regulatory documents (source: Carlucci et al., 2018)

1.2 Thermal Indices

Acceptable outdoor thermal standards and conditions have yet to be standardized though organizations like the ASHRAE 55 have been regulating indoor thermal comfort conditions since the late 1960's. OTC as a discipline is a relatively new area of research and as a result relies largely on thermal comfort principles intended for indoor environments. The outdoor environment is dynamic and when compared to interior spaces it entails much wider ranges of air temperature, relative humidity, wind and solar radiation, all of which are in constant fluctuation on a daily,

seasonal and annual basis. OTC studies have emerged since the early 2000's using a variety of approaches involving thermal indices primarily designed for interior applications and others more recently developed to accommodate exterior conditions.

As stated in the previous section, Fanger's six basic parameters for thermal analyses are air temperature, relative humidity, wind speed, mean radiant temperature, clothing insulation values, and metabolic rate (Fanger, 1970). Because these criteria are in constant flux and subject to high variability, it is required to combine these variables into a simplified representational weather variable, known as a thermal index. The intention of thermal indices is to provide an equivalent steady-state snapshot of the effect that the environment is having on the human body. They provide a sense of how a person's body feels. The Predicted Mean Vote (PMV) by Fanger (1970) and the Standard Effective Temperature (SET) by Gagge (1973) for example, are two of many thermal indices created in the past century, and were included in ASHRAE-55 for standardizing indoor comfort requirements. With increased interest in recent years with regards to outdoor thermal environments, new indices have been created solely for exterior applications (i.e., PET, UTCI, etc.). The following subsections describe the four thermal indices used in this study.

Predicted Mean Vote and Percentage of People Dissatisfied

The PMV is a comfort index developed by Fanger (1970) to determine the well-being of a person in various indoor environmental scenarios. Fanger had student subjects sit in an enclosed test chamber where he changed the environmental conditions, while having participants fill out questionnaires. When provided with the four main weather variables, clothing insulation and metabolic rate of a hypothetical scenario, the predicted average vote of a person could be expressed as a number between -3 (cold) and +3 (hot), 0 being neutral. For typical indoor applications, Fanger's PMV range is based on this 7-point scale, though in an exterior application, PMV can overestimate the comfort conditions of a person by obtaining a PMV that exceeds the intended range or simply results in an overall poor correlation between PMV and actual thermal sensation (Höppe, 2002; Stathopoulos et al., 2004; Nikolopoulou et al., 2011; Cheng et al., 2012). Fanger's (1970) experiments and research showed that there is a significant correlation between PMV results and the degree of discomfort. Out of this emerged a second equation used to

determine the percentage of people dissatisfied (PPD). The PPD can be described as the anticipated percentage of people who are likely to complain about the conditions being assessed, and is obtained using an equation that relies solely on the PMV:

$$PPD\% = 100 - 95\exp(-0.03353PMV^4 - -0.2179PMV^2)$$

Based on ASHRAE 55 (2017), thermal comfort is achieved when an environment yields a PMV between +0.5 and -0.5 or in other words, the PPD is less than 10%. For an interior application, all other PMV values that are outside of the range are deemed uncomfortable for occupants, and therefore mechanical systems must modify the conditioned indoor space to meet the comfort standard (Figure 4).

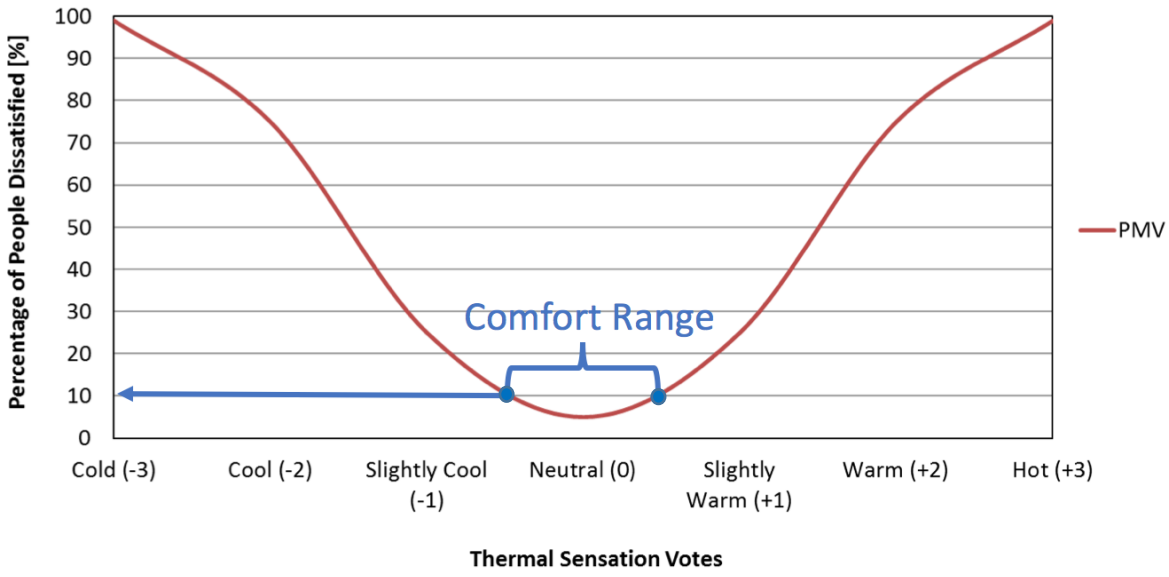


Figure 4. Predicted mean vote and corresponding percentage of people dissatisfied (source: Fanger, 1970).

Standard Effective Temperature

SET is a two-node model of human temperature regulation first introduced by Gagge et al. (1973). The two-node model is a simplified version of the complex 25-node thermal model of Stolwijk & Hardy (1977) that reduces the human body into two cylindrical shapes while maintaining the principles of heat transfer, heat balance, thermal physiology and thermoregulation combined

with human anatomy to mathematically represent the thermoregulatory system of the human body. The inner core node represents the core of the human body and the outset node represents the extremities, or in other words, the shell of the body. Figure 5 is a visual representation of the two nodes in which clothing is represented by the dotted lines.

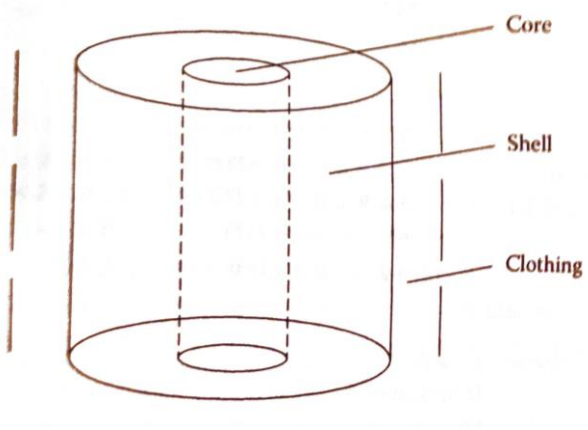


Figure 5. Representation of the two-node model (source: Nishi & Gagge, 1977).

SET is expressed in degrees Celsius and can be defined as the air temperature of a hypothetical environment at 50% relative humidity and still air for people who would be wearing clothing considered regular for the activity being performed in the actual environment (ASHRAE, 2017). Table 1 reports the relationship between SET outputs, thermal sensation and physiological state. The SET is an extension of the Effective Temperature which previously did not consider the clothing insulation values and activity levels of a typical person. For consistency in predictions over a wide range of hot and cold conditions, the clothing insulation in the standard environment changes depending on the activity level (Nishi & Gagge, 1977). For example, for a metabolic rate of 58W/m^2 or 1 MET, the clothing insulation would be 0.67 clo whereas a 1.1 MET would slightly reduce the clo to 0.6. These values could be obtained using the following formula:

$$I_{cls} = \frac{1.33}{Met - Wk + 0.74} - 0.095$$

where:

I_{cls} = clothing insulation in the standard environment (clo)
Met = metabolic rate
Wk = mechanical work

Table 1. SET index levels and corresponding thermal sensations (source: Parsons, 2002).

SET [C]	Sensation	Physiological State
>37.5	Very hot, very uncomfortable	failure of regulation
34.5 - 37.5	hot, very unacceptable	profuse sweatng
30 - 34.5	warm, uncomfortable, unacceptable	sweating
25.6 - 30	slightly warm, slightly unnaceptable	slight sweating, vasodilation
22.2 - 25.6	comfortable and acceptable	neutrality
17.5 - 22.2	slightly cool, slightly unacceptable	vasoconstriction
14.5 - 17.5	cool and unacceptable	slow body cooling
10 - 14.5	cold, very unacceptable	shivering

Universal Thermal Climate Index

UTCI is based on the Fiala multi-node model (Fiala et al., 2001) and provides a hypothetical reference condition that best represents the actual environmental conditions being assessed. The UTCI reference conditions are as such: 0.3 m/s wind speeds at 1.1 m height, mean radiant temperature is equal to air temperature, and relative humidity of roughly 50% (Lai et al., 2014). A major consideration for the UTCI index is that the calculator used for this study assumes metabolic rate and clothing insulation levels. For all calculations, the metabolic rate is fixed at 2.3 MET (person walking at 4 km/h) while the clothing insulation level adjustment is made to consider the seasonal clothing adaptation of Europeans based on field survey data (Matzarakis et al., 2016).

Physiological Equivalent Temperature

The PET is the equivalent air temperature at which, in a hypothetical indoor scenario with no windows, the heat balance of the body is in equilibrium with the outdoor conditions being assessed (Höppe, 1999). The theoretical or conceptual indoor environment in this case represents an environment where the MRT is equal to the air temperature, the air velocity is minimal (0.1 m/s), and the relative humidity is approximately 50% at 20°C. The PET index is a heat balance equation derived from the Munich Energy Balance Model for Individuals (MEMI), and widely recognized in Germany as a standard for urban planning (Salata et al., 2015).
Fanger's six basic parameters can be used to determine their equivalent thermal index, whether it be in the form of PMV, PET, or SET using the online calculator RayMan (Matzarakis et al., 2006).

The RayMan calculator is a free software developed by Andreas Matzarakis and his team at the University of Freiburg, Germany, and is used largely for urban climate studies and applied climatology. The UTCI is calculated using a separate online tool and can also be downloaded for free. The benefit of many thermal indices is that they are expressed in degrees Celsius making them more comprehensible to urban planners who have likely never been exposed to human-biometeorological methods (Matzarakis et al., 1999).

1.2.1 Consideration of Thermal Comfort Indices

It is important to note that thermal indices such as SET, UTCI and PET are not intended to be completely reflective of a person's physiological sensation and instead serve more as a means of conceptualizing complex environmental scenarios. Because the assessment of outdoor conditions can involve many factors, thermal indices can simplify overall conditions by combining the effects of multiple weather variables into a single unit, usually expressed in degrees Celsius. For example, a PET of 35°C can be calculated for the following two scenarios: the first scenario is a person with a clothing insulation value of 0.75clo and a metabolic rate of 2MET in an outdoor environment that has an air temperature of 31°C, relative humidity of 66%, a wind speed of 1.2m/s, and a MRT of 37.2°C; the second scenario is a person with a clothing insulation value of 0.45 clo and a metabolic rate of 2MET in an outdoor environment that has an air temperature of 32°C, relative humidity of 63%, a wind speed of 0.8m/s, and a MRT of 33.6°C. Because the people in both scenarios are experiencing different thermal environments, it can be difficult to classify or compare them without using thermal indices.

Thermal indices can also be helpful in other ways. For example, Höppe (1999) explains that direct solar exposure on a hot day can increase a person's PET beyond the actual air temperature by more than 20°C. Let's assume that the environmental scenario in Höppe's example results in a person experiencing a PET of 40°C. A second person (with equal clo and MET values) may be experiencing an environment with slightly warmer air temperature, similar solar exposure and relative humidity, however much windier conditions resulting in, say, a PET of 36°C. Again, the people in this example are not literally experiencing a PET of 36°C or 40°C, since outdoor conditions rarely in a steady state. Instead, thermal index values can allow to more easily deduce that between these two outdoor scenarios, the subject with the PET of 40°C is feeling warmer.

1.3 CFD Simulations: ENVI-met

In recent years, there has been increased public concern and research interest in how land usage affects urban microclimates (Singh & Laefer, 2015). As a result, microclimate research investigating urban heat island (UHI), heat mitigation strategies and outdoor thermal comfort has become more relevant. With the advance of computational fluid dynamic software such as ENVI-met, it is possible to more easily investigate the interactions between weather and the built environment. ENVI-met is a three-dimensional microclimate CFD model capable of simulating interactions between surfaces, plants and air in an urban environment (Figure 6).

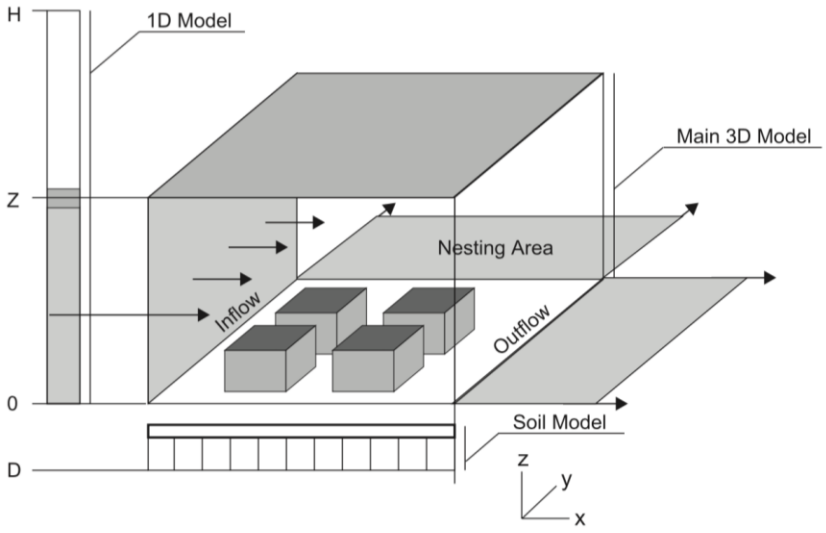


Figure 6. Schematic overview of the ENVI-met model layout. (source: Wania et al., 2012).

The tool uses a Eulerian approach for calculation of incoming and outgoing energy (budget), mass and momentum (Wania, Bruse, Blond, & Weber, 2012). ENVI-met relies on the Reynolds-averaged Navier-Stokes (RANS) equations for fluid flow, with a non-hydrostatic, microscale, obstacle-resolving model and advanced functions for simulations of surface, plant and air interactions (Bruse & Fleer, 1998). Compared to Large Eddy Simulations (LES), traditional RANS simulations are fast, require less effort and produce sufficient average values (Cheng et al., 2003). A benefit of the software is that its simulated vegetation is integrated as a 3D object and is detailed enough to consider the evapotranspiration of leaves and the interaction of soil and water (ENVI-met 4.2.0). ENVI-met's BioMet program also allows for detailed thermal comfort

analysis. Simulation outputs can include thermal indexes such as Physiological Equivalent Temperature (PET), SET, and Universal Thermal Climate Index (UTCI).

1.4 Summary

In all, this introduction has outlined how the human heat balance is a dynamic concept, especially in outdoor scenarios that are highly variable and can be easily influenced by the built environment. As demonstrated, thermal indices are one way of simplifying the human and environmental interactions to allow for comparable analyses. With increased interest in OTC and microclimate research, emerging technologies are providing more opportunities to explore OTC using a variety of scenarios and case study environments. The following section, Chapter 2, provides further insight into the state of the art of thermal indices and overall comfort, individual weather variables, simulated urban vegetation and microclimates, and previous microclimate studies in Toronto. The methodology, found in Chapter 3, is an outline of the process and procedures implemented in this study to address the following three questions: First, among the thermal indices discussed in this chapter, which has the strongest correlation with mean thermal sensation votes of pedestrians in Toronto? Second, how does thermal sensation in Toronto compare with other investigated climates? Third, how does the presence of urban vegetation affect OTC within the case study environment? In Chapter 4, the results from both the field survey and simulation data are presented and described. Interpretations and a deeper analysis of results with respect to the three main research questions are discussed in Chapter 5. Finally, Chapter 6 summarizes the conclusions of this study.

2 Literature Review

This literature review focuses on some of the many thermal indices being used in the field and explains the rationale behind those chosen for this study. It also reviews best practices for obtaining primary data that can be analyzed with respect to OTC, for example, to determine site-specific physiological sensations for a given sample or provide a deeper understanding of variables that may influence thermal discomfort. Because this study will also focus on the effect of urban vegetation for OTC, the current state of knowledge of urban vegetation and microclimate interactions are outlined as well, with particular interest in simulated results. Finally, previous microclimate studies performed in Toronto are discussed.

2.1 Outdoor Thermal Comfort

Thermal Indices & Overall Comfort Ranges

Upon reviewing 26 OTC peer-reviewed studies, Johansson et al. (2013) found that between 2001 and 2013, more than half of the OTC studies were conducted using the Physioligical Equivalent Temperature (PET), followed by the PMV and the SET (Figure 7).

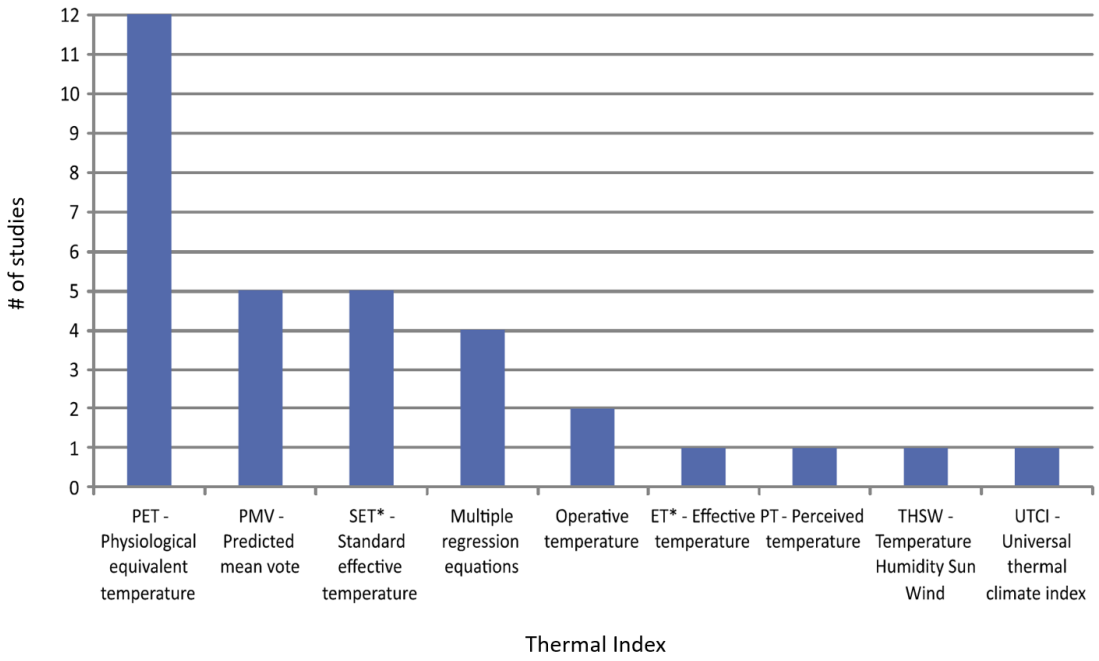


Figure 7. Thermal index frequency distribution for OTC peer-reviewed studies: 2001 to 2013 (source: Johansson et al., 2013).

Since 2013, PET has continued to dominate the OTC research field with the vast majority of studies relying solely on this index to assess comfort in different ways. Table 2 lists some contemporary OTC studies, most of which are using the PET as their thermal index of choice. On this basis, the PET is clearly an important thermal index to explore. However, to be certain of the validity of PET in a cold continental climate condition such as Toronto, Ontario, the correlation between PET and the average thermal sensation votes of pedestrians was investigated and compared with the results from the PMV, SET and the UTCI thermal indices.

Table 2. Contemporary OTC studies and applied thermal indices.

Year	Title	Author(s)	Thermal Index
2017	Calibration of the physiological equivalent temperature index for three different climatic regions	Krüger E., et al.	PET
2017	The effect of pavement characteristics on the thermal comfort in a new urban open space	Taleghani M., et al.	PET
2016	Study on the Outdoor Thermal Comfort Threshold of Lingnan Garden in Summer	Xiao Y. & Xue S.	PET
2016	Effect of the position of the visible sky in determining the sky-view factor on micrometeorological and human thermal comfort conditions in urban street canyons	Qaid A., et al.	PET
2016	Outdoor thermal comfort in the Mediterranean area. A transversal study in Rome, Italy	Salata F., et al.	PET
2016	Street Orientation and Side of the Street Greatly Influence the Microclimatic Benefits Street Trees Can Provide in Summer	Sanusi R., et al.	PET
2015	Outdoor thermal comfort within five different urban forms in the Netherlands	Taleghani M., et al.	PET
2015	Assessment of predicted versus measured thermal comfort and optimal comfort ranges in the outdoor environment in the temperate climate of Glasgow, UK	Oertel A., et al.	PMV/PET
2015	Outdoor thermal comfort: Impact of the geometry of an urban street canyon in a Mediterranean subtropical climate – Case study Tunis, Tunisia	Achour-Younsi S. & Kharrat F.	UTCI

OTC studies exploring the PET are often interested in the neutral, preferred and PET comfort range. These results can be found through field questionnaires and simultaneous micro-meteorological data collection. Researchers in various climates were able to determine a preferred PET using the McIntyre 3-point scale. For each PET bin of 1°C, OTC analysts calculated the percentage of people preferring it be cooler (-1) and people preferring it to be warmer (+1), excluding those who preferred no change (0) for both hot and cool seasons. The plotted results in Figure 8 illustrate eventual convergence between the percentage of people who prefer to be cooler and those who prefer to be warmer. The two points in which these percentages converge show that the preferred PET in Rome for hot and cool season is 24.8°C and 22.5°C respectively. These preferred PET values are very similar to those found in Taichung City, Taiwan where Lin (2009) found 24.5°C and 23°C to be the preferred values for summer and winter season. Sydney, Australia found preferredl PET values of 23.4°C during the winter and 30.9°C during the summer months (Spagnolo & de Dear, 2003).

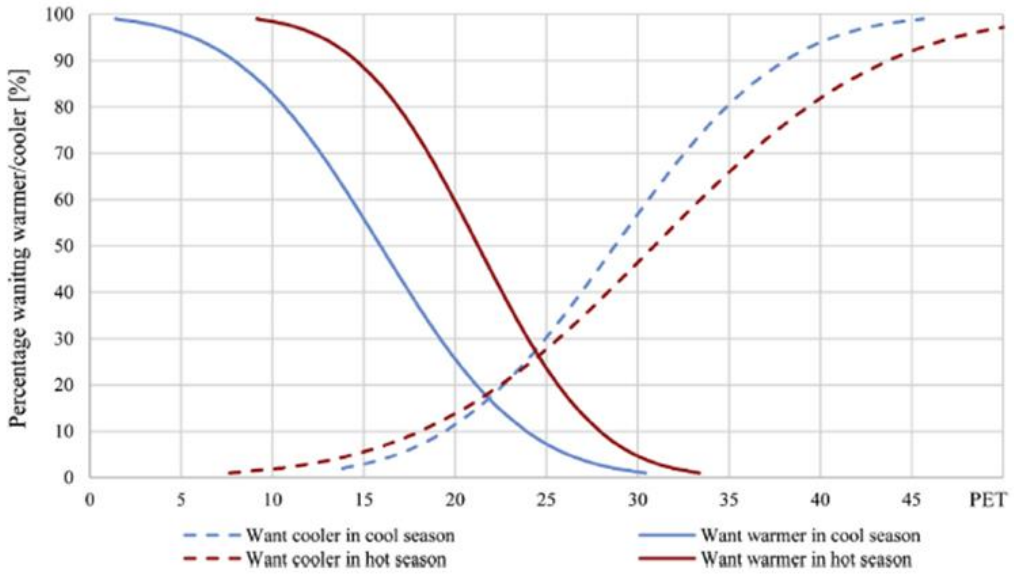


Figure 8. Preferred PET for Rome, Italy (source: Satala et al., 2016).

The neutral PET, or the temperature in which pedestrians feel neither cold nor warm was also examined by Salata et al. (2016) using the MTSV and corresponding PET scatterplot (Figure 9). Regression lines were determined and the neutral PET value was found where MTSV = 0: in

summer, the neutral PET for Rome was 26.9°C in hot season and 24.9°C in cool season. Other studies have obtained the neutral PET values of pedestrians in other locations and climates using this approach. For example, in Cairo (Egypt) neutral PET values of 27.4°C for summer and 26.5°C for winter season were found, respectively (Mahmoud, 2011). Taichung City in Taiwan showed a neutral PET of 25.6°C and 23.7°C for summer and winter season respectively (Lin & Matzarakis, 2008), whereas Hong Kong (China) was slightly lower at 25°C and 21°C for summer and winter (Cheng et al., 2012). Finally, pedestrians of Sydney (Australia) had a neutral PET of 22.9°C and 28.8°C in summer and winter seasons, respectively (Spagnolo & de Dear, 2003).

Using the ASHRAE-55 (2017) thermal comfort approach discussed in Chapter 1, a thermal comfort range can be determined. For example, the PET values that lie between MTSV 0.5 and MTSV -0.5 (highlighted area in Figure 9) are considered by many studies (Krüger et al., 2013; Lai et al., 2014; Mayer & Matzarakis, 1996; Andrade et al., 2011; Salata et al., 2016; Lin, 2009; Lin & Matzarakis, 2008) as a thermal comfort range. The example in Figure 9 shows summer and winter comfort ranges, however most studies have identified an annual comfort range using a whole-year regression line combining both summer and winter values in one regression only.

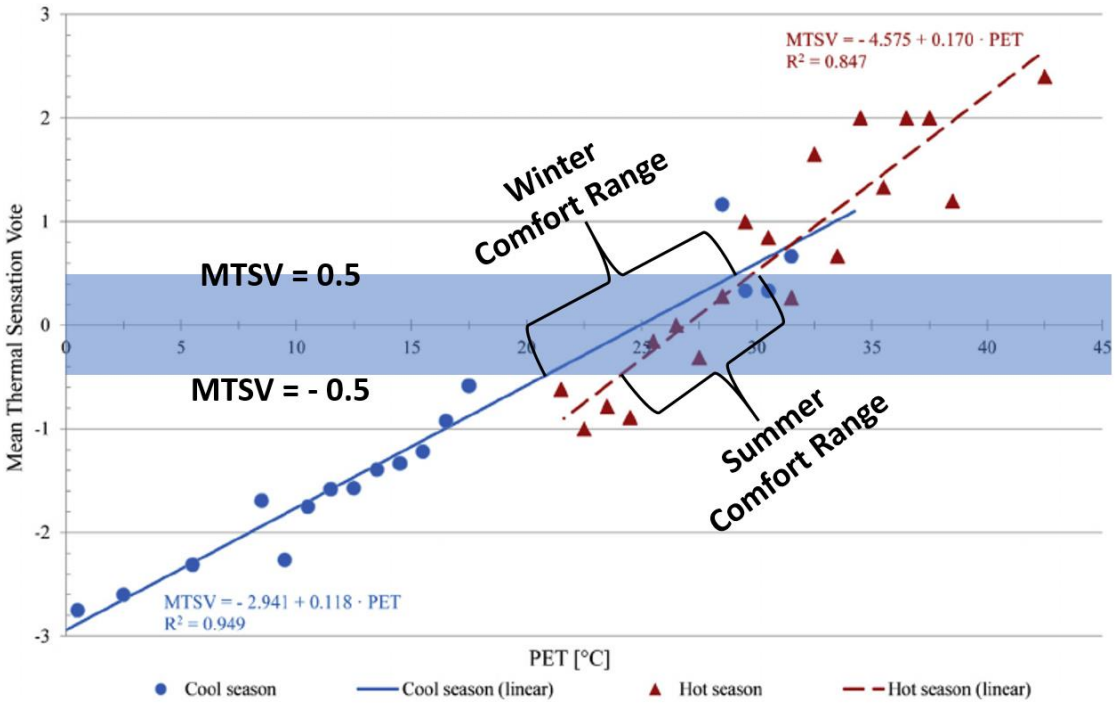


Figure 9. PET and MTSV correlation in winter and summer for Rome, Italy (source: Salata et al., 2016).

The comfort range is not a universal value, but instead can vary significantly across regions. For example, it was found that the thermal comfort range for Rome, Italy is between 21.1°C and 29.2°C (Salata et al., 2016). Similarly, different comfort ranges have been established in other climates. The comfort range for Glasgow, Scotland was between 9°C and 18°C (Krüger et al., 2013). Tianjin, China has a thermal comfort range between 11°C and 24°C (Lai et al., 2014). The thermal comfort range for Western/Middle Europe is between 18°C and 23°C (Mayer & Matzarakis, 1996). Lisbon, Portugal reported a thermal comfort range between 21°C and 23°C (Andrade et al., 2011). Two different cities on the same island reported different thermal comfort ranges, where Sun Moon Lake, Taiwan reported a thermal comfort range between 26°C and 30°C (Lin & Matzarakis, 2008) while Taichung City, Taiwan's thermal comfort range is between 21.3°C and 30°C (Lin, 2009). The Taiwan example is interesting since Sun Moon Lake is a remote area in the mountainous region of Nantou County situated 75 km away from from Taichung, a large urban city. Figure 10 is a graph summarizing the different comfort ranges for the locations outlined above.

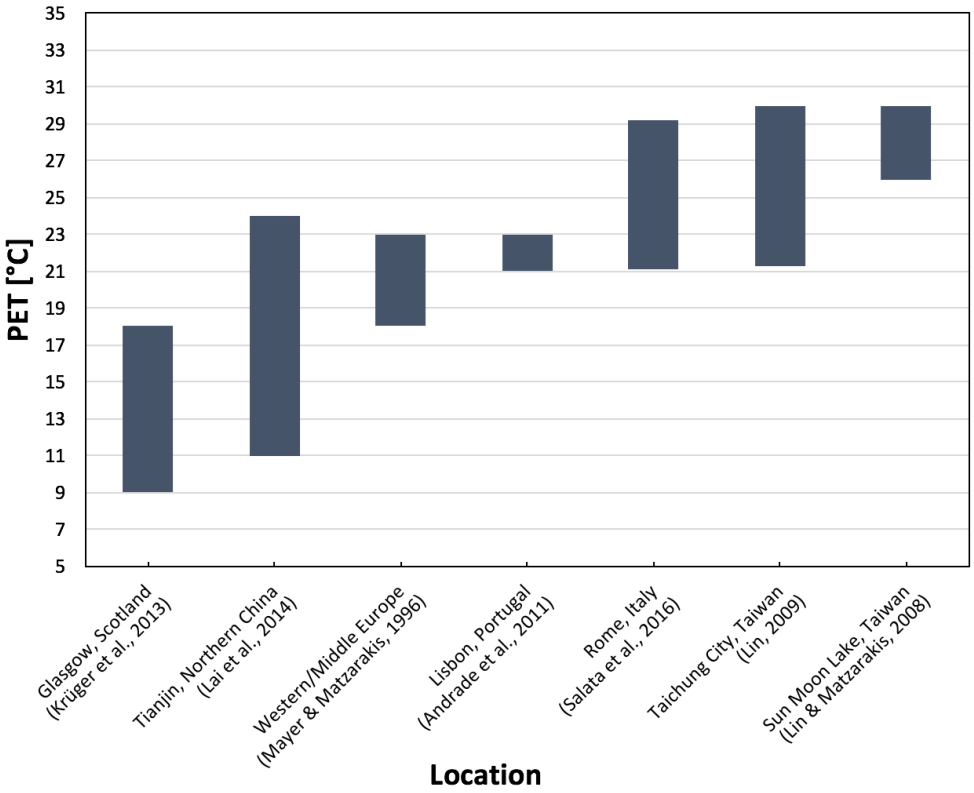
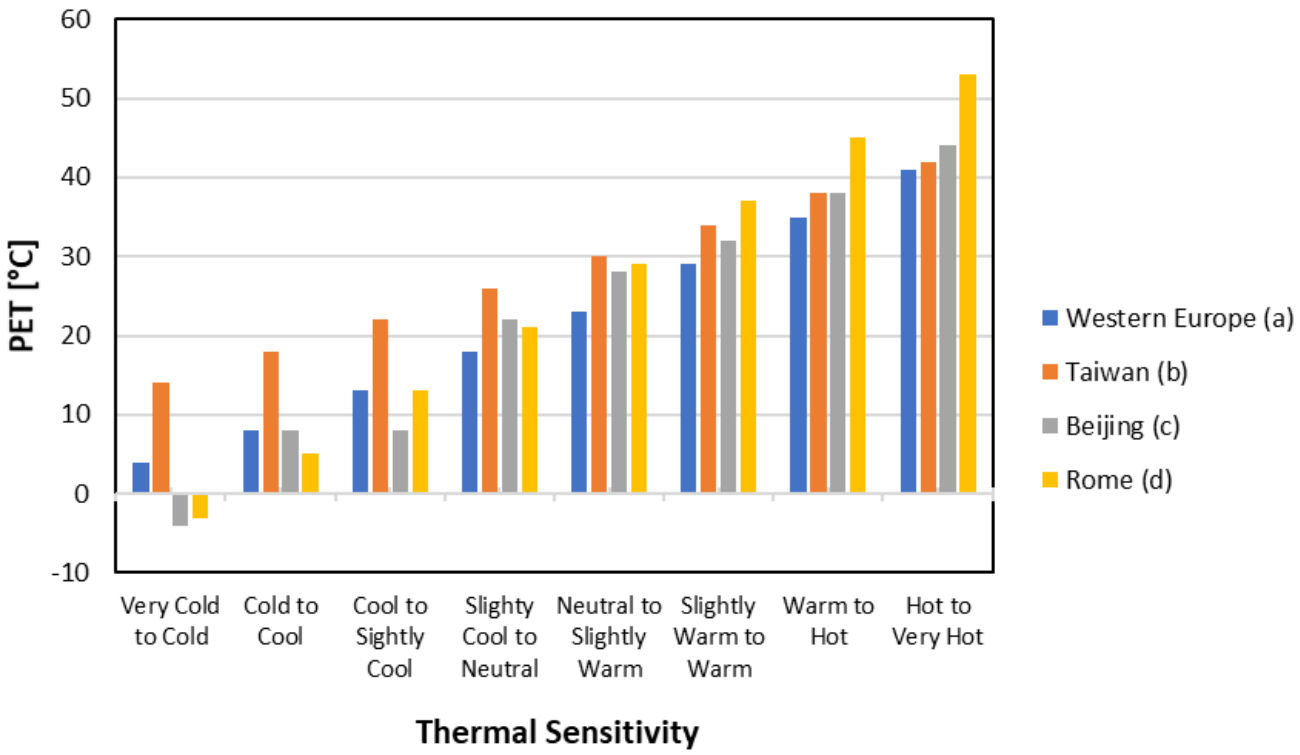


Figure 10. Annual PET comfort range for different locations.

Some studies have explored beyond the neutral PET to include a thermal sensation classification associated with the range of PET results. Figure 11 is a combination of differing PET scales for four different climates and how they correspond to each other based on the thermal sensation classification first established by Mayer & Matzarakis (1996) for Western/Middle Europe that was later modified for Taiwan (Lin & Matzarakis, 2008), Beijing (He et al., 2015) and Rome (Salata et al., 2016) using the same approach. Note how the neutral (comfort) values in Figure 11 are determined using the same MTSV comfort range method between -0.5 and 0.5. Again, these values are based on regression lines from scattered results with varying coefficients of correlation. It is important to understand that extreme values (hot and cold) may not have been experienced but instead extrapolated by extending the regression lines. The same approach for finding the neutral (comfort) range is used to determine each thermal sensitivty range, where the extreme 'very cold to cold' range begins where PET equals -3.5 MTSV, 'cold to cool' thermal sensitivity range begins where PET equals -2.5 MTSV, and so on. Therefore, some extreme values are not actual experienced results, but instead rely on extrapolated results based on extended regression lines. For visual clarification, review Figure 9 to see that the minimum value on the Y axis is -3 and the lowest actual MTSV is above PET of 0°C.



(a) Mayer & Matzarakis (1996), (b) Lin & Matzarakis (2008), (c) He et al. (2015), (d) Salata et al. (2016)

Figure 11. Thermal sensation classification of PET values for four different climates.

Individual Weather Variables

A study was conducted in Montreal, Canada by Stathopoulos et al. (2004) investigating the relationship between OTC and individual weather variables. The research investigated wind speed, air temperature, relative humidity and solar radiation on pedestrian perception, preference and overall comfort during shoulder seasons. Through questionnaire surveys, they asked participants for each individual weather variable, how they perceived the current environment, what they would prefer, and if they were comfortable overall.

From the survey, it was found that 68% of comfortable pedestrians (overall comfort = 2) did not feel that wind was strong (wind perception = -2 or -1), yet 61% of participants that were not comfortable (overall comfort = -2) felt that wind was strong (wind perception = +2 or +1). Only

8% of participants wanted stronger winds (wind preference = +2 or +1), while less wind was preferred in general (wind preference = -2 or -1), especially for pedestrians who felt that wind was too strong. Figure 12 illustrates the participant results for wind combining preference, perception and overall comfort. Air temperature was analyzed in the same way, and there was an explicit preference for higher temperatures. The 76% of uncomfortable participants felt that the air temperature was too low, and 83% preferred higher temperatures. Of all participants, only 5% preferred lower air temperatures. Overall, it was stated that air temperature played the most significant role in determining comfort. Wind and relative humidity however had significant negative impacts on the overall human comfort for most cases. The study also added that the perception of wind was largely dependent on the air temperature. Results showed that wind is less important during warm conditions as compared to low temperature conditions, and that low temperatures affected wind perception in a negative way (Stathopoulos et al., 2004).

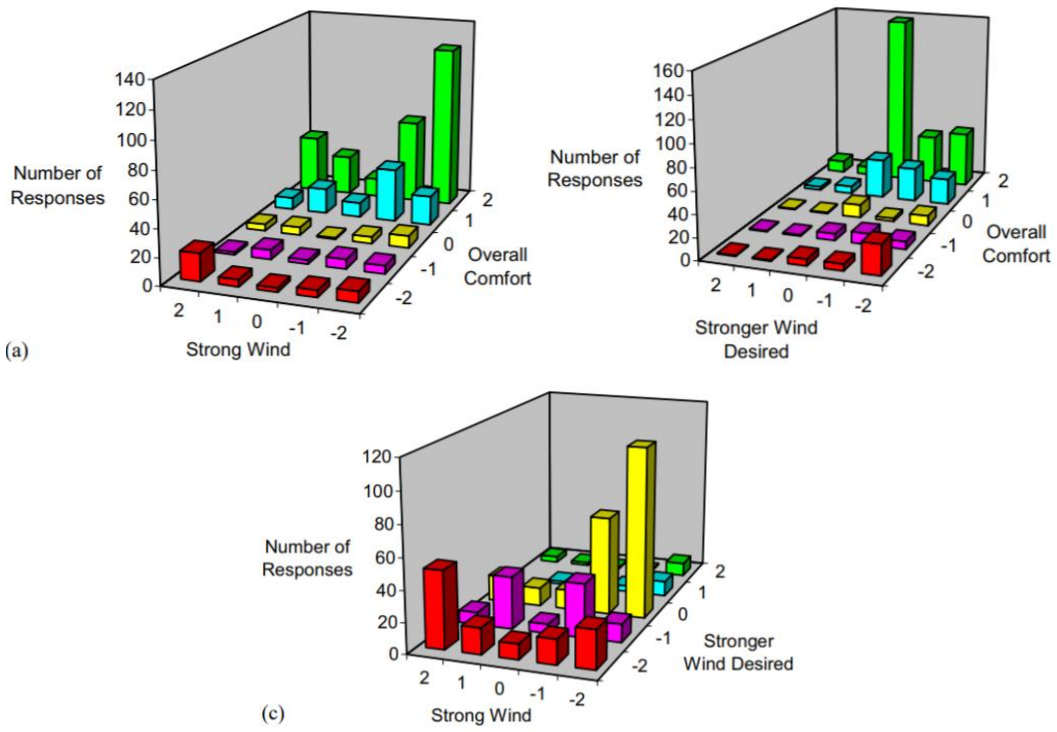


Figure 12. Thermal response distribution from Montreal study (source: Stathopoulos et al., 2004).

2.2 Simulated Urban Vegetation

Currently, there are at least six 3D outdoor comfort simulation tools available: CitySim Pro, ENVI-met V.4, RayMan 1.2, Honeybee, Ladybug, and Autodesk CFD (Naboni et al., 2017). Of all the available software, CitySim Pro and ENVI-met have the ability to simulate both various ground types and contexts with trees and green entities (Table 3). Because this research is also concerned with urban vegetation, it was decided that ENVI-met was a suitable software for this specific application. Also, the two areas in which ENVI-met is only partially capable of proper modelling, i.e., complex geometry and free-standing objects, are not relevant in this study.

Table 3. Context of applicability for five outdoor CFD tools (source: Naboni et al., 2017).

	CitySim Pro	ENVI-met	RayMan	HoneyBee & Ladybug	Autodesk CFD
Context with various ground types	Yes	Yes	No	No	No
Fields with simple buildings	Yes	Yes	Yes	Yes	Yes
Fields with geometrically complex buildings	Yes	Partially	No	Yes	Yes
Fields with free-standing objects (canopies and curtains)	Partially	Partially	No	Partially	Yes
Calm places (airflow)	Yes	Yes	Yes	Yes	Yes
Windy places	No	Yes	No	No	Yes
Contexts with trees and green entities	Yes	Yes	Partially	No	No

Urban vegetation can influence microclimates via shading, evapotranspiration and wind shielding. Many OTC, UHI and heat mitigation studies have relied on ENVI-met for its sophisticated vegetation and soil detail. The physical properties of trees can offer shade and obstruct wind while also considering the porosity of the soil and how the moisture content affects the evapotranspiration process.

Plant evapotranspiration uses the sun's energy to evaporate water (i.e., latent cooling). It was found that this cooling effect can be doubled on clear and hot days compared to cooler and cloudy days. Significant temperature reductions have been found within and downwind of vegetated areas due to shading and evapotranspiration (Gartland, 2008). In one case, the simulated addition of trees demonstrated a maximum instantaneous decrease in air temperature of 27°C (Ketterer & Matzarakis, 2015).

Shade caused by tree canopies can intercept short-wave radiation that would otherwise be absorbed into urban materials. This interception keeps surfaces cooler, reducing the amount of heat transferred to the air or even within building interiors. The shade from trees can also offer cooler environments that are more comfortable for humans.

The following are vegetation-related studies using the ENVI-met software. For a residential case study, Lee et al. (2016) simulated trees and grass to replace concrete in an urban setting and found that trees have a relatively greater mitigation effect. They found that on average, the trees could reduce the air temperature by 2.7°C, the mean radiant temperature by 39°C and the PET by 17°C, whereas the grass reduced air temperature by 3.4°C, mean radiant temperature by 7.5°C and PET by 4.9°C. Large canopies creating shade account for a large mean radiant temperature reduction caused by shading. Ketterer & Matzarakis (2015) found that shade from tree canopies can reduce PET values by at least 25°C. Tsilini et al. (2014) found that with the introduction of urban vegetation, there is potential for a decrease in surface temperatures by as much as 10°C on days with high temperatures. Mean hourly surface temperature reductions by 1°C during a hot day were simulated in a UK case study with an increase of 5% mature trees (Skelhorn et al., 2014). In the same study, removing all the vegetation resulted in an increase in mid-day surface air temperatures by 3°C. A study in Phoenix, Arizona by Middel et al. (2015) concluded that the relationship between air temperature reduction and canopy cover percentage is linear. They stated that a reduction of 0.14°C can occur for every percent of tree canopy coverage.

As OTC varies seasonally, it is important to consider the implications of comfort strategies in both summer and winter scenarios. Morakinyo & Lam (2016) tested the impact of tree configuration, planting pattern and wind conditions of street canyons and found that the pattern of the trees can affect the difference in PET values. Another study in Beijing, China explored comfort related with the Sky View Factor (SVF), which is percentage of exposed visible sky. They found that compared to moderately shaded ($0.3<SVF<0.5$) and slightly shaded areas ($SVF >0.5$), highly shaded areas ($SVF <0.5$) experience higher frequencies of comfortable conditions in summer, but experience more frequent periods of discomfort in winter (He et al., 2015). They suggest creating moderately shaded areas to balance comfort in both summer and winter. It is also important to

consider that trees can grow and mature over time, with a potential for more shade and greater temperature reductions (Wang & Zacharias, 2015).

2.2.1 Microclimate Simulations in Toronto

A study was conducted in Toronto by Wang et al. (2015) looking at the effect of UHI mitigation techniques on different microclimates. The study used numerical modeling to demonstrate the implementation of cool pavements, cool roofs and urban vegetation in high-rise, mid-rise and detached home scenarios. Results showed that UHI mitigation techniques perform differently depending on the density of an urban form. For example, by adding 10% more vegetation it was discovered that the air temperature could decrease 0.6°C for the mid-rise area and 0.8°C for the high-rise and detached area. It was found that urban vegetation yielded much higher mean radiant temperature reductions with decreases of 3.8°C and 4.1°C in the morning and evening for mid-rise area, 4.4°C and 7.4°C for high-rise, and 27.3°C and 15.3°C for detached area (Figure 13).

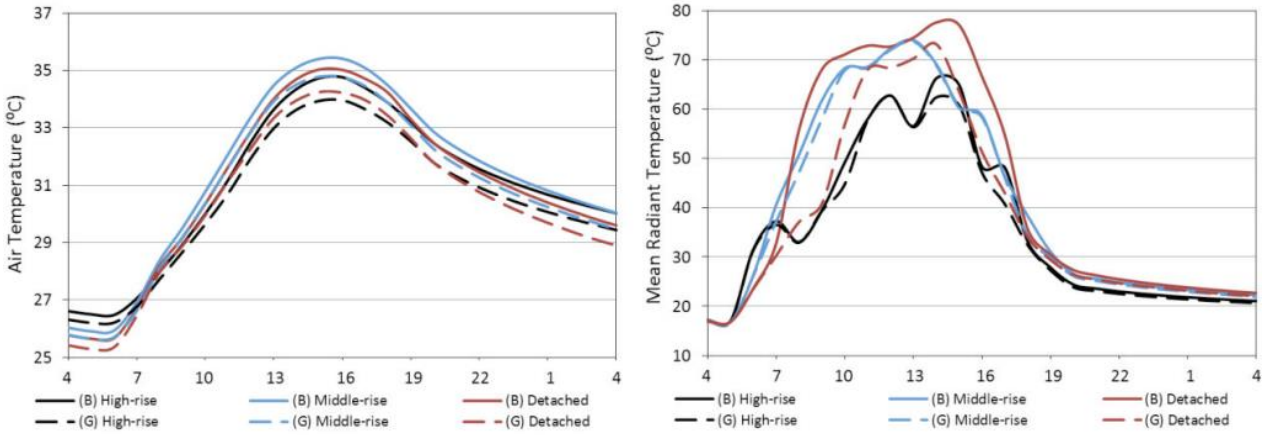


Figure 13. Simulated air temperature and mean radiant temperature between base model areas (B) and adding 10% more vegetation (G) (source: Wang et al., 2015).

When analyzing the cumulative effects of green roofs, white roofs, and urban vegetation, it was found that increased vegetation provides the greatest overall heat mitigation during summer. However, in winter, these three UHI mitigation strategies explored in this study were found to have an insignificant UHI reduction (i.e., they did not make the environment cooler), but the

increased vegetation caused the air temperature to rise slightly during winter in all three scenarios due to the lower albedo of plants compared to concrete.

While exploring the albedo of surface materials on thermal comfort, Taleghani & Berardi (2017) simulated pedestrian comfort in a public plaza in Toronto. The plaza is largely open space with dark granite tiles with low albedo. What they found is that by increasing the ground albedo from 0.1 to 0.5, the average air temperature decreased by 0.5 °C while the mean radiant temperature increased. As a result of higher radiant temperatures, the PET of a typical pedestrian also rose. The results of Taleghani et al. (2014) and Taleghani & Berardi (2017) show that air temperature alone is not a sufficient metric for analyzing urban heat reduction.

2.3 Summary

Amongst all the variability in the methods and outcomes of previous OTC results, a consistent procedure across many peer-reviewed articles is the combination of collecting thermal perception data from local pedestrians, simultaneous micro-meteorological measurements and statistical analysis revolved around a 7-point thermal sensation scale. This approach allows for the appropriate data to determine thermal sensation classification and comfort ranges. The methodology for this study is therefore a combination of these methods as well as less common approaches to assess OTC for pedestrians in Toronto, Canada. The review demonstrates the value of OTC studies for comfort ranges, since relying on results from a different area or climate would likely produce inaccurate thermal comfort predictions. It is also apparent that the PET index dominates the OTC field, but based on this review alone, it is still largely uncertain which thermal index would relate best with pedestrians in Toronto.

3 Methodology

The literature review in Chapter 2 unveiled that, if the comfort conditions of an area are largely unknown, it is recommended to conduct a site-specific OTC field study in the form of survey questionnaires and simultaneous micrometeorological measurements. By following a similar method to Salata et al. (2016), an OTC transversal field survey was conducted during summer 2016 and winter 2017. For this process, a questionnaire was created and distributed to pedestrians to collect pertinent information. The first part of the questionnaire focused on personal information such as the pedestrian's age, gender, approximate height and weight, how long they had been outdoors, what activity they were performing before the survey, and whether they were standing in the direct sunlight or shade. The second part had questions regarding the immediate microclimatic conditions occurring during the survey period. Pedestrians were asked first asked if they were comfortable overall, followed by a set of questions regarding their thermal perception (i.e., how they perceive the outdoor thermal environment) and preferences (i.e., how they would change the outdoor thermal environment, if they had the choice) with respect to both individual weather variables and overall conditions. During the survey period, questionnaire information from 723 pedestrians was collected in conjunction with corresponding micro-meteorological weather data. The PET, PMV, SET and UTCI were calculated for each participant. The data from the surveys and micrometeorological equipment was collected, compared and analyzed. Next, Computational Fluid Dynamics (CFD) modelling was used to recreate the OTC field study environment and surrounding microclimate to investigate the environmental effects associated with the existing urban vegetation. The existing vegetated fraction of the case study environment was reduced from 0.4 to 0 and simulated results were measured at 9 different measurement points. Finally, results from the ENVI-met simulations were interpreted with results from the OTC field study to understand how the absence of urban vegetation would affect pedestrian thermal comfort within the case study environment.

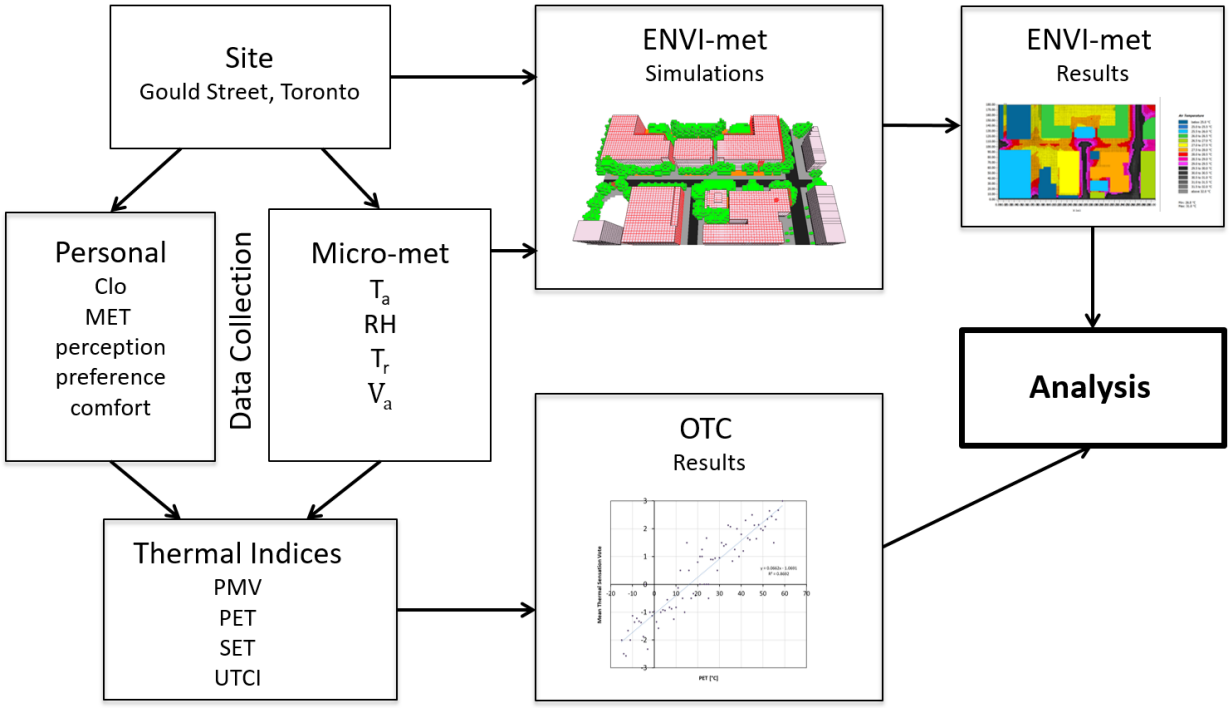


Figure 14. Flow diagram of overall methodological process.

3.1 Site Selection

Toronto is Canada's largest urban city with a growing population of nearly 3 million people. The city is situated along the northern edge of Lake Ontario, and as defined by the Köppen-Geiger Climate Classification, it is a moist, continental climate with reasonable precipitation and warm summers exceeding 22°C, more commonly known as class 'Dfb'. Figure 15 presents Toronto's extreme seasonal climate change, as the average temperature of -5.5°C in January can increase to 21.5°C in July.

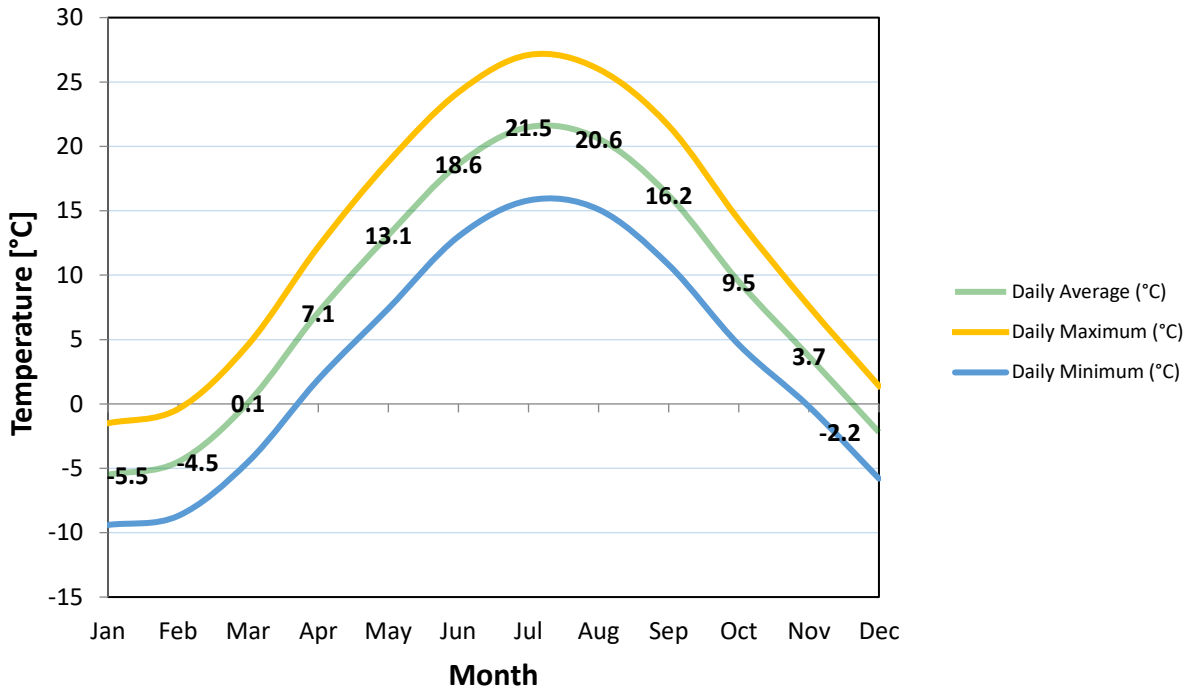


Figure 15. Normalized temperature and precipitation for 1981 to 2010 Toronto climate (data: Government of Canada, 2017).

Gould Street as a survey site was chosen due to the street's unique pilot project initiative, and for the high volume of long-term Toronto residents, as opposed to popular touristic areas. Gould Street is located within the core of Ryerson University campus and has been deemed a pedestrian-only street equipped with barriers to restrict cars as well as chairs and tables on the paved roadway to promote pedestrian activity and social congregation. During the summer months, the street itself hosts a wide range of social activities including sitting areas, reading, bicycling, skateboarding, and a weekly local market. During winter, it is largely a transition space to guide pedestrians from one conditioned University building to another. A unique aspect of Gould Street is its large urban vegetation; the vegetated fraction of the Gould Street canyon is 0.4 as the vegetation covers 40% of the street while the remaining 60% is comprised of asphalt streets and concrete sidewalks (Figure 17).

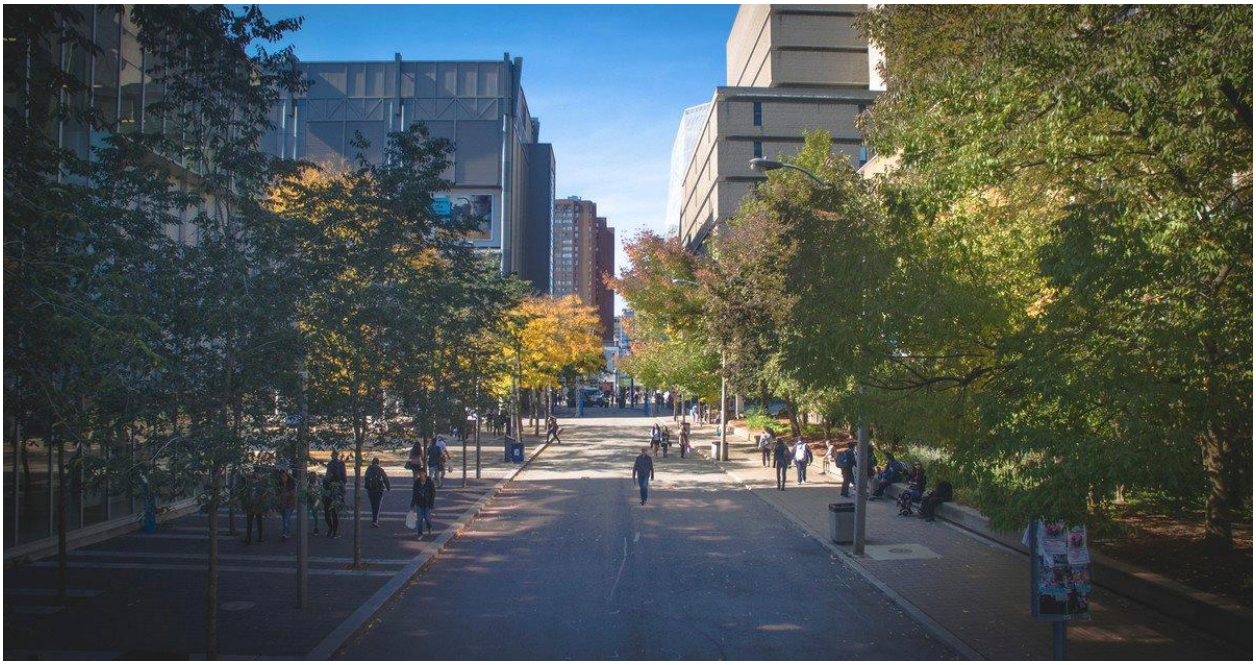


Figure 16. Gould Street photographed facing west.

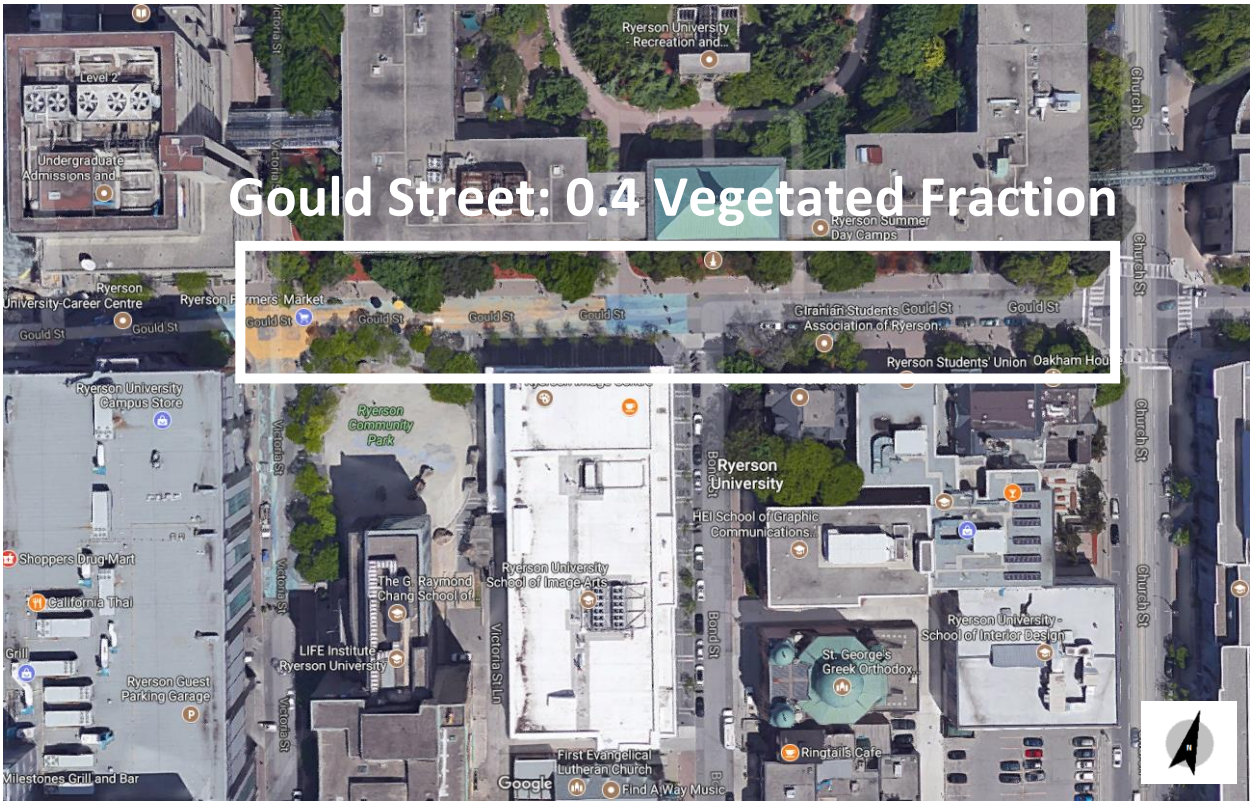


Figure 17. Aerial plan view of Gould Street.

The surveyed portion of the street has an average height-to-width ratio of 0.6, implying that the street is wider than the height of buildings. The buildings adjacent to Gould Street are between 3 and 5-storeys above grade and oriented 17° NE-SW.

A shallow urban canyon allows for more direct solar exposure to reach the ground surface compared to a deeper configuration. As a result, the trees along the sidewalk of Gould Street contribute to reduced direct solar exposure by creating shade for parts of the north facing façades. A deeper canyon with a height-to-width ratio, for example greater than 1, would block most of the solar exposure with the buildings themselves, and therefore tree canopy shade would be less significant.

3.2 Questionnaire

A questionnaire approved by the Research Ethics Board (REB) of Ryerson University was distributed to pedestrians along Gould Street (Appendix 1). The questionnaire was divided into two sections: the first section focuses on personal information while the second portion retrieves information related to the pedestrian's thermal perception, preference, and overall comfort.

Questionnaire Part 1: Personal Information

To begin, participants were asked to select their age range in 10-year intervals (i.e., 20-29, 30-39, etc.) as a less intrusive means of acquiring the participant's age. From an ethical perspective, participants 18 years of age or younger were not considered for this study. This study also excluded pregnant mothers and anyone who has not lived in the surveyed city for less than six months, a strategy taken in a previous OTC study as well (Salata et al., 2015). Metabolic rate was calculated based on participant responses of whether they were sitting (1 MET or 60 W), standing (1.2 MET or 70 W), walking (2 MET or 115 W) or running (3 MET or 200 W) before filling the questionnaire. They were also asked to indicate which activity they were performing 0.5 hours prior to taking the survey. Based on the suggestion of Salata et al. (2015), a weighted approach was used where the total metabolic rate is divided into 70% of activity performed immediately before survey and the remaining 30% for the activity performed 30 minutes prior to survey. Age and gender also affect the metabolic rate of a person, and serve as integral variables for calculating some thermal indices. Other psychological mechanisms such as experience,

knowledge, beliefs, and thermal history have been considered in other studies (i.e., Nikolopoulou et al. 2001**;** Nikolopoulou & Lykoudis, 2006) and in some cases, a 50% variance has been found between objective and subjective evaluation of thermal comfort (Nikolopoulou & Steemers, 2006). However, a thorough exploration in psychological mechanisms beyond thermal preference and perception is beyond the scope of this study which is primarily focused on physiological thermal sensation of pedestrians.

Participants were then asked to circle all items that most accurately represented what they were wearing during the time that they filled out the survey. A table listing different clothing options for head, body, legs, feet and other were provided, ranging from shorts and t-shirts to jackets, heavy pants and boots. An individual clo value was assigned to each article of clothing (Table 4) and total clo values per participant were established by adding each article of clothing, as specified by the ISO 9920 (2007).

Table 4. Corresponding clothing insulation values (clo) for different articles of clothing.

Head		Body		Legs		Feet		Assumed	
Bandana	0.02	undershirt	0.04	short	0.1	sandals	0.02	bra & panties	0.04
Scarf	0.03	T-shirt	0.08	tights	0.15	ankle socks	0.02	underwear	0.02
Light Hat	0.03	button up	0.25	light pants	0.15	long socks	0.02		
Heavy Hat	0.05	sweater	0.3	heavy pants	0.24	shoes	0.04		
Hijab/Turban	0.03	jacket / vest	0.4	snow pants	0.5	boots	0.1		

The following question on the survey asked if the person filling out the survey had been living in the Greater Toronto Area for at least six months. Known as the inclusion/exclusion criteria, this question allows to discern between which participants would be included in the study between those that would be excluded. The cut-off period was based on Salata et al. (2015) study on the assumption that anyone who has been living within the area for at least half a year would be acclimatized to that area. This is relevant as someone visiting Toronto for a short period of time who resides in a completely different climate may misrepresent the average pedestrian and skew the overall collected data.

The final section of the personal information portion of the questionnaire asked participants if they were either indoors or outdoors 0.5 hours prior to the questionnaire. This was useful in

determining what percentage of people were outdoors for extended periods of time or whether they were commuting outdoors from one conditioned space to another.

Questionnaire Part 2: Thermal Perception, Preference & Overall Comfort

This portion of the questionnaire had a variety of multi-point scales (i.e., 3-point, 5-point, 7-point). The rationale for so many different scales was to be able to compare the results with previous studies that did not choose one single scale. The 7-point scale is associated with how the participant feels overall, and is used to compare results of this study with ASHRAE's current method for assessing thermal comfort (ASHRAE, 2017). The 5-point scale is used to determine participant thermal perception and preference for individual weather variables, with the ability to compare with existing research conducted in Montreal, Canada within the same Köppen Climate Class 'Dfb' as Toronto (Stathopoulos et al., 2004). Consistency in the 5-point scale for overall comfort allows for individual weather variables to be compared for a deeper understanding of how each microclimate variable relates to the overall comfort. Finally, the 3-point scale pertains to thermal preference in its simplest form: using the McIntyre 3-point scale, participants can establish whether they would prefer it to be cooler (-1), warmer (+1), or no change (0).

The first question of Part B deals with general thermal perception by using the ASHRAE 7-point scale to acquire the participant's Actual Thermal Sensation Vote (ATSV). The participants are asked how they feel at that very moment, and are given the choice between 7 different options; cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), and hot (+3).

For a detailed understanding of participant thermal perception and preference, the questions were divided into individual weather variables. For air temperature, wind velocity, relative humidity and solar radiation, participants were asked how they perceived and preferred each variable at the moment of the questionnaire, using a 5-point scale. The numbers were assigned as such: -2 for preference meant conditions were too low or there not enough and -2 for preference meant pedestrians preferred less, while +2 for perception meant conditions were too high and +2 for preference meant pedestrians wanted more. If the participant chose 0, they were 'satisfied' with the variable and preferred 'no change'. This method was used in a similar study conducted in Montreal, Quebec (Stathopoulos et al., 2004) and is compared with results from

this study in Chapter 4. The additional benefit of this comparison is that both Toronto and Montreal are considered by the Köppen Climate Classification System as class Dfb. Participants are asked, “Are you comfortable overall?” to which they could reply: disagree (-2), somewhat disagree (-1), uncertain (0), somewhat agree (+1), or agree (+2).

Lastly, a 3-point scale referred to as the McIntyre scale (McIntyre, 1980) was used to collect a simplified response to the immediate overall conditions by asking the participants if they preferred to be cooler (-1), no change (0) or warmer (+1). Derived from indoor thermal comfort methodology, this approach has been used by Salata et al. (2015) to determine preferred thermal conditions.

3.3 Micrometeorological Data

The second most important information required for OTC analysis, next to subjective personal information, is the collection of the four main environmental weather variables occurring during the time that the questionnaire is filled out. This approach allows for the opportunity to make direct correlations between human physiology and the exterior environment.

The equipment used to collect the micrometeorological data is the Delta Ohm 32.3, a tool capable of simultaneously acquiring dry bulb air temperature (T_a), wind velocity (V_a), relative humidity (RH), and mean radiant temperature (T_r). Although it is primarily used for indoor thermal comfort applications, the outdoor variables never exceeded the accurate ranges of the equipment, except for the occasional wind velocity logged at above 5 m/s. The measurement equipment and probes have sufficient accuracy and sensitivity for logging the four weather parameters based on both the ISO 7726 (1998). For further information regarding the Delta Ohm HD 32.3 equipment see Appendix 2 – Delta Ohm 32.3 Specification Sheets.

Table 5. Delta Ohm 32.3 micrometeorological data logger: ranges and accuracy.

Micro-met Variable	Probe Name	Probe Description	Accuracy	Range
Wind [Va – m/s]	AP3203.2	probe with omnidirectional wire	+/- 0.05 m/s	0.05 m/s ÷ 5 m/s
Air Temperature [Ta – °C]	HP3217.2R	combined probe: Thin film Pt100	1.3 DIN	-10°C ÷ 80°C
Relative Humidity [RH – %]	HP3217.2R	combined probe: Capacitive sensor	+/- 2.5%	5% ÷ 98%
Mean Radiant Temperature [MRT – °C]	TP3276.2	globe thermometer probe (50mm diameter) copper, painted black	Class 1/3 DIN	-10°C ÷ 100°C

3.4 Surveying & Data Collection

The surveying and data collection timeframe was divided into two separate sessions: summer and winter. The first session was completed between June 5th and July 10th, 2016 and the second between January 23rd and March 23rd, 2017. The overall goal was to achieve as wide of a range of individual weather parameters as possible.

During the survey process, questionnaires were handed out to pedestrians throughout the Gould Street area, mostly during weekdays from 10:00am to 4:00pm to yield the highest volume of participants. As the participants filled out the questionnaire, the micrometeorological data collector was positioned on the ledge as close as possible to their core at roughly 1m from the ground (Johansson et al., 2013), without allowing for their body to interfere with the data collection. On average, it took participants three minutes to complete questionnaires. The micro-met data collector was set to log the weather variables every fifteen seconds, the shortest time interval possible with this equipment. Therefore, logs comprised of between 10 and 20 measurements for each weather variable were collected for every questionnaire.

Once all the appropriate information was collected, the data was then transferred to electronic worksheets. The results were first separated based on the inclusion and exclusion criteria discussed previously. Valid questionnaires were manually transferred to the worksheets where they could be more easily manipulated as needed. For example, the clothing that was circled by

participants was added up to represent their garment insulation value in clo. Similarly, the activities performed immediately before the survey and 0.5 hours prior were used to create an individually weighed metabolic rate for each person.

3.5 Field Measurements

The purpose of collecting further weather data beyond what was collected during the questionnaire periods is to measure diurnal micro-meteorological data to understand the microclimate conditions occuring within the Gould Street canyon. The process began with field measurements during the summer of 2017 where the author placed the Delta Ohm 32.3 micro-meteorological data logger within the Gould Street canyon for an entire day at 1m above the ground (Figure 18). This field would provide a comparable reference when creating the simulation. Using 15-minute increments, the weather data was collected on August 3rd and 20th of 2017 only to find that weather conditions made it difficult to log an entire day without eventual cloud cover. The summer of 2017 was not nearly as hot compared to 2016, which experienced several prolonged heat waves.



Figure 18. Delta Ohm 32.3 measuring the diurnal microclimate of Gould Street.

As an alternative, the weather data from the 2016 survey period was investigated in an attempt to understand the actual weather conditions of the Gould Street canyon during an extreme heat period. Figure 19 and Figure 20 report the air temperature and mean radiant temperature of the field measurements taken during two separate days in both summer 2016 and summer 2017 for comparison. An ideal measurement to use as a reference for calibrating a virtual model would be a stable hourly measurement since the simulations are simplified, assuming clear sky conditions. Therefore, it is best to use data that is constant, such as the measurements from 2016, as opposed to highly variable conditions such as those that were measured in 2017. The air temperature was higher during 2016 (solid lines) and more stable compared to 2017 results (dotted lines) which are more constant through the day. The variablity or spiking of air temperature for both days in 2017 may have been caused by occasional periods of cloud cover, which can be more clearly seen in Figure 20, where spiking of mean radiant temperature for days in 2017 (dotted lines) is evident.

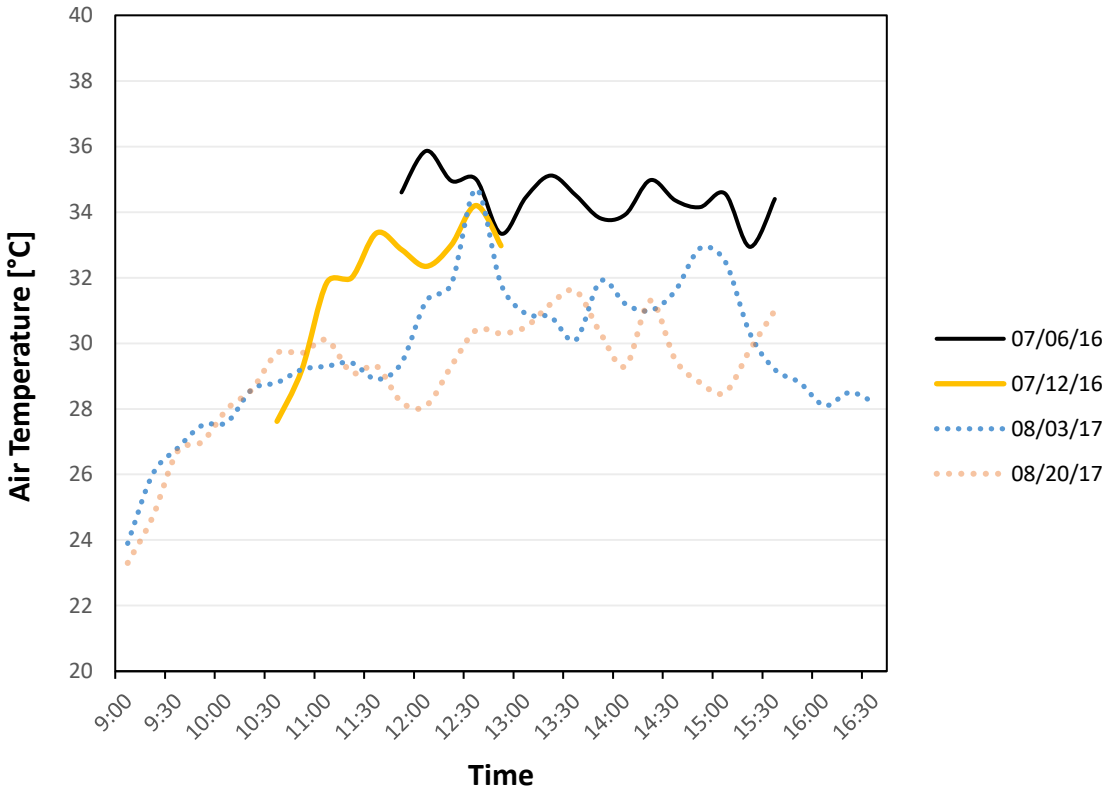


Figure 19. Air Temperature field measurements collected on Gould Street during summer 2016 and 2017.

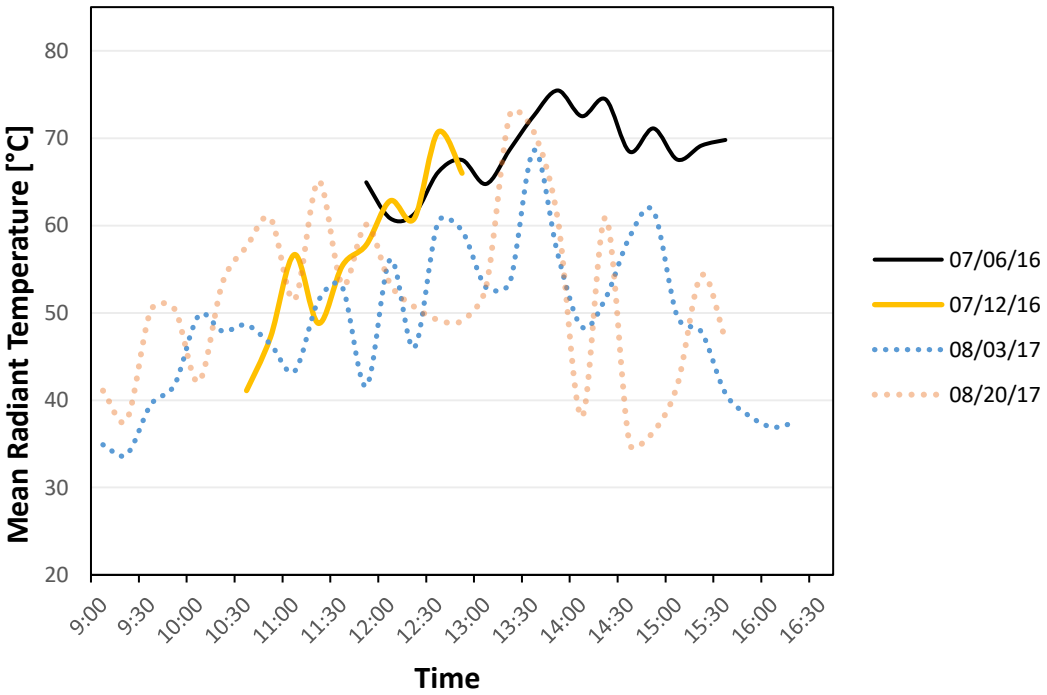


Figure 20. MRT field measurements collected on Gould Street during summer 2016 and 2017.

Althought the measurements from 2016 have higher temperatures with likely clearer skies compared to the days in 2017, there are much fewer daily measurement points during the days in 2016. This occurred for two reasons: the original scope of the research did not include microclimate simulations and the data from 2016 was collected during the period when the author was standing direct in those extreme conditions while surveying pedestrians. During the measurement process of 2017, the equipment could be placed and supervised from a cooler, more comfortable area, allowing for longer daily measurement sessions. The data from June 6th, 2016 (black solid line '07/06/16') was therefore chosen as a reference to guide the ENVI-met simulation since it is the relatively hottest and most stable scenario. For the winter scenario, field measurements could not be taken within the timeframe of this research and therefore data previously collected during questionnaire surveying from March 22nd, 2017 was chosen for it produced the coldest temperatures and lowest PET values of the measured winter period.

3.6 Numerical Modelling of Urban Microclimates with ENVI-met

The ENVI-met 4.2.0 software is not simply one program, but instead five separate programs that are used to generate physical form, manipulate weather conditions, calculate thermal comfort, run simulations, and visualize data (Bruse, 2016). The following section will go through the method of each program individually.

3.6.1 Spaces

First, a free online tool called Daft Logic Distance Calculator in conjunction with Google Maps was used to measure the footprint of buildings and canyons within the studied Gould Street and the surrounding area. A grid was then created in the Spaces program, called an Area Input File that is 149 x 149 x 35 as to avoid any boundary phenomenon provoked by the proximity of the 150 x 150 x 35 limits of the ENVI-met simulation program. Each pixel chosen for the simulations measured 2m^3. Building heights were entered into the program and drawn within the grid in plan view, so they could later be observed in either 2D or 3D format. Trees were then added within the canyon to represent a vegetated fraction of 0.4 as in the current Gould Street (Figure 21 and Figure 22). Once the physical form of the area was complete, the physical properties of the Gould Street canyon were modified and compared with the default 'all concrete' model. It

was found that changing the physical properties of the Gould Street canyon to reflect reality did not significantly affect the distribution of weather variables. Because the scope of this study is not concerned with physical characteristics of the outdoor environment, it was decided that the model be defaulted to concrete buildings to simplify the study. Soil and surface materials however were added as the sidewalks on Gould Street have large planters with trees and exposed soil.

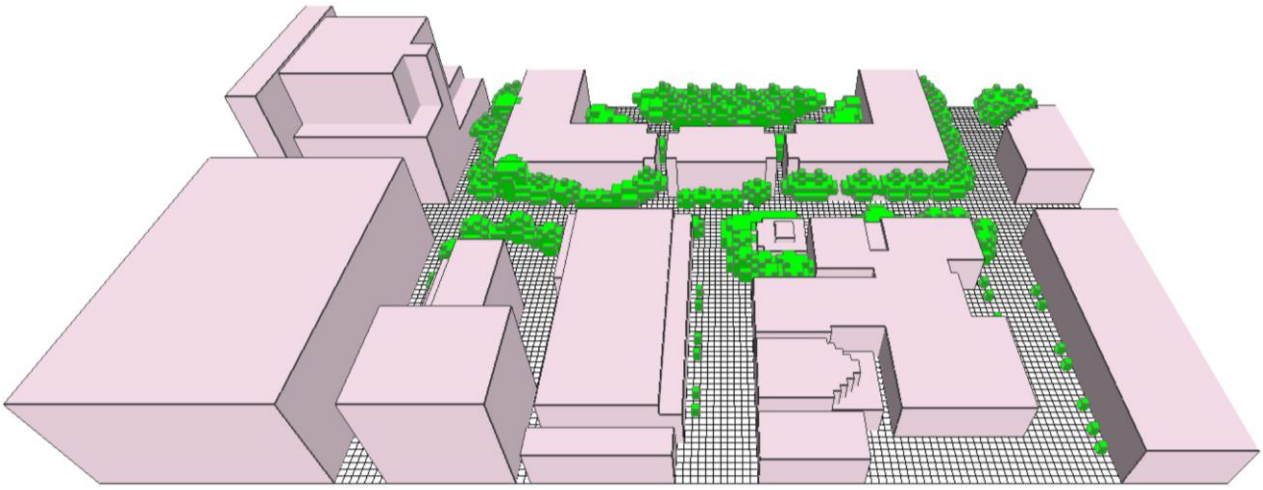


Figure 21. 3D image of case study environment from ENVI-met Spaces program.

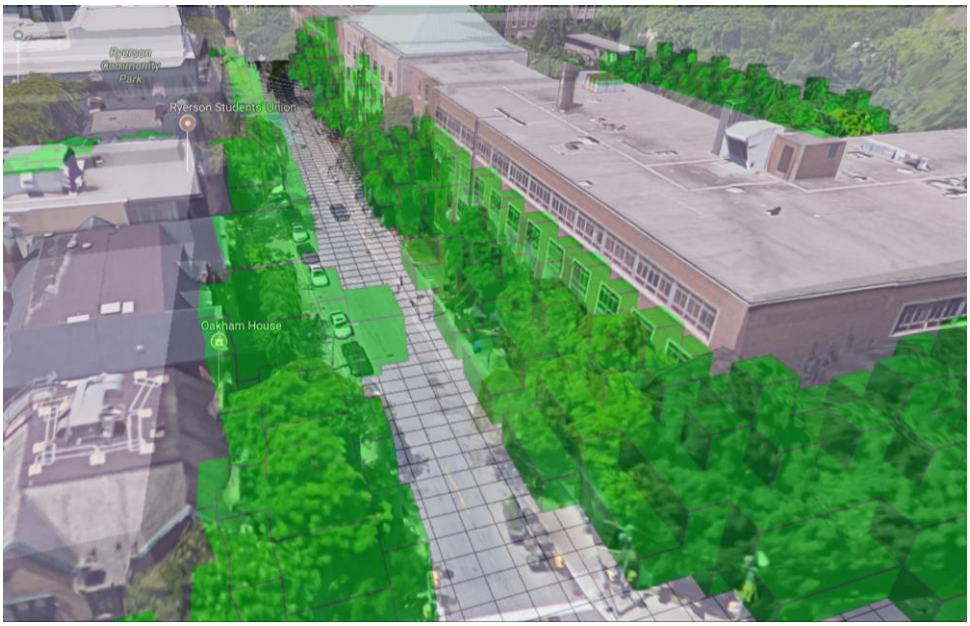


Figure 22. Elevated view of Gould St. looking west with semi-transparent ENVI-met 3D model overlay.

3.6.2 Configuration Wizard

The Area Input File from the Spaces program is then transferred to the ConfigWizard application where the environmental conditions are determined. The air temperature and relative humidity can either be entered as an initial value (i.e., at the time interval that the simulation is set to begin) or can be forced on an hourly basis. Because field measurements were collected, it was decided that a forced hourly temperature was most suitable. Available weather file data for Toronto is recorded at the Toronto International Airport (YYZ) and the Toronto City Centre (YTZ) airport. Because they are situated in different parts of the city and therefore collecting slightly different results, deciding which source to use as a modelling input is sometimes a difficult task. There is often a debate in regards to which weather file is best suited for a specific application. For this model, the Toronto City Centre (YTZ) weather file data was chosen for its proximity to Toronto's urban core where Gould Street is situated (Figure 23).

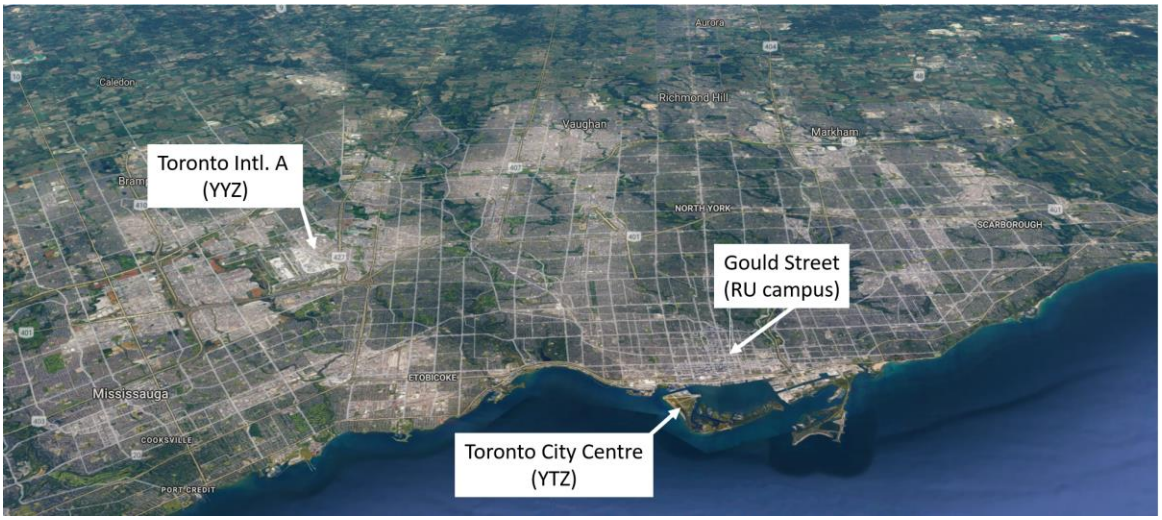


Figure 23. Map of Toronto's airports relative to case study location.

June 6th was chosen for the simulation. The MRT cannot be modified in ENVI-met if clear skies are assumed. The simulated MRT values are therefore a result of the sun path, physical form and materials of the studied environment. The start time for the simulations were set begin at 6:00am to reveal a 9:00am to 5:00pm analysis. Half-day analyses were chosen over 24-hour simulations

due to the significant increase in simulation run-time associated with the larger 150 x 150 grid sizes.

It was found that the unmodified YTZ air temperature data for June 7th, 2016 and March 22nd, 2017 were significantly different than the air temperature values recorded on Gould Street during those same days. The discrepancies between the YTZ data and field data could be a result of where the measurements are taken. For example, the YTZ is recorded on an island, probably at 10m height, just south of the downtown Toronto waterfront, whereas Gould street is located in a dense urban part of the city. The forced hourly air temperatures in summer were therefore modified so that ENVI-met outputs would resemble more accurately the field measurements taken on site (Figure 24). The relative humidity was adjusted and forced on an hourly basis similar to the air temperature procedure.

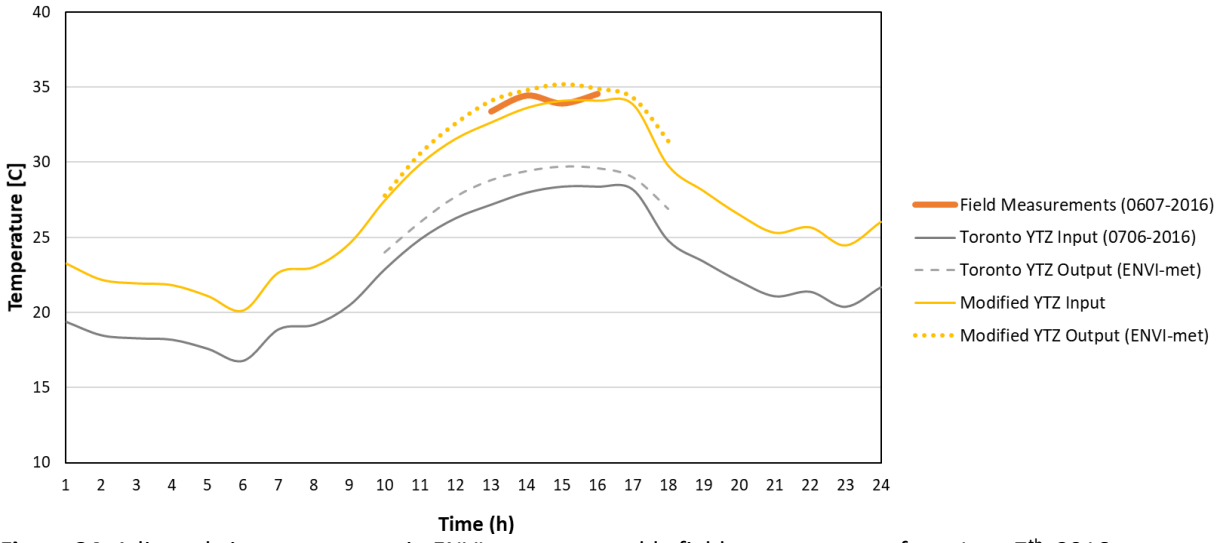


Figure 24. Adjusted air temperatures in ENVI-met to resemble field measurements from June 7th, 2016.

The wind speed and direction cannot be forced on an hourly basis but instead are input as an initial condition. The wind speed and direction was found to be fairly constant throughout the simulations, whereas a realistic scenario would be highly variable. The initial wind speed is to be set at a height of 10m so the YTZ weather file was referenced where the average wind speed and direction for the specific day was used. This usually resulted in lower simulated wind speeds compared to the field measurements. Increasing the wind speed only slightly increased

simulated wind speeds (i.e., iteration 1 to 2 on Table 6) whereas changing the direction of the wind yielded results that were more consistent with field measurements (i.e., iteration 1 to 4 in Table 6). It was decided to begin simulations with the average YTZ wind directions and iteratively change the wind direction first by 45 degrees and then smaller rotations until the simulated results resembled field measurements.

Table 6. Iterative process for adjusting wind speed for summer simulation.

Iteration	**ENVI-met** wind speed input **(m/s)**	**ENVI-met** wind direction input **(degrees)**	**field measurement** wind speed **(m/s)**	**ENVI-met** wind speed output **(m/s)**
#1	3.6*	200**	1.3	0.6
#2	4.5	200**	1.3	0.8
#3	3.6*	110	1.3	1.7
#4	3.6*	155	1.3	1.1

* YTZ average wind speed for 07/06/16 = 3.6 m/s

** YTZ average wind direction for 07/06/16 = 200 degrees

The roughness length at the measurement site options are either 0.1m, 0.01m, or 0.001m. Hansen (1993) explains that increasing the height or density of roughness elements will increase the surface and RANS stresses for the mean wind flow and alters the wind velocity in both speed and direction. Manipulating the mean flow affects the predicted mean wind speed and direction, turbulent intensities, flux of sensible and latent heat or the evapotranspiration. Consequently, the surface roughness length must be considered as an integral part of modeled atmospheric processes (Hansen, 1993). Any grouping of a small number of buildings will aid in altering the mean flow near the surface by increasing the roughness length. Because the case study environment is situated downtown Toronto, 0.1mm was the roughness length used to best resemble a dense urban boundary surrounding the Gould Street microclimate.

3.6.3 ENVI-met

The simulation files containing the physical and micrometeorological properties were run in the ENVI-met program. The 0.4 vegetated fraction models and the zero vegetation models are

identical aside from the removal of all trees and replacement of soil with concrete sidewalk in the zero-vegetation model.

3.6.4 BioMet

Once the output files have been created by the ENVI-met software, this data can be opened in the BioMet software. The value of this program is its ability to calculate the thermal indices explored in this study (PMV, PET, UTCI, and SET), while only PET was given by ENVI-met. Data collected by the questionnaires was used to input the personal human parameters. For example, the typical pedestrian for the simulations assumed to be a 25-year old male, 85kg, 1.75m tall with a clothing insulation level of 0.4 clo and a metabolic rate of 2 Met. By modifying the YTZ data to reflect field measurements, ENVI-met could simulate PET values in summer more accurately.

3.6.5 LEONARDO 2014

The LEONARDO 2014 program is used for visualizing the results of the simulation in either 2D or 3D. For this analysis, the pedestrian-level results are of interest, so all analyses were conducted at 1m above ground in 2D plan view. For the comparison of field measurements and simulation outputs, a single measurement point that represented the field measurement location on Gould Street was used. For the comparison between the vegetated and non-vegetated models, 9 measurement points were analyzed in the models; 3 of which are on the north sidewalk, 3 in the middle of the street and 3 on the south sidewalk (Figure 25).

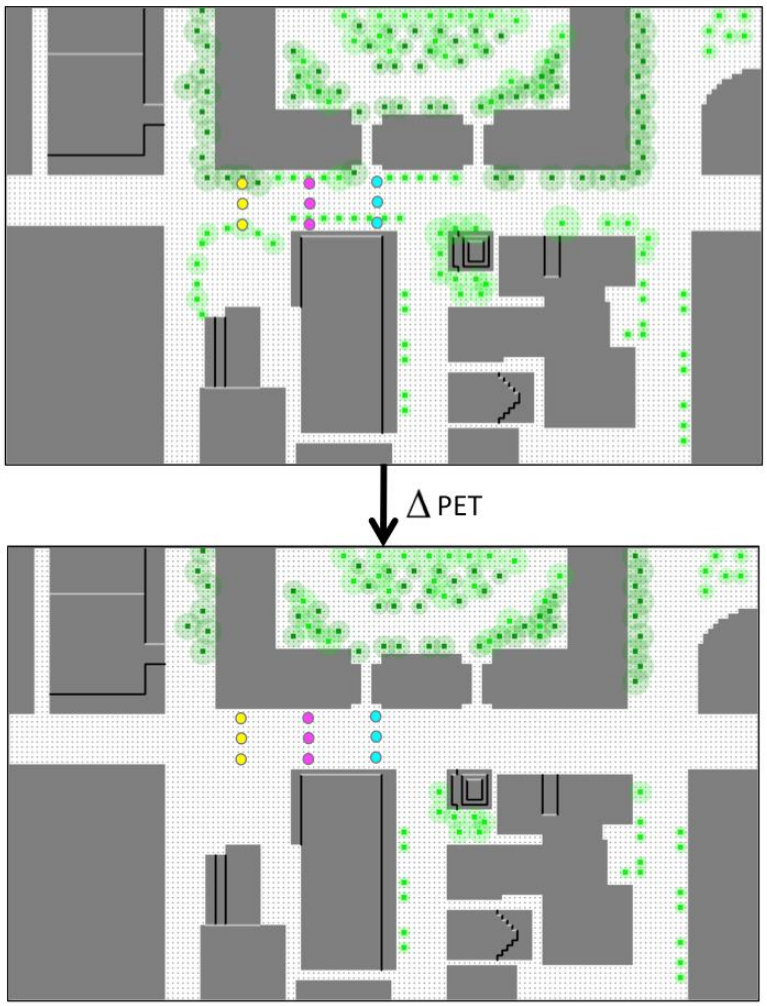


Figure 25. Plan view of Gould Street in ENVI-met program with measurement points for vegetated and non-vegetated scenario.

4 Results

4.1 Outdoor Thermal Comfort Results

4.1.1 General

This section provides general information pertaining to the sample of pedestrians who completed the survey questionnaire. The participant demographic, range of environmental conditions and results related to overall thermal comfort and discomfort are presented. As per the results shown on the left pie chart in Figure 26, more than half of the pedestrians were between the ages of 20 and 29 years old. These results were somewhat foreseeable given that the surveying was conducted on a University campus, where students are most likely to be passing by. The pie chart on the right shows that 59% of the pedestrians identified as male and 41% identified as female.

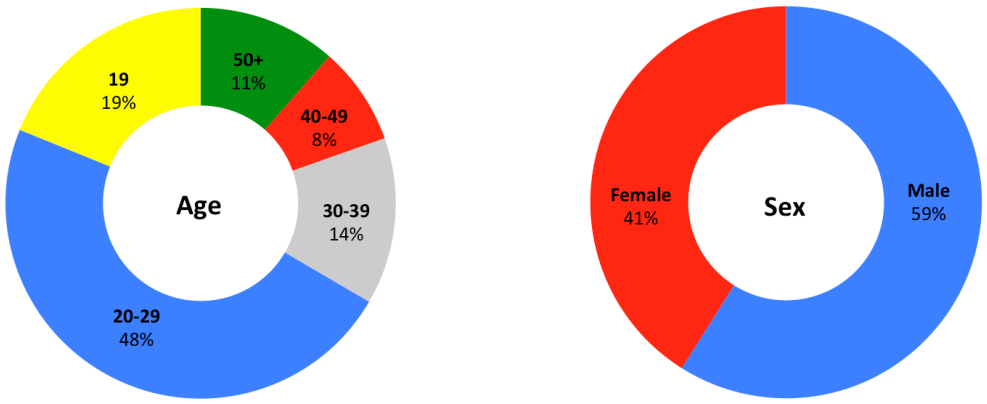


Figure 26. Total participant distribution for summer and winter season.

It was also found that 84% and 82% of participants were walking just before survey was taken during winter and summer respectively. It is also important to note that 76% (summer) and 92% (winter) of participants were indoors 0.5 hours prior to taking the survey. This is to say that the area investigated can be considered a transition space, where most pedestrians were seen to be commuting from one conditioned space to another, most of which were exposed to the outdoors for less than 30 minutes. Many of the participants were either students or workers from the area, and therefore had to be exposed to outdoor conditions as a partial means of executing daily

tasks. The results from this study could have been different if participants, for example, had chosen to be exposed to outdoor conditions as more of a recreational activity.

The environmental conditions of the case study environment vary significantly from season to season. In summer, for example, the mean air temperature was nearly 30°C higher than during the winter period with higher overall mean radiant temperatures and relative humidity levels compared to winter. During winter, Gould street experienced significantly higher wind speeds compared to the summer season. Table 7 shows the range of the different thermal variables separated seasonally.

Table 7. Micro-meteorological and personal variable ranges for summer and winter.

	Micro-Meteorological				Personal	
SUMMER	**Ta [C]**	**RH [%]**	**Va [m/s]**	**Tr [C]**	**Clo**	**MET**
Max	35.9	76.2	2.3	80.4	0.5	3
Mean	31.0	54.7	1.0	46.7	0.4	2
Min	23.5	33.0	0.3	28.4	0.3	1
WINTER	**Ta [C]**	**RH [%]**	**Va [m/s]**	**Tr [C]**	**Clo**	**MET**
Max	15.7	98.0	5.4	64.7	1.9	3
Mean	2.5	50.1	1.7	21.8	1.5	2
Min	-6.1	18.4	0.6	-3.7	1.0	1

Figure 27 and Figure 28 display the distribution of people's thermal perception and preference during both the summer and winter season in Toronto. For thermal perception, the results are logical in that the majority of people feel slightly cool to cold (<0) in winter and slightly warm to hot (>0) in summer. During winter, the high frequency of pedestrians perceiving that they feel slightly cool (-1) as opposed to cool (-2) or cold (-3) could be associated with higher clothing insulation levels worn in winter causing people to feel warm despite cold weather conditions.

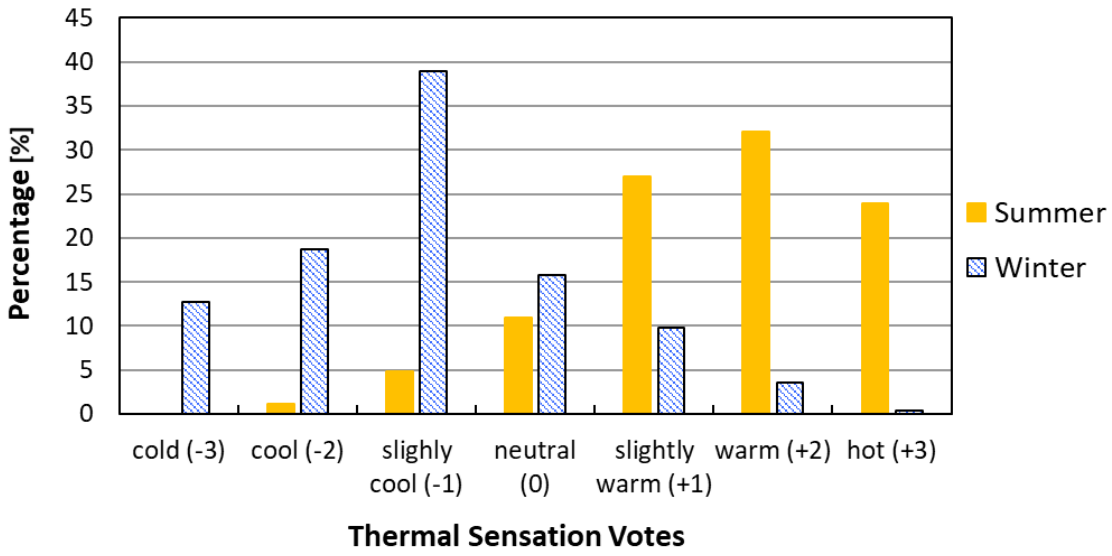


Figure 27. Overall thermal perception of pedestrians during summer and winter season.

The results from Figure 28 are also showing that the majority of pedestrians prefer the weather to be cooler (-1) in summer and warmer (+1) in winter. Note that there is a significantly higher percentage of people preferring no change (0) in summer compared to winter. Again, this further reinforces a perceived discontent with cool and cold weather conditions.

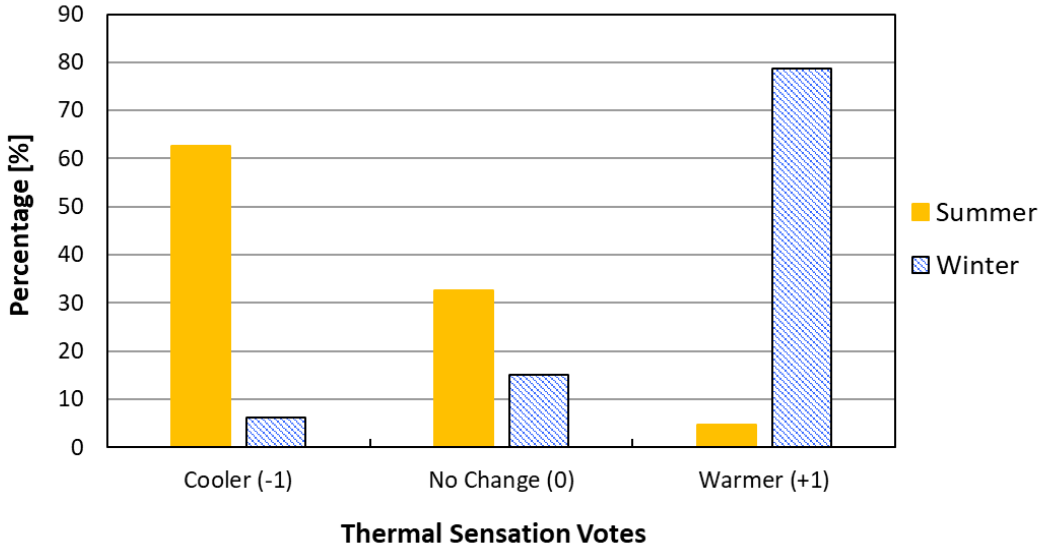


Figure 28. Overall thermal preference of pedestrians during summer and winter season.

When plotting the distribution of overall comfort for pedestrians in both summer and winter, it is interesting that the distribution of both pie charts are very similar (Figure 29). Over half of the pedestrians in both summer (63%) and winter (64%) wrote that they were either in somewhat agreement or full agreement with the fact that they were comfortable, some of whom were exposed to extreme heat and cold.

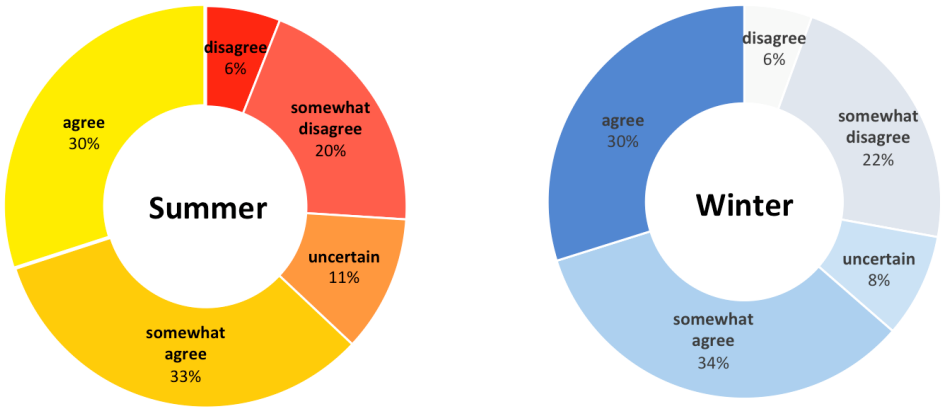


Figure 29. Overall distribution for the question "Are you comfortable overall?" for summer and winter season.

Further investigation was then focused on those who were comfortable during summer and winter (i.e., the 30% in summer and winter who chose 'agree' from Figure 29). The summer and winter populations were separated by their actual thermal sensation votes to find that the thermal votes between comfortable people in summer and winter differ substantially. Figure 30 represents for each actual thermal sensation vote, the percentage of people who were in complete agreement with being comfortable during the survey period. For example, during summer period over 30% of participants that agreed they were comfortable were either warm or hot. In contrast, less than 10% of comfortable participants were cold or cool. These results demonstrate that pedestrians have a higher tolerance for warm weather.

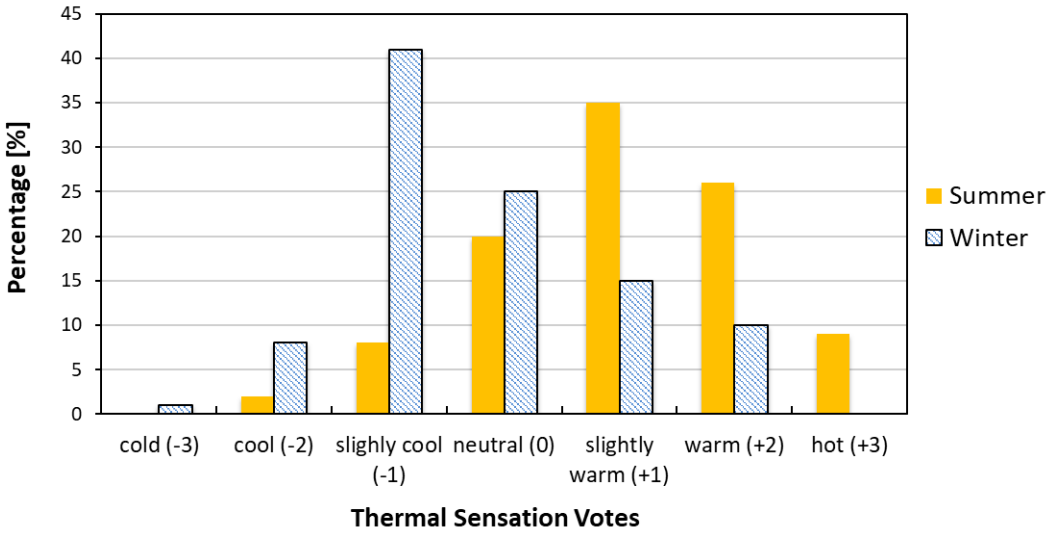


Figure 30. Thermal perception of comfortable pedestrians during the survey.

The trend toward cold weather being more disfavored compared to warm conditions is further reinforced by Figure 31**.** The graph represents the percentage of people who somewhat disagreed or disagreed that they were comfortable overall for each thermal sensation vote. For example, out of the 134 participants who expressed to be warm (+2) in summer, 24% of them were not comfortable overall during the survey period, while out of the 31% of participants who expressed to be cool (-2), nearly 50% of them were not comfortable. It is evident that the PPD increase is greater as pedestrians vote for colder compared to warm conditions.

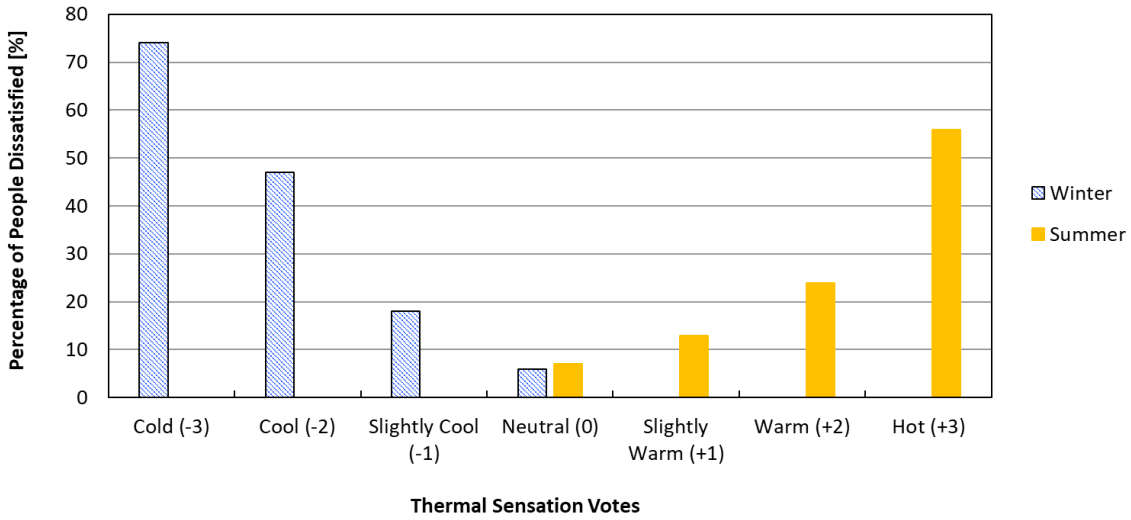


Figure 31. Percentage of people dissatisfied within 0.5 hours of outdoor exposure.

4.1.2 Thermal Perceptions and Preferences: Summer & Winter

The following section focuses less on results of participants' thermal perception and preferences (5-point scale) with regards to each individual weather variable during the summer and winter, and instead demonstrates how to read and interpret the collected data. An example of the wind as the individual weather variable has been left in this section while all other results can be found in Appendix 3 - Individual Weather Variables: Results from Surveys. A discussion of the overall results for individual weather variables in summer and winter are summarized in Chapter 5.

For perception, a vote of "2" would imply that the person is perceiving "too much" of that particular weather variable, whereas voting "-2" would imply that there is "not enough", and "0" is content. For preference, a vote of "2" implies that the person would "prefer more", voting "-2" indicates a preference for less, and again "0" is content. For overall comfort, a vote of "2" implies that the person is in full agreement, whereas a vote of -2 implies disagreement, and a vote of "0" is uncertain. The following demonstrates how these results can be useful in understanding thermal comfort and individual weather variables using wind in summer and winter as an example variable.

Summer Wind – Perception

Of the 263 participants who stated overall comfort equal to +1 and +2, 11% (31 of 263) felt that the wind was too strong (wind perception = +1 and +2), 59% (154 of 263) were content with wind conditions (wind perception = 0), and 30% (78 of 263) felt that there was not enough wind (wind perception = -1 and -2). Of the 109 participants who stated overall comfort equal to -1 and -2, 6% (7 of 109) felt that the wind was too strong, 26% (28 of 109) were content with wind conditions, and 68% felt that there was not enough wind. Furthermore, regardless of overall comfort, 41% or 172 of the total 418 participants, found that the wind was not strong enough, 49% (206 of 418) were content with wind conditions, and 9% (38 of 418) felt that the wind was too strong.

Summer Wind – Preference

Out of the total participants who expressed to be comfortable overall, 51% preferred more wind, 43% preferred no change, and 6% preferred less wind. Of the total participants who expressed

they were not comfortable overall, 70% preferred more wind, 16% preferred no change, and 14% preferred less wind. Of all summer participants 57% preferred more wind, 34% preferred no change, and 9% preferred less wind.

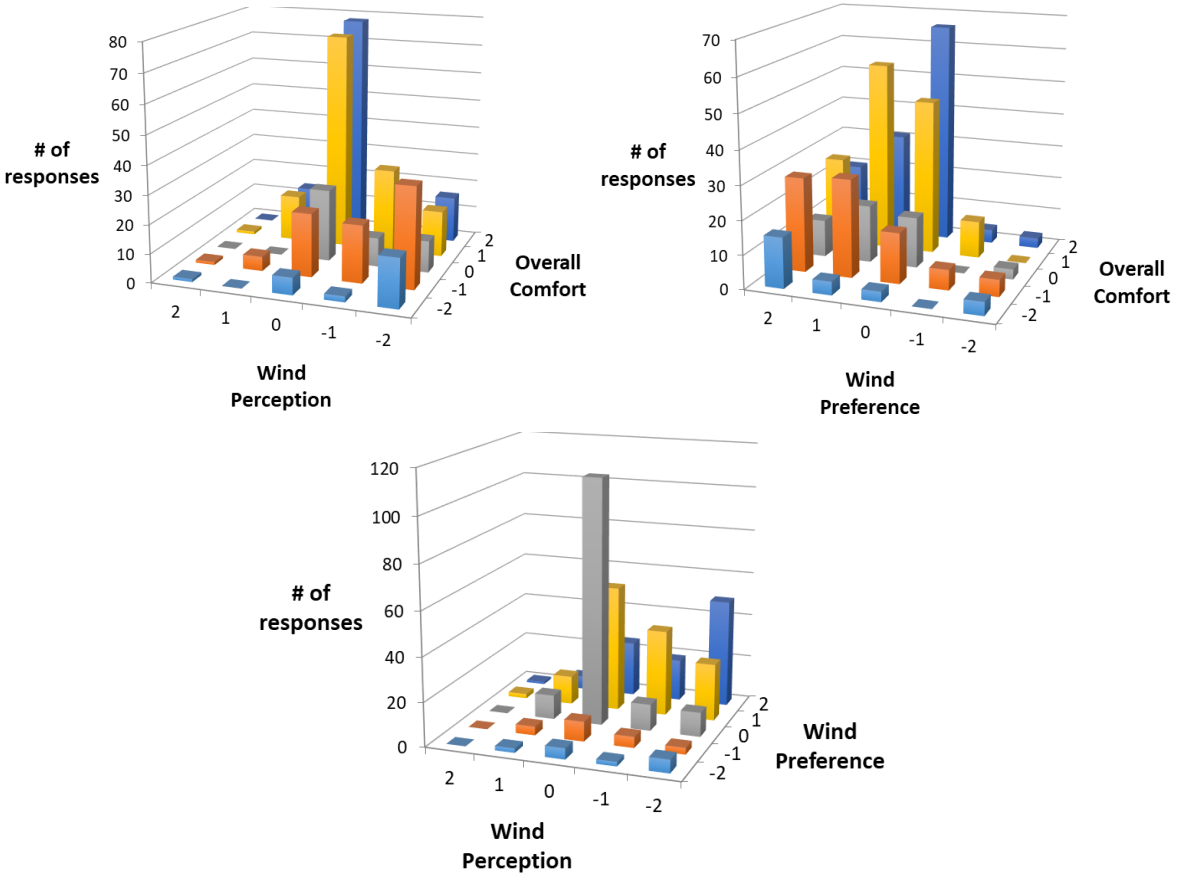


Figure 32. Distribution of responses to questions of wind preference, perception and overall comfort in summer.

Winter Wind – Perception

Of the 194 participants who stated overall comfort equal to +1 and +2, 28% (54 of 194) felt that the wind was too strong (wind perception = +1 and +2), 55% (106 of 194) were content with wind conditions (wind perception = 0), and 17% (34 of 194) felt that there was not enough wind (wind perception = -1 and -2). Of the 85 participants who stated overall comfort equal to -1 and -2, 52% (44 of 85) felt that the wind was too strong, 30% (26 of 85) were content with wind conditions, and 18% (15 of 85) felt that there was not enough wind. Furthermore, regardless of overall comfort, 36%, or 110 of the total 305 participants found that the wind was too strong, 46% (141

of 305) were content with wind conditions, and 18% (54 of 305) felt that the wind was not enough.

Winter Wind – Preference

Of the total participants who expressed to be comfortable overall, 11% preferred more wind, 40% preferred no change, and 49% preferred less wind. Of the 109 participants who stated overall comfort equal to -1 and -2, 5% preferred more wind, 28% preferred no change, and 67% preferred less wind. Again, regardless of overall comfort, 9% of all winter participants preferred more wind, 35% preferred no change, and 56% preferred less wind.

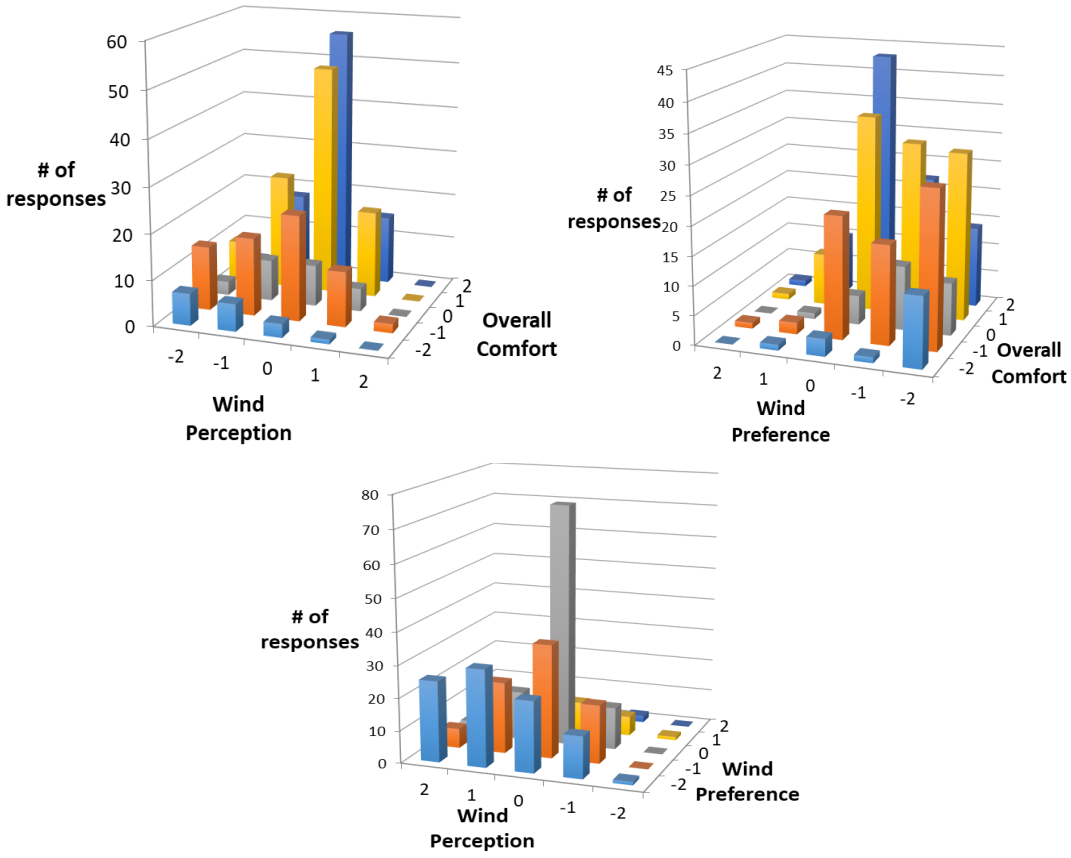


Figure 33. Distribution of responses to questions of wind preference, perception and overall comfort in winter.

4.1.3 Thermal Indices and Actual Thermal Sensation Votes

Using the RayMan calculator, the PMV results were calculated for each participant in both summer (Figure 34) and winter (Figure 35). Because the PMV is intended for interior comfort applications, these two figures demonstrate how it cannot accurately predict outdoor comfort in either season. What is occurring in both graphs is the PMV is overestimating the MTSV of pedestrians in both summer and winter. This is likely due to the extreme heat and cold conditions experienced outdoors in Toronto that extend far beyond the standard comfort conditions for indoors. Note that the graphs are arranged based on ascending PMV and how the actual thermal sensation votes (ATSV) shows only a somewhat, yet weak similarity in ascending pattern. The results are however somewhat flawed in that pedestrians were asked to fill out their thermal sensation on a 7-point scale which did not include values as high as 10. The fact that pedestrians were able to reasonably provide their thermal sensation within a smaller range demonstrates how a 7-point scale is a feasible range for assessing both indoor and outdoor thermal comfort, meaning that a PMV could potentially be created for outdoor applications if properly calibrated.

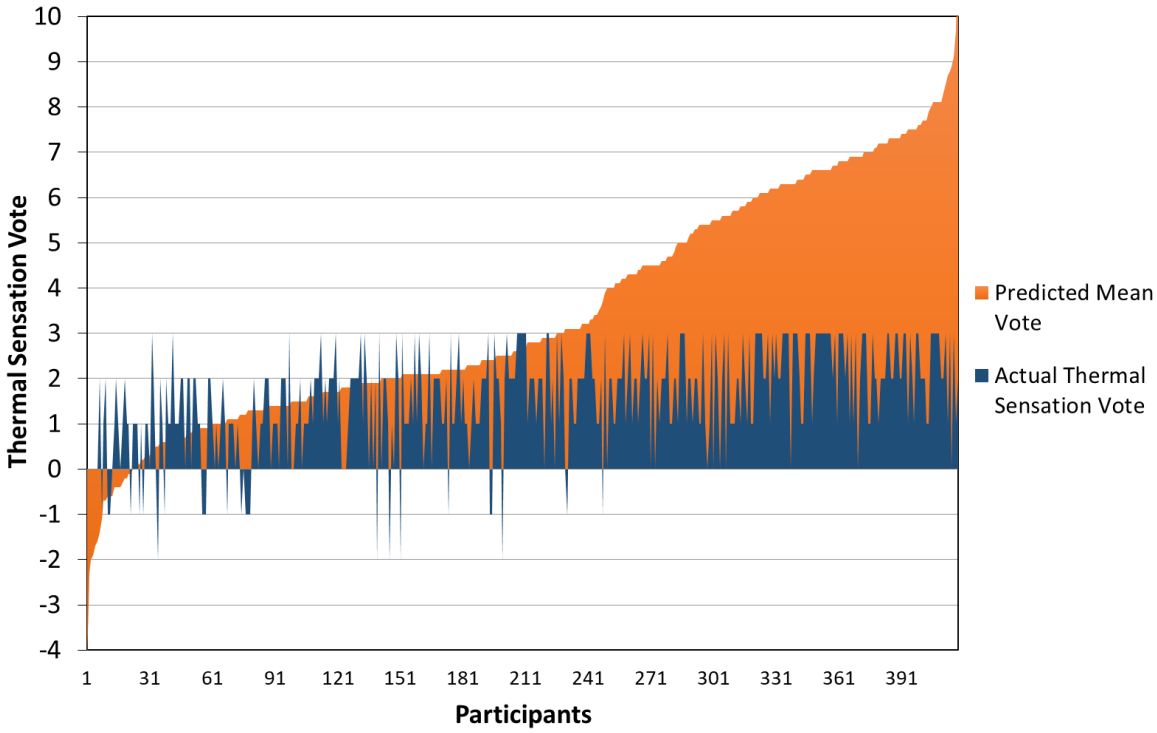


Figure 34. PMV and ATSV in summer season across the 418 participants.

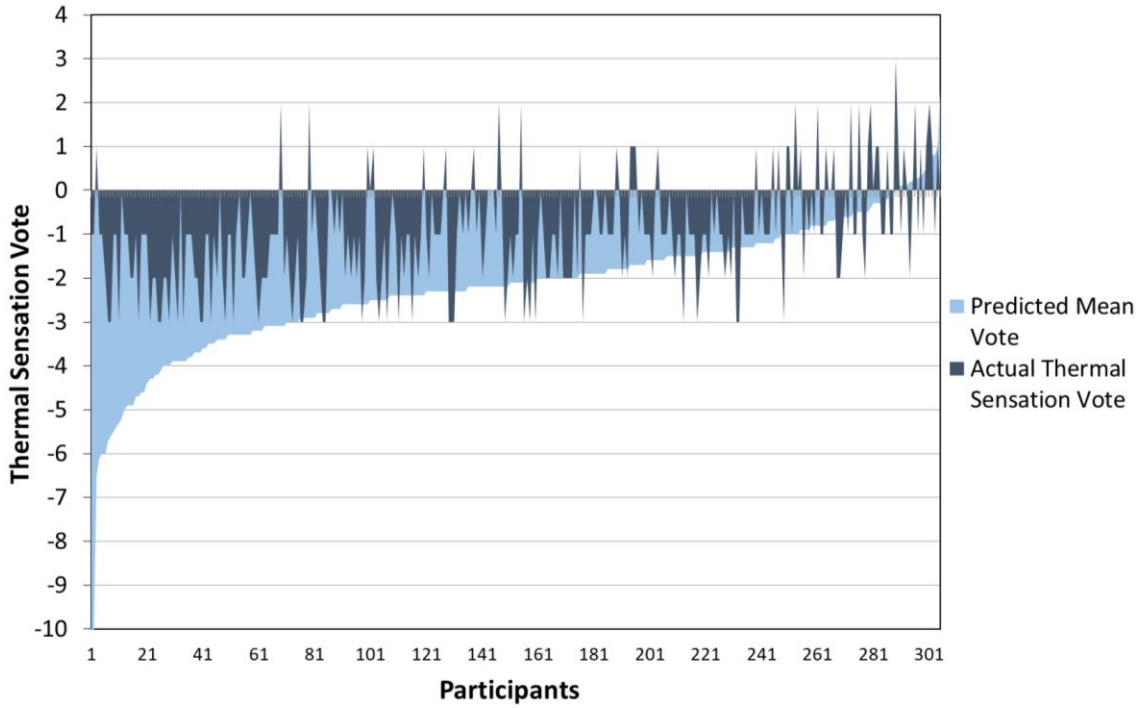


Figure 35. PMV and ATSV in winter season across the 305 participants.

Table 8 is the resulting correlation values between MTSV and all three thermal indices explored in this study. Values are shown for winter, summer and annual cases. PET had the annual highest correlation (R^2 = 0.87) between all three thermal indices, but resulted in the lowest summer correlation (R^2 = 0.66). The SET index has a slightly lower annual correlation (R^2 = 0.82) compared to PET, but a higher summer correlation (R^2 = 0.79) compared to summer PET (R^2 = 0.66) The UTCI index had the poorest annual correlation (R^2 = 0.45) despite having the strongest overall summer correlation (R^2 = 0.85). This could be since the UTCI index assumes clothing and metabolic rate of the person despite the author having actual data for these variables. The assumed clo could also explain why UTCI winter correlation is so low (R^2 = 0.36). The plotted graphs for these results can be seen throughout Figure 36 to Figure 41.

Table 8. Correlation between mean thermal sensation vote and thermal indices.

Thermal Index	Index & MTSV R-square		
	Winter	Summer	Annual
PET	0.63	0.66	0.87
SET	0.63	0.79	0.82
UTCI	0.36	0.85	0.45
	n=305	n=418	n=723

When analyzing the MTSV and PET correlation, Figure 36 results show that the winter linear regression line is slightly steeper than in summer. The gradual summer slope implies that PET increases have less of an effect on MTSV when compared to decreasing PET values in winter. The scatterplot in winter also shows a slightly weaker trend (R^2 = 0.63) compared to the summer results (R^2 = 0.66). Most of the winter outliers are occurring during warmer conditions and could be affected by high clothing insulation values. For example, the weather conditions may be cold but because the pedestrians have high clothing insulation values and they may feel warm. Although the seasonal regression lines are slightly different, their similar trajectory results in a higher correlation (R^2 = 0.87) compared to the annual results of other thermal indices explored (see Figure 37). The annual MTSV and PET regression line is similar to the seasonal breakdown and yields similar results as shown in Section 4.1.5.

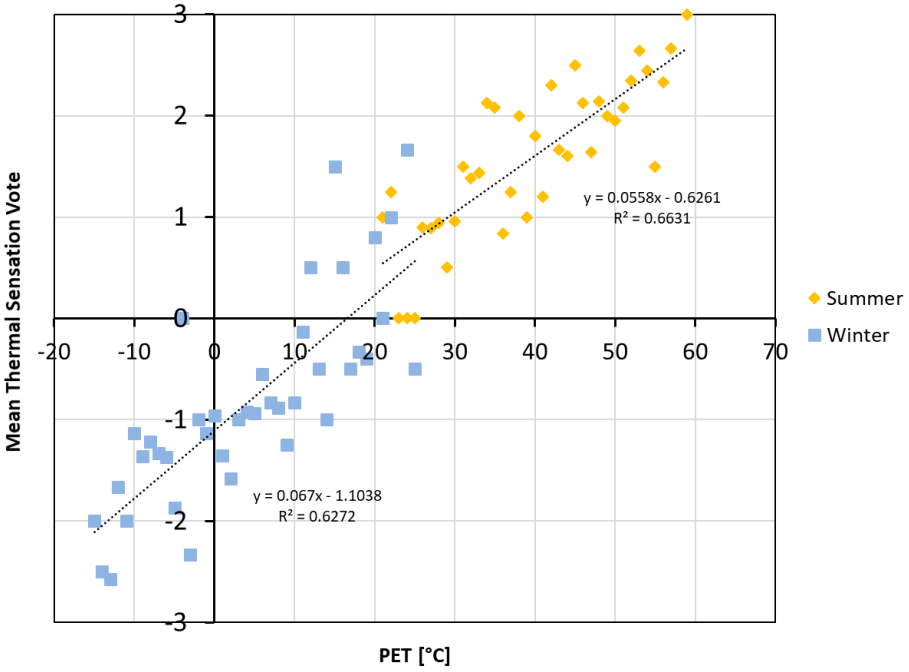


Figure 36. MTSV and PET correlation for summer and winter.

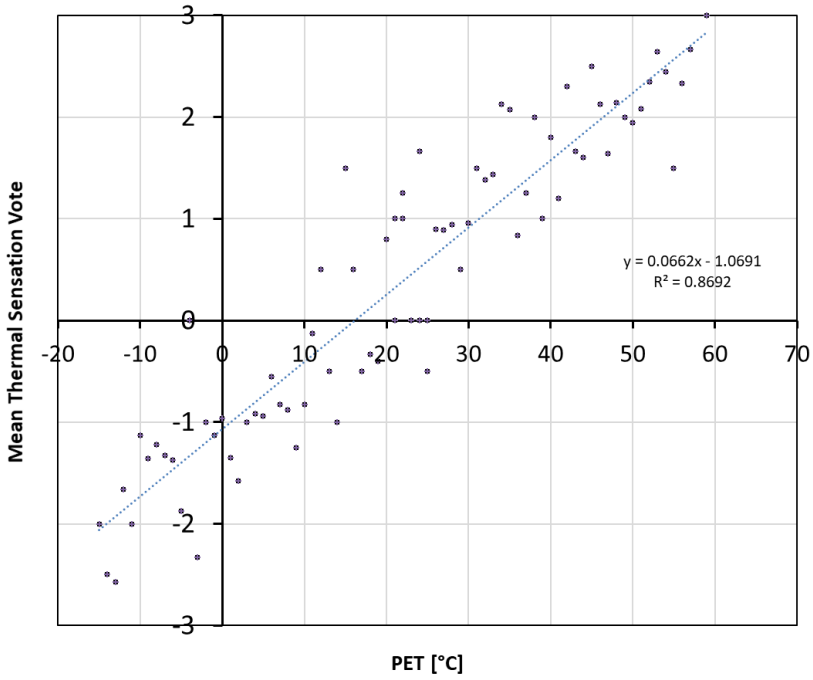


Figure 37. Annual MTSV and PET correlation.

The seasonal MTSV and SET results shown in Figure 38 are similar to those of seasonal PET in that the winter regression line is slightly steeper, implying again the greater effect on MTSV with

decreasing SET values. The SET results differ however in the transition between summer and winter regression lines. As opposed to the seasonal PET lines that were nearly touching with only a slight deviation, the seasonal SET lines in summer and winter are sloped in different trajectories. This is most apparent with the neutral SET (MTSV = 0) in summer which is 5°C while the winter neutral SET is 19.5°C. These results suggest that during the summer the average pedestrian would feel neither hot or cold at a PET of 5°C whereas during the colder season this neutral feeling would occur around 20°C. This implies that pedestrians in Toronto experience thermal SET adaptation of nearly 15°C between summer and winter. It also implies a greater thermal adaptation compared to PET, which is explored in greater detail in Chapter 4.1.5.

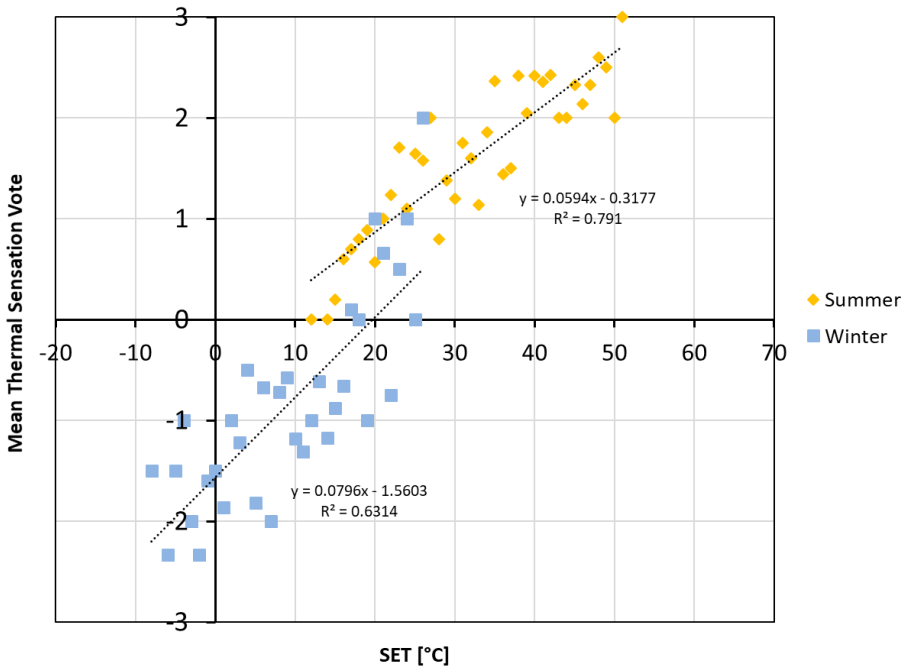


Figure 38. MTSV and SET correlation for summer and winter.

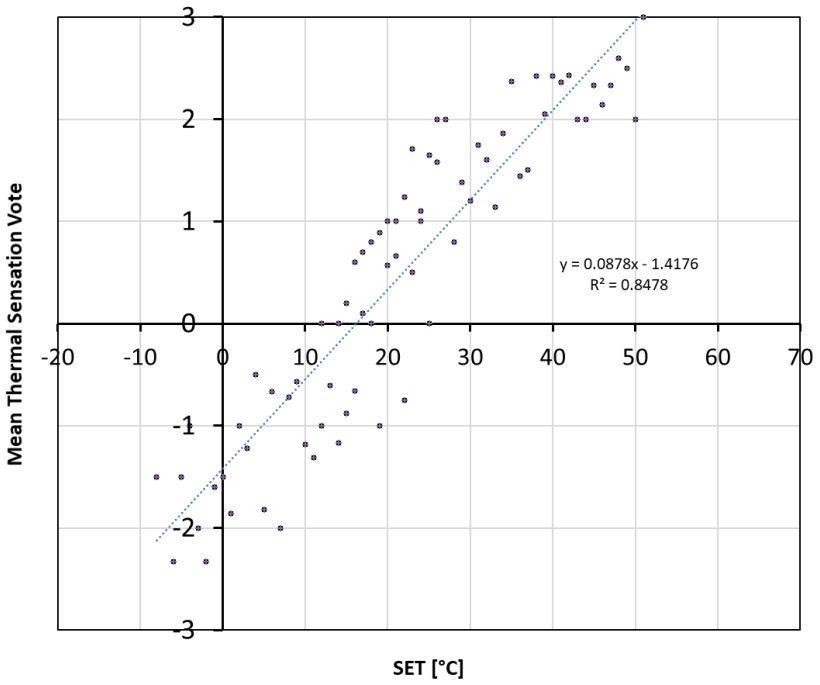


Figure 39. Annual MTSV and SET correlation.

The seasonal MTSV and UTCI results presented in Figure 40 differ considerably compared to the PET and SET results. The most evident comparison is during the winter season where the majority of MTSVs lie above zero. This is likely due to the assumed MET and clo values embedded within the UTCI calculator. As discussed in Section 1, the metabolic rate is fixed at 2.3 MET while the average metabolic rate from the surveys was 2 MET, so there is not much of a difference between the assumed and actual MET results. The assumed clothing insulation levels however are calibrated to resemble a typical Western/Middle European exposed to more temperate conditions compared to Toronto. In other words, because conditions are colder in Toronto, assumed clothing insulation values should be higher than they are currently set. The inability to input measured clo values likely resulted in skewed winter UTCI values. The current results show that the neutral UTCI in winter is -12°C which is an unlikely statement. The neutral UTCI in summer of 20°C seems reasonable and with a correlation of 84%, therefore it may be appropriate to rely on UTCI for summer applications only. However, in winter, an annual neutral UTCI of -11°C is found (Figure 41) is not likely to be accurate.

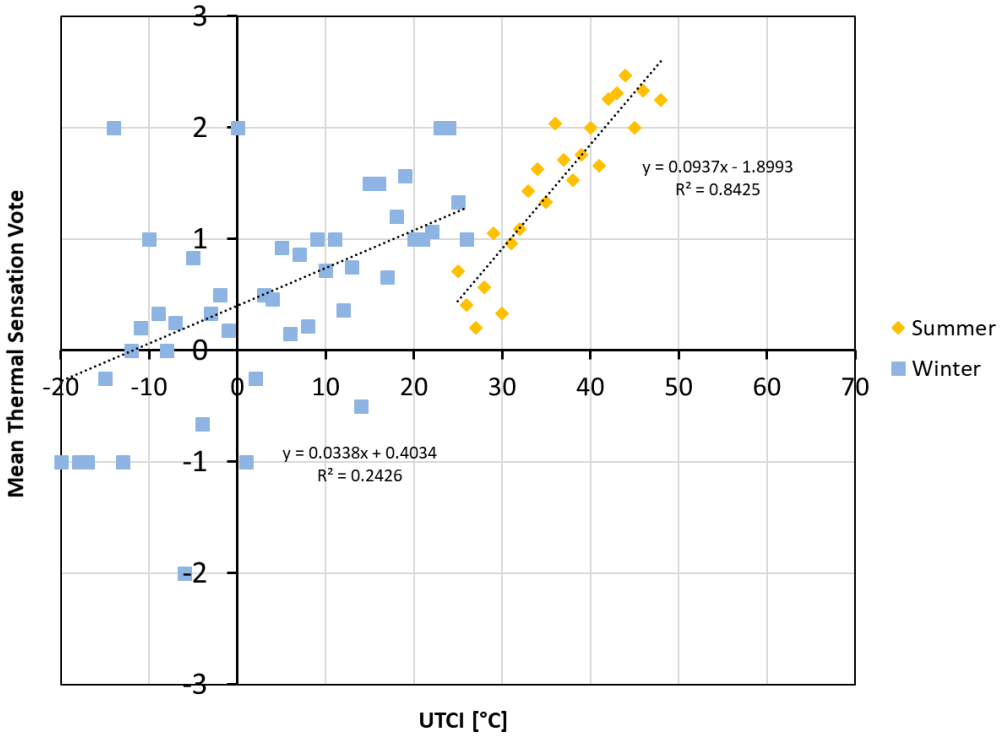


Figure 40. MTSV and UTCI correlation for summer and winter.

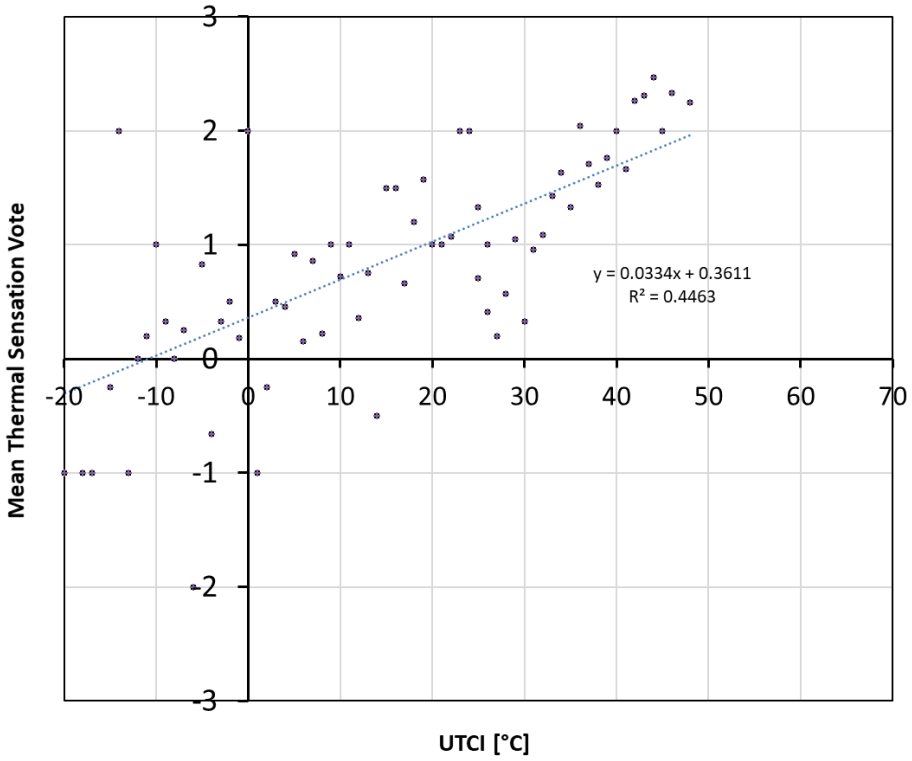


Figure 41. Annual MTSV and UTCI correlation.

4.1.4 PET: Neutral, Preferred, and Comfort Range

The preferred PET can be established by first plotting the percentage of participants who have stated that they prefer to be warmer or colder, separated (across the X axis of Figure 42) by bins of ascending PET values. In theory, as the PET increases, the percentage of people who prefer to be warmer should decline while the percentage of people who prefer to be colder will increase. The point at which the two percentage lines intersect is known as the preferred value. The preferred PET values for Toronto were found to be between 21°C and 30°C (Figure 42). Unfortunately, there was a lack of participant data around this temperature range seeing as the survey periods were taken during summer and winter where PET values were on average less than 21°C in winter and more than 30°C in summer. This absence of data was also why the author was forced to use 4°C PET bins (i.e., -5°C to 0°C, 1°C to 5°C, 6°C to 10°C, etc.) Also, when comparing to Salata et al. (2016), the seasonal preferred PETs weren't possible to determine due to the very low percentages of people preferring cooler temperatures in winter and vice versa in summer.

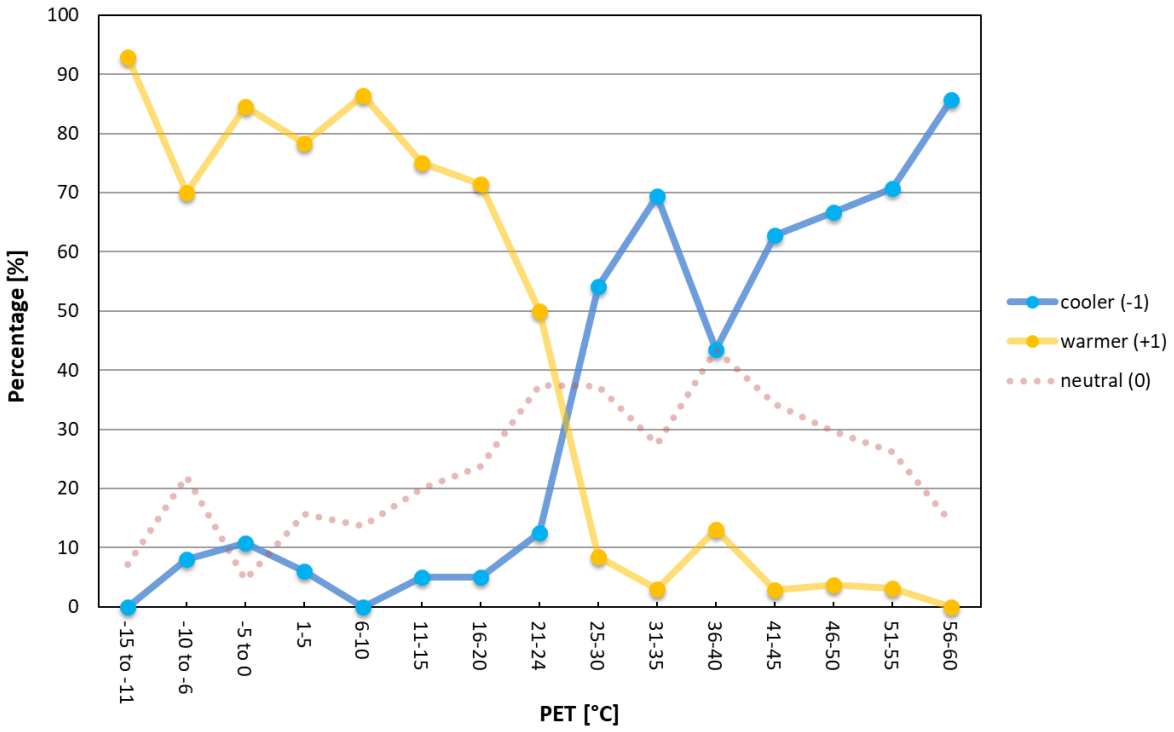


Figure 42. Preferred PET between 21°C and 30°C.

The neutral PET values for summer were respectively found to be 11.2°C in summer, 16.5°C in winter season and 16°C annually. This was found using the linear regression equations in both the seasonal and annual scatterplots. Where MTSV = 0, the corresponding PET is found to be the neutral value. The neutral PET was also determined for the annual MTSV and PET correlation where the neutral value was found to be 16°C, which is similar to the winter PET neutral value of 16.5°C. The comfort ranges are found the same way and are defined as the PET values that lie within MTSV -0.5 and 0.5. Separating seasonally between summer and winter resulted in a PET comfort range between 9°C and 20°C, whereas following the approach of Salata et al., (2016) using the annual PET comfort range is between 9°C and 24°C. Note that discovered PET values within the comfort range were less reliant on recorded data and instead largely derived by extending the seasonal regression lines until they reach the MTSV = 0. Chapter 2 explains how, because recorded data was collected during milder climates, the extreme value that they established may be less accurate because, in order to understand these extreme, they must extrapolate regression lines (i.e., MTSV = 3 or MTSV = -3). This also happened for the current study but instead of extrapolating the data to get extreme values, the regression lines were instead created using extreme data and extrapolated regression lines to determine the neutral thermal sensation values where MTSV = 0. Therefore, an additional OTC analysis that instead focuses on shoulder seasons, as opposed to summer and winter, may reveal different results.

Table 9. MTSV and PET intersections for summer, winter and annual with corresponding percentage of people dissatisfied.

Season	Equation	R-squared	MTSV	PET [°C]	PPD [%]
summer	MTSV = 0.0558*PET-0.6261	0.66	3.5	74	
			3.0	65	56
			2.5	56	
			2.0	47	24
			1.5	38	
			1.0	29	13
			0.5	20	
			0.0	11	7
winter	MTSV = 0.067*PET-1.1038	0.63	0.0	16	9
			-0.5	9	
			-1.0	2	17
			-1.5	-6	
			-2.0	-13	47
			-2.5	-21	
			-3.0	-28	74
			-3.5	-36	
annual	MTSV = 0.0662*PET-1.0691	0.87	3.5	69	
			3.0	61	56
			2.5	54	
			2.0	46	24
			1.5	39	
			1.0	31	13
			0.5	24	
			0.0	16	8
			-0.5	9	
			-1.0	1	17
			-1.5	-7	
			-2.0	-14	47
			-2.5	-22	
			-3.0	-29	74
			-3.5	-37	

To clarify, the PET range does not explicitly imply that a hypothetical indoor condition between 9°C and 24°C would be comfortable for a typical person. For a clearer understanding of what this PET range equates to in individual weather parameters, Table 10 is a range of conditions that were collected that are equivalent to the annual comfort PET range of 9°C and 24°C. That is to

say, as these individual parameters exceed these ranges enough to force the PET below 9°C or above 24°C, the PPD will increase beyond the typical definition of comfort.

Table 10. Range of individual parameters collected during field survey for PET comfort range boundary values.

PET [°C]	9	24
Air Temperature [°C]	3 - 6	24 - 26
Relative Humidity [%]	18 - 22	50 - 55
Mean Radiant Temperature [°C]	31 - 40	29 - 33
Wind Speed [m/s]	1 - 1.5	0.8 - 1.6
Clothing Insulation Levels [clo]	1.2 - 1.9	0.4 - 0.7
Metabolic Rate [MET]	1 - 2	1 - 2

Using the linear regression equations for both summer and winter, PET values were determined for each of the seven MTSV values (-3 to +3). From the previous discomfort results derived from the questionnaire, the PPD for each MTSV could be assigned an actual PET value (see PPD column in Table 9). For example, a PET of 47°C correlates to a MTSV of 2 which based on surveys would result in roughly 24% of the pedestrians in that area to be dissatisfied with the thermal environment within the first 0.5 hours. Figure 43 is a simplified visual scale created to provide designers and policy makers with a tool to understand PET values and their effect on thermal discomfort in cold climates. As shown in Chapter 2, when PMV = 0 there is still a roughly 5% PPD. Similarly, from the surveying period it was found that for all of the participants who chose overall ATSV = 0, between 5% and 7% of the participants voted that they were not comfortable. Therefore, the conditions that suggest thermal neutrality in Figure 43 will still cause discomfort in a small percentage of pedestrians.

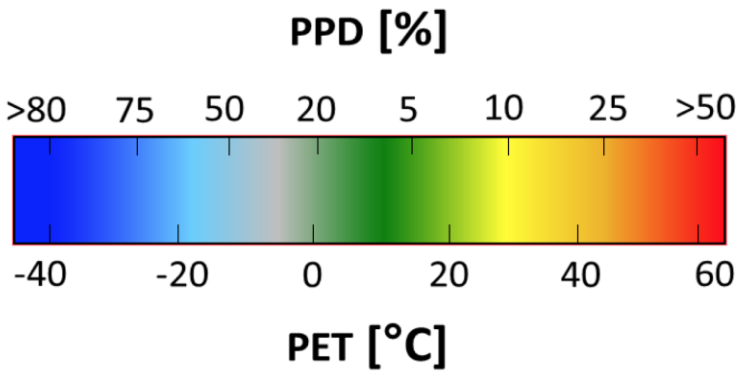


Figure 43. Cold climate scale for estimating the percentage of people dissatisfied within 0.5 hours based on PET.

4.2 Simulated Urban Vegetation Results

The ENVI-met modelling software was used to simulate the existing Gould Street canyon with a vegetated fraction of 0.4 as well as a hypothetical scenario in which all the vegetation was reduced. The purpose of this exercise is to understand how the existing urban vegetation affects the microclimate within the urban canyon with respect to OTC. To do so, hourly PET values were calculated at 1m above ground level for both the vegetated and non-vegetated scenarios. Figure 44 and Figure 45 visually display the hourly PET values within the Gould Street canyon during a summer scenario from 9:00am to 5:00pm. What is most evident is the significantly higher PET values found within the urban canyon of the vegetated scenario, with some areas exceeding a PET of 60°C in the afternoon. The vegetated model displays overall much lower PET values within the urban canyon, especially along the north and south sides of the street where incoming solar radiation is intercepted by tree canopies.

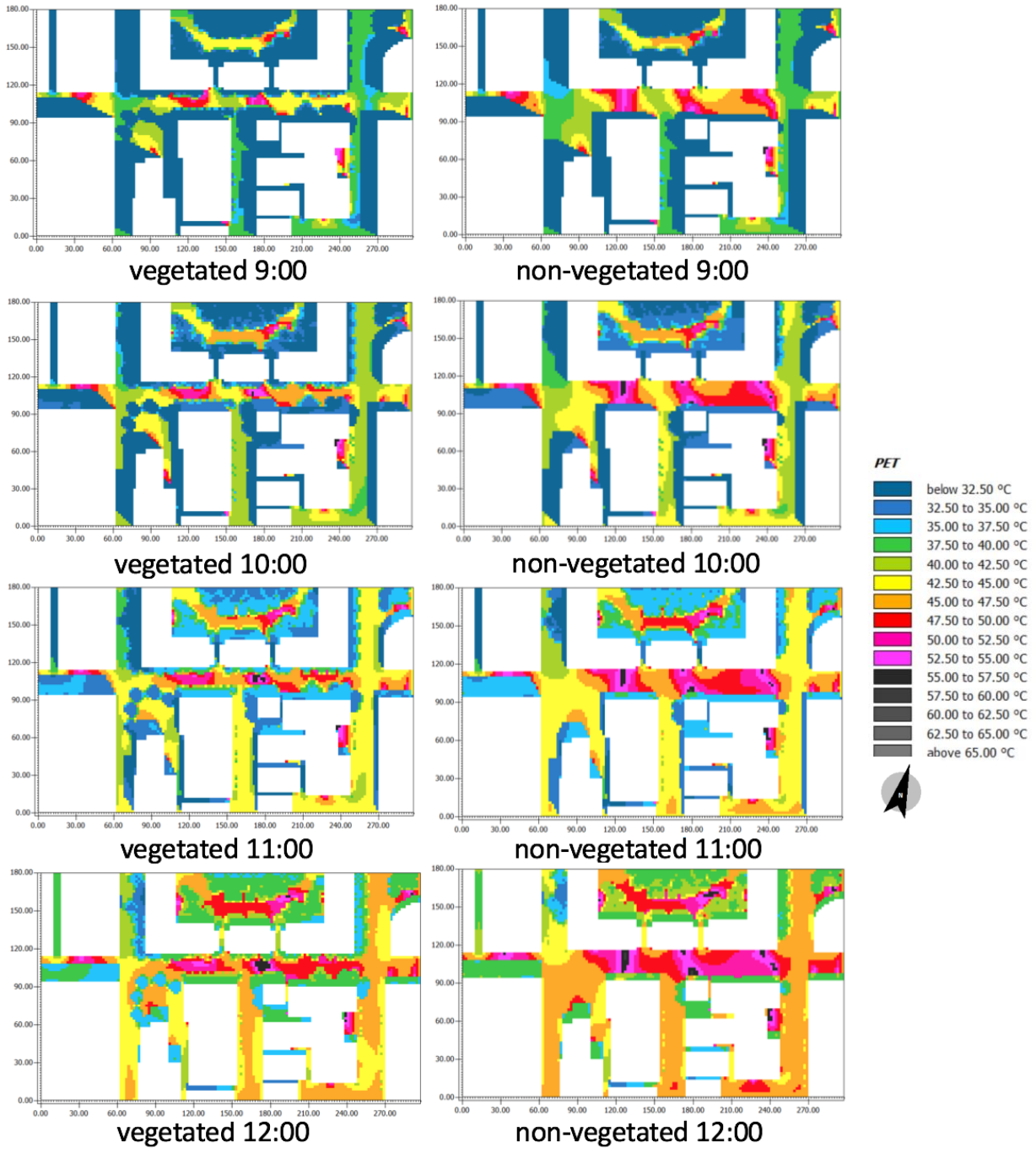


Figure 44. Summer PET comparison between 'vegetated' model and non-vegetated model (9:00-12:00).

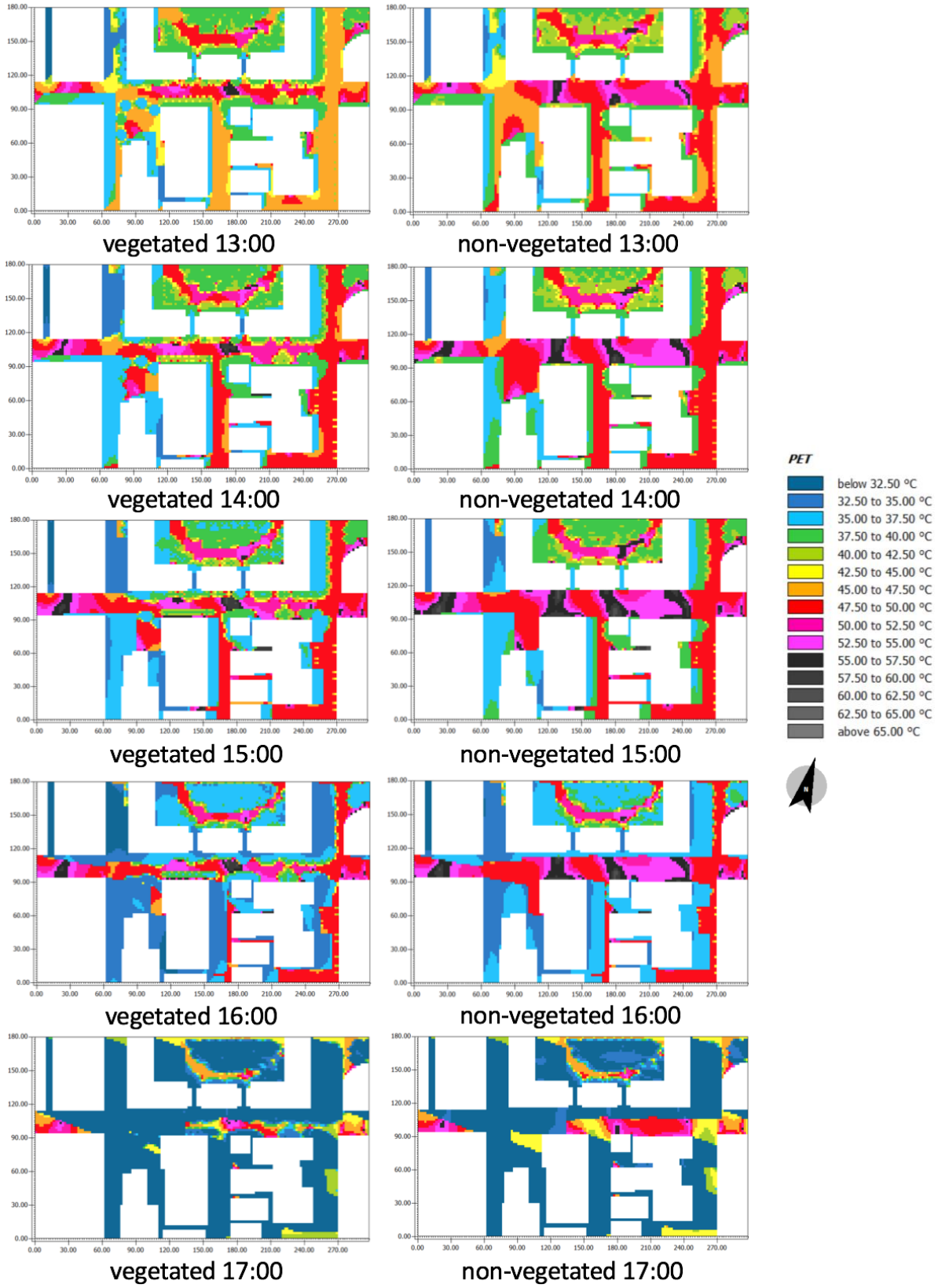


Figure 45. Summer PET comparison between 'vegetated' model and non-vegetated model (13:00-17:00).

Nine measurement points were also placed throughout both the simulated urban canyons along the north, south and middle of the street. Figure 46 further demonstrates how tree canopies along the north and south portions of the vegetated scenario are contributing to greater overall reductions in PET compared to the non-vegetated scenario. For example, the average PET values on the south sidewalk of the non-vegetated scenario were found to be 10°C higher than the vegetated scenario. However, in the middle of the canyon, which is absent of urban vegetation in both scenarios, shows a difference of only 1°C between both cases. Therefore, the presence of vegetation did not significantly affect OTC throughout the entire urban canyon. In this case, the results imply that the urban vegetation is more effective in reducing the mean radiant temperature by intercepting incoming solar radiation, or in other words by shading pedestrians, than it is at cooling the surrounding ambient air. Figure 47 illustrates the hourly distribution of PET values, at each measurement point, from 9:00am to 5:00pm for the vegetated and non-vegetated scenario.

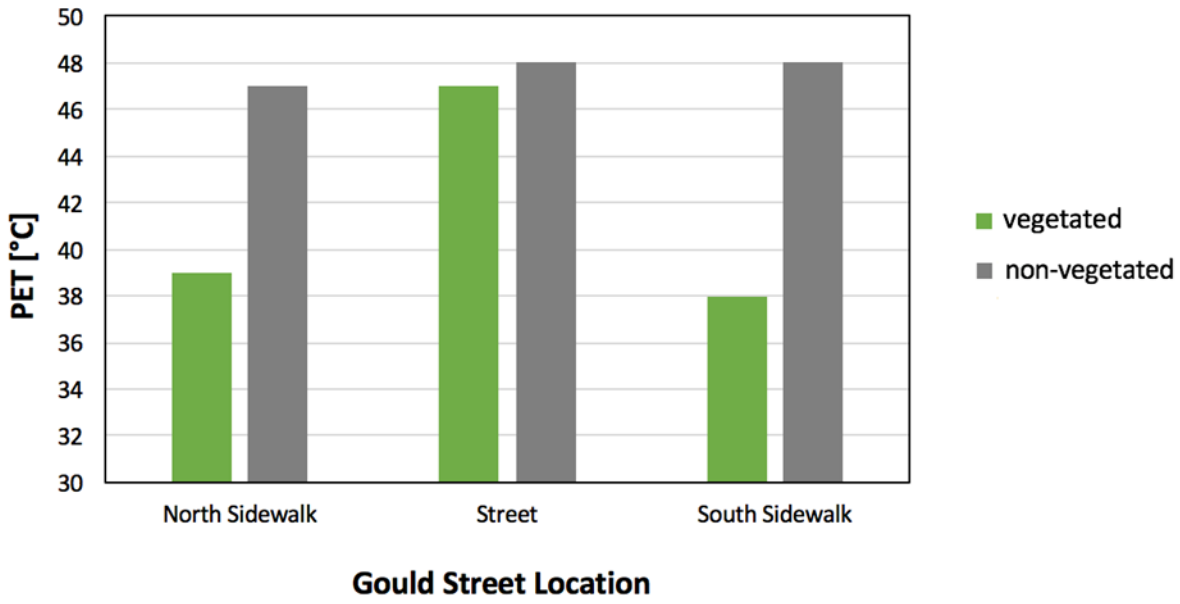


Figure 46. Average simulated PET by location within the urban canyon.

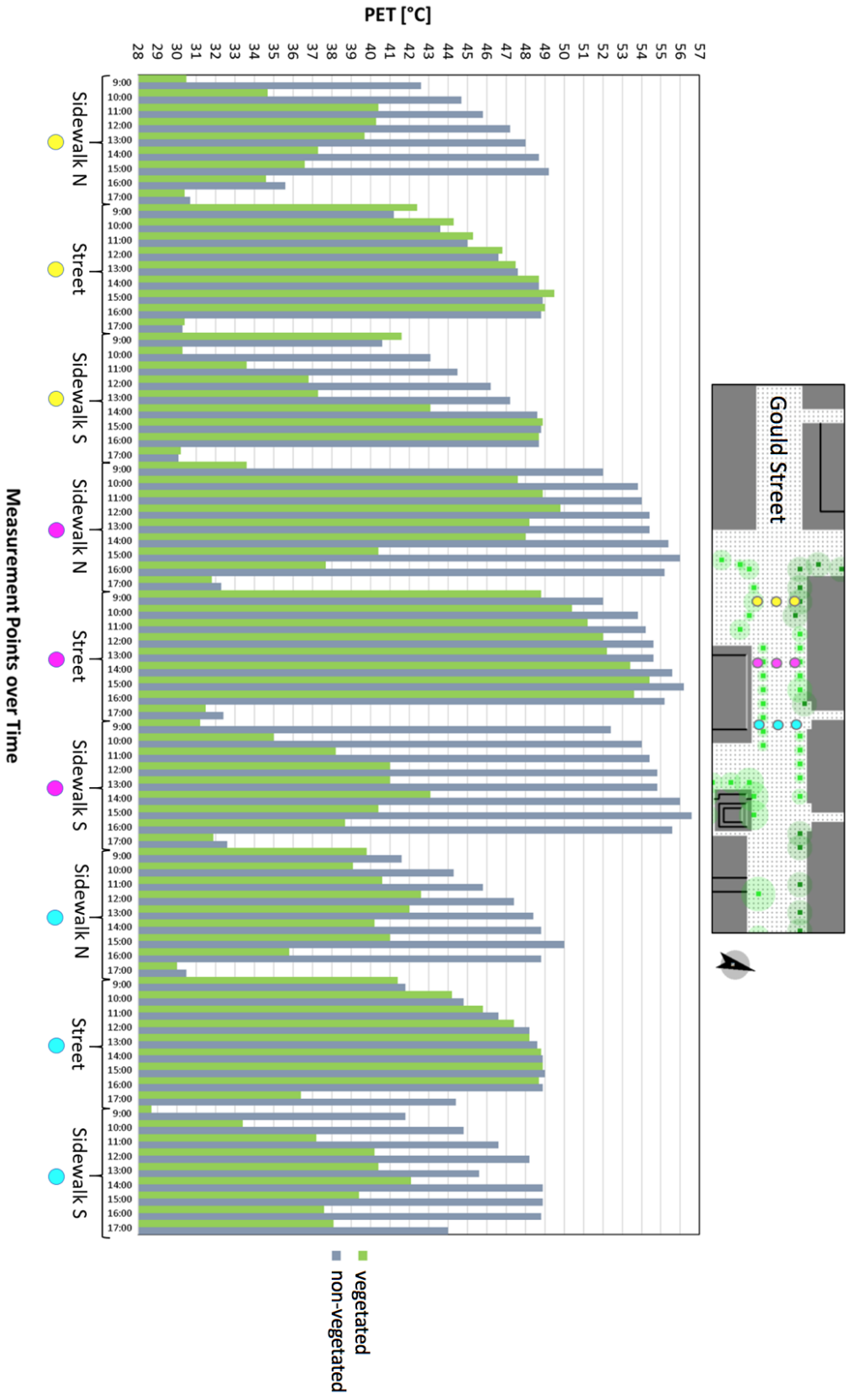


Figure 47. Hourly PET results for vegetated and non-vegetated scenario at various measurement points.

5 Discussion

Overall Comfort

In this study, overall thermal comfort for pedestrians in Toronto, Canada was explored using four different thermal indices: PMV, SET, UTCI, and PET. PMV, an index created primarily for indoor thermal comfort assessment, proved to be largely unsuccessful as a metric for predicting OTC, as the environmental conditions which occur outdoors in Toronto often lie beyond the ideal comfort conditions for indoors. As a result, the PMV value for each participant, which is intended to lie within a 7-point scale between -3 (cold) and +3 (hot), was often overestimated and provided values that were either lower or higher than the 7-point scale (see Figure 34 and Figure 35). However, the surveys distributed to pedestrians did include a question, "How are you feeling now?" to which participants had the option of responding based on the same 7-point scale as the PMV index output. Participants were also asked, "Are you comfortable overall?" to which they could respond based on a 5-point scale where -2 means that the participant disagrees, +2 means they agree, and 0 meaning they are uncertain. An analysis was performed based on the results of these two questions where first, all participants were divided into seven groups based on their response to "How are you feeling now?". Next, for each group, the total number of participants who responded either -1 or -2 (disagree) to the question "Are you comfortable overall?" were summed and established as a percentage based on the total group. This process was repeated for all seven groups. The purpose of this exercise was to determine the percentage of people dissatisfied, similar to Fanger's (1970) PMV/PPD correlation discussed in Chapter 1, though derived from actual survey data instead of the PPD equation used for indoor applications. Figure 48 illustrates the difference between Fanger's (1970) PMV/PPD curve and the Actual Thermal Sensation Vote (ATSV)/PPD curve determined in this study. Note that the PMV/PPD curve has a normal distribution, implying that if the thermal perception of a person was to change in either direction (hot or cold), an equal percentage of people will likely be dissatisfied. What can be seen with the ATSV/PPD curve is that thermal sensation votes straying from neutral towards colder conditions yields a higher PPD. In other words, this graph implies that pedestrians in Toronto have a higher tolerance for warm conditions (+2 ATSV = 24% PPD) compared to cold conditions (-2 ATSV = 47% PPD).

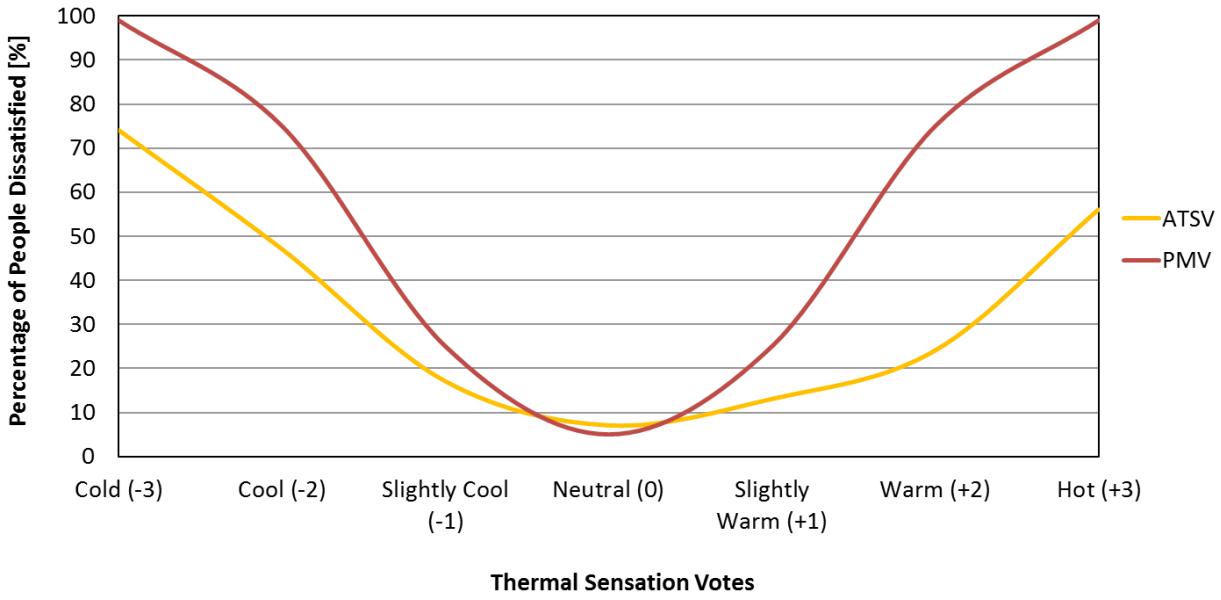


Figure 48. Comparison of the PPD for Predicted Mean Vote (PMV) and the Actual Thermal Sensation Vote (ATSV) of Toronto pedestrians.

The viability of SET, UTCI and PET were also explored as metrics for predicting OTC in Toronto. To recap the results from Table 8, PET has the strongest correlation with MTSV of pedestrians in Toronto (R^2 = 0.87), followed by SET (R^2 = 0.82). SET also showed a strong seasonal correlation with MSTV in summer (R^2 = 0.79), slightly higher than PET (R^2 = 0.66). Both PET and SET had the same seasonal winter correlation with MTSV (R^2 = 0.63). UTCI also had a strong seasonal correlation in summer (R^2 = 0.85), though expressed a relatively weak seasonal correlation in winter (R^2 = 0.36). In other words, all three indices could be used to reasonably predict seasonal OTC in summer. SET and PET could also reasonably predict seasonal OTC in winter, whereas using UTCI may be problematic. Recall that UTCI's low seasonal correlation with MTSV in winter is likely due to the UTCI calculator used for this study, where clothing insulation values are assumed and cannot be modified (see UTCI section in Chapter 1.2). It is therefore recommended, for future work, that a UTCI calculator with either modifiable clo values or higher assumed clo values be used for a cold continental climate like Toronto. Overall comfort results from this study show that winter comfort is an important part of OTC in Toronto, and therefore an annual scope is

strongly recommended. Because SET and PET have strong seasonal and annual correlation with MSTV of pedestrians in Toronto, either index could be used to reasonably assess OTC.

One reason to encourage the use of PET is to relay information and knowledge using a common metric within the academic community. As Chapter 2.1 outlines, PET is becoming a dominant index for assessing OTC. Table 11 is a list of some of the many PET ranges being discovered in different climates around the world. As the figure shows, the results of this study are significantly different compared to the other studied climates, particularly with respect to strong and extreme physiological stress values in both hot and cold thermal sensitivities. Also, note how the slightly cool to neutral range for Toronto begins at 9°C whereas other climate's neutral ranges begin generally above 18°C.

Table 11. Thermal sensation classification of PET values for five different climates including current study.

Thermal Sensitivity	Physiological Stress	PET [°C] Western/Middle Europe (a)	PET [°C] Taiwan (b)	PET [°C] Beijing (c)	PET [°C] Rome (d)	PET [°C] Toronto
Köppen Climate Class		Cfb	Cfa	Cfa	Csa	Dfb
Very Cold	Extreme Cold Stress	4	14	-4	-3	-37
Cold	Strong Cold Stress	8	18	8	5	-22
Cool	Moderate Cold Stress	13	22	16	13	-7
Slightly Cool	Slight Cold Stress	18	26	22	21	9
Neutral (Comfortable)	No Thermal Stress	23	30	28	29	24
Slightly Warm	Slight Heat Stress	29	34	32	37	39
Warm	Moderate Heat Stress	35	38	38	45	54
Hot	Strong Heat Stress	41	42	44	53	69
Very Hot	Extreme Heat Stress					

(a) Mayer & Matzarakis (1996), (b) Lin & Matzarakis (2008), (c) He et al. (2015), (d) Salata et al. (2016)

In Chapter 2.1, PET comfort ranges for seven different studies in various locations and climates were listed. The PET comfort range for this study was added in Figure 49 where it is evident that, among all the locations explored, Toronto has the widest comfort range spanning from 9°C to 24°C.

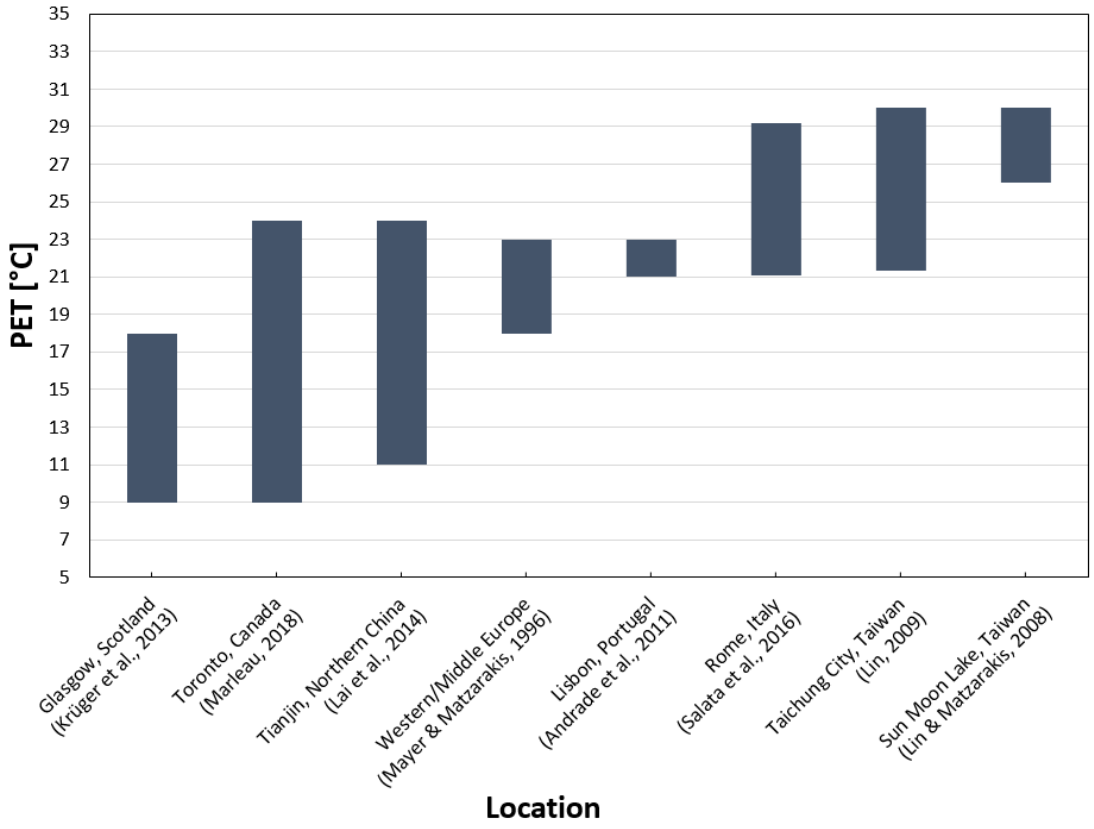


Figure 49. PET comfort range for various locations including Toronto, Canada (current study).

The reason for Toronto's wide PET comfort range compared to all other locations studied so far can be explained with reference to the steepness and length of Toronto's PET regression lines found in Figure 50. The first key aspect to note in Figure 50 is how relatively gradual the Toronto regression lines are compared to Rome, Hong Kong and Tianjin, China. What this difference implies is that, compared to these other locations, the average pedestrian in Toronto would require a greater increase or decrease in PET in order for them to change their thermal sensation vote. In other words, the average pedestrian from these other locations are more sensitive to

changes in the overall outdoor environment compared to the average pedestrian of Toronto, Canada.

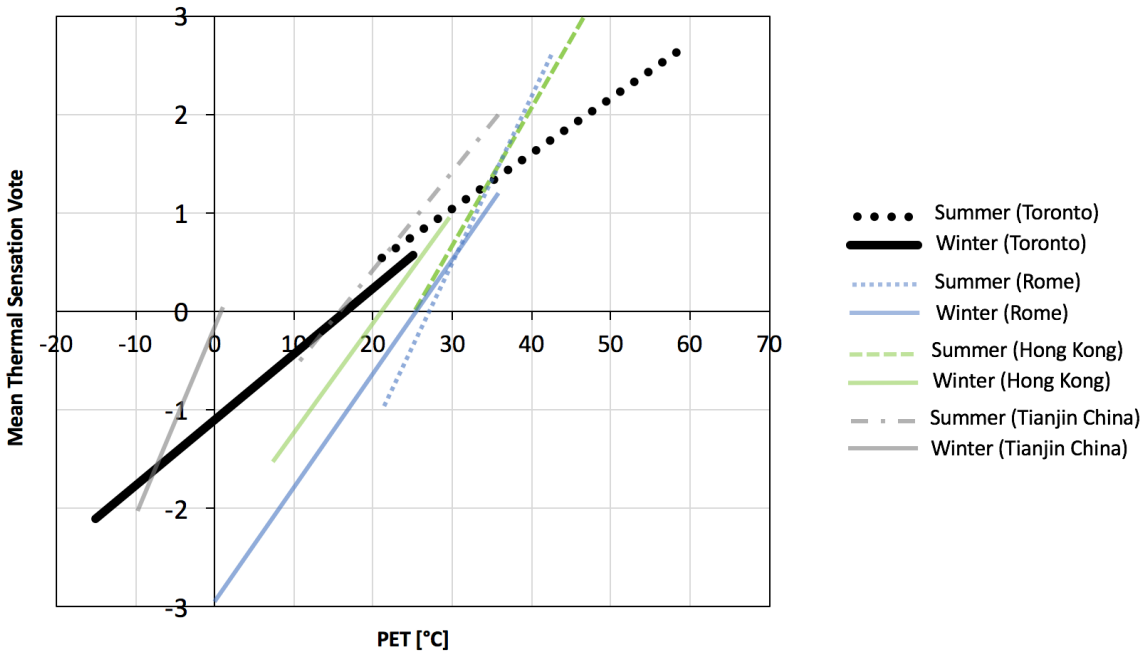


Figure 50. Comparison of seasonal MTSV & PET linear regression of Toronto, Canada and other various locations.

A rationale for this relatively higher tolerance for changes in environmental conditions may be related to the extensive length of Toronto's regression lines. Based on the field surveys, PET values experienced by pedestrians in Toronto can exceed those of all other studies, in either direction. For example, Figure 50 shows that it is possible for a pedestrian of Toronto to experience a PET below -10°C in winter and nearly 60°C during the summer. The figure illustrates that pedestrians in these other locations generally experience less extreme PET values, with the exception of winter in Tianjin, Northern China. Negative PET extremes recorded in Tianjin reach as low as -10°C, however the relatively steeper regression line indicates a lower tolerance for cold conditions. Also, it is important to note that Tianjin, Northern China had the second widest PET comfort range in Figure 49, spanning from 11°C to 24°C. However, the comfort range for Tianjin China is based solely on seasonal summer PET values and not annual PET values, as most studies (including this current study) have declared. Because of Tianjin's relatively poor PET correlation in winter, merging the two seasonal regression lines would affect the slope resulting

in unlikely results (similar to winter and annual UTCI results for Toronto in Chapter 4.1.3). Nonetheless, it is evident that Tianjin and Toronto both experience a wide range of PET values from summer to winter. This suggests that thermal perception, preference and overall comfort of pedestrians is relative to the outdoor thermal range they are exposed to.

Individual Weather Variables

Individual weather variables can significantly affect overall comfort and therefore it is beneficial to understand, particularly from an urban design perspective, how each element is perceived. To maximize OTC, it is important to use the information provided by pedestrians of Toronto to assist in designing spaces. It is equally important to consider how comfort measures will affect OTC in both summer and winter. For example, the survey results in summer show that 68% of participants felt that there was not enough wind and 70%, mostly uncomfortable pedestrians, voted for more. However, results from the winter surveys show that 52% of pedestrians felt that there was too much wind and 67% shared a preference for less. This means that designing features that, say, augment wind to increase OTC in summer may have an adverse effect on OTC for pedestrians during winter. A similar issue presents itself with respect to solar exposure, where 73% of uncomfortable pedestrians in summer expressed that there was too much solar radiation, though 59% of uncomfortable pedestrians in winter felt that there was not enough sun and 69% of participants preferred more. Designing solar shading devices, for example, to increase summer OTC would have to be angled properly to allow for solar penetration during winter when the sun is at a lower angle. Deciduous trees can also be beneficial as their leaves can shade outdoor spaces during the summer and allow for winter sun exposure when their leaves have fallen. Reducing the mean radiant temperature by intercepting or reflecting incoming solar radiation can also reduce overall ambient air temperature, which can either increase or decrease OTC depending on the season. In summer, results showed that 62% of participants, including comfortable pedestrians, preferred lower air temperatures. In winter, 76% preferred higher air temperatures and 60% felt that air temperature was too low. Relative humidity was a concern for pedestrians in summer, where 67% of participants, including those who expressed they were comfortable overall, preferred less humidity. However, 66% of all participants were satisfied with the humidity levels in winter, including uncomfortable pedestrians. The results for relative

humidity suggest that the potential for this variable to contribute to discomfort increases as the perception of air temperature increases. In all, results from pedestrian responses further demonstrate how important an annual OTC analysis can be to ensure optimal comfort is being achieved, particularly as thermal perceptions and preferences for individual weather variables change with the seasons.

Simulations vs. Field Measurements

Outdoor microclimates can be complex, highly variable environments and therefore difficult to accurately simulate with CFD modelling. Due to the intricacies of outdoor environments, simplifying microclimate models in ENV-met is recommended to yield reasonable results. Also, field measurements are encouraged, if possible, when simulating microclimate environments, as the inputs from City Centre Toronto (YTZ) weather files did not generally reflect the data collected within the case study environment. The YTZ files therefore had to be modified based field measurements to produce a simulated environment that reflected actual conditions experienced within the Gould Street urban canyon. As stated in Chapter 1, inaccurate simulation output values of even a single individual weather variable can result in incorrect assumptions of PET values or other thermal index results. Ensuring that model inputs are closely representative of an existing environment can produce a more reliable analysis of the OTC in an area. Although there were issues in the collection of significant diurnal weather data within Gould Street (see Chapter 3.5), it is felt that manipulating the YTZ data so that the simulated PET results reflected values measured in the canyon (Figure 24), was a reasonable approach to re-creating the case study environment in ENVI-met.

Urban Vegetation & Outdoor Thermal Comfort

A CFD model of the case study environment, Gould Street, was created to test the environment effect of removing all of the urban vegetation within the urban canyon. PET was the thermal index chosen as a metric to measure thermal comfort. Based on the results from the simulation, it is evident that urban vegetation can be an effective measure for reducing PET during hot conditions. The simulated PET reductions from urban vegetation in this study are consistent with the results from Chapter 2.2, as most other studies have found that urban vegetation can

contribute to reductions in air temperature, MRT, PET, and overall comfort. However, simulations can only quantify the environmental conditions between the two simulated scenarios, though they fail to provide a sense of how the difference in PET values relate to overall comfort for the typical pedestrian of Toronto. For example, results from the simulation showed that, during an extreme heat scenario, the removal of trees on the south side of Gould Street could increase the average PET by 10°C, from 38°C to 48°C (Figure 51). These results alone are difficult to interpret, however when paired with the results from the survey questionnaires, they can provide useful information based on pedestrian responses to OTC. Using part B and C of Figure 51, it is reasonable to suggests that a PET increase from 38°C to 48°C can cause physiological stress of pedestrians to change from slight to moderate heat stress, and cause a conservative estimate of 15% increase in PPD. This approach can help inform architects and urban space designers of their project's impact on pedestrian OTC. Recall in Chapter 1.2 that acceptable outdoor thermal conditions have yet to be standardized, and therefore, should an urban design team decide to incorporate OTC metrics in their design, it is recommended that they work with their local municipalities to determine an acceptable PPD. It was also found that the urban vegetation, largely on the north and south sidewalk did not significantly reduce PET values in the center of the street. Because Gould Street has been converted from a street that once prioritized vehicle traffic to a fully pedestrian-only street, further testing of the OTC effect trees can provide if planted in the center of the street should be examined in future work. In addition, the lifespan and potential growth of the trees is not considered in this study and could result in greater reductions in PET as tree canopies expand over time.

A)

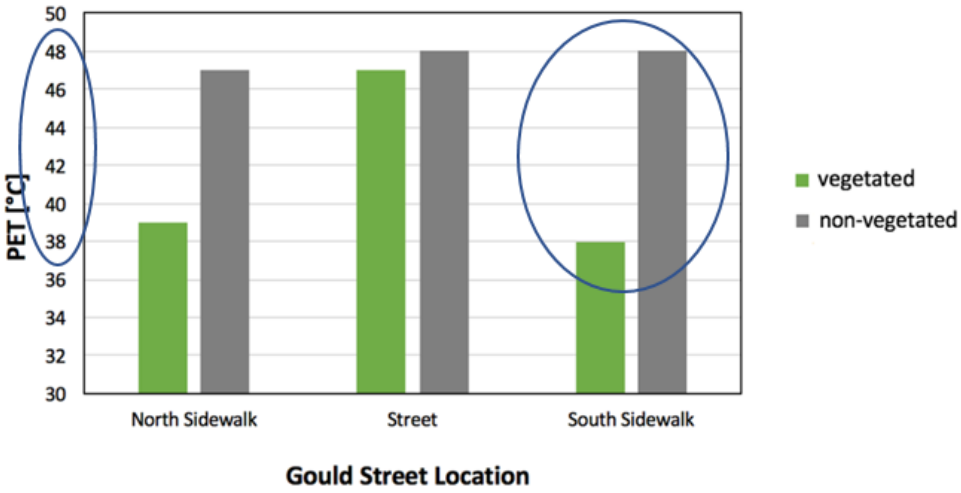


Figure 46. Average PET by location within the urban canyon.

B)

Table 12. Thermal sensation classification of PET values for five different climates including current study.

Thermal Sensitivity	Physiological Stress	PET [C] - Western/Middle Europe (a)	PET [C] - Taiwan (b)	PET [C] - Beijing (c)	PET [C] - Rome (d)	PET [C] - Toronto
Köppen Climate Class		Cfb	Cfa	Cfa	Csa	Dfb
Very Cold	Extreme Cold Stress	4	14	-4	-3	-37
Cold	Strong Cold Stress	8	18	8	5	-22
Cool	Moderate Cold Stress	13	22	16	13	-7
Slightly Cool	Slight Cold Stress	18	26	22	21	9
Neutral (Comfortable)	No Thermal Stress	23	30	28	29	24
Slightly Warm	Slight Heat Stress	29	34	32	37	39
Warm	Moderate Heat Stress	35	38	38	45	54
Hot	Strong Heat Stress	41	42	44	53	69
Very Hot	Extreme Heat Stress					

(a) Mayer & Matzarakis (1996), (b) Lin & Matzarakis (2008), (c) He et al. (2015), (d) Salata et al. (2016)

C)

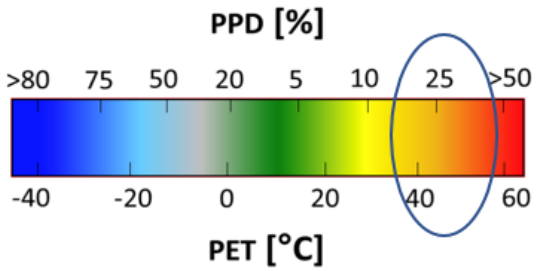


Figure 43. Cold climate scale for estimating the percentage of people dissatisfied within 0.5 hours based on PET.

Figure 51. Exemplary method for estimating physiological stress and PPD for pedestrians of Toronto. See appropriate figures listed for full resolution graphics.

5.1 Limitations

OTC Limits

- Surveying was conducted on a university campus to maximize the potential participants though unfortunately this resulted in a higher concentration of post-secondary students. The sample resulted in a demographic mainly consisting of post-secondary students between the ages of 20 and 29 years old, whereas an OTC analysis of an older demographic may also be insightful from a health and safety perspective.

- During the winter survey period, it was apparent that during cold conditions people with lower clothing insulation values weren't dressed enough to stand for several minutes to fill out the information required and were less likely to complete the surveys. This would result in higher clo values than what is representative of the Gould Street population. Overestimated average clo values could result in higher PET results than would be produced using a lower, more representative clothing insulation value on average.

- Surveying was conducted during daytime work hours (9:00am-5:00pm) in order to intercept the highest volume of pedestrians. Surveys were not taken during early mornings, later afternoons or at night. Surveys were also not taken during snow or rain events to protect the micro-meteorological equipment from being damaged.

Simulation Limits

- In the ENVI-met ConfigWizard program, wind speed or direction cannot be forced during hourly intervals as was done for air temperature and relative humidity. Instead, wind speed and direction are set and initiated only for the beginning of the simulation period. The limitation of this input is that in a natural setting wind speed and direction are in constant fluctuation. Wind speed was collected during field measurements and therefore simulation outputs could be compared and inputs could be changed accordingly, while wind direction was not collected.

- Simulations for this research were conducted on a 12-hour basis. To allow for a reasonable number of iterations for the summer base model, it was not feasible from a time management perspective to conduct 24-hour simulations. In addition, surveys and field measurements were on average taken between 9:00am and 5:00pm so evening and overnight analysis were not considered for this study. Because the air temperature and humidity were forced on an hourly schedule, it was felt that 12-hour simulations from 6:00am to 6:00pm could produce sufficient results for a 9:00am to 5:00pm analysis.

6 Conclusions

Using a compound approach of field investigation and microclimate modelling of a pedestrian-only street in Toronto, Canada, this study investigated urban outdoor thermal comfort (OTC) in a cold climate. Questionnaires were distributed to pedestrians and microclimate data was logged at 15-second intervals while participants completed the 5-minute survey. Thermal sensation votes and corresponding micrometeorological data for 723 participants was collected and analyzed using four different thermal indices as metrics for comparing and assessing the thermal comfort information. The predicted mean vote (PMV), typically used for indoor applications, did not correspond well with votes of pedestrians in Toronto during an outdoor application. Of the remaining three indices, the Physiological Equivalent Temperature (PET) had the highest annual correlation ($R^2 = 0.87$) with Mean Thermal Sensation Votes (MTSV) of pedestrians in Toronto. The Standard Effective Temperature (SET) had a slightly lower annual correlation ($R^2 = 0.82$), however also showed strong seasonal correlations in summer and winter. Results suggest that, of the indices explored, both SET and PET are viable metrics for reasonably predicting the thermal sensation of pedestrians in Toronto.

Individual weather variables can significantly affect overall comfort and therefore it is important to understand how each element is perceived. Results from field surveys show that individual weather variables can have a significantly different effect on overall comfort depending on the season. For example, most pedestrians in summer felt that there was too much direct solar exposure and not enough wind. In winter, the majority felt that there was not enough solar exposure and shared a preference for more. Therefore, from an urban design perspective, it is important to consider how OTC measures (i.e., increased wind, solar shading, etc.) will seasonally affect pedestrian comfort. These results also reinforce the importance of an annual OTC analysis to provide a more complete understanding of thermal comfort.

The PET and MTSV correlation was further explored and results from this study were compared with other locations. It was determined that the annual PET comfort range for pedestrians of Toronto is between 9°C and 24°C (neutral PET = 16°C). This range is generally wider than other locations of previous studies and is likely due to Toronto's relatively more gradual and wider PET and MTSV regression line. In other words, the extreme PET values experienced in Toronto are

greater in summer and winter compared to other studied locations, and as a result, a greater change in PET is required for the average pedestrian to change their thermal sensation vote. It was also discovered that the so-called comfort range is lower than the preferred PET range, which lies roughly between 20°C and 30°C. The difference in values demonstrates that thermal perception on a 7-point scale as a sole index is not sufficient in determining outdoor comfort. Unlike the PMV for indoor applications, a neutral thermal perception for pedestrians of Toronto does not necessarily imply comfort. It is therefore recommended that OTC questionnaires include the McIntyre 3-point thermal preference scale (-1 cooler, 0 neutral and +1 warmer) for a broader understanding of thermal perception, preference and overall comfort. Also, results from this study reflect the demographic of questionnaire participants, largely post-secondary students, whom may have a higher tolerance for extreme outdoor conditions. Future research should aim to assess the OTC thresholds of vulnerable populations in Toronto.

The pedestrian-only street and surrounding microclimate was modelled using ENVI-met, a Computational Fluid Dynamics (CFD) modelling software, where a summer scenario was simulated based on diurnal field measurements collected within the case study environment. Two scenarios were simulated: a base model with the existing vegetated fraction (0.4) and a hypothetical model where the urban vegetation was completely removed. Simulated results show that the non-vegetated model produced much higher overall PET values at 1m height from ground. Interception of incoming direct solar radiation via tree canopy shading in the vegetated model was found to significantly reduce PET values along the sidewalks where trees are planted. The most significant PET decrease was along the south sidewalk, where an average difference of 10°C, from 48°C to 38°C, between the non-vegetated to vegetated model was found. In the middle of the street, where urban vegetation was not present in either model, differences in PET were not significant. Therefore, to maximize OTC within the case study environment, it is recommended to introduce urban vegetation evenly throughout the urban canyon. Future work may include the OTC effect of various vegetated fractions within urban canyon configurations, optimal distribution and spacing of urban vegetation, or more specific research related to how tree types and canopy growth over time can affect OTC.

In all, direct responses from pedestrians in conjunction with simultaneous micrometeorological measurements proved to be a useful method for assessing OTC in an urban microclimate in Toronto. It is evident that acquisition of primary data to understand the thermal preferences and perceptions of pedestrians for a certain area is integral, as OTC can vary significantly. As the discipline matures, universal standards for acceptable outdoor conditions, in particular PPD, should be defined. As we experience higher frequencies of unpredictable weather patterns and unprecedented temperature extremes around the world, standardization of acceptable conditions can assist with the integration of OTC in contemporary urban space design.

Appendices

Appendix 1 - Survey Questionnaire

Outdoor Thermal Comfort Questionnaire

A) PERSONAL INFORMATION Log #: _____

Age < 19 20-29 30-39 40-49 50 +

Gender male female

Approx. Height (ft) _____

Approx. Weight (lbs) _____

Clothing						
	Head	bandana	scarf	light hat	heavy hat	hijab / turban
	Body	undershirt	sleeveless top	Short-sleeve T	Long-sleeve T	jacket / vest / button ups
	Legs	Heavy Skirt	Light Skirt	Shorts	Light Pants	Heavy Pants
	Feet	Ankle Socks	Long Socks	Sandals	Shoes	Boots
	other:					

Have you been a resident of Toronto for at least 6 months? Yes No

Before survey, you were: sitting standing walking running

You are currently in: sunlight shade

30 minutes ago, you were: indoors outdoors

Activity performed 30 mins. ago: sitting standing walking running

other:

Appendix 1a. Questionnaire (page 1 of 2).

Outdoor Thermal Comfort Questionnaire

B) THERMAL PERCEPTION AND PERSPECTIVE

How are you feeling now?

cold	cool	slightly cool	neutral	slightly warm	warm	hot
-3	-2	-1	0	1	2	3

What do you think of the wind at this moment

	not enough		content		too much	
	-2	-1	0	1	2	

What do you think of the humidity at this moment

	too damp		content		too dry	
	-2	-1	0	1	2	

If sunny, what do you think of the sun at this moment

	not enough		content		too much	
	-2	-1	0	1	2	

For each category, which would you prefer?

Air Temperature	cooler		no change		warmer
	-2	-1	0	1	2
Wind	less wind		no change		more wind
	-2	-1	0	1	2
Humidity	less humid		no change		more humid
	-2	-1	0	1	2
Sunlight	less sunlight		no change		more sunlight
	-2	-1	0	1	2

Are you comfortable overall?

	disagree		uncertain		agree	
	-2	-1	0	1	2	

Would you prefer it to be...?

	cooler		no change		warmer	
	-1		0		1	

Appendix 1b. Questionnaire (page 2 of 2).

Appendix 2 – Delta Ohm 32.3 Specification Sheets

HD32.3
HD32.3A
WBGT-PMV-PPD



HD 32.3, HD32.3A
INSTRUMENT FOR THE ANALYSIS OF THE INDICES: WBGT - PMV - PPD

HD32.3 – WBGT - PMV Index is an instrument made by **Delta Ohm Srl** for:
- Analysis of hot environments using **WBGT** index (Wet Bulb Glob Temperature: wet bulb temperature and Globe thermometer) in presence or absence of solar radiation.
- Analysis of the moderate warm environments using **PMV** index (Predicted Mean Vote) and **PPD** index (Predicted Percentage of Dissatisfied).

Reference standards:
ISO 7243: Hot environments. Estimation of the heat stress on working man, based on WBGT index (wet bulb globe Thermometer).
ISO 8996: Ergonomics of the thermal environment. Determination of metabolic rate.
ISO 7726: Ergonomics of the thermal environment – Instruments for measuring physical quantities.
ISO 7730: Moderate thermal environments. Determination of PMV and PPD index and specification of the condition for thermal comfort.

The instrument is provided with three inputs for probes with SICRAM module: the SICRAM module is an interface between the instrument and connected sensor and communicates the sensor parameters and calibration data to the instrument.

All SICRAM probes can be plugged into any of the inputs: they are automatically recognized upon turning on the instrument.
The **main features** of the instrument are:
- **Logging:** data acquisition and logging in the internal instrument memory. Storage capacity: **64 different logging sections, sample interval, user selectable.**
- Start and stop can be set automatically with the **auto-start function**,
- Selectable **measurement unit** of the temperature: °C, °F, °K.
- The display of **maximum, minimum, medium** statistic parameters.
- The data transfer via RS232 or USB serial port.

HD32.3 instrument can detect simultaneously the following quantities:
- Globe thermometer temperature **Tg** with **TP3276.2 (or TP3275)** probe.
- Natural wet bulb temperature **Tn** with **HP3201.2 (or HP3201)** probe.
- Environment temperature **T** with **TP3207.2** probe **(or TP3207).**
- Relative humidity **RH** and environment temperature **T** with **HP3217.2 (or HP3217R)** probe.
- Air speed **Va** with **AP3203.2 (or AP3203)** probe.

Starting from the measured values, HD32.3 can **calculate** and **display,** with **TP3207.2 (or TP3207), TP3276.2 (or TP3275),** and **HP3201.2 (or HP3201)** probes, the following indexes:
- **WBGT (in)** Index (Wet Bulb Glob Temperature: wet bulb temperature and globe thermometer) in absence of solar radiation.
- **WBGT (out)** Index (Wet Bulb Glob Temperature: wet bulb temperature and globe thermometer) in presence of solar radiation.

Starting from the measured values, the HD32.3 instrument can **calculate** and **display,** with **HP3217.2R (or HP3217R), TP3276.2 (or TP3276 or TP3275),** and **AP3203.2 (or AP3203)** probes, the following indexes:
- Medium radiant temperature **Tr**.
- **PMV** Index (Predicted Mean Vote).
- **PPD** Index (Predicted Percentage of Dissatisfied).

WBGT index
WBGT (Wet Bulb Globe Temperature – wet bulb and globe temperature) is one of the indexes used to determinate the occupational heat exposure.
It represents the value, related to the metabolic expenditure linked to a specific work activity, that causes a thermal stress when exceeded.
WBGT index combines the measurement of wet bulb temperature t_{nw} with natural ventilation with the globe thermometer temperature t_g and, in some situations, with the air temperature t_a.
The calculation formula is the following:
- inside and outside the buildings in absence of solar radiation:
  $WBGT_{close\ environments} = 0{,}7\ t_{nw} + 0{,}3\ t_g$
- outside the buildings in presence of solar radiation:
  $WBGT_{outside\ environments} = 0{,}7\ t_{nw} + 0{,}2\ t_g + 0{,}1\ t_a$

where:
t_{nw} = wet bulb temperature with natural ventilation;
t_g = globe thermometer temperature;
t_a = air temperature.

The measured data should be compared with the limit values prescribed by the regulations;
when exceeded you have to:
- reduce directly the thermal stress on the examined work place;
- proceed to a detailed analysis of the thermal stress.

In order to measure the WBGT index, the following probes should be connected:
- **Natural wet bulb HP3201.2 (or HP3201).**
- **TP3276.2 (or TP3275 or TP3276) Globe thermometer probe.**
- **TP3207.2 (or TP3207) Dry bulb temperature, of the measurement is performed in presence of solar radiation.**

In order to measure the WBGT index, you should refer to the following regulations:
- **ISO 7726**
- **ISO 7243**
- **ISO 8996**

PMV - PPD indexes
Human thermal comfort is defined by ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers INC) as the state of mind that expresses satisfaction with the surrounding living or working environment.
The evaluation of this subjective condition can be objectified and quantified using integrated index that consider the micro climatic environment parameters (Ta, Tr, Va, RH), and the work-related energy metabolic expenditure MET, and the typology of clothing (thermal insulation CLO) commonly used.
Among these indexes, the most precise one reflecting the influence of the above mentioned physical and physiological variables on thermal comfort is **PMV** (Predicted Mean Vote).
Synthetically, it comes from the equation of the thermal balance whose result is compared to a scale of psycho - physical health and expresses the average opinion (average foreseen vote) about the thermal sensations of a group of subjects.
From PMV is derived a second index called **PPD** (Predicted Percentage of Dissatisfied) that quantifies the percentage of subjects who will be dissatisfied with some micro climatic conditions.
ISO 7730 regulations suggests PMV use in presence of following variables that influence the thermal balance:
- Metabolic expenditure = 1 ÷ 4 met
- Thermal resistance of clothing = 0 ÷ 2 clo
- Dry bulb temperature = 10 ÷ 30°C
- Medium radiant temperature = 10 ÷ 40°C

MW-16

- Air speed = 0 ÷ 1 m/sec
- Water vapour pressure = 0 ÷ 2,7 kPa

PMV is a particularly suitable index for the evaluation of **work places with moderate microclimate** such as houses, schools, offices, research laboratories, hospitals, and is useful to predict the number of people likely to feel uncomfortably warm or cool.

According to ISO 7730 PMV values range between + 0,5 and - 0,5, provides comfort conditions corresponding to a percentage of dissatisfied (PPD) lower than 10%. (see table below).

Table 1: valuation scale of the thermal environment

PMV	PPD %	EVALUATION THERMAL ENVIRONMENT
+3	100	Hot
+2	75,7	Warm
+1	26,4	Slightly warm
+0,85	**20**	**Acceptable thermal condition**
-0,5 < PMV < +0,5	**< 10**	**Comfortable**
-0,85	**20**	**Acceptable thermal condition**
-1	26,8	Cool
-2	76,4	Cold
-3	100	Extremely cold

To calculate PMV and PPD indices, it's necessary to know:
- the working load (energy expenditure);
- the clothing thermal insulation.



HD40.1

Example of immediate data printing of PMV, obtained with HD40.1 printer

```
========================
  ISO 7730  PMV Index
========================
Model HD32.3 WBGT - PMV
Firm.Ver.=01.00
Firm.Date=2008/12/05
SN=12345678
ID=0000000000000000
------------------------
Probe ch.1 description
Type: Hot wire
Data cal.:2008/10/15
Serial N.:08109460
------------------------
Probe ch.2 description
Type: Pt100 Tg 50
Data cal.:2008/10/01
Serial N.:08109452
------------------------
Probe ch.3 description
Type: RH
Data cal.:2008/10/15
Serial N.:08109464
========================
Date=2008/11/21 15:00:00
Va              0.00 m/s
Tg              22.0 °C
Ta              22.0 °C
RH              39.1  %
MET             1.20
CLO             1.00
PMV             0.10
PPD             5.10  %
========================
```

NOTES

Reference standard

Instrument model
Version of the instrument firmware
Date of the instrument firmware
Serial number of the instrument
Identification Code

Description of the probe connected to input 1

Description of the probe connected to input 2

Description of the probe connected to input 3

Date and time
Air speed
Globe thermometer temperature
Dry bulb temperature
Relative humidity
Metabolic expenditure
Resistance of clothing
PMV – Predicted Mean Vote
PPD – Predicted Percentage of Dissatisfied



MW-17

Average radiant temperature T,
The average radiant temperature is defined as the temperature of thermally uniform simulated environment that would exchange with a man the same thermal radiation power exchanged in the real environment.
In order to evaluate the average radiant temperature, it is necessary to measure: the globe thermometer temperature, the air temperature, and the air speed measured close to the globe thermometer.

TECHNICAL FEATURES

Instrument

Dimensions (Length x Width x Height)	185x90x40 mm
Weight	470 g (batteries included)
Materials	ABS, rubber
Display	Back light, dot-matrix 160x160 points, visible area 52x42mm

Working Conditions

Working temperature	-5 … 50°C
Storage temperature	-25 … 65°C
Working relative humidity	0 … 90% RH no condensation
Protection Degree	**IP65**

Instrument uncertainty	± 1 digit @ 20°C
Power supply	Mains power supply (cod. SWD10) 12Vdc/1A
Batteries	4 batteries 1.5V type AA
Autonomy	200 hours with 1800mAh alkaline batteries
Power absorbed with instrument off	< 45µA
Safety of the stored data	Unlimited

TP3207.2 (TP3207) temperature probe

Sensor type:	Pt100 with thin film
Accuracy:	Class 1/3 DIN
Measurement range:	-40 ÷ 100 °C
Resolution:	0.1°C
Temperature drift @20°C:	0.003%/°C
Drift after 1 year:	0.1°C/year
Connection:	4 wires plus SICRAM module
Connector:	8 female poles DIN45326
Dimensions:	Ø=14 mm L= 150 mm
Response time T_{95}:	15 minutes

TP3276.2 globe thermometer probe Ø=50 mm (Ø=150 mm TP3275)

Sensor type:	Pt100
Accuracy:	Class 1/3 DIN
Measurement range:	-10 ÷ 100 °C
Resolution:	0.1°C
Temperature drift @20°C:	0.003%/°C
Drift after 1 year:	0.1°C/year
Connection:	4 wires plus SICRAM module
Connector:	8 female poles DIN45326
Stem dimension:	Ø=8 mm L= 170 mm
Response time T_{95}:	15 minutes

HP3201.2 (HP3201) Natural wet bulb

Sensor type:	Pt100
Accuracy:	Class A with platinum wire
Measurement range:	4 °C ÷ 80 °C
Resolution:	0.1°C
Temperature drift @20°C:	0.003%/°C
Drift after 1 year:	0.1°C/year
Connection:	4 wires plus SICRAM Module
Connector:	8 female poles DIN45326
Stem dimension:	Ø=14 mm L= 170 mm
Braid length:	10 cm. at least
Tank capacity:	15 cc.
Tank autonomy:	96 hours with RH=50%, t = 23°C
Response time T_{95}:	15 minutes



HP3217.2R (HP3217R) Combined temperature and relative humidity probe

Sensor type:	Pt100 with thin film for temperature Capacitive sensor for relative humidity
Temperature accuracy:	1/3 DIN
Relative humidity accuracy:	± 1.5%RH (0 ÷ 90 %RH) ± 2.0%RH remaining range, for T=15…35°C ± (1.5+1.5% of measure)%RH in the remaining temperature range
Measuring range:	temperature: -40…+100°C relative humidity: 0…100%RH
Connection:	4 wires plus SICRAM Module
Connector:	8 female poles DIN45326
Dimensions:	Ø=14 mm L= 150 mm
Response time T_{95}:	15 minutes
Resolution:	0.1%RH, 0.1°C

AP3203.2 (AP3203) *Omnidirectional hot wire probe*

Sensor type:	NTC 10kohm
Accuracy:	± 0.2 m/s (0÷1 m/s) ± 0.3 m/s (1÷5 m/s)
Measuring range:	0.1…5 m/s 0 °C ÷ 80 °C
Connection:	7 wires plus SICRAM Module
Connector:	8 female poles DIN45326
Stem dimension:	Ø=8 mm L= 230 mm



Protection dimension:	Ø=80 mm
Resolution:	0.01 m/s
Temperature drift @20°C:	0.06% /°C
Drift after 1 year:	0.12 °C/years

Connections

Input for SICRAM module probes	3 Connectors 8 male poles DIN 45326

USB Interface

Type	USB 1.1 or 2.0 insulated
Connection	M12-8 poles
Baud rate	460800 baud.

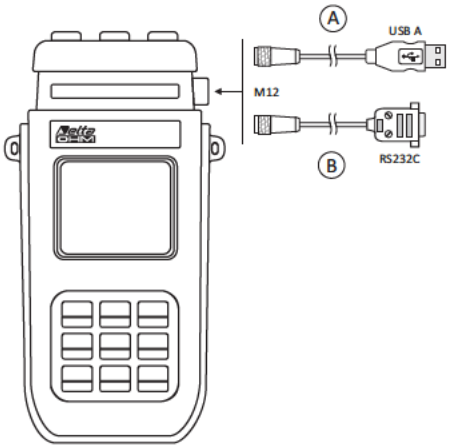
RS232C Serial interface:

Pin:	M12-8 poles.
Type:	RS232C (EIA/TIA574) insulated
Baud rate:	from 1200 to 38400 baud.
Data bit:	8
Parity:	None
Stop Bit:	1
Flow Control:	Xon-Xoff
Cable length:	max 15m

Memory

	divided in 64 blocks.
Storage capacity	67600 memorizations for each of 3 inputs.
Logging interval	selectable among: 15, 30 seconds, 1, 2, 5, 10, 15, 20, 30 minutes and 1 hour.

Logging interval	Storage capacity
15 seconds	Approx. 11 days and 17 hours
30 seconds	Approx. 23 days and 11 hours
1 minute	Approx. 46 days and 22 hours
2 minutes	Approx. 93 days and 21 hours
5 minutes	Approx. 234 days and 17 hours
10 minutes	Approx. 1 year and 104 days
15 minutes	Approx. 1 year and 339 days
20 minutes	Approx. 2 years and 208 days
30 minutes	Approx. 3 years and 313 days
1 hour	Approx. 7 years and 261 days



A USB connection to PC using type A USB - M12 cable, code HD2110USB. **USB drivers are required.**

B RS232C connection to PC. It allows you to connect the RS232C serial port of a PC or the printer HD40.1 with the cable HD2110RS.

ORDERING CODES

HD32.3 is composed of:

- Instrument **HD32.3**, 4 alkaline batteries 1.5V type AA, instruction manual, case. **DeltaLog10 Software for the analysis of WBGT, PMV and PPD indexes. Probes and cables have to be ordered separately.**

HD32.3A is composed of:

- Instrument **HD32.3**, 4 alkaline batteries 1.5V type AA, instruction manual, case. **DeltaLog10 Software for the analysis of WBGT, PMV and PPD indexes. Probes and cables have to be ordered separately.**

The **probes** required for **WBGT** measurement are:

- **TP3207.2 (TP3207)** Dry bulb temperature probe.
- **TP3276.2 (TP3275 or TP3276)** Globe thermometer probe.
- **HP3201.2 (HP3201) Natural w**et bulb temperature probe with natural ventilation.

The **probes** required for **PMV** measurement are:

- **HP3217.2R (HP3217R)** Combined e temperature and relative humidity probe
- **AP3203.2 (AP3203)** Omni-directional hot wire probe.
- **TP3276.2 (TP3275 or TP3276)** Globe thermometer probe.

Probes for HD32.3 (without cable)

TP3207.2: Temperature probe with Pt100 sensor. Probe stem Ø 14mm, length 150mm. Equipped with SICRAM module. **Used for WBGT measurement.**

TP3276.2: Globe thermometer sensor Pt100, globe Ø 50 mm. Stem Ø 8 mm, length 170 mm. Equipped with SICRAM module. **Used for WBGT, PMV and PPD measurements.**

HP3201.2: Natural wet bulb. Pt100 sensor. Probe stem Ø 14 mm, length 170 mm. Equipped with SICRAM module, spares of braid and 50 cc of distilled water. **Used for WBGT measurement.**

HP3217.2R: Combined temperature and relative humidity probe. Capacitive RH sensor, Pt100 temperature sensor. Probe stem Ø 14 mm, length 150 mm. Equipped with SICRAM module. **Used for PMW and PPD measurement.**

AP3203.2: Omni-directional hot wire probe. Measuring range: air speed 0.1÷5 m/s, temperature 0÷80 °C. Probe stem Ø 8 mm, length 230 mm. Equipped with SICRAM module. **Used for PMW and PPD measurement.**

Probes for HD32.3 version A (with cable):

TP3207: Temperature probe with Pt100 sensor. Probe stem Ø 14mm, length 150mm. Cable 2m long. Equipped with SICRAM module. Used for the calculation of the following indices: **PMV, PPD, WBGT.**

TP3275: Globe thermometer sensor Pt100, globe Ø 150 mm. Stem Ø 14 mm, length 110 mm. Cable 2m long. Equipped with SICRAM module. **Used for Mean radiant temperature, WBGT.**

HP3201: Natural wet bulb. Pt100 sensor. Probe stem Ø 14 mm, length 110 mm. Equipped with SICRAM module, spare braid and 50 cc of distilled water. **Used for WBGT measurement.**

HP3217R: Combined temperature and relative humidity probe. Capacitive RH sensor, Pt100 temperature sensor. Probe stem Ø 14 mm, length 150 mm. Equipped with SICRAM module. **Used for PMV and PPD measurement.**

AP3203: Omni-directional hot wire probe. Measuring range: air speed 0.1÷5 m/s, temperature 0÷80 °C. Probe stem Ø 8 mm, length 230 mm. Equipped with SICRAM module. **Used for PMV and PPD measurement.**

Accessories:

VTRAP30: Tripod to suit instrument with a maximum height of 280 mm

HD32.2.7: Probe holder, **to be fixed on standard tripod. For version HD32.2A.**

HD2110RS: Connection cable with M12 connector from the instrument side and with SubD female connector 9 poles for RS232C from PC side.

HD2110USB: Connection cable with M12-8 poles that attaches to instrument side and USB 2.0 on PC side.

SWD10: 100-240Vac/12Vdc-1A mains voltage stabilized power supply.

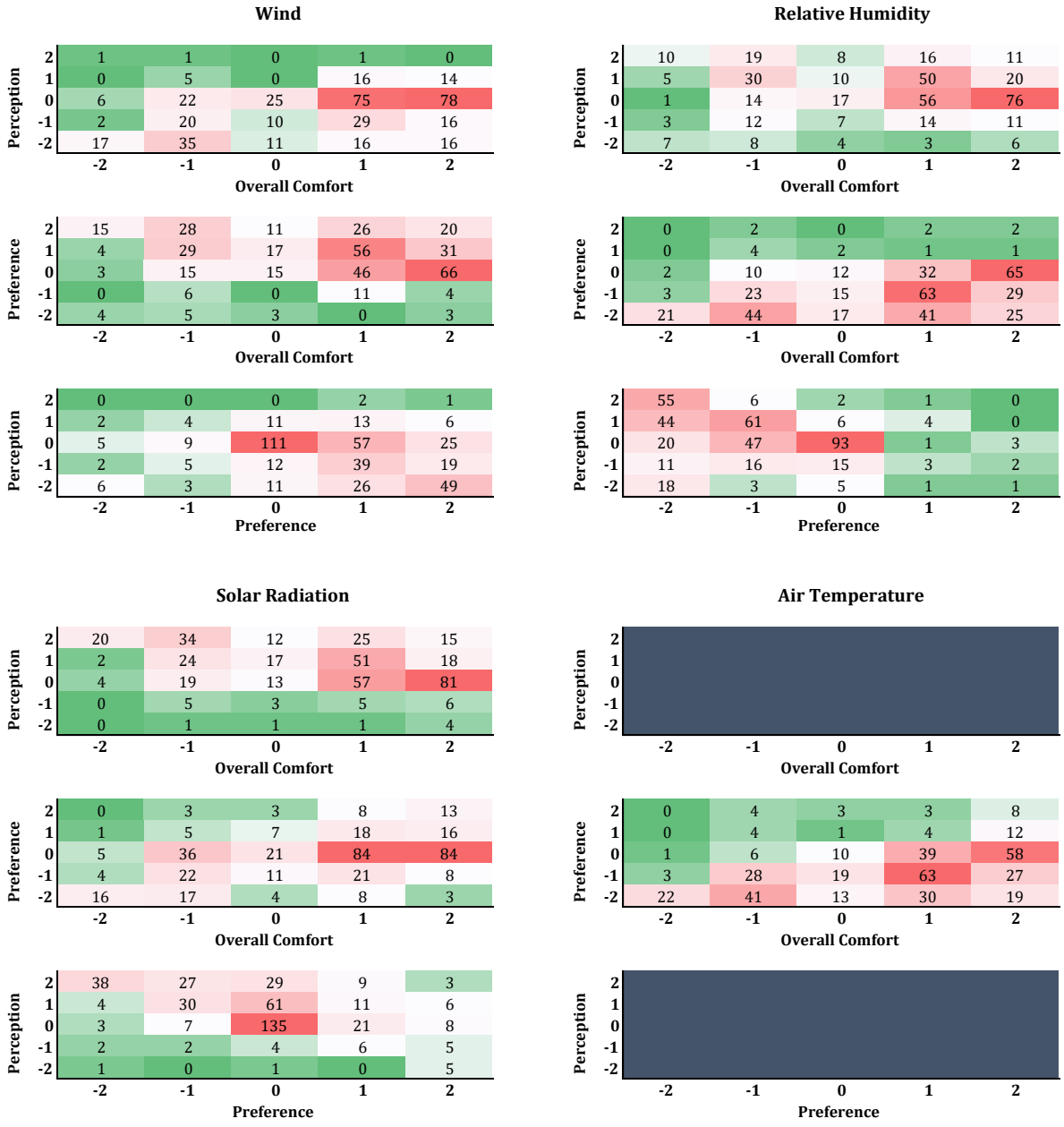
AQC: 200cc. of distilled water and n° 3 braids for HP3201 or HP3201.2 probes

HD40.1: 24-column portable printer (uses **HD2110RS** cable)

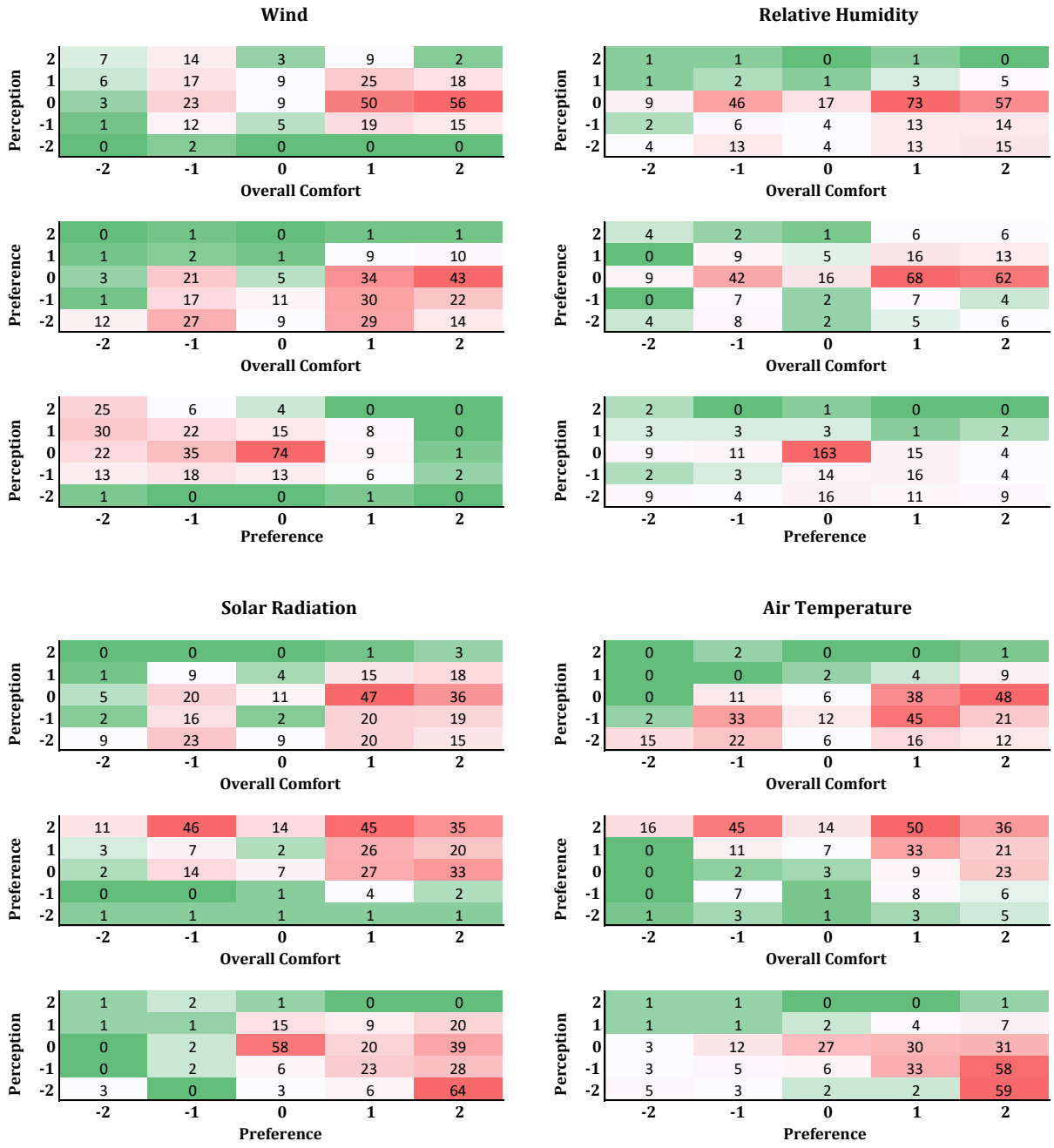
BAT.40: Spare battery pack for HD40.1 printer with built-in temperature sensor.

RCT: The kit includes 4 thermal paper rolls, wide 57mm, diameter 32mm.

Appendix 3 - Individual Weather Variables: Results from Surveys



Appendix 2a.
Summer participant distribution for thermal preference, perception of individual weather variables. For perception, a vote of "2" would imply that the person is perceiving "too much" of that particular weather variable, whereas voting "-2" would imply that there is "not enough", and "0" is content. For preference, a vote of "2" implies that the person would "prefer more", voting "-2" indicates a preference for less, and again "0" is content. For overall comfort, a vote of "2" implies that the person is in full agreement, whereas a vote of -2 implies disagreement, and a vote of "0" is uncertain. The following demonstrates how these results can be useful in understanding thermal comfort and individual weather variables using wind in summer and winter as an example variable. Note: a question for air temperature perception was missing from the summer survey.



Appendix 2b.

Winter participant distribution for thermal preference, perception of individual weather variables. For perception, a vote of "2" would imply that the person is perceiving "too much" of that particular weather variable, whereas voting "-2" would imply that there is "not enough", and "0" is content. For preference, a vote of "2" implies that the person would "prefer more", voting "-2" indicates a preference for less, and again "0" is content. For overall comfort, a vote of "2" implies that the person is in full agreement, whereas a vote of -2 implies disagreement, and a vote of "0" is uncertain. The following demonstrates how these results can be useful in understanding thermal comfort and individual weather variables using wind in summer and winter as an example variable.

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