

UNIVERSITY OF CALGARY

Thermal Performance of the Extensive Green Roof in Semi-Arid and Cold Climates

by

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A THESIS

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ABSTRACT

Green roofs have recently gained popularity worldwide to reduce building energy consumption for heating and cooling. Many studies have shown the thermal benefits of green roofs in enhancing building energy efficiency in different climates, particularly in hot and temperate climates. However, studies in cold-climate regions are still limited, especially in cold and semi-arid regions. Therefore, this thesis aimed to provide region-specific knowledge by statistically analyzing the thermal performance of an extensive green roof and a reference roof in the City of Calgary, Alberta, in this climate context.

In this thesis, data including roof temperature at several layers, heat flux, meteorological variables, media temperature, and moisture collected from 2017 to 2018, were used. Several statistical analyses were conducted to examine the thermal behaviour of the green roof and the impacts of media moisture on its thermal performance on hot, normal, and cold days. The results showed that the green roof mitigated spatial variations in temperature and heat flux and improved horizontal heat distribution on hot and normal days compared to the reference roof. Additionally, the green roof provided cooling effects by reducing temperatures at various common layers on hot days compared to the reference roof while offering warming effects on cold and normal days by increasing temperatures. The increased thermal resistance provided by the green roof further reaffirmed these cooling and warming effects. Moreover, the green roof decreased roof temperatures vertically from its top layer to the bottom layer, particularly during the daytime when the air temperature was higher, thereby absorbing and retaining more heat. Conversely, during nighttime, the green roof increased roof temperatures vertically when the air temperature was lower, thus retaining more heat inside the building. In addition, higher moisture content was found to be beneficial in reducing the temperature of the growing media at the bottom layer and reducing

vertical temperature differences. These results confirmed the benefits of green roofs in reducing building energy consumption in the study case climate. Yet, there is a need for more elaborate quantification of the thermal benefits of green roofs at finer spatial and temporal resolutions.

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Dr. Babasaheb Ambedkar

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I dedicate this thesis to Dr. Babasaheb Ambedkar.

&

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LIST OF SYMBOLS AND ABBREVIATIONS

List of symbols

<u>Symbol</u>	<u>Definition</u>
R	Thermal resistance
ΔT	Temperature difference
T_{ex}	External surface temperature
T_{in}	Internal surface temperature
Q	Heat flux passing through the roof
T_{GR}	Roof temperature of a layer of the green roof
T_{RR}	Roof temperature of a layer of the reference roof

List of abbreviations

<u>Abbreviation</u>	<u>Definition</u>
UHI	Urban heat island
GHG	Greenhouse gas
SW	Southwest
NW	Northwest
NE	Northeast
SE	Southeast
TCIUS	Thermocouple at underside of concrete roof slab
TCM	Thermocouple at top of concrete slab
TCTDB	Thermocouple at below drainage board
TCTOI	Thermocouple at top of insulation

TCBGM	Thermocouple at bottom of growing media
TCMGM	Thermocouple at middle of growing media
TCTGM	Thermocouple at top of growing media
HFT	Heat flux transducer
GR	Green roof
RR	Reference roof
HDD	Heating degree days
CDD	Cooling degree days
STR	Surface temperature reduction

CHAPTER 1: INTRODUCTION

While the global human population is constantly growing, the majority of the worldwide population has become urban residents (The World Bank, 2018). This trend is anticipated to continue, reaching 66% by 2050 (United Nations, 2014). Due to this rapid urbanization and population growth, more buildings are being constructed in urban cities and anthropogenic activities are intensifying. These factors are some of the major human-induced contributors to climate change and a local warming phenomenon known as the Urban Heat Island (UHI) effect (Grimmond, 2007; Kalnay & Cai, 2003). As a result of these changes, there has been an increase in outdoor temperatures in urban areas, resulting in uncomfortable indoor environments in buildings (Constantinescu et al., 2016; Krüger, 2015; Santamouris et al., 2015). This has led to a notable rise in energy demand over the past decades, primarily for cooling purposes. In urban settings, the building sector (residential, commercial, and institutional buildings) is one of the highest energy consumers, accounting for approximately 40% of total global energy consumption (Costa et al., 2013; GhaffarianHoseini et al., 2013; Zhou et al., 2014). Consequently, buildings are responsible for 33% of Greenhouse Gas (GHG) emissions globally (Costa et al., 2013). A substantial portion of energy consumption is dedicated to cooling and heating to maintain indoor thermal comfort. Globally, China and the United States are the top two energy-consuming countries. In the United States, the building sector accounted for 38.9% of the total primary energy consumption in 2006. By 2014, this figure had risen to 41%, with 35% used for space heating, ventilation, and air conditioning (Kwok & Rajkovich, 2010; Ma et al., 2017; Waite et al., 2017). In China, the building sector consumed 27.5% of the total national energy use in 2001, with projections indicating an increase to approximately 35% by 2020 (Yao et al., 2005). It is projected

that China will reach a similar level of energy consumption for space heating, ventilation, and air conditioning as the USA in the next few years (Waite et al., 2017). While building energy consumption accounts for 40% in Europe, 23% in Spain, 39% in the United Kingdom, and 25% in Japan, a substantial portion of this usage is dedicated to space heating and cooling (Abu Bakar et al., 2015; Masoso & Grobler, 2010; Zhao & Magoulès, 2012).

Furthermore, Canada produced approximately 1.6% of the total global GHG Greenhouse Gas emissions, with the building sector contributing 11.9% to Canada's total GHG emissions in 2014 (Government of Canada, 2016). The energy consumption of residential, commercial, and industrial buildings in Canada is approximately 60% due to space heating and 5% due to space cooling (NRCan, 2020). In British Columbia, residential and commercial buildings consume approximately 22% of the province's total energy (Government of Canada, 2024b). In Ontario, these buildings account for about 35% of the total energy consumption and contribute around 25% of greenhouse gas emissions. Similarly, in Manitoba, residential and commercial buildings use about 36% of the total consumption, contributing 14% of the total GHG emissions (Government of Canada, 2024b). In Alberta, the residential sector is the third-largest consumer of energy (Farahbakhsh et al., 1998; Subramanyam et al., 2015). The average energy consumption per household in Alberta is much higher than in other provinces and has shown an increasing trend over several decades (Government of Canada, 2024a). Notably, from 1990 and 2021, there was a 39% increase in overall energy consumption and a 28% rise in GHG emissions within Alberta's residential sector (NRCan, 2015; StatisticsCanada, 2013). Within this sector, space heating and cooling account for approximately 64% of total energy consumption, the highest among all sub-sectors (i.e., water heating, appliances, and lighting) (NRCan, 2015; Subramanyam & Kumar,

2012). Therefore, reducing energy consumption for heating and cooling by buildings would largely reduce total energy consumption and, thus, total GHG emissions.

To reduce energy consumption in the building sector, numerous technologies have been investigated to enhance building indoor thermal comfort. These include the use of thermal and acoustic insulating materials made from natural and recycled resources (Asdrubali et al., 2015), the development of heat-dissipative cooling techniques through natural ventilation, evaporative and radiative cooling, and solar shading for roofs (Gupta & Tiwari, 2016; Prakash, 2017), the use of high-albedo materials (Taha et al., 1992), the utilization of phase change materials (PCMs) for thermal energy storage (Jeon et al., 2013; Song et al., 2018), and the use of phase change humidity control materials (PCHCMs) to enhance indoor hygrothermal condition by absorbing and releasing heat and moisture (Wu et al., 2018).

Apart from these technologies, green infrastructure in urban settings, like green roofs and bioretention systems, has recently become popular for enhancing indoor and outdoor thermal comfort, thereby mitigating the energy consumption of buildings, along with their other benefits. Bioretention systems have showcased their ability to enhance outdoor comfort by reducing land surface temperatures and cooling the surrounding environment, thereby mitigating the UHI effect, in addition to their benefits in managing and improving stormwater (Kridakorn Na Ayutthaya et al., 2023; H. Shao & Kim, 2022; Timm et al., 2020; Vijayaraghavan et al., 2021). Green roofs have demonstrated their benefits in various aspects. Green roofs offer environmental benefits such as reducing stormwater runoff, decreasing peak flows, delaying runoff onset, enhancing biodiversity, and reducing air and noise pollution (Czemieli Berndtsson, 2010, 2010; W. C. Li & Yeung, 2014; Mentens et al., 2006; Yang et al., 2008). Additionally, they provide economic and social benefits by improving the appearance of buildings and neighborhoods, lowering life-cycle costs, and

extending roof lifespan (Carter & Keeler, 2008; H. Feng & Hewage, 2018; Kim et al., 2018). Apart from the above-mentioned environmental, social, and economic benefits, green roofs have been demonstrated to have the potential to reduce building energy consumption and mitigate the UHI effect, particularly in urban settings (Mutani & Todeschi, 2020; Razzaghmanesh et al., 2016; Susca, 2019; Yang et al., 2018; Zinzi & Agnoli, 2012). Therefore, the implementation of green roofs has attracted more attention worldwide due to their multiple benefits.

To date, numerous research studies have demonstrated the thermal behaviour of green roofs and their efficacy in reducing building energy consumption across various climatic conditions and geographic locations. Previous research studies revealed that green roofs benefit buildings by reducing cooling and heating loads, mitigating temperature fluctuations on roofs, and preventing undesirable heat transmission in hot and semi-hot climates (He et al., 2020; Jim & Tsang, 2011; La Roche & Berardi, 2014; Mahmoud et al., 2017; Permpituck & Namprakai, 2012). Similarly, green roofs have shown their effectiveness in reducing/increasing the surface and indoor temperature of buildings, mitigating heat loss and gains, and resulting in energy savings for cooling and heating in Mediterranean and temperate climates (Ávila-Hernández et al., 2020; Bevilacqua et al., 2016; Jaffal et al., 2012; Parizotto & Lamberts, 2011). Additionally, green roofs have been demonstrated to have similar thermal advantages for buildings in cold climates as well (Berardi, 2016; Collins et al., 2017; Ebadati & Ehyaei, 2020).

While the thermal benefits of green roofs are evident across all climate conditions, their effects on roof thermal behaviour and, consequently, their efficiency in reducing building energy consumption vary across different climate conditions, geographic locations, and green roof designs and configurations. For example, increasing the thickness of the growing media enhances soil water retention capacity and evapotranspiration, thereby reducing overall energy consumption for

buildings in warm and temperate climates (Khabaz, 2018; Silva et al., 2016; Zeng et al., 2017). On the contrary, increasing the depth of the growing media did not enhance the thermal performance of green roofs or contribute to building energy savings in temperate climates (Maiolo et al., 2020). Furthermore, many research studies have shown that varying levels of moisture content in the growing media help reduce energy consumption and improve the thermal performance of green roofs by providing cooling effects to buildings in diverse climatic conditions and geographic locations (Jim & Peng, 2012a; Lazzarin et al., 2005; Nyuk Hien et al., 2007; Vera et al., 2015). Conversely, some studies conducted in various climates have found that the moisture content has shown either no effect or a reverse effect on the thermal performance of green roofs (Costanzo et al., 2016; Virk et al., 2014, 2015). On the other hand, the impact of vegetation on the thermal performance of green roofs varies significantly depending on the type of vegetation, its evapotranspiration rate, seasons, and climatic conditions (Chagolla-Aranda et al., 2017; Chan & Chow, 2013; M. (Max) Liu, 2014; Olivieri et al., 2013; Refahi & Talkhabi, 2015). Vegetation species planted on green roofs are largely determined by climate conditions and regions, among others.

The previous varying and contradictory knowledge among different climatic conditions and regions suggests the need to conduct climate- and regional-specific studies to examine the green roof's benefit in reducing building energy consumption. Additionally, while many previous research studies have extensively investigated the thermal behaviour of green roofs and their advantages in energy savings for cooling and heating in different climatic conditions, especially in hot and temperate climates, studies conducted in cold and semi-arid climatic conditions are still very limited. Therefore, a quantitative investigation of the effects of green roofs on roof thermal

performance is still desired to build more confidence in their implementation for reducing building energy consumption in this climatic condition.

The City of Calgary, Alberta, Canada, which has a cold and semi-arid climate, has experienced rapid population growth in recent years. The population of Calgary increased by 5.5% from 2016 (1,239,220) to 2021 (1,306,780) (City of Calgary, 2023). This increasing trend is expected to continue in the coming years. Due to this rapid population growth, urbanization in the city is increasing consistently, leading to a notable increase in the demand for building energy consumption. The total annual expenditure of Calgary on energy consumption across all sectors is \$2.6 billion (Sudmant et al., 2020). As mentioned above, the residential sector is the third-largest consumer of energy in Alberta, with space cooling and heating accounting for the largest portion of total energy consumption. As the most populated city in Alberta, Calgary contributes a significant portion of the total energy consumption, especially for space cooling and heating in Alberta. In addition, during the winters, Calgary experiences several cold snaps, which drastically increases the heating demand. Therefore, using green roofs might be an effective option to help mitigate the increased energy consumption for heating and cooling by buildings in the city.

In the last decade, the City of Calgary initiated research to quantify the benefits of green roofs from the urban stormwater management perspective. A field-pilot extensive green roof and a conventional/reference roof (for comparison purposes) were installed in 2014 on the Municipal Building. Acknowledging the thermal benefits of green roofs, the pilot study roofs were also instrumented to collect roof temperature at various layers and heat flux data to evaluate their thermal performance. In this thesis, the data collected from these roofs were utilized to examine the effects of the green roof on thermal performance by comparing it with the reference roof. The study outcomes would quantitatively showcase the roles of green roofs on roof thermal behaviour

and performance in contrasting seasons (e.g., warm and cold seasons) and provide evident-based knowledge to the city for the potential large-scale implementation to reduce building energy consumption.

CHAPTER 2: LITERATURE REVIEW

2.1 Green roof structure and benefits

2.1.1 Structure and types of green roofs

A green roof, also known as a living roof, eco-roof, or vegetated roof, is a roof of a building that is partially or completely covered with a layer of engineered growing media and vegetation. In general, a green roof consists of five main layers, including a root membrane and waterproofing membrane, a drainage layer, a filter layer, a growing media layer, and vegetation, arranged from the bottom to the top. Green roofs are broadly classified into intensive, semi-intensive, and extensive types based on the thickness of the growing media. Intensive green roofs typically have a thicker layer of growing media (20 to 200 cm deep), allowing for cultivating a wide variety of plants, including shrubs and small trees. However, the high capital cost, the high maintenance requirements (e.g., fertilizing, weeding, and watering), and the need for additional structural reinforcement of the roof due to the increased weight have limited their application, particularly on existing buildings. Semi-intensive green roofs have a layer of growing media typically ranging from 15-20 cm deep. They can support small herbaceous plants, ground covers, grasses, and small shrubs, but require regular maintenance. Unlike intensive green roofs, extensive green roofs have a thinner layer of growing media, typically less than 15 cm deep. Consequently, extensive green roofs require minimal maintenance, have low capital and maintenance costs, and can be installed on sloped roofs. In addition, extensive green roofs can be planted with different vegetation, including grasses, herbs, mosses, and a few succulents (e.g., sedums). Due to their lighter weight, extensive green roofs do not require additional structural support, making them more common. Among the three types of green roofs, extensive green roofs are the most common, primarily due

to their low cost, minimal maintenance requirements, and the fact that they typically do not require additional structural support.

2.1.2 Benefits of green roofs

Green roofs have attracted worldwide attention in recent years, as they have been demonstrated to have numerous environmental and economic benefits. Their environmental benefits include improving stormwater management by reducing stormwater runoff volumes, attenuating peak flows, delaying the initial time of runoff and the occurrence of peak flow, reducing contaminant loadings/concentration (Czemiel Berndtsson, 2010; Mentens et al., 2006; Nawaz et al., 2015; Razzaghmanesh & Beecham, 2014), enhancing biodiversity by restoring aquatic habitat and increasing natural habitat for wildlife (Czemiel Berndtsson, 2010; Schrader & Böning, 2006), and reducing noise and air pollution (W. C. Li & Yeung, 2014; Van Renterghem & Botteldooren, 2011; Yang et al., 2008). Apart from this, green roofs have showcased their potential to mitigate the urban heat island effect by increasing roof albedo, thereby reducing ambient temperatures (Alexandri & Jones, 2008; Gill et al., 2007; J. Li et al., 2010; Santamouris, 2014). On the other hand, green roofs have social and economic benefits, such as enhancing the aesthetic of buildings and neighbourhoods, reducing life cycle costs, and increasing the lifespan of the roof (Carter & Keeler, 2008; Feng & Hewage, 2018; Kim et al., 2018). In addition to the aforementioned benefits, green roofs have shown their effectiveness in reducing building energy consumption for heating and cooling, as described in the following sections. Due to their multifaceted benefits, including environmental, social, and economic, green roofs have attracted attention from municipalities in Canada and worldwide.

2.2 Green roofs for reducing building energy consumption

2.2.1 Heat transfer mechanisms/processes

The thermal properties of green roofs differ from conventional roofs due to the presence of growing media, vegetation, and water (within their growing media). Therefore, several heat transfer processes influence the thermal performance of green roofs. The heat transfer processes in green roofs are mainly influenced by conduction, convection, radiation, evapotranspiration, and heat storage (Liu, 2011; Sailor, 2008; X. Tang, 2015; Wark, 2010). In general, conduction is the process of heat transfer through a solid material from higher-temperature regions to lower-temperature regions. The heat transfer rate through the material is primarily governed by its thermal conductivity. The greater the thermal conductivity, the more effective heat transfer is. The soil and vegetation layers of green roofs act as thermal insulation, as they affect the roof's overall thermal conductivity by reducing its thermal mass – thermal mass refers to the capacity of the building mass to control heat storage and temperature fluctuations. In convection, heat is transferred through the movement of matter. The presence of water moving through growing media and drainage layers of green roofs can influence the overall temperature of the roof. Additionally, the impact of wind blowing around the roof could also be a contributing factor.

Radiation is the process by which heat is transferred from warmer surfaces to cooler surfaces. Both conduction and radiation are processes by which heat is transferred. However, unlike conduction, radiation does not require a medium to transfer heat and can occur through “empty” spaces. Roofs are exposed to solar radiation, which they absorb and then reflect into the atmosphere. The vegetation and growing media layers of green roofs absorb and reflect solar radiation, reducing heat transfer and influencing the roof's overall temperature. The evapotranspiration process combines evaporation and plant transpiration from a vegetated surface

to the atmosphere. The absorption of heat energy is required for water to change its state from liquid to vapour. In green roofs, water stored in growing media evaporates into the surrounding air. Additionally, vegetation absorbs water through its roots and transpires it through its leaves into the atmosphere. This process helps to cool roofs. Furthermore, the capacity for heat storage depends on the thermal mass of materials. Both growing media of green roofs and water within growing media can store more heat due to their high thermal mass, thereby helping to stabilize the roof's temperature.

2.2.2 Thermal benefits of green roofs on buildings in different climatic zones

To date, numerous research studies have demonstrated the effectiveness of green roofs in enhancing thermal performance, thereby reducing building energy consumption across various geographic and climatic conditions. In the hot climates of Phoenix, Los Angeles, and Chicago, green roofs have reduced annual energy consumption by 9.13%, 8.92%, and 2.11%, respectively (La Roche & Berardi, 2014). Similarly, in Shanghai, the green roof reduced the cooling and heating loads by 3.6 and 6.2%, respectively (He et al., 2020). In another study conducted in the hot climate of Hong Kong, growing media effectively reduced heat penetration into the building and mitigated temperature fluctuations (Jim & Tsang, 2011). A study in the hot and humid climate of Bandar Abbas, Iran, showed that green roofs reduced annual energy consumption for heating and cooling by 23% (Ebadati & Ehyaei, 2020). In a similar climatic condition in Saudi Arabia, energy consumption was found to be reduced by green roofs by 24% to 35% (Mahmoud et al., 2017). In the hot and arid climate of Cairo, Egypt, green roofs mitigated annual energy consumption by 17% to 25% (Wahba et al., 2018). Furthermore, a study conducted in the hot and moist climate of Singapore demonstrated that green roofs reduced annual energy consumption by up to 15% and

space cooling loads by up to 70% (Wong et al., 2003a). In a semi-hot and moist climate in Thailand, a study showed that green roofs reduced building energy consumption by 37% and mitigated heat transfer by 20.65% compared to conventional roofs (Permpituck & Namprakai, 2012). A study conducted in the Mediterranean climate of Italy showed that the surface temperature of the green roof was reduced by 12°C due to the insulation provided by the growing media layer compared to the conventional roof, thereby mitigating the heat transfer into the building (Bevilacqua et al., 2016). In the temperate climatic conditions of Southern Brazil, green roofs demonstrated their ability to mitigate heat gain by 92% to 97% during the warm period while reducing heat loss by 52% during the cold period (Parizotto & Lamberts, 2011). In similar climatic conditions, annual energy consumption was reduced by 16.3% in France and 6% in Iran (Ebadati & Ehyaei, 2020; Jaffal et al., 2012). In addition, in Mexico, with a temperate climate, green roofs decreased the cooling energy demand by up to 99% (Ávila-Hernández et al., 2020). Additionally, green roofs can potentially mitigate the urban heat island effect (Berardi, 2016), and thereby indirectly help reduce building energy consumption in cold climates.

In cold climates, green roofs can also improve roof thermal performance and reduce energy consumption by buildings. A study in the cold climate of Toronto, Canada, showed that green roofs enhanced indoor comfort levels and reduced building energy demand by 3% (Berardi, 2016). Another experimental study in Toronto (Zhao & Srebric, 2012) found that extensive green roofs reduced heat gain by 70-90% in summer and heat loss by 10-30% in winter, reducing overall building energy consumption. In the dry and cold climate of Tabriz, Iran, the annual energy consumption for heating and cooling was found to be reduced by 12.5% due to the use of green roofs (Ebadati & Ehyaei, 2020). In addition, a study conducted in the wet and cold climate of the Hunan Province, China, by Xing et al. (2019) demonstrated that green roofs reduced heat loss from

the building compared to the reference room under heating conditions, leading to a reduction in energy consumption for heating by 18% due to their additional thermal insulation. Similarly, in Finland's cold climatic conditions, green roofs outperformed bare roofs by retaining more heat in winter and saving energy (Collins et al., 2017).

2.2.3 Evaluation of green roof's thermal benefits

Several studies have investigated the thermal benefits of green roofs. These studies have employed various evaluation metrics to quantify their benefits. A large number of studies have examined heat fluxes to compare heat gains and heat losses between green roofs and conventional roofs to quantify the thermal benefits of green roofs in reducing energy consumption (Bevilacqua et al., 2016; D'orazio et al., 2012; Eksi et al., 2017; Getter et al., 2011a; Olivieri et al., 2013; Squier & Davidson, 2016). Apart from this, researchers have utilized the temperatures of the roofs (e.g., surface temperature, indoor temperature, and growing media temperature, etc.) to assess the thermal performance of green roofs. For instance, Anwar et al. (2020) assessed the thermal performance of green roofs by comparing the indoor temperatures of buildings. In the experimental study, they converted two shipping containers into an office building, one with a green roof and the other without, and evaluated their thermal performance under two scenarios: with air conditioning and without air conditioning. Kumar et al. (2015) and Morakinyo et al. (2017) compared the inner and outer surface temperatures of the green roof to evaluate its thermal performance. In an experimental study by Chagolla-Aranda et al. (2017) to quantify the benefits of green roofs, the outer surface temperature of the green roof slab was compared with that of the concrete roof slab. Furthermore, this study assessed the thermal performance of the growing media by analyzing the temperatures of the vegetation, the media surface, and the upper surface of the

green roof slab relative to the volumetric water content. Similarly, another study by Bevilacqua et al. (2016) evaluated the thermal performance of three green roofs with different characteristics compared to a traditional roof. This study compared the indoor environment of the buildings by analyzing the internal air temperature underneath the green roofs and the traditional roof. Additionally, the external surface temperature of the traditional roof was compared to the temperature at the interface with the structural roof of the green roofs.

On the other hand, some studies have assessed the thermal performance of green roofs by evaluating their impact on the surrounding microclimates. Several studies have compared the air temperatures above green roofs and conventional roofs to assess their thermal performance (e.g., Kumar et al., 2015; Moghbel & Erfanian Salim, 2017; Morakinyo et al., 2017; Solcerova et al., 2017; Zheng et al., 2021). For example, Zheng et al. (2021) conducted a study to analyze the air temperature collected at three different heights (i.e., 30 cm, 60 cm, and 120 cm) above the extensive green roof and the bare roof. The air temperature difference was calculated between the extensive green roof and the bare roof at three heights on different temporal scales to assess the warming and cooling effects of the extensive green roof. Solcerova et al. (2017) investigated the impact of several green roofs on the air temperature measured at 15 cm and 30 cm above the roofs. The same study also evaluated the effect of various substrate moisture levels on the air temperature at different heights relative to the white gravel roof to quantify the warming and cooling effects of green roofs. In addition, some other studies compared the relative humidity and wind speed measured above green roofs and conventional roofs to quantify the thermal benefits of green roofs (e.g., Amir et al., 2018; Jim & Peng, 2012b; Moghbel & Erfanian Salim, 2017; Santamouris, 2014).

Furthermore, Tang & Zheng (2019) compared the equivalent thermal resistance of the green roof to that of the common bare roof. Additionally, they analyzed the influence of indoor critical

air temperature on the equivalent thermal resistance and correlation between climatic parameters and thermal behaviour of both roofs. In another study, Collins et al. (2017) evaluated the thermal performance of green roofs by measuring the thermal conductivity of each layer of the green roof, as well as the equivalent thermal resistance of the complete green roof and compared with that of the conventional roof. Shao et al. (2021) examined the thermal benefits of green roofs by investigating the thermal conductivity of the substrate at various temperatures and moisture content levels. D’orazio et al. (2012) calculated the thermal transmittance (*U*-value) of the extensive green roof to quantify its effectiveness in preventing heat transfer. This study also compared the thermal transmittance of the extensive green roof with that of six different types of roofs, considering different coverings and slabs. Some other studies have also used temperature reduction indexes to quantify the potential of green roofs in reducing or increasing temperature. For instance, Bevilacqua et al. (2017) and He et al. (2020) calculated surface temperature reduction (STR) on different temporal scales to quantify the decrease or increase in the outer surface temperature caused by green roofs compared to that of reference roofs.

In addition, some researchers have analyzed the vertical temperature profiles of green roofs to evaluate their impact on the upward and downward transmission of heat, thus potentially reducing energy consumption. For instance, to investigate the passive warming and cooling of green roofs, Jim (2012), (He et al., 2020), and Teemusk & Mander (2010) analyzed the vertical temperature profiles of green roofs. These studies analyzed vertical heat transmission by evaluating temperatures measured at different layers of green roofs, including air temperature at various heights above roofs.

2.2.4 Variables influencing green roof's thermal performance

Growing media, moisture content, and vegetation are key variables that influence the efficiency of green roofs in enhancing their thermal performance (Jamei et al., 2023; Susca, 2019). However, the impact of these variables on the thermal performance depends significantly on the prevailing climate conditions. Therefore, the role of these variables on the thermal performance of green roofs in relation to the background climatic conditions is discussed in this section.

2.2.4.1 Impact of growing media

The growing media is one of the key factors that govern the thermal performance of green roofs. Its thermal insulation properties play a crucial role in enhancing the overall thermal performance of green roofs. Several studies have demonstrated that insulation provided by the growing media reduces heat loss and heat gain, thereby reducing the energy consumption demand of buildings (Sailor, 2008; Theodosiou, 2003; Wong et al., 2003a). However, the impact of growing media layer largely varies depending on the climatic conditions and the thickness and types of media. In the warm climate of Portugal, a study by Silva et al. (2016) concluded that increasing the thickness of growing media enhanced soil water retention capacity and evapotranspiration, consequently improving overall energy efficiency. In contrast, in another study by Maiolo et al. (2020) found that increasing the thickness of growing media did not affect the thermal performance of green roofs and the energy consumption of buildings in the Mediterranean climate. Another study conducted in three different climates of China revealed that 0.3 m is the optimal thickness for growing media to maximize building energy savings in both summer and winter (Zeng et al., 2017). Similarly, in the tropical climate of Madagascar, it was found that soil layers thicker than 4 cm did not notably affect the thermal performance of an extensive green roof

(Rakotondramiarana et al., 2015). A study in hot climate regions of China found that growing media with specific characteristics could offer thermal benefits equivalent to traditional insulation of 125 mm, effectively reducing the building's cooling energy consumption. However, if the growing media's characteristics are not optimized, their energy savings for cooling can decrease to those of less than a 25-mm-layer of thermal insulation (Kokogiannakis & Darkwa, 2014). The same study also revealed that in some regions of China, where heating loads are dominant for buildings, the growing media can provide the same thermal benefits as traditional insulation of 25 mm. The thickness of growing media can also influence the soil moisture in all climates (Kokogiannakis & Darkwa, 2014). For example, in arid climates, the growing media tends to dry out quickly, which can restrict the plant's evapotranspiration processes. In such climates, the use of non-irrigated green roofs may have negligible or even adverse effects on roof thermal performance when compared to traditional roofs (Pérez et al., 2015).

In a warm climate, the thermal performance of extensive, semi-intensive, and intensive green roofs, each with growing media thicknesses of 10 cm, 35 cm, and 70 cm, respectively, was compared. The results showed that, due to the increased thickness of growing media, the intensive and semi-intensive green roofs reduced cooling energy demand by 5.9 and 2.8 times more, respectively, compared to the extensive roof. Whereas all three green roofs showed similar energy savings for heating (Silva et al., 2016). While the impact of growing media on providing insulation to buildings is evident across different climatic conditions, its efficiency is different based on factors such as thickness and type of media, specific soil characteristics, and climatic factors.

2.2.4.2 Impact of moisture

Several studies have confirmed that the presence of moisture content in growing media can influence the thermal performance of green roofs. However, different moisture levels and climatic conditions could affect the thermal performance of green roofs differently (Costanzo et al., 2016; Sailor, 2008; Tan et al., 2017). In the hot and moist climate of Singapore, a study by Nyuk Hien et al. (2007) found that the surface temperature of an extensive green roof was higher when the media was dry compared to the bare roof. Conversely, the surface temperature was cooler by 18°C when the media was wet. In the warm climates of two Italian cities, Rome and Catania, the potential of green roofs to reduce energy demand was evaluated under both irrigation and non-irrigation scenarios in a study by Costanzo et al. (2016). The findings of this study demonstrated that in both cities, irrigated green roofs outperformed non-irrigated green roofs in enhancing thermal and energy performance. Similarly, research conducted in Hong Kong (Jim & Peng, 2012a) explored the relationship between temperatures and three substrate moisture states (wet, moist, and dry). The findings revealed that substrates with higher moisture could effectively cool the substrate temperature on sunny days while maintaining warmth on rainy and cloudy days. In the semi-warm climate of Cuernavaca, Mexico, the irrigated green roof notably decreased the temperature of the growing media and the slab by 4.8°C and 1.3°C, respectively, compared to the non-irrigated green roof (Chagolla-Aranda et al., 2017). In the semi-arid climate of Santiago de Chile, it was found that maintaining adequate moisture levels can enhance the thermal performance of green roofs, leading to a reduction in energy consumption for cooling (Vera et al., 2015). Moreover, in two different studies by Yeom & La Roche (2017) and Zheng & Weng (2020) in the hot dry climate of California and Los Angeles, respectively, the energy savings attributed to green roofs showed a positive correlation with moisture levels.

On the other hand, varying moisture levels can influence the evapotranspiration rate differently. For instance, research conducted in Vicenza, Italy, by Lazzarin et al. (2005) revealed that wet media increased the evapotranspiration rate compared to dry media in summer, contributing to the reduction in thermal gains and the cooling of the room temperature underneath. Another study conducted in France by Djedjig et al. (2012) demonstrated that media with high moisture content could increase evapotranspiration, thereby enhancing latent-heat cooling of the surface. Furthermore, the thermal properties of media depend greatly on media moisture content. Moisture content can enhance media thermal conductivity, its capacity to store heat and facilitate heat transmission. For instance, in cold climates of Canada, research by Shao et al. (2021) have shown that moist soil is more conductive compared to dry media and indicated a positive correlation between the moisture content and the thermal conductivity of growing media. In another study by Al-kayssi et al. (1990), the impact of increasing media moisture on temperature and heat storage of growing media was examined and found that an increase in moisture facilitates downward heat transmission and increases solar energy absorption, leading to a higher heat storage capacity of the growing media. In contrast, a field experiment in China (Feng et al., 2010) demonstrated that an increase in moisture content reduces the heat storage within growing media.

While numerous studies have demonstrated the positive impact of moisture in enhancing the thermal performance of green roofs in various climatic conditions, some studies have indicated contrasting results. Studies conducted in London (Virk et al., 2014, 2015), which examined green roofs under both irrigated and non-irrigated scenarios, showed that in both cases, the green roofs achieved similar energy savings. This implies that the influence of moisture content on the thermal performance of green roofs is minimal. Similarly, research examining the thermal performance of green roofs in Milan, Italy (Costanzo et al., 2016) found that dry media has better thermal

performance than moist media. Moreover, another study conducted in the cold climate of Canada (MacIvor et al., 2016) concluded that irrigating media had no notable effect on the thermal performance of an extensive green roof. Overall, different impacts of moisture content on the thermal performance of growing media have been shown in previous studies.

2.2.4.3 Impact of vegetation

Vegetation is another crucial element that has a major influence on the thermal and energy performance of green roofs. Selecting vegetation based on its evapotranspiration rate considering background climate conditions can enhance the thermal and energy performance of green roofs (La Roche & Berardi, 2014; Refahi & Talkhabi, 2015). Numerous studies have demonstrated that vegetation in green roofs can impact evapotranspiration and the amount of solar energy reaching the media surface, consequently reducing energy demand for cooling across various climates (Kokogiannakis & Darkwa, 2014; M. (Max) Liu, 2014; Refahi & Talkhabi, 2015; Vera et al., 2015). In a Mediterranean climate, the thermal behaviour of a fully vegetated green roof was compared to that of a bare soil roof during the summer season and it was found that the fully vegetated green roof reduced heat gains by 60% compared to the bare soil roof, attributed to the activity of plants (Olivieri et al., 2013). In another study comparing the thermal performance of a green roof and a bare roof on a commercial building in Hong Kong (Chan & Chow, 2013), the green roof's evapotranspiration reduced heat flux gains during summer. Furthermore, vegetation can exhibit different thermal behaviours during different seasons. In general, plant transpiration rates are higher in summer than in winter. For instance, to assess the energy-saving potential, the thermal behaviour of vegetation was evaluated in Mediterranean climate conditions during both summer and winter seasons in Chagolla-Aranda et al. (2017). The results of this study showed that

vegetation could reduce energy consumption for cooling by 19% in summer and for heating by 11% in winter and argued that vegetation coupled with irrigation can demonstrate superior thermal performance compared to non-irrigated vegetation.

2.2.5 Need of regional specific study of green roofs

Overall, the quantitative thermal benefits of green roofs vary widely in different studies as discussed above. This variability underscores the region-specific characteristics of green roofs and their exposure to diverse environmental conditions, which differ significantly across geographical locations. Additionally, the literature review shows that the elements that govern the thermal performance of green roofs (e.g., growing media, moisture content, vegetation, etc.) behave differently based on their specific characteristics. These elements also have varying effects depending on the prevailing climate conditions and geographic locations. For instance, moisture content in the growing media can enhance the cooling effect of green roofs as it facilitates the evapotranspiration process, in general. However, this effect of moisture content is not necessarily observed in all climatic conditions. In some studies, the moisture content in growing media has been found to have no influence or even a negative impact on their thermal performance. Similarly, the effectiveness of growing media and vegetation in providing insulation to the building depends on their specific characteristics and the surrounding environmental factors, which vary according to climate conditions. Additionally, the effects of all these variables on the thermal performance of green roofs can be influenced by seasonal variations, as they have different impacts in summer and winter seasons. All of these argue for the need for a regional-specific study for green roofs.

To date, a large number of studies have extensively examined the thermal performance of green roofs and their potential for energy savings in different climate regions, predominantly in hot and

temperate climate conditions. While some research has focused on investigating the thermal performance of green roofs in cold climates, studies in this climate, especially in cold and semi-arid climates are limited. Further studies in cold and semi-rid climates can help build more confidence in implementing green roofs in such climatic conditions to reduce building energy consumption.

2.3 Research objectives

The City of Calgary, Alberta, Canada, which has a cold and semi-arid climate, has the intention to implement green roofs to improve urban stormwater management, acknowledging their other benefits, such as reduction of building energy consumption. A field-scale extensive green roof was constructed on the City of Calgary's Municipal Building, to examine its benefits, especially in managing urban stormwater runoff and affecting roof thermal performance, by comparing it with a conventional reference roof, which is also situated on the same building. To provide evidence-based knowledge for the wide implementation of green roofs in the city, this thesis aims to investigate the effects of green roofs on roof thermal performance. To achieve the objective, the data collected from the extensive green roof and the reference roof were used for the analysis. The detailed objectives of this research study include:

- a) Examining the spatial variations (both horizontally and vertically) in temperature and heat flux of the roofs;
- b) Investigating and comparing the thermal performance of the roofs in terms of thermal indices including thermal resistance and surface temperature reduction; and
- c) Examining the impact of substrate moisture on the thermal performance of the extensive green roof.

CHAPTER 3: STUDY MATERIALS AND METHODOLOGY

3.1 Study site and field monitoring

3.1.1 Study area and green roof structure

In this thesis, a full-scale extensive green roof (called the green roof throughout this thesis) located in the City of Calgary, Alberta, Canada was constructed and monitored to evaluate its effectiveness in managing stormwater as well as improving the thermal performance of roofs. For comparison purposes, a nearby reference/conventional roof was also monitored. Note that this thesis only focused on examining the thermal performance of the green roof.

The City of Calgary is situated about 80 km to the east of the front ranges of the Canadian Rockies, in the transition zone between the Rocky Mountain Foothills and the Canadian Prairies. The City of Calgary experiences four seasons, namely spring (March-May), summer (June-August), fall (September-November), and winter (December-February). Calgary's climate is categorized as semi-arid and cold in winter. Over the past 30 years (1981-2010), the average annual rainfall, snowfall, and precipitation in Calgary are 326.4 mm, 128.8 cm, and 418.8 mm, respectively. The city is also characterized by low relative humidity. The annual potential evapotranspiration exceeds 900 mm, which is greater than the annual precipitation amount. Throughout a year, temperature typically ranges between -11°C to 24°C , with rare instances of dropping below -25°C or rising above 30°C . January is the coldest month of the year, with an average low temperature of -15.1°C and a high of -1°C , whereas July is the hottest month, with an average high temperature of 22.9°C and a low of 11°C . During winters, the temperature typically remains below 0°C . However, the cold winters are frequently interrupted by the arrival of warm and dry winds, locally known as Chinooks, that blow into Alberta over the mountains. Chinook

winds significantly raise the air temperature (above 0°C) in a short period, resulting in repeated freeze-thaw cycles. In contrast, summers are generally warm and relatively short, with only a few days surpassing +30°C.

The green roof and the reference roof were constructed and installed in 2014 on the 5th and 4th floors, respectively, of the east side of the Municipal Building (51°02'44.6"N and 114°03'21.3"W) in downtown Calgary (Figure 3.1). Both roofs were built with the same surface area of 335 m², and have similar architectural characteristics, including a 1% roof slope and based layers (Figure 3.2). Their base layers consist of a root barrier (WSF 40), a 12 mm drainage mat (DBV 12) attached with filter fabric, 100 mm rigid insulation and a diffusion/separation membrane (TGV 21) from the bottom to the top. On the top of the base layer, the green roof has a drainage board (Floradrain FD 25-E with holes facing up) with a separate filter sheet (SF) and engineered growing media at a depth of 150 mm, while the reference roof has a drainage board (DBV 12) and 75 mm thick concrete pavers. The growing media of the green roof is ZinCoblend-SI, which is comprised of high-quality recycled materials and minerals, and enriched with a superior compost element. The total nitrogen and total phosphorous content contents of the media are 239.40 mg/kg and 130.80 mg/kg, respectively. The average particle size of the growing media is 3.75 mm, with a dry density of 0.84 g/cm³, and a field capacity of 38.28%. The insulation layer was provided by Owens Corning Canada, while materials for all other layers, including the growing media, were supplied by Zinco Canada Inc. The green roof was planted with a mix of nine different native vegetation species at a typical spacing of 150 mm. This vegetated area occupied approximately 50% of the surface of the extensive green roof. The vegetation was irrigated during warm and dry periods using drip tubes to support vegetation growth. The amount of irrigation was recorded by a flow meter. Additionally, the green roof and the reference roof were exposed to the same ambient

environmental conditions, such as facing east, having a concrete and glass facade to the north, and featuring an overhanging condition on the west side (Figure 3.1).

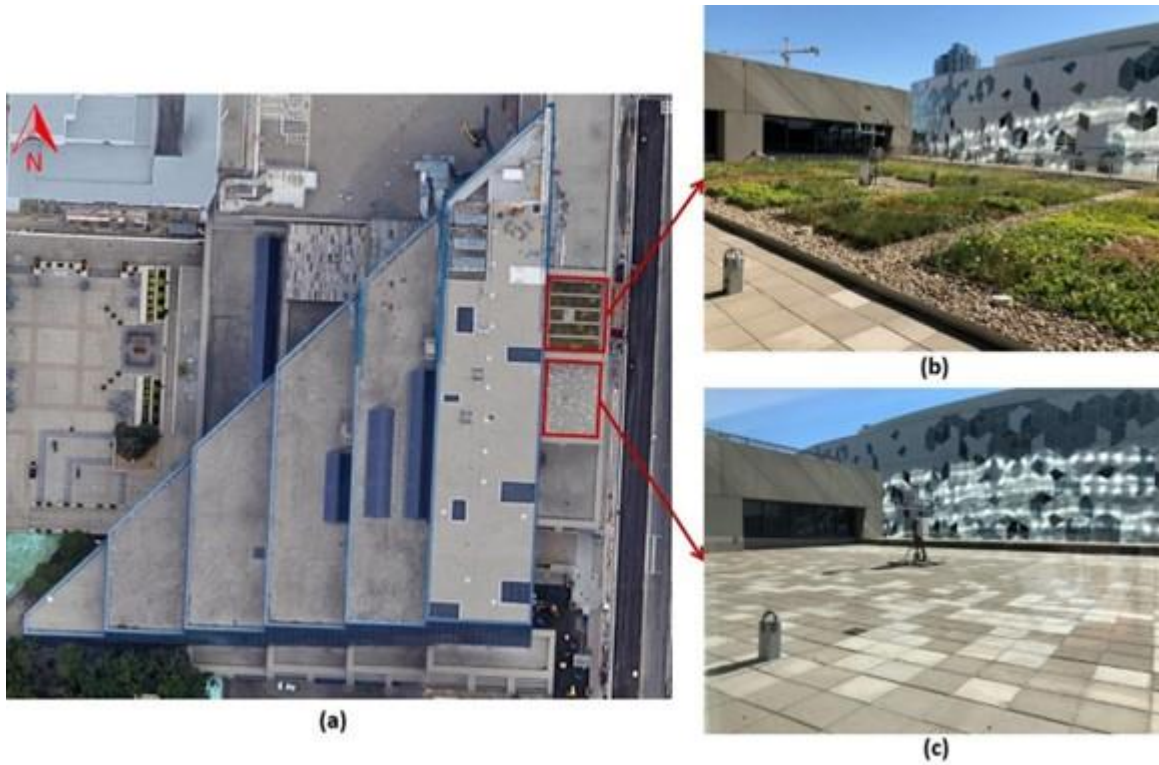


Figure 3.1 (a) Bird view of rooftops of Calgary's Municipal Building highlighting the locations of the study roofs, (b) the full-scale extensive green roof on the 5th floor, and (c) the reference roof on the 4th floor (Akther, 2020).

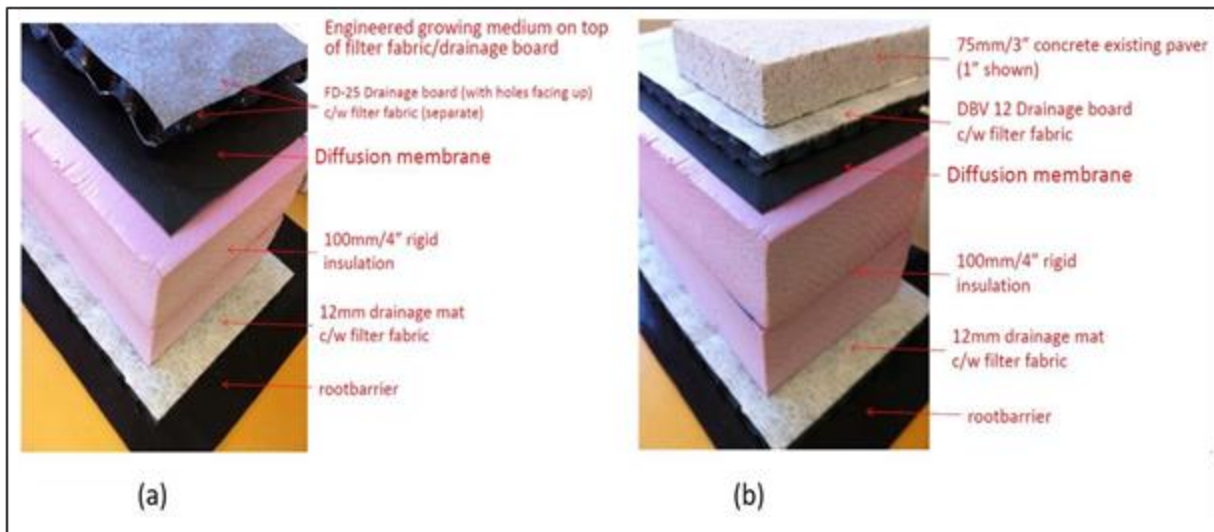


Figure 3.2 The structure of (a) the green roof and (b) the reference roof (Akther, 2020).

3.1.2 Field monitoring and data collection

The green roof and the reference roof were equipped with individual monitoring systems to record roof temperature at several layers and heat flux at one layer continuously. In addition, the media temperature and moisture content of the green roof were monitored. Considering the size of the roofs, temperature, heat flux, and/or moisture content were monitored at four quadrants, namely SW, NW, NE, and SE, of each roof. The roof temperature and heat flux were monitored using the thermocouples and heat flux transducer (HFT). The media temperature and moisture of the green roofs were continuously measured by the 105T-L Type T Thermocouple Probe and CS650 soil water content reflectometer, respectively. Figure 3.3 shows the locations of sensors on the green roof and the reference roof, respectively, and the monitoring equipment is summarized in Table 3.1. On both the green roof and the reference roof, the roof temperature was measured from four layers, including the top of the insulation (TCTOI), below the lower drainage board (TCTDB), top of the concrete slab (TCM1 and TCM2), and the underside of the concrete roof slab (TCIUS). An HFT was embedded on the top of the concrete slab (TCM) at each roof. In the

growing media of the green roof, the thermocouples were deployed at three depths (i.e., bottom (TCBGM), middle (TCMGM), and top (TCTGM)), while the moisture sensors were placed in the middle of the growing media.

In addition, a meteorological station was deployed on the green roof and the reference roof to record the climatological variables, including, air temperature, solar radiation, rainfall, relative humidity, and wind speed and direction. All the measurements were recorded continuously at 5-minute intervals. The data recorded from January 2017 to December 2018 were used in this study. Note that the roof temperature collected from the TCTDB layer for both roofs was excluded from this study as a systematic error was suspected in the measured temperature. Specifically, the temperature measurements obtained from this layer displayed a considerable disparity compared to all other layers. Therefore, three common layers of the green roof and reference roof, namely TCTOI, TCM1/TCM2, and TCIUS, as well as three layers of growing media of the green roof, namely TCTGM, TCMGM, and TCBGM, were considered for this study.

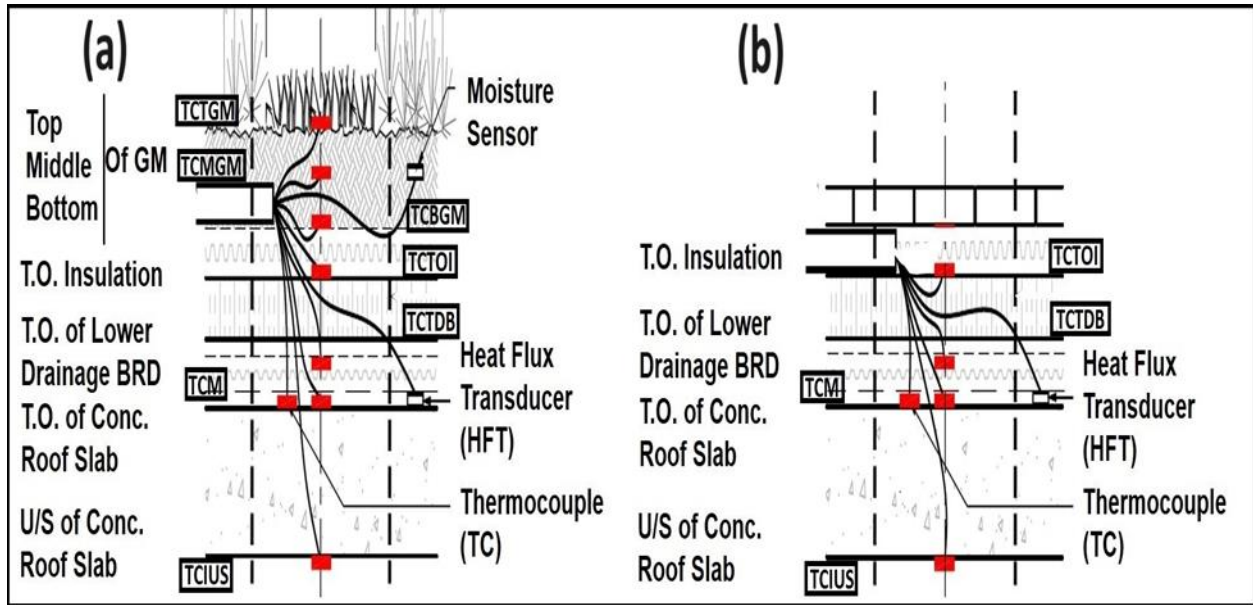


Figure 3.3 The side view of sensor locations for (a) the extensive green roof and (b) the reference roof. Thermocouples were installed at common layers of both roofs, including TCIUS (underside of the concrete roof slab), TCM1/TCM2 (top of the concrete slab), TCTDB (below the lower drainage board), and TCTOI (top of the insulation), as well as in the green roof's growing media at TCBGM, TCMGM, and TCTGM (bottom, middle, and top depths of the growing media, respectively). Heat Flux Transducer (HFT) was installed at TCM (top of the concrete slab) for both roofs, while moisture sensor was installed at TCMGM (middle layer of the growing media).

Table 3.1 Instrumentation for both the green roofs and reference roof monitoring

Instrument/Sensor		Measured environmental variables	Brand and model
Weather station	Wind sensor	Wind speed and direction	Young wind monitor, Model 05103
	Air temperature probe	Air temperature	BetaTherm 100K6A11A thermistor, Model 107-L
	Radiation sensor	Solar radiation	K and Z silicon Pyranometer
	Tipping rain gauge	Rainfall	TE525-L, rain gauge
	Infrared radiometer	Surface temperature	SI-111, infrared radiometer
Temperature profile	Thermocouple	Temperature	105T-L, Type T Thermocouple probe
Moisture sensor*	Soil water content reflectometer	Soil moisture content	CS650, Soil water content reflectometer
Irrigation system*	Irrigation controller	-	Base station 1000
	Irrigation flow meter	Irrigation volume	BaseLine BFM Series

*Only for the green roof.

3.2 Data categorization

In this thesis, to examine the roof thermal performance (for both the green roof and the reference roof), the data (i.e., the roof temperature and heat flux data) were grouped into three categories based on air temperature. Similarly, to investigate the impact of the moisture on the thermal performance of green roof, the media moisture and media temperature data were also categorized into three groups based on air temperature.

Green roofs show the potential to enhance the insulation properties of buildings by mitigating incoming heat transfer into buildings and thereby helping to maintain cool indoor temperatures on hot days. Conversely, on cold days they also have the capability to absorb and retain outgoing heat and accordingly help in maintaining indoor temperatures (Bevilacqua et al., 2017; Getter et al.,

2011b; Jim, 2014; M. Tang & Zheng, 2019b). Thus, green roofs function distinctively on cold and hot days in terms of heat transfer and increase/decrease in roof and indoor temperatures. Therefore, the data were grouped into three categories, namely cold, hot, and normal days, to evaluate the thermal differences at different layers between the green roof and the reference roof. In this thesis, the heating degree days (HDD) and cooling degree days (CDD) were used to group the data into the cold and hot days, as these metrics are often employed to calculate the heating and cooling loads of buildings (Harvey, 2020; Lindelöf, 2017). The mean daily air temperature is commonly used to determine the HDD and CDD. Therefore, the mean daily temperature, which is the average of the daily maximum and minimum air temperatures, was used to classify the days as hot, cold, or normal days. The days with a mean daily air temperature of above 18°C and below 10°C were categorized into hot and cold days, respectively (ASHRAE, 2009). The days, i.e., those that have a mean daily temperature between 10°C and 18°C, are classified as normal days. Throughout this thesis, the hot, normal, and cold days are also called hot, normal, and cold seasons, respectively. As aforementioned, the reason for dividing the seasons in this way was due to the distinct thermal behaviour of green roofs on hot and cold days, irrespective of the actual seasons. For instance, in Calgary, during the winter, certain days could experience a drastic rise in air temperature due to Chinook winds, and thus, can be defined as normal days rather than cold days. Conversely, in summer, some days have moderate air temperatures, thus requiring no cooling. As a result, the evaluation of the performance of roofs in a particular season could be biased, as the thermal functions of roofs can be different on different days in an actual season (i.e., winter, spring, summer, or fall).

On the other hand, the previous studies indicate that the influence of moisture on the thermal performance of green roofs can vary significantly depending on soil/media moisture levels. In

general, the thermal conductivity of growing media tends to rise with an increase in moisture content. With higher moisture content, the soil/media can absorb more heat energy, resulting in a decrease in media temperature and a reduction in heat transfer (Al-kayssi et al., 1990; Jim & Peng, 2012a). In addition, considering the diurnal fluctuations in air temperature as well the roof temperatures, heat can transfer in opposite directions, namely from the inside of the building to the outside, and vice versa in a day. Therefore, in this thesis, the data of media moisture and media temperature were differentiated into two different groups based on the positive and negative values of the daily average temperature difference (ΔT) between the top and bottom layers (TCTGM and TCBGM) of the growing media for hot, cold, and normal days. Note that the positive values of ΔT indicate the days when the heat was transferred from the atmosphere to the building inside, while the negative values denote days when the heat was transferred from the building inside to the atmosphere.

3.3 Statistical analysis and data analysis

3.3.1 Statistical analysis for variations

In this thesis, several statistical analysis techniques were used to detect significant differences (i.e., in medians and variances) in the variables of interest (e.g., roof temperature, etc.) among different locations (in both horizontal and vertical dimensions) and between the green roof and the reference roof. Broadly speaking, statistical analysis can be categorized into parametric and nonparametric analysis. Parametric analysis relies on the assumption that the data follows a specific probability distribution, such as a normal distribution. In contrast, nonparametric analysis does not require an assumption of a particular distribution and thus offers robust results when the distributional assumption is violated. To select either parametric statistical tests or nonparametric

tests (when available), the normality of datasets was tested using the Kolmogorov-Smirnov test (Massey Jr., 1951). This test is useful for assessing normality across a broad range of sample sizes. In this study, none of the datasets of interest (i.e., temperature and heat flux) were found to follow a normal distribution, and consequently, nonparametric statistical tests were selected and used herein.

For sample comparison, the Mann-Whitney test (Mann & Whitney, 1947) was used to compare the medians of two independent samples, while the Kruskal-Wallis test (Kruskal & Wallis, 1952) was used to compare the medians of more than two samples. In particular, the roof and media temperatures and heat flux measured at the four quadrants were compared in terms of medians using the Kruskal-Wallis test for the green roof and the reference roof, respectively. In addition, the medians of roof temperature among the three common layers of the green roof and the reference roof and among the three layers of growing media of the green roof were also compared using the Kruskal-Wallis test. The Mann-Whitney test was employed to compare the medians of air temperature, heat flux, and roof temperature measured at common layers between the green roof and the reference roof. The medians of diurnal temperature variation and thermal resistance between both roofs were also compared using the Mann-Whitney test. In addition, the Brown-Forsythe test (Brown & Forsythe, 1974) was employed to assess whether the variances of samples, for example, roof and media temperature and heat flux between the green roof and reference roof and among the four quadrants of each roof are statistically equivalent. Apart from this, the variances of roof temperature among the three common layers of the green roof and the reference roof, as well as among the three layers of growing media of the green roof, were assessed using this test. Furthermore, to examine the potential impact of moisture on the thermal performance of the green roof, correlation analysis using the Spearman's correlation coefficient (Spearman, 1910))

was performed to investigate the relationship between the moisture content and temperature of the growing media. In all the statistical tests, the significance level of 5% was adopted.

When examining the thermal behaviour of the roofs on hot, cold, and normal days, the daily samples (temperature and heat flux) were used to investigate the spatial variation in the roof and media temperature and heat flux for the green roof and the reference roof, respectively, to explore the presence of spatial variability in the thermal behaviour of each roof. In addition, the comparison between the green roof and reference roof (at common layers) was also performed at the daily and seasonal temporal resolutions to demonstrate the differences in their thermal behaviour.

3.3.2 Evaluation metrics for the roof thermal performance

To assess the thermal performance of the green roof and reference roof, two evaluation metrics, namely the thermal resistance (R) index and the surface temperature reduction (STR) were used. To examine the impact of media moisture on the thermal performance of the green roof, the correlation coefficient was used as the evaluation metric.

The R is widely adopted for assessing the insulation capacity of building envelopes. The R of roofs are commonly calculated using on-site measurements of roof temperature and head flux based on the method defined by ISO 9869: 2014 and ISO 6946: 2007 regulations (International Organization for Standardization (ISO), 2014 and 2007). The R is the temperature difference between the external and internal surface roof temperatures divided by the heat flux passing through the roof and is calculated by (D’Orazio et al., 2012; M. Tang & Zheng, 2019a):

$$R = \frac{T_{ex} - T_{in}}{Q}$$

where T_{ex} and T_{in} refer to the external and internal surface temperatures (K) of a roof, respectively; and Q is the heat flux (W/m^2) passing through the roof.

In the calculation of the R , the temperature of the vegetation canopy layer, which accounts for the shading effect of vegetation, has been used as T_{ex} . A few previous studies have also considered the soil surface temperature or soil temperature as T_{ex} of the green roof (Nocera, 2016; Squier & Davidson, 2016; Wong et al., 2003b). In this study, the temperatures at the top surface of growing media (namely, TCTGM) and at the top of the insulation layer (namely, TCTOI) were used as T_{ex} for the green roof and reference roof, respectively. It is worth mentioning that the temperature measures at TCTGM in fact are affected by vegetation shading. Whereas the temperatures at the underside of the concrete roof slab (namely, TCIUS) for both roofs were considered as T_{in} . In this thesis, the daily average roof temperature and heat flux were used to calculate the R and assess and compare the thermal performance between the green roof and the reference roof in terms of their insulation capabilities at a daily temporal scale for hot, cold, and normal days, respectively.

The index known as the STR was used to evaluate the average thermal performance of the green roof relative to the reference roof. The STR is defined as the ratio of the average roof temperature at the same layer of the green roof to the average roof temperature at the same layer of the reference roof and is calculated by the following equation (Bevilacqua et al., 2017; He et al., 2020).

$$STR = \frac{T_{GR}}{T_{RR}}$$

where T_{GR} and T_{RR} refer to the average roof temperature of a layer of the green roof and the reference roof, respectively.

An STR value of less than 1 indicates that the green roof reduced the roof temperature at the layer relative to the reference roof. Hence, it suggests that the green roof has a cooling effect by

decreasing the heat transfer from the outside to the inside of the building. Conversely, an STR greater than 1 signifies that the green roof increased the roof temperature of the layer relative to the reference roof. This indicates that the green roof has an insulating effect by reducing heat transfer from the inside to the outside of the building. In this thesis, the STR was calculated at three common layers of the green roof and reference roof, namely the layers of TCTOI, TCM1/TCM2, and TCIUS for hot days, cold days, and normal days, respectively. The STR was calculated across two temporal scales, namely at the daily and seasonal scales.

3.3.3 Vertical temperature profile

Apart from the air temperature, the temperature was measured at TCTGM, TCMGM, and TCBGM layers for the growing media of the green roof and TCTOI, TCM, and TCIUS (common layers) for the green roof and the reference roof. The examination of the vertical temperature profile was conducted to analyze temperature variations within the roofs and in turn to understand thermal dynamics of different layers of the roofs. In this thesis, the roof and media temperatures and air temperature were used to analyze the vertical temperature profile of the green roof and the reference roof. Throughout the study period, the vertical temperature profile was examined on six typical days in both 2017 and 2018, falling within the range of daily air temperature throughout the years. The days with daily average air temperatures of approximately -20°C , -10°C , and 0°C were chosen to represent the cold days, 10°C as the normal days, and 20°C and 30°C as the hot days. Moreover, to demonstrate the diurnal variation in the vertical temperature profile, the temperatures at 4-hour intervals starting from midnight 00.00 hr to 24.00 hr on each selected day were shown in the temperature vertical profile. Therefore, it allowed the qualitative comparison of

the thermal performance in both nighttime and daytime between the green roof and the reference roof.

3.3.4 Impact of media moisture on green roof thermal performance

In general, moisture in growing media can substantially influence the thermal properties of growing media, and consequently affect the thermal performance of green roofs. Especially, media moisture can alter media thermal conductivity and heat capacity (Shao et al., 2021; Tan et al., 2017). To investigate the potential impact of media moisture on the thermal performance of the green roof, an examination of the correlation between the media temperature and moisture content of the growing media was conducted. The media temperatures collected at the top and bottom of the growing media (TCTGM and TCBGM), along with moisture content measured at the middle of the growing media (TCMGM) were used. The media of the green roof remained frozen from November to March in both years when there were no prominent fluctuations observed in moisture content. The average daily moisture content during frozen conditions, in particular, ranged from 10% to 11%. The consistent low moisture suggested a prolonged frozen state of the growing media throughout these months. It is worth mentioning that during frozen conditions, moisture sensors are unable to measure the water content of frozen water. Hence, the measured water content under such conditions do not accurately reflect the actual water content. Therefore, the data collected between April and October in 2017 and 2018 was used to investigate the relationship between media temperature and moisture. It is also important to note that to examine the impact of moisture on the green roof's thermal performance, the data used were grouped based on the daily average temperature difference (ΔT) between the top and bottom layers (TCTGM and TCBGM) of the growing media.

The impact of moisture on the green roof thermal performance was investigated by exploring the moisture-temperature relationships under two scenarios on hot, cold, and normal days, respectively, using the non-parametric Spearman's correlation analysis. The two scenarios are referred to as positive and negative ΔT . When ΔT is positive, heat transmits from the atmosphere to the building interior. When ΔT is negative, heat transmission occurs in the reverse direction, namely from the building inside to the atmosphere. Furthermore, the correlations between the daily average moisture content and the daily average temperature recorded at the middle layer of the growing media (TCMGM), along with the relationship between the daily average air temperature and the daily average temperature at TCMGM were also examined.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Spatial variations in temperature and heat flux of the roofs

The spatial variations in the daily average temperature and heat flux were examined using the Kruskal-Wallis test to identify differences in the medians among the four quadrants of the green roof and the reference roof, respectively. The test was conducted for the TCTOI, TCM1/TCM2, and TCIUS layers of both roofs, and three additional layers of growing media of green roof (i.e., TCTGM, TCMGM, and TCBGM), on hot, cold, and normal days, respectively, in 2017 and 2018. The test results are summarized in Table 4.1. For the reference roof, the spatial variations in temperature at these layers and heat flux at the TCM layer among the four quadrants were observed on hot, cold, and normal days, as significant differences in the medians of daily average temperature and heat flux were detected in both years. For the green roof, on cold days, spatial variations in the daily average temperature across all the layers and heat flux at the TCM layer were detected in both years. On hot days, significant differences in the medians of the daily average temperature and heat flux were found among the quadrants at all the layers in 2018, while only in the medians of the daily average temperature at TCM and TCIUS layers in 2017. Whereas on normal days, significant differences in the medians of the daily average temperature were observed only at the TCM and TCIUS layers in both years. Although the significant differences in temperature and heat flux were not always detected on hot, cold, and normal days in the two years, the significant differences demonstrated the spatial variations in temperature and heat flux among the four quadrants of both roofs.

Table 4.1 Summary of the significant differences in the medians of daily average temperature and heat flux at all layers of the green roof and the reference roof on hot, cold, and normal days, respectively, in 2017 and 2018. Yellow cells indicate no spatial variation, while green cells indicate significant spatial variation.

Significant difference in medians		Green roof			Reference roof		
		Hot days	Cold days	Normal days	Hot days	Cold days	Normal days
2017							
Temperature	TCTGM	×	✓	×	-	-	-
	TCMGM	×	✓	×	-	-	-
	TCBGM	×	✓	×	-	-	-
	TCTOI	×	✓	×	✓	✓	✓
	TCM	✓	✓	✓	✓	✓	✓
	TCIUS	✓	✓	✓	✓	✓	✓
Heat flux	TCM	×	✓	×	✓	✓	✓
2018							
Temperature	TCTGM	✓	✓	×	-	-	-
	TCMGM	✓	✓	×	-	-	-
	TCBGM	✓	✓	×	-	-	-
	TCTOI	✓	✓	×	✓	✓	✓
	TCM	✓	✓	✓	✓	✓	✓
	TCIUS	✓	✓	✓	✓	✓	✓
Heat flux	TCM	✓	✓	×	✓	✓	✓

Figure 4.1 further shows the daily average temperatures measured at four quadrants of common layers of the green roof and reference roof (i.e., TCIUS, TCM1/TCM2, and TCTOI) as well as three layers of growing media of the green roof (i.e., TCTGM, TCMGM, and TCBGM) on hot days in 2017, as examples. As shown in the figure, the differences in the median of daily average temperature among the quadrants were notable for all layers of the reference roof, whereas differences were specifically noted at the TCM and TCIUS layers of the green roof. Especially at

both the TCM and TCIUS layers of the green roof, the SE quadrant exhibited a higher median temperature, while the SW quadrant accounted for the lowest. On the other hand, for the reference roof, among the four quadrants, the median of daily average temperature at the NW and SE quadrants was highest at the TCM and TCIUS, respectively. However, the spatial variations in temperature were not detected from all growing media layers as well as TCTOI of the green roof. Conversely, the TCTOI layer of the reference roof showed apparent spatial variations in temperature among the quadrants, with the highest temperatures at the NE quadrant. These results demonstrate that the growing media having the potential to buffering and mitigating temperature variations could lead to heat/temperature more evenly distributed with the media and consequently at the underlying layer of growing media (i.e., TCTOI).

Moreover, on hot days, the green roof showcased notably different effects between 2017 and 2018, as significant differences in the medians of daily average temperature at all layers and heat flux at the TCM and growing media layers were detected in 2018 (Table 4.1). It is worth mentioning that in 2018, the NE quadrants consistently had a higher median temperature at all layers except the TCIUS layer and also showed a higher median heat flux. In contrast, the SW quadrants consistently noted the lower median temperature (except the TCTGM) and heat flux (data not shown). This consistent temperature pattern at these quadrants from the top layer to the bottom layer indicates the spatial consistency of the thermal behaviour of the green roof throughout the hot season. Furthermore, similar to 2017, spatial variations were found at all layers, and heat flux for the reference roof in 2018. However, in contrast to the green roof, the quadrants from which the higher and lower median temperatures were observed differ among the layers (data not shown).

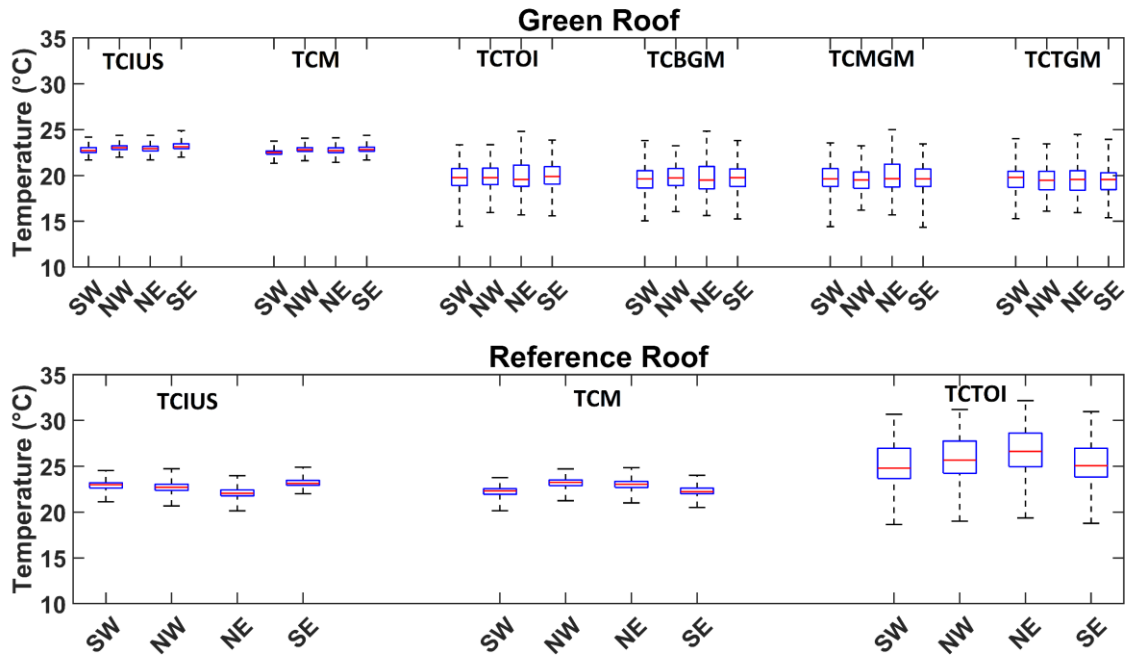


Figure 4.1 Box-whisker plot of daily average temperature measured at various layers in four quadrants of the green roof and the reference roof on hot days in 2017.

On cold days, as illustrated in Figure 4.2, noticeable differences in the medians of daily average temperature among the quadrants were observed across all common layers of the green roof and reference roof, as well as the three layers of growing media in 2017, reaffirming the significant differences in the medians detected in the Kruskal-Wallis test (Table 4.1). For the green roof, the SE quadrants consistently demonstrated higher median temperatures at all layers and heat flux, while the NE quadrants consistently showcased lower median temperatures (excluding the TCMGM and heat flux at the TCM). However, differing from the green roof, the median temperature was generally higher at the NW or NE quadrant of the layers while lower at the SE or SW quadrant of the layers for the reference roof. In 2018, for the green roof, the SE quadrant showed higher median temperatures across all layers (excluding all three layers of growing media) and heat flux, while the NE quadrant demonstrated lower median temperatures (excepting the

TCMGM and heat flux at the TCM) (data not shown). However, for the reference roof, the NW or NE quadrant showed higher median temperatures, while the SE or SW demonstrated lower median temperatures across all layers, similar to those observed in 2017. Differing from the hot season, these results from both years indicate that the green roof did not mitigate spatial variations among the quadrants during the cold season.

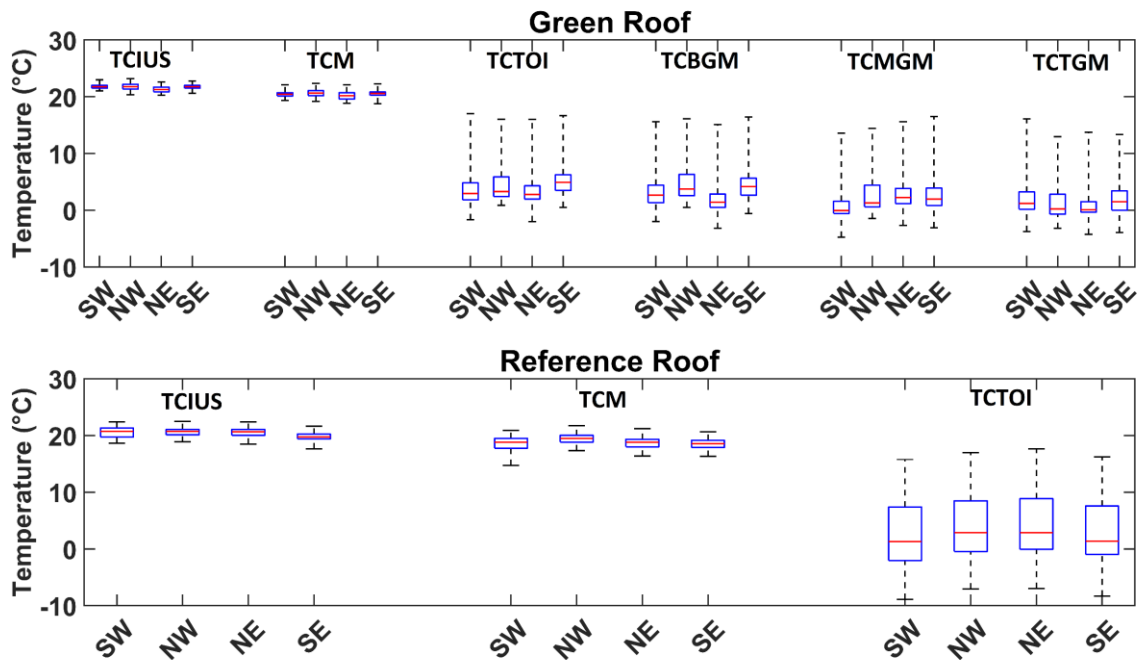


Figure 4.2 Box-whisker plot of daily average temperature measured at various layers in four quadrants of the green roof and the reference roof on cold days in 2017.

Moreover, on normal days, the green roof displayed significant differences in the medians of daily average temperatures at the TCM and TCIUS layers. In contrast, no differences were found at other layers and in heat flux in both years (Table 4.1). At the TCM and TCIUS layers, the NW and SW quadrants recorded the highest and lowest median temperature among the four quadrants, respectively, in both years. On the contrary, for the reference roof, spatial variations were identified

in temperatures at all layers and heat flux in both years. Notably, the NW and SE quadrants had the highest and lowest median temperature and heat flux, respectively. Overall, these findings, specifically on normal and hot days, suggest that the green roof can potentially mitigate spatial variations in temperature and heat flux, and, in turn, the thermal behaviour of the green roof compared to the reference roof.

Besides comparing the medians in the daily average temperature and heat flux among the four quadrants at the layers, their variances were also compared using the Brown-Forsythe test. Table 4.2 illustrates the results of significant differences in the variance among the four quadrants of the green roof and reference roof. It is worth highlighting that the same results were observed for both 2017 and 2018. For the green roof, the variances in the daily average temperature and heat flux at all layers of the green roof were not significantly different among the four quadrants in both years in general, except at TCM (temperature and heat flux) and TCIUS (temperature) on cold days. For the reference roof, although the significant difference in the variances among the four quadrants was not detected on normal days, but it was detected on hot and cold days at TCIUS (temperature) and TCM (heat flux and/or temperature). Especially on hot days in 2017, the SE quadrant recorded the highest variance in the daily average temperature at the TCIUS layer, while the NE quadrant exhibited the highest variance in the daily average heat flux; conversely, the SW quadrants showed the lowest variances in both daily average temperature and heat flux. Whereas in 2018, the SW quadrant displayed the highest variances in daily average temperature, and the NE quadrant exhibited the highest variances in daily average heat flux. Compared to the reference roof, these results indicate that the green roof could also mitigate the spatial variations in both temperature and heat flux, especially on hot days.

Table 4.2 Summary of significant differences in the variances of daily average temperature and heat flux among four quadrants at all layers of the green roof and the reference roof on hot, cold, and normal days, respectively, in 2017 and 2018. Yellow cells indicate no differences in variances, while green cells indicate significant differences in variances.

Significant difference in variances		Green roof			Reference roof		
		Hot days	Cold days	Normal days	Hot days	Cold days	Normal days
2017							
Temperature	TCTGM	×	×	×	-	-	-
	TCMGM	×	×	×	-	-	-
	TCBGM	×	×	×	-	-	-
	TCTOI	×	×	×	×	×	×
	TCM	×	✓	×	×	✓	×
	TCIUS	×	✓	×	✓	✓	×
Heat flux	TCM	×	✓	×	✓	✓	×
2018							
Temperature	TCTGM	×	×	×	-	-	-
	TCMGM	×	×	×	-	-	-
	TCBGM	×	×	×	-	-	-
	TCTOI	×	×	×	×	×	×
	TCM	×	✓	×	×	✓	×
	TCIUS	×	✓	×	✓	✓	×
Heat flux	TCM	×	✓	×	✓	✓	×

Although the above results demonstrate that the green roof might be capable of mitigating the spatial variations in both medians and variances of temperature and/or heat flux among the four quadrants, their spatial variations were also observed. As a result, the average temperature and heat flux over the four quadrants at each layer were used in the rest of the thesis.

4.2 Differences in temperature and heat flux between the roofs

Although the green roof and the reference roof are nearby, the ambient climatic condition was compared in terms of air temperature and wind speed between the two roofs to examine if microclimate might be a potential factor influencing their thermal behaviour. Figure 4.3 depicts the daily average air temperature measured on the green roof and the reference roof on hot, cold, and normal days, respectively, in both 2017 and 2018. Differences in the medians and variances of the air temperature between the green roof and reference roof on hot, cold, and normal days were not shown nor detected in the Mann-Whitney U and Brown-Forsythe tests in both years. Previous studies have shown that green roofs have the potential to positively influence surrounding microclimatic conditions including outdoor air temperature (Kumar et al., 2015; Moghbel & Erfanian Salim, 2017; Morakinyo et al., 2017; Solcerova et al., 2017). This has been ascribed to vegetation on green roofs, which can cool the surrounding air through evapotranspiration by releasing water vapour into the air. However, such an effect was not observed from the green roof. Moreover, the comparison was further conducted on other meteorological variables, including relative humidity, wind speed, solar radiation, and rainfall. No significant differences in the medians and variances of daily average relative humidity, solar radiation, and rainfall were detected in the Mann-Whitney U and Brown-Forsythe tests, respectively, on hot, cold, and normal days in both 2017 and 2018. Therefore, the impact of the green roof on ambient climate was not apparent in this study. However, it is worth mentioning that noticeable and significant differences in the medians (not the variances) of daily average wind speed were observed on cold days in both years (Figure 4.4).

It has been acknowledged that high wind speeds can potentially increase the convective heat loss from buildings by enhancing the heat transfer from buildings, thereby influencing the indoor

environment (Amir et al., 2018; Jim & Peng, 2012b; Santamouris, 2014). Consequently, the relatively lower wind speed on the green roof could be beneficial for the green roof to retain heat within the building, contributing to improved energy efficiency. This is further supported by the lower average outgoing heat flux of the green roof on cold days compared to that of the reference roof.

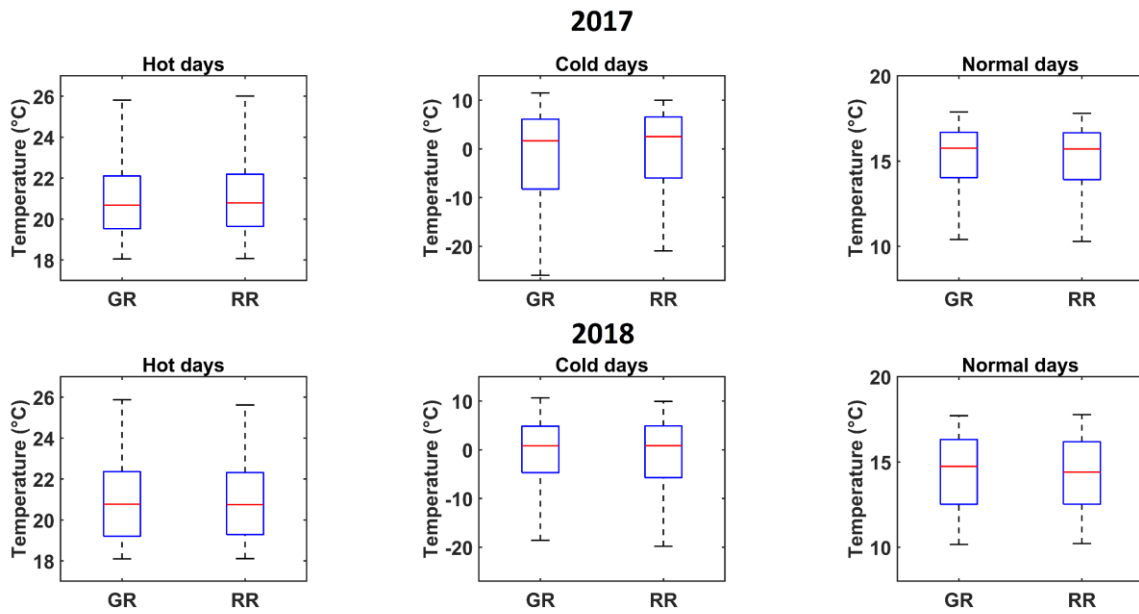


Figure 4.3 Box-whisker plot of the daily average air temperature on the green roof (GR) and reference roof (RR) on hot, cold, and normal days in 2017 and 2018.

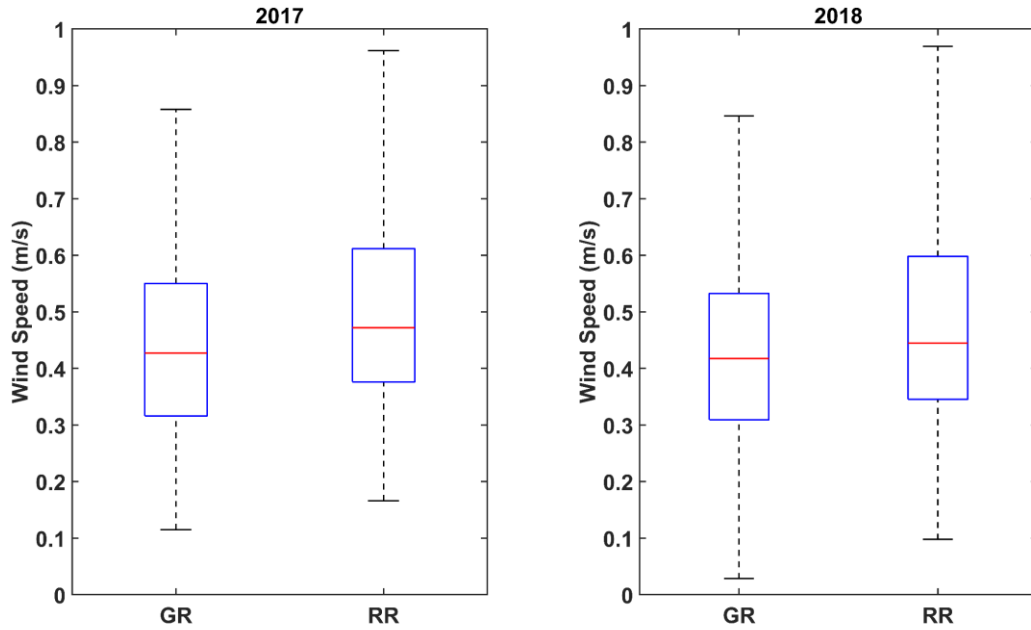


Figure 4.4 Box-whisker plot of daily average wind speed collected above the green roof (GR) and reference roof (RR) on cold days in 2017 and 2018.

Note that the temperatures at the TCM layer were collected using two different thermocouples (TCM1/TCM2) for both the green roof and the reference roof. It is worth mentioning that no significant differences in the medians and variances of temperatures between the TCM1 and TCM2 layers of the green roof and reference roof were detected in the Mann-Whitney U and Brown-Forsythe tests, respectively (Figure 4.5). Therefore, data from only one thermocouple at the TCM layer was used for further analysis. This also confirmed that the thermocouples at all layers collected accurate data for both roofs, ensuring the reliability of the data used in this study.

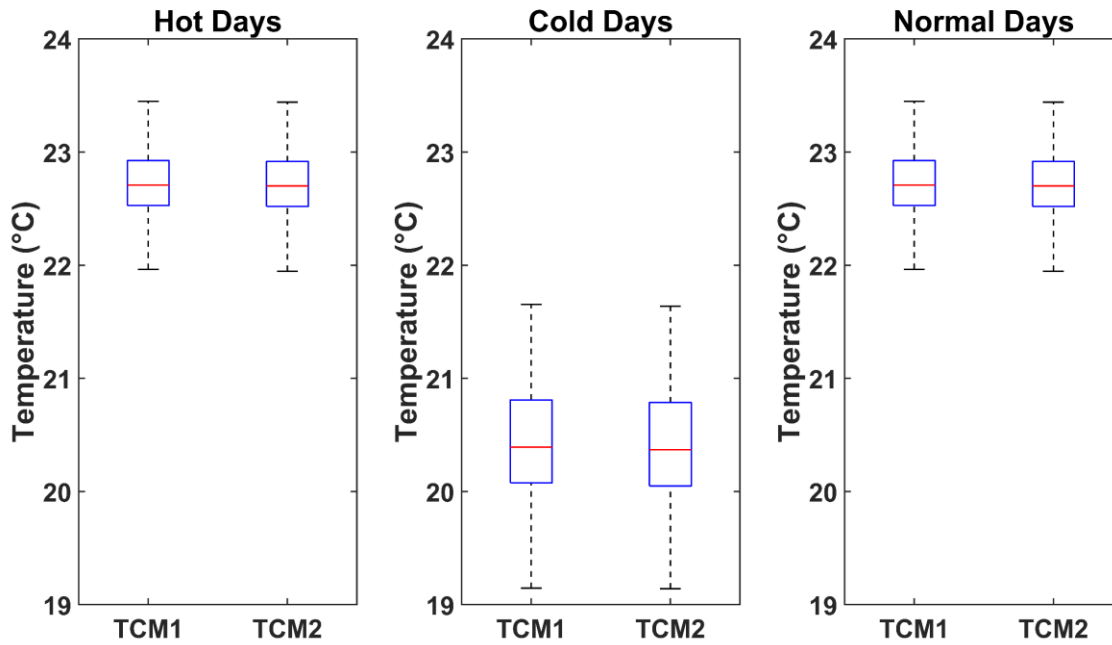


Figure 4.5 Box-whisker plot of daily average temperature collected at TCM1/TCM2 layers of the green roof on hot, cold, and normal days in 2017.

Under the same/similar ambient climatic conditions on the green roof and the reference roof, significant differences in the medians of daily average temperature and heat flux between the roofs were detected at their common layers (except at the TCM layer on hot days in 2017) in the Mann-Whitney U test (Table 4.3). On hot days, the daily average temperature medians at the TCIUS and TCTOI layers of the green roof were higher and lower, respectively, in both years compared to those of the reference roof. Meanwhile, at the TCM layer, no difference in the temperature medians between the roofs was found in 2017, but it was higher for the green roof in 2018. Whereas the daily average heat flux median of the reference roof was higher in both years than that of the green roof. On cold days, the daily average temperature median of the green roof at all common layers (TCIUS, TCM, and TCTOI) were higher, while the daily average heat flux median was lower in

both years relative to the reference roof. Additionally, on normal days, the daily average temperature medians at the TCIUS and TCM layers of the green roof were higher, while the daily average temperature median at the TCTOI and the daily average heat flux of the green roof were lower than those of the reference roof in both years.

Table 4.3 Results of significant differences in the medians of the daily average temperature and heat flux at various layers between the green roof (GR) and the reference roof (RR) on hot, cold, and normal days, respectively, in 2017 and 2018. Green cells indicate that the green roof median is significantly smaller than the reference roof, yellow cells indicate a significantly higher median for the green roof, and red cells indicate equal medians between the roofs.

Significant difference in medians		2017			2018		
		Hot days	Cold days	Normal days	Hot days	Cold days	Normal days
Temperature	TCTOI	GR<RR	GR>RR	GR<RR	GR<RR	GR>RR	GR<RR
	TCM	GR=RR	GR>RR	GR>RR	GR>RR	GR>RR	GR>RR
	TCIUS	GR>RR	GR>RR	GR>RR	GR>RR	GR>RR	GR>RR
Heat flux	TCM	GR<RR	GR=RR	GR<RR	GR<RR	GR=RR	GR<RR

As depicted by the box-whisker plots in Figure 4.6, on hot days, the median of daily average temperature at the TCTOI layer of the green roof was lower relative to the reference roof in 2017, while the median of daily average temperature at the TCIUS was higher. In addition, a significant difference was found in the heat transfer between the roofs. It is worth noting that the direction of heat flux of the green roof was opposite to that of the reference roof (Figure 4.7), especially heat was transferred from the outside to inside of the building for the reference roof, whereas from the inside to outside of the building for the green roof. The observed reverse heat flux direction of the

roofs was consistent with the difference in temperature between the TCTOI and TCIUS layers of the roofs. The temperature at TCTOI of the reference roof was higher than that at TCIUS, and vice versa for the green roof. The results found in 2018 further corroborate the thermal behaviour of the roofs. In that year, the median of temperature at the TCTOI layer of the green roofs was also lower than that at the TCIUS and TCM1/TCM2, while it was also higher for the reference roof (data not shown). Furthermore, on hot days in 2017, significant differences in variances of daily average temperatures at all layers and heat flux were detected between the roofs, with the reference roof showing higher variances. Similar results were found in 2018, but the differences in variances were identified only at the TCTOI layer and in heat flux in 2018 (data not shown). Therefore, the green roof did not showcase its effect in mitigating temperature variance at the TCIUS and TCM1/TCM2 layers in 2018 but in 2017.

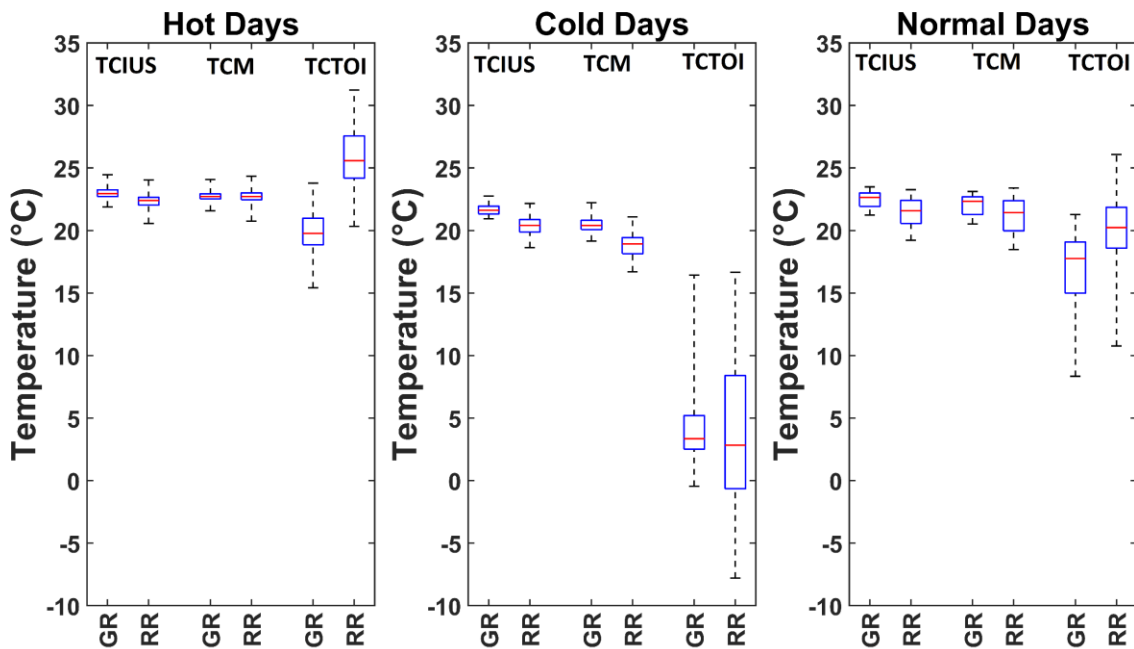


Figure 4.6 Box-whisker plot of daily average temperature measured at common layers of the green roof (GR) and the reference roof (RR) on hot, cold, and normal days, respectively, in 2017.

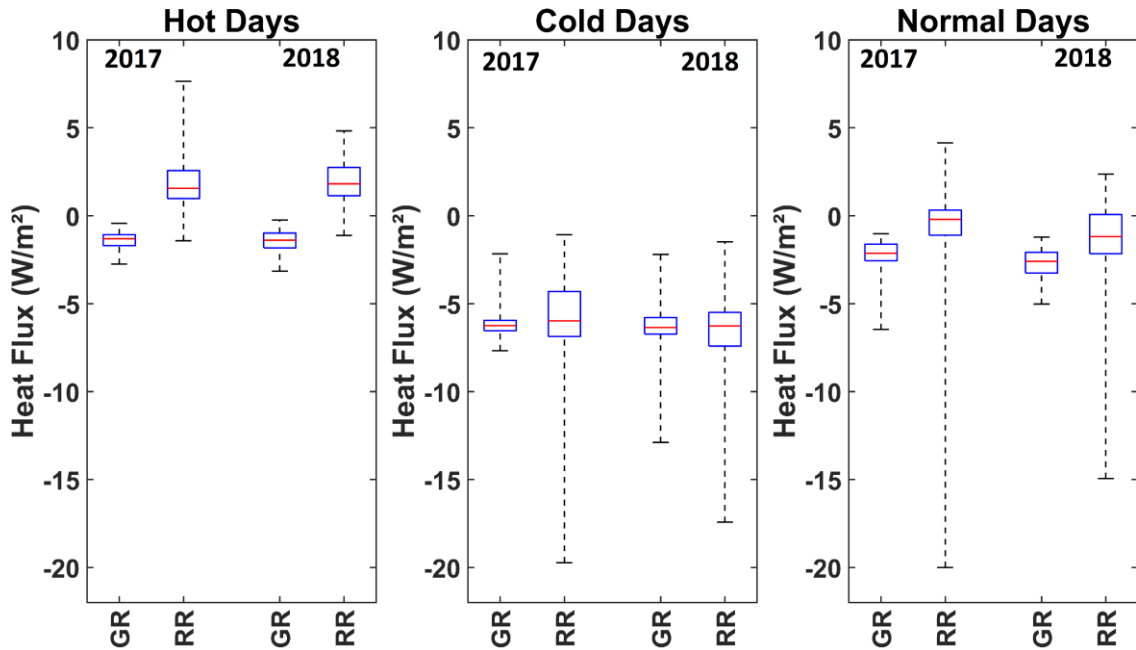


Figure 4.7 Box-whisker plot of daily average heat flux measured at the TCM layer of the green roof (GR) and the reference roof (RR) on hot, cold, and normal days, respectively, in 2017 and 2018.

Overall, relative to the reference roof, the effect of the green roof in reducing roof temperature and its variations was observed at the TCTOI layer, although not at the TCM and TCIUS layers. The low temperature and its variance at the TCTOI layer as well as the heat flux direction (from the inside to outside of the building) of the green roof suggest low energy consumption for cooling on hot days.

On cold days, the green roof notably increased temperatures at all layers (Figure 4.6), as the higher medians of temperatures were detected in the Mann-Whitney U test. However, no significant difference in the medians of daily average heat flux between the roofs was found in the test (Table 4.3). Although the green roof maintained higher temperatures across all layers, it did

not mitigate the outgoing heat transfer from the building on cold days. The growing media of the green roof acted as additional insulation, leading to increased temperatures at all layers. The higher daily average temperature median at the TCIUS layer suggests that the green roof was beneficial in reducing energy consumption for building heating. In addition, the higher variances of temperatures and heat flux of the reference roof in both years suggest the ability of the green roof to reduce fluctuations in the temperatures and heat flux during the cold season. In general, the TCTOI layer of both roofs had the highest variability in temperature among the other common layers. However, the reference roof showed higher variability at this layer than the green roof (Figure 4.6). This variability could be attributed to the absence of growing media, the additional layer for insulation. On the other hand, the green roof had higher temperature medians at all layers except the TCTOI layer and lower heat flux than the reference roof on normal days in both years. Overall, the green roof performed better than the reference roof on cold days by effectively insulating the building through its warming effects. On normal days, the green roof provided insulation at the TCIUS and TCM layers by maintaining higher temperatures than the reference roof. Additionally, the green roof mitigated the fluctuations in temperature and heat flux, ensuring a more uniform heat transfer across all layers on cold and normal days, in general. This contributed to maintaining a comfortable indoor environment and enhancing overall energy efficiency.

4.3 Differences in diurnal temperature variation between the roofs

In this section, the diurnal temperature variations of the green roof and the reference roof were examined, namely by examining the statistical differences in the medians of daily temperature variation between their common layers (i.e., TCTOI, TCM, and TCIUS) on hot, cold, and normal days, respectively, in 2017 and 2018 using the Mann-Whitney U test.

Table 4.4 illustrates the average diurnal temperature variations (difference between average maximum and minimum temperatures) at common layers of the green roof and the reference roof on hot, cold, and normal days in 2017 and 2018. On hot days, the TCTOI layer of the green roof was recorded to have average maximum and minimum temperatures of 21°C and 19°C in 2017, and 21.5°C and 18.9°C in 2018, respectively. In the reference roof, due to the lower thermal inertia resulting from the absence of the growing media layer, temperatures were elevated above those of the green roof. The TCTOI layer of the reference roof experienced average maximum and minimum temperatures of 40.7°C and 15.3°C in 2017, and 42.5°C and 15.5°C in 2018, respectively. As shown in Table 4.4, the green roof largely reduced the average diurnal temperature variation at TCTOI layer by 23.4°C and 24.4°C in 2017 and 2018, respectively. The TCM layer of the green roof registered average maximum and minimum temperatures of 23°C and 22.5°C in 2017, and 23.3°C and 22.8°C in 2018, respectively. Whereas the average maximum and minimum temperatures at this layer for the reference roof were slightly higher than those of the green roof in both years. As a result, the green roof reduced average diurnal temperature variation at the TCM by a marginal difference of 1°C and 1.1°C in 2017 and 2018, respectively (Table 4.4). At the TCIUS layer, the average maximum and minimum temperatures for both roofs were almost the same in both years, resulting in similar average diurnal temperature variations. The absence of temperature fluctuations at this layer for both roofs could be attributed to the controlled room temperature. In general, the green roof evenly distributed heat across common layers, leading to reduced temperature fluctuations on hot days.

Table 4.4 Summary of average diurnal temperature variations at common layers of the green roof and the reference roof on hot, cold, and normal days, respectively, in 2017 and 2018.

Layers	Average diurnal temperature variation (°C)						Average diurnal temperature variation reduced by the green roof (°C)		
	Green roof			Reference roof			Hot days	Cold days	Normal days
	Hot days	Cold days	Normal days	Hot days	Cold days	Normal days			
2017									
TCTOI	2	0.8	2.6	25.4	7.7	22	23.4	6.9	19.4
TCM	0.5	0.3	0.5	1.5	0.8	1.3	1	0.5	0.8
TCIUS	0.9	0.5	0.7	0.9	0.8	1.1	-	0.3	0.4
2018									
TCTOI	2.6	0.9	2.2	27	5.6	19.8	24.4	4.7	17.6
TCM	0.5	0.4	0.4	1.6	1	1.3	1.1	0.6	0.9
TCIUS	1	0.6	0.8	1	0.7	1.2	-	0.1	0.4

During cold days, similar to hot days, the green roof recorded the highest reduction in average diurnal temperature variation at the TCTOI layer among all layers in both years. The reduction in average diurnal temperature variation by the green roof at this layer was 6.9°C in 2017 and 4.7°C in 2018. At the TCM and TCIUS layers in 2017, the green roof observed average diurnal temperature variations of 0.3°C and 0.5°C, respectively. In 2018, these variations remained very close to those in 2017 (Table 4.4). On the other hand, the reference roof had slightly higher temperature variations at the TCM and TCIUS relative to the green roof in both years. The average diurnal temperature variation was 0.8°C at both the TCM and TCIUS layers in 2017, while in 2018, these variations were 1°C and 0.7°C, respectively. In both years, the green roof marginally decreased the average diurnal temperature variations at the TCM and TCIUS layers (Table 4.4).

In addition, on normal days, the highest reduction in average diurnal temperature variation by the green roof was observed at the TCTOI layer in both years, similar to hot and cold days. The green roof effectively reduced temperature variations by 19.4°C in 2017 and 17.6°C in 2018 at this layer. In 2017, the TCM and TCTOI layers of the green roof were recorded to have average diurnal temperature variations of 0.5°C and 0.7°C, respectively. In contrast, these variations were 1.3°C and 1.1°C for the reference roof, respectively. In 2018, these variations remained very close to those in 2017 for both roofs.

Overall, these results demonstrate that the green roof had better efficiency in mitigating diurnal temperature variations across all layers irrespective of hot, cold, and normal days in both years. In addition, the impact of the green roof on mitigating diurnal temperature fluctuations at the TCTOI layer was more prominent than in other layers. This resulted from additional shading of the growing media above the TCTOI layer on the green roof. As a result, the green roof evenly distributed heat across all layers and reduced temperature fluctuations, leading to enhanced building energy-saving efficiency.

Furthermore, significant differences in the medians of diurnal temperature variation at all common layers between the green roof and the reference roof were detected in the Mann-Whitney U test on hot, cold, and normal days in both 2017 and 2018 (except at TCIUS on hot days). The box-whisker plot in Figure 4.8 illustrates the daily temperature variation at the common layers (i.e., TCIUS, TCM, and TCTOI) of the green roof and reference roof on hot, cold, and normal days in 2017. As shown in the figure, the medians of diurnal temperature variation at the TCM and TCTOI for the green roof were relatively lower than those of the reference roof, while no difference was found at the TCIUS layer. The absence of significant differences at the TCIUS layer between the roofs could be attributed to the controlled room temperatures. On the other hand,

on cold and normal days, the medians of diurnal temperature variation at all common layers for the green roof were significantly lower than those of the reference roof. In 2018, the findings were exactly the same as those observed in 2017 (data not shown). It is worth noting that, the reference roof observed the highest fluctuations at the TCTOI layer among the other layers regardless of hot, cold, and normal days in both years. This can be attributed to the presence of concrete pavers above the TCTOI layer for the reference roof, which stored more heat energy due to their higher thermal mass, thereby contributing to increased fluctuations. In contrast, the green roof showed relatively lower fluctuation at this layer compared to the reference roof. This reaffirms that the growing media of the green roof helped to distribute heat more uniformly across all layers, thereby reducing temperature fluctuations. As a result, the green roof could be beneficial in enhancing building energy-saving efficiency.

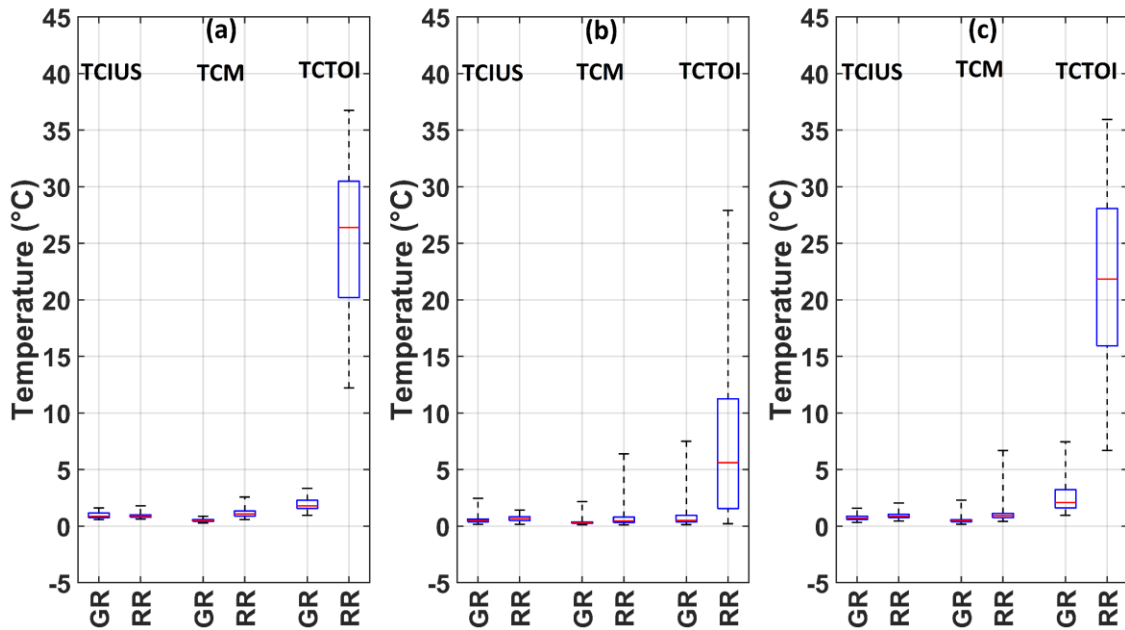


Figure 4.8 Box-whisker plots of diurnal temperature variation observed at the common layers of the green roof (GR) and the reference roof (RR) on (a) hot, (b) cold, and (c) normal days, respectively, in 2017.

4.4 Thermal resistance of the green roof and the reference roof

Table 4.5 presents the average R of the green roof and reference roof and the percentage increase in R of the green roof relative to the reference roof on hot days, cold days, and normal days, respectively, in 2017 and 2018. As shown, the green roof had a higher average R than the reference roof across hot, cold, and normal days in both years. This indicates that the green roof offered higher resistance to heat transfer than the reference roof, both from the outside to the inside of the building and vice versa. In other words, the green roof offered a better thermal insulation capacity for the building, which is also reflected by the increase in R of the green roof relative to

the reference roof (Table 4.5). In addition, over the two years, on hot days in 2017, the average R of the green roof was largely improved by 22.27% compared to the reference roof, reflecting the highest impact of the green roof on the insulation capacity of the building relative to that of the reference roof, which had the lowest R .

Table 4.5 The calculated average R of the green roof and reference roof on hot, cold and normal days, respectively, in 2017 and 2018.

Thermal resistance (R) ($m^2.K/W$ (square meter Kelvin per Watt))						
2017				2018		
Roofs	Hot days	Cold days	Normal days	Hot days	Cold days	Normal days
Green Roof	2.36	3.29	3.09	2.30	3.25	3.37
Reference Roof	1.93	2.98	2.70	2.01	2.85	2.98
Improvement by the green roof (%)	22.27	10.4	14.4	14.4	14.0	13.0

On hot days in 2017, the average and maximum daily air temperatures were approximately 21°C and 26°C, respectively. The average T_{ex} of the green roof and reference roof were 20°C and 26°C, respectively. On hot days in 2018, the average and maximum daily air temperatures were approximately 21°C and 29°C, respectively. The average T_{ex} were 19°C and 26°C for the green roof and reference roof, respectively. Therefore, the green roof consistently maintained its average T_{ex} slightly below the average air temperature in both years, whereas the reference roof presented higher T_{ex} closer to the maximum daily air temperatures. The green roof, on average, lowered T_{ex} by approximately 30% in 2017 and 37% in 2018 relative to the reference roof. Given the air

temperature is the same for both roofs, the lower T_{ex} of the green roof reaffirmed its improved insulation capacity.

Besides, on hot days in 2017, the average and maximum daily heat flux values (magnitude) measured at TCM were about -1.42 and -2.75 W/m², and 1.96 and 7.64 W/m² for the green roof and reference roof, respectively. In 2018, they were -1.47 and -3.15 W/m², and 1.99 and 4.82 W/m² for the green roof and the reference roof, respectively. Here, it is worth noting that the negative and positive signs associated with heat flux values indicate the direction of heat transfer, while the measurements refer to the absolute heat flux measured at TCM, irrespective of signs. Negative heat flux values denote heat transfer from inside to outside of the building and vice versa for positive heat flux values. For the green roof, the average heat flux values were negative in both years, indicating that heat transferred from the inside to the outside of the building. Whereas for the reference roof, the heat was transmitted toward the interior of the building, as indicated by the positive heat flux values at TCM. All these results showed that, above the TCM layer, the green roof mitigated the entrance of incoming heat from the atmosphere on hot days. This could be ascribed to the additional insulating capability of growing media of the green roof, which can facilitate an evaporative cooling process via water retained in media and increase the albedo effect and consequently reduce the solar radiation absorption.

However, it is worth mentioning that on hot days, the average T_{in} for the green roof exceeded the average temperature measured above the TCIUS, including average T_{ex} , while the average T_{in} of the reference roof surpassed the average temperature measured at TCM, suggesting that heat dissipated from the building. The heat flux measured at TCM indicated that, on average, heat dissipated from the interior of the building for the green roof, whereas it transmitted into the building for the reference roof on hot days. The different heat transmission direction of the green

roof could result from the indoor thermal settings of the building. The growing media of the green roof prevented incoming heat from the ambient atmosphere to the building, while the higher inside roof temperature (reflected by the higher T_{in}) could reverse the heat transmission. In contrast, for the reference roof, the consistently higher T_{ex} than T_{in} resulted in the heat transmission from the ambient atmosphere into the interior of the building on hot days.

On cold days in 2017, the average air temperature was about $-1.5\text{ }^{\circ}\text{C}$, while the average T_{ex} were around 4°C and 2°C for the green roof and reference roof, respectively. The average T_{ex} of both roofs was higher than the average air temperature. The difference of $2\text{ }^{\circ}\text{C}$ in the average T_{ex} between the green roof and the reference roof suggests that the green roof was more efficient in retaining heat within the roof than the reference roof. This difference translated into a roughly 8% reduction in the average heat transfer from the inside of the building to the ambient atmosphere compared to the reference roof. Consequently, the green roof had a R 10.4% higher than the reference roof (Table 4.5). It is also worth mentioning that the average T_{in} of the green roof was around 22°C , approximately 1.5°C warmer than the average T_{in} of the reference roof. Moreover, the higher of the T_{ex} affirms that the green roof reduced the heat loss (from the building) and accordingly had insulation capacity to retain heat of building. In 2018, similar results were observed. Quantitatively, the green roof had a slightly smaller average heat flux (-6.1 W/m^2) than that of the reference roof (-6.7 W/m^2). The green roof reduced the average heat flux by about 10%, which is 2% higher than that in 2017, while it increased the average T_{ex} and T_{in} by approximately by 2°C , respectively, relative to the reference roof. These combined results support that the green roof outperformed the reference roof in retaining heat inside the building and within the roof. All these resulted in that the average R of green roof was improved by 4% compared to the previous year.

Moreover, on normal days, the green roof exhibited behaviour similar to cold days in both years. It kept the average T_{in} warmer by roughly 2°C in 2017 and 1.5°C in 2018, while reducing the average heat transfer from the building by approximately 12% and 9%, respectively, compared to that of the reference roof. The average T_{ex} of the green roof (approximately 16°C in 2017 and 15.5°C in 2018) consistently exceeded the average air temperature of 15.5°C in 2017 and 14°C in 2018. Thus, the green roof retained the heat over normal days, namely that the roof provided a passive warming effect to the building, which refers to its ability to insulate the building, reduce heat loss, and potentially lower the demand for heating. As a result, the green roof had an improved average R (by 14.4% and 13% in 2017 and 2018, respectively) relative to the reference roof (Table 4.5). Overall, on hot days, the green roof mitigated heat gain, while on cold and normal days, it retained more heat within the roof than the reference roof.

The box-whisker plot in Figure 4.9 further illustrates the daily R of both the green roof and the reference roof on hot, cold, and normal days in 2017 and 2018. As shown in this figure, the green roof had a higher median daily R compared to the reference roof consistently over hot, cold, and normal days in both years. On hot days, the green roof consistently maintained a daily R above 1 m². K/W, while on most hot days, the green roof had a daily R above 2 m². K/W as the lower interquartile R was higher than 2 m². K/W. In contrast, on most hot days, the reference roof had a daily R above 2 m². K/W as the upper interquartile R was lower than 2 m². K/W. In addition, the medians of the daily R of the green roofs were found to be significantly higher than those of the reference roof on hot days in both 2017 and 2018 in the Mann-Whitney U test. However, in 2018, the differences in the lower and upper interquartile and the median of daily R were not as prominent as those in 2017. This might suggest that apart from the green roof itself, other factors (e.g.,

moisture of growing media of the green roof) might also play a role in affecting the insulation capacity of green roofs.

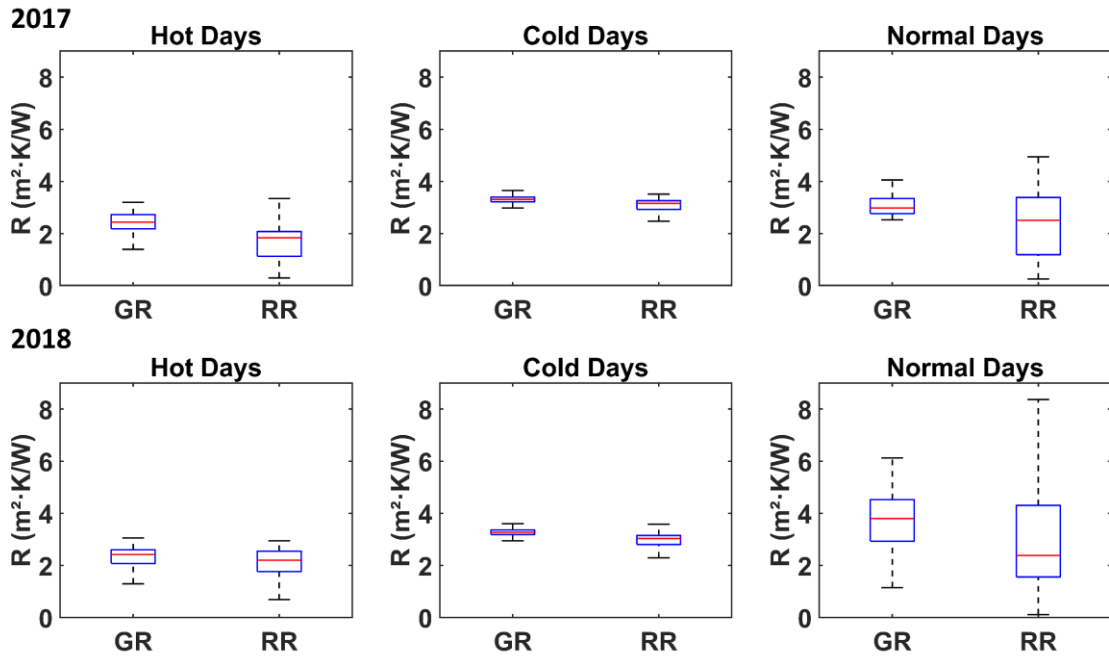


Figure 4.9 Box-whisker plot of the daily thermal resistance (R) of the green roof and reference roof on hot, cold, and normal days, respectively, in 2017 and 2018.

Different from the hot days, on cold and normal days, the green roof and the reference roof appeared to perform equivalently in these two years. Namely, in general, the lower and upper interquartile and the median of the daily R of the green roof were higher than those of the reference roof. In addition, on both cold and normal days, the medians of the daily R of the green roof were significantly higher than those of the reference roof for both years (Mann-Whitney U test). Therefore, over cold and normal days in these two years, the green roof outperformed the reference roof in terms of thermal insulation capacity.

The above results demonstrate that, in general, at the seasonal (hot, cold, or normal days) and daily temperature scales, the thermal insulation capacity of the green roof was superior to that of the reference roof when the roof played its role in both heating and cooling. Thus, green roofs can mitigate the energy consumption of building by reducing the energy consumption for both heating and cooling.

4.5 Surface temperature reduction of green roof

Figure 4.10 displays the average STR of the green roof over hot, cold, and normal days at the TCIOI, TCM, and TCIUS layers for 2017 and 2018, respectively. The STR shown in the figure clearly indicates that, in general, the green roof mitigated temperature at the TCTOI layer relative to the reference roof on hot days, whereas on cold and normal days, it increased temperatures across all layers (excluding the TCTOI layer on normal days) in both 2017 and 2018. On hot days, the STR for the TCTOI layer was lower than one (i.e., 0.77 in both years). This indicates that the green roof reduced the average temperature by 23% at this layer compared to that of the reference roof, thereby providing a cooling effect on the building by preventing incoming heat transfer. However, the cooling effect of the green roof was not evident at the TCM layer, as the STR was equal to one in 2017, while it exceeded one in 2018 (i.e., 1.03). Similarly, no cooling effect was observed at the TCIUS layer, as the STRs were above the threshold in both years (i.e., 1.03 in 2017 and 1.06 in 2018). The ability of the green roof to reduce temperatures at these two layers might be influenced by the difference in the indoor thermal settings between both roofs. During cold days, STR values above one for all layers suggest that the green roof increased the average temperatures at these layers relative to the reference roof, indicating a warming effect on the building in both years. The STR for the TCTOI layer was 1.36 in both 2017 and 2018. This

indicates that the green roof showed the highest insulation effect at this layer among other layers by increasing the average temperature by 36% compared to the reference roof in both years. At the TCM layer, the green roof increased the average temperature by 10% in both 2017 and 2018, with the STR slightly above one (i.e., 1.10 in both years). Similarly, at the TCIUS layer, it elevated the average temperature by 9% in both years, with STRs recorded as 1.09 during these years on cold days.

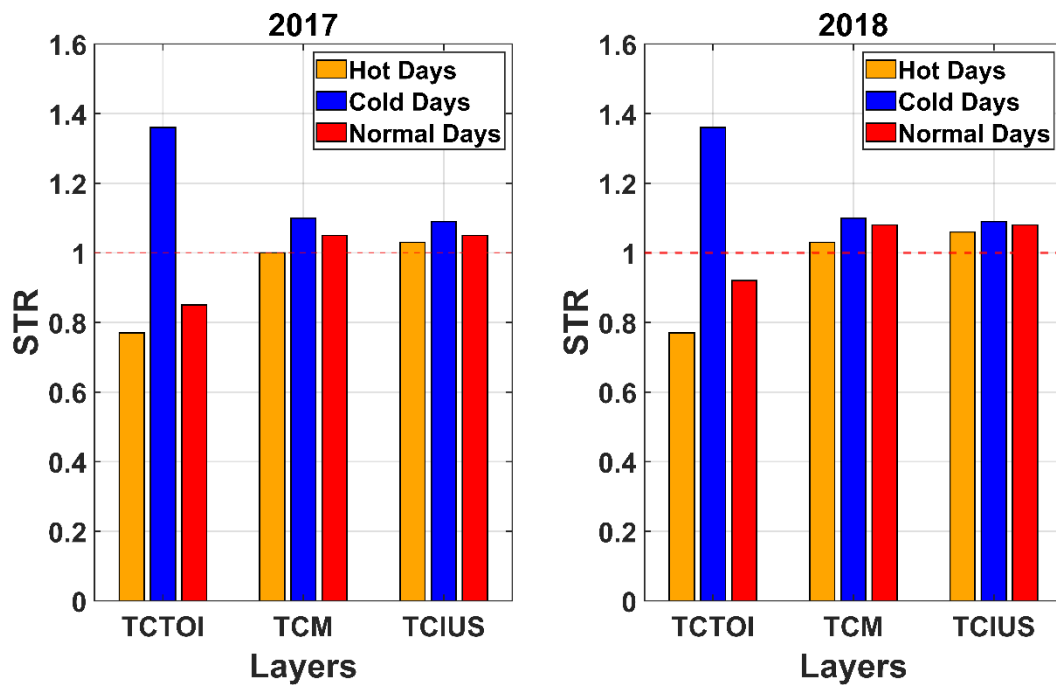


Figure 4.10 The average surface temperature reduction (STR) of the green roof on hot, cold, and normal days at the TCTOI, TCM, and TCIUS layers in 2017 and 2018. The red dotted line represents the threshold at which the green roof temperature is equal to the reference roof temperature, indicated by a STR equal to one.

In addition, like cold days, STR values exceeding thresholds for all layers on normal days (excluding the TCTOI layer) imply that the green roof elevated the average temperatures at these

layers, thereby contributing to building insulation through its warming effect over both years. For both the TCM and TCIUS layers, the green roof increased the average temperature by 5% in 2017, indicated by the STR of 1.05 for both layers. In 2018, it further raised the average temperature by 7% for both layers, with the STR of 1.07. However, no warming effect was observed at the TCTOI layer, as the STR was slightly below one in both years. It is worth noting that the average thermal performance of the green roof was consistent across both years, as the STRs for all layers in 2017 were very close to those in 2018. Overall, these results suggest that the green roof demonstrated its ability to decrease the roof temperature on hot days by preventing incoming heat transfer through its cooling effect. In contrast, during cold and normal days, it showed its potential to increase the roof temperature by retaining more heat within the building, providing insulation through its warming effect. Consequently, this contributed to maintaining a comfortable indoor environment, thereby reducing the energy consumption of the building.

Figures 4.11 and 4.12 further present the daily STR of the green roof at the TCIUS, TCM, and TCTOI layers for hot, cold, and normal days in 2017 and 2018, respectively. The daily STR at the TCTOI layer showed a large variation compared to that at the TCM and TCIUS layers, irrespective of hot, cold, and normal days in both years. This variation is attributed to the huge fluctuations in the daily temperatures observed at the TCTOI layer of the reference roof over the years. On hot days, the daily STR consistently remained below one in both years (i.e., ranging between 0.65 to 0.9 in 2017 and 0.6 to 1 in 2018), indicating that the green roof reduced the daily temperature at this layer throughout the hot season. In contrast, the daily STRs for the TCM and TCIUS layers were consistently above one in both years, showing no cooling effect of the green roof. However, there was an exception in 2017, where the lower interquartile STR for the TCM remained below the threshold, suggesting the cooling effect of the green roof on certain days. As mentioned above,

the green roof's capacity to decrease temperatures at the TCM and TCIUS layers may be impacted by the difference in the indoor thermal configurations between the two roofs. On cold days, the daily STRs for all layers exceeded one in both years, except for the TCTOI layer, where some days recorded STRs below the threshold. In both years, the daily STRs for the TCM and TCIUS layers consistently ranged between 0.9 and 1.3 (Figure 4.11 and 4.12), while for the TCTOI layer, it ranged between 0.5 and 2.7 in 2017 and 0.6 and 1.9 in 2018.

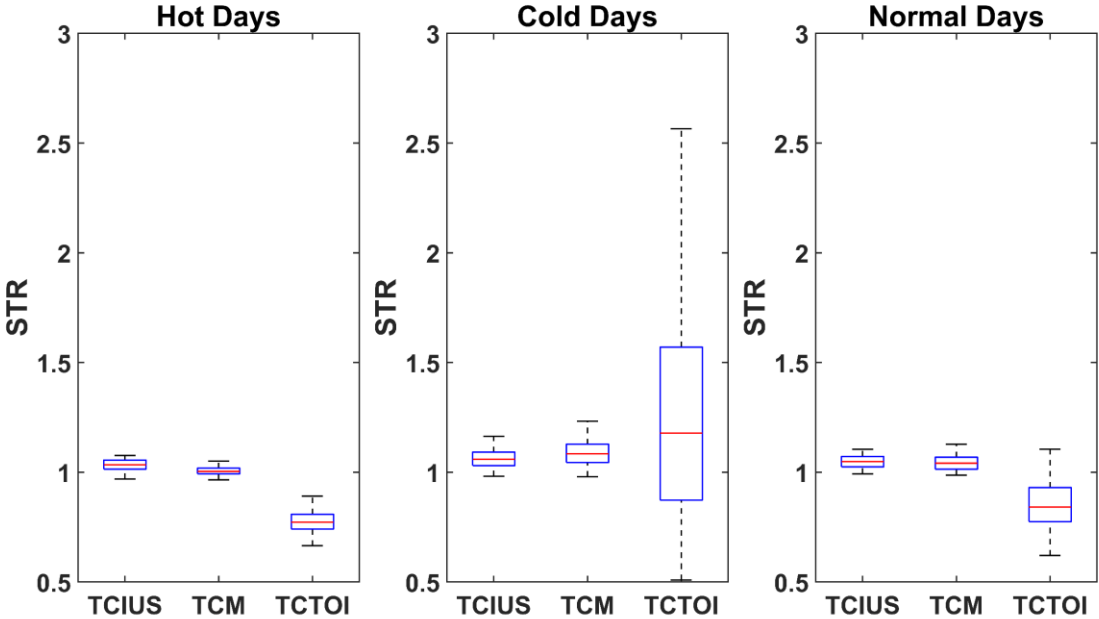


Figure 4.11 Box-whisker plot of daily surface temperature reduction (STR) of the green roof on hot, cold, and normal days at the TCIUS, TCM, and TCTOI layers in 2017.

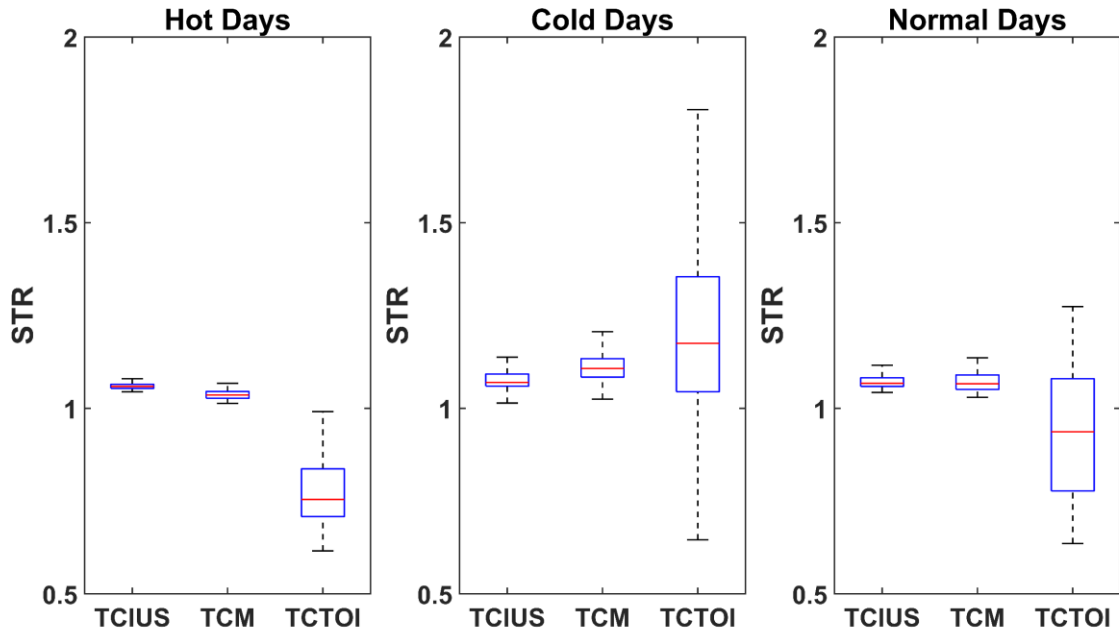


Figure 4.12 Box-whisker plot of daily surface temperature reduction (STR) of the green roof on hot, cold, and normal days at the TCIUS, TCM, and TCTOI layers in 2018.

The daily STRs values above one for all layers confirm that the green roof consistently had higher daily roof temperatures relative to the reference roof during cold days in both years, thereby suggesting a warming effect of the green roof. Furthermore, the green roof demonstrated its potential to increase daily temperatures, particularly at the TCM and TCIUS layers, as indicated by the daily STRs surpassing the threshold for these layers throughout the normal period in both 2017 and 2018 (i.e., ranging between 0.95 to 1.2 in 2017, and 1 to 1.2 in 2018 for both layers). On the other hand, similar to hot and cold days, a large variation in the daily STRs for the TCTOI layer was observed in both years. In contrast to the TCM and TCIUS layers, the daily STRs for the TCTOI consistently remained below one (i.e., ranging between 0.6 to 1.3 in both years), with some instances where it exceeded the threshold. This reverse pattern of STRs below one at this

layer may be attributed to the impact of the moisture in the growing media, which led to a reduction in daily temperatures at the TCTOI relative to the reference roof.

In general, all these findings indicate that the green roof effectively insulated the building by mitigating incoming heat transfer through its cooling effect at the TCTOI layer. Conversely, it exhibited the ability to raise roof temperatures on cold and normal days by trapping heat within the building, thereby providing insulation through its warming effect. All these collectively contributed to maintaining a comfortable indoor environment and enhancing the energy efficiency in the building.

4.6 Vertical distribution of temperature

In this section, the vertical temperature variations of the green roof and the reference roof were examined in two ways, namely by examining the statistical difference in the medians and variances of roof temperatures among their common layers (i.e., TCTOI, TCM, and TCIUS), and the three growing media layers of the green roof (i.e., TCTGM, TCMGM, and TCBGM), and by analyzing the vertical temperature profile at several time slices over a day among the layers of the green roof and the reference roof. Additionally, the vertical temperature profiles are presented for two typical hot, cold, and normal days at seven time slices (at 4-hour steps) over each day.

4.6.1 Vertical differences in roof temperature

The daily average roof temperatures were compared in terms of their medians among the three common layers of the green roof and reference roof (i.e., TCIUS, TCM, and TCTOI), as well as the three growing media layers of the green roof (i.e., TCTGM, TCMGM, and TCBGM) using the Kruskal-Wallis test. These comparisons were performed for both roofs on hot, cold, and normal

days in 2017 and 2018. Besides comparing the medians of the daily roof temperatures among the layers of the roofs, their variances were also compared using the Brown-Forsythe test. Significant differences were detected in the medians and variances of the daily average roof temperatures among the common layers for both roofs on hot, cold, and normal days in both years.

As shown in Figure 4.13, on hot days, the median daily average temperatures were consistently higher at the TCIUS among the other common layers of the green roof, while lower at the TCTOI in both years. In contrast, for the reference roof, the median daily average temperatures at the TCIUS and TCTOI were significantly lower and higher, respectively, in both years. This indicates that heat was transmitted from the building to the atmosphere for the green roof while in the opposite direction for the reference roof. Furthermore, for both roofs, the variance in temperature at TCTOI was significantly higher than the other two layers in both 2017 and 2018. However, the variance in temperature at TCM and TCIUS was significantly lower than other layers of the green roof and reference roof, respectively, in both years.

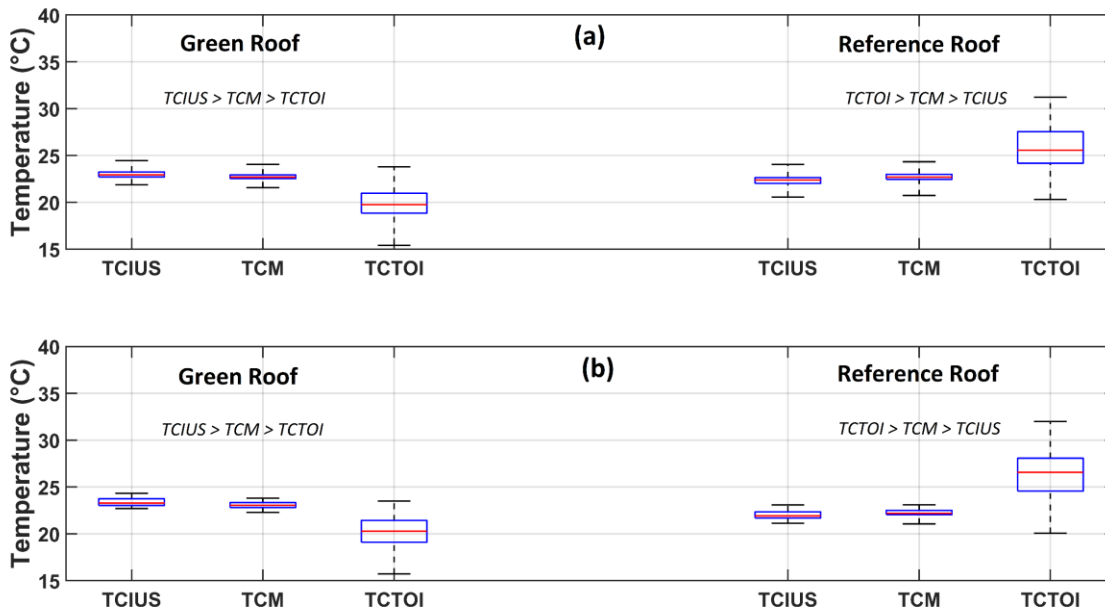


Figure 4.13 Box-whisker plot of daily average temperature measured at common layers of both the green roof and the reference roof on hot days in (a) 2017 and (b) 2018.

Interestingly, on cold and normal days in both years, both the green roof and the reference roof exhibited the highest and the lowest daily average roof temperature medians at TCIUS and TCTOI, respectively (data not shown). Additionally, in both years, the daily average temperature median at TCM was significantly lower than that at TCIUS but higher than that of TCTOI for both roofs. This result clearly demonstrates that heat was transmitted from the building to the atmosphere for both roofs on cold and normal days. On the other hand, both the green and reference roofs showed significantly the highest and lowest variance in temperature at TCTOI and TCIUS, respectively. It is not surprising to observe the lowest variance at TCIUS for both roofs, as the temperature at this layer was largely influenced by the indoor thermal settings. Conversely, the highest variance at TCTOI could be because this layer is more susceptible to variations in air temperature.

Furthermore, in the green roof, no significant differences in the medians of daily average temperatures among the three growing media layers (i.e., TCTGM, TCMGM, and TCBGM) were detected on hot and normal days in both years. However, the median daily average temperatures were statistically significant on cold days in both years (Figure 4.14). The results on hot and normal days indicated that the green roof approximately uniformly distributed heat across all layers of the growing media (from top to bottom layers), thereby reducing the temperature difference between the top and bottom layers (TCTGM and TCBGM) of the growing media. This could be attributed to the presence of moisture content in the growing media, which enhances the thermal conductivity of the soil and facilitates vertical heat transmission (Al-kayssi et al., 1990; Shao et al., 2021). On cold days, no such effect was observed. The daily average temperatures at the bottom layer (TCBGM) of the growing media were consistently higher than the other two layers on cold days, while lower at the top layer (TCTGM) in both years, indicating heat transmission from inside the building to the atmosphere (Figure 4.14). In addition, no significant differences in variances were observed among the three layers of growing media on hot, cold, and normal days in both years. This suggests that the growing media effectively mitigated temperature fluctuations among the layers, regardless of the weather conditions.

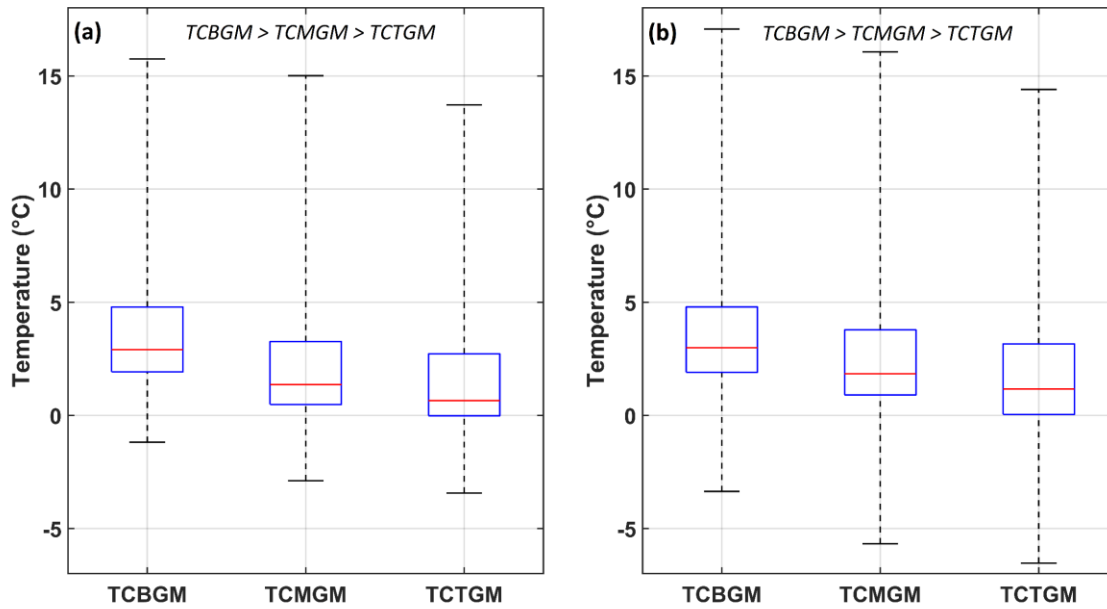


Figure 4.14 Box-whisker plot of daily average temperature measured at three growing media layers of the green roof on cold days in (a) 2017 and (b) 2018.

4.6.2 Vertical temperature profile on hot days

Figure 4.15 depicts the vertical temperature profile of both green and reference roofs on a very hot day (June 26th, 2017), when the daily average air temperature was approximately 24°C. As shown, the air temperatures gradually decreased from midnight (00.00 hr) and reached a minimum in the morning at 08.00 hr. Thereafter, temperatures rapidly increased during the late morning and continued to rise until the late afternoon, reaching a maximum at 16.00 hr. Subsequently, it dropped late at night. During the period from midnight to early morning (i.e., from 00:00 to 08:00 hr), when the air temperature decreased, the roof temperature of the green roof (including the growing media layers) increased vertically from the top layer TCTGM to the layer TCIUS, largely governed by the controlled room temperature. It is worth mentioning that the roof temperatures at TCM and TCIUS were approximately the same. During this period (from 00:00 to 08:00 hr), the

roof temperatures at all layers were also higher than the air temperature (except at 0:00 hr), indicating heat loss from the building. The vertical variations in temperature of the reference roof were similar to those of the green roof. From noon (12:00 hr) to early night at 20:00 hr, the green roof temperatures decreased vertically from the top to the bottom of the roof growing media and then increased up to TCIUS afterwards. Note that the air temperature was higher than the green roof temperature at TCTGM. This indicates heat transmission vertically in two directions: from the top of the growing media to the TCTOI (incoming heat transfer) and from the TCIUS to the TCTOI (outgoing heat transfer). The reverse heat transmission from TCIUS to TCTOI was driven by the controlled room temperature, which was higher than TCTOI. However, different vertical temperature variations were observed in the reference roof during the same period, with temperatures decreasing from the top to the bottom of the reference roof overall. Note that from 14:00 to 20:00 hr, in contrast to the green roof, the air temperature was generally lower than that of its top layer TCTOI. As mentioned before, the reference roof had concrete pavers above this layer, which stored more heat energy due to their higher thermal mass and released heat very slowly. This clearly demonstrates that the green roof is effective in reducing energy consumption. The growing media in the green roof used absorbed heat energy for the evapotranspiration process, thereby retaining less heat through its media, particularly during the daytime when air temperature is higher, and energy is consumed for cooling.

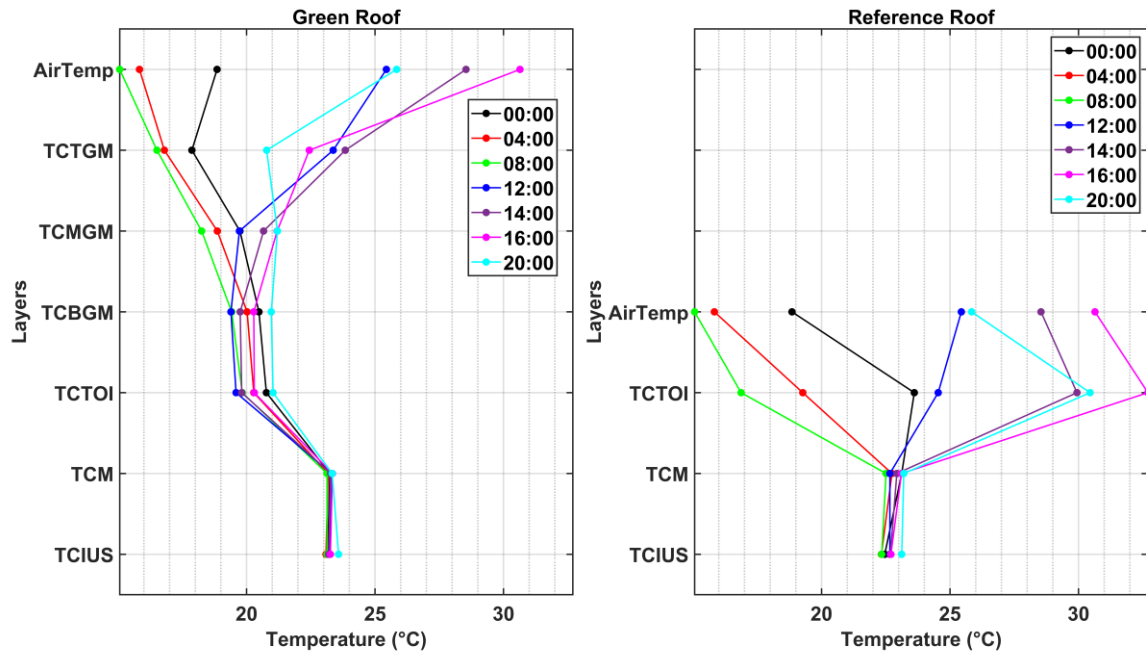


Figure 4.15 Vertical temperature profiles of the green roof and the reference roof on June 26th, 2017, a hot day with a daily average air temperature of 24°C.

Furthermore, the vertical temperature profiles of both green and reference roofs were shown on another hot day on April 28th, 2018, when the daily average air temperature was approximately 20°C (Figure 4.16). As shown, on this day, the air temperature declined from midnight (00:00 hr) and reached its lowest at 04:00 hr. Subsequently, there was a slight increase until 08:00 hr, followed by a drastic rise at 12:00 hr and then a nearly constant temperature throughout the rest of the day. The vertical temperature profiles of both roofs on this day mirrored those observed on June 26th, 2017, during the period from midnight to early morning (i.e., from 00:00 to 08:00 hr) and from noon to early night (i.e., from 12:00 to 20:00 hr) in general. However, the roof temperature at TCM was slightly lower than that at TCIUS throughout the day, but slightly higher than those at TCIUS on June 26th, 2017. Recall that June 26th, 2017, was hotter, with a higher daily average temperature. Overall, it is evident that on hot days, the green roof could reduce the roof

temperature at the surface compared to the reference roof, particularly during the daytime when the air temperature is higher. This demonstrates that the green roof absorbs and retains less heat in growing media, thereby mitigating the energy consumption of the building for cooling.

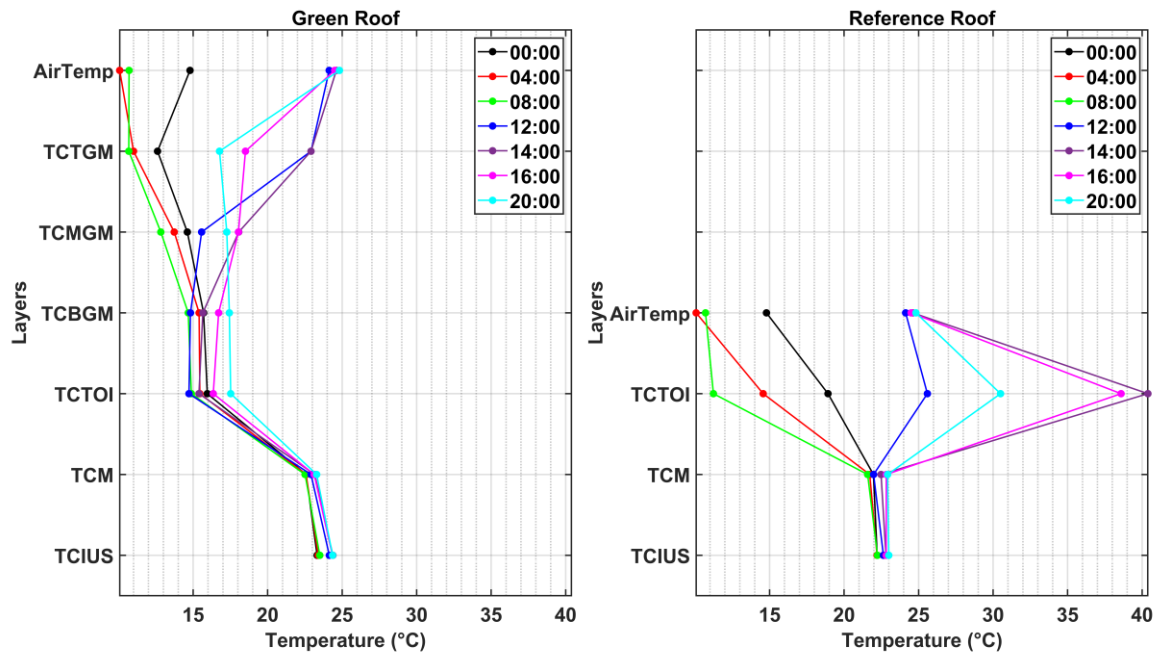


Figure 4.16 Vertical temperature profiles of the green roof and the reference roof on April 28th, 2018, a hot day with a daily average air temperature of 20°C.

4.6.3 Vertical temperature profile on cold days

Figure 4.17 displays the vertical temperature profile of both the green roof and the reference roof on an extremely cold day (January 9th, 2017), with a daily average temperature of around -20°C. It is also worth mentioning that the air temperature was more or less constant, having a very small diurnal variation. Consequently, it is not surprising to observe the same vertical temperature profiles over the entire day, namely, the roof temperatures increased vertically from the top (TCMGM) to the bottom (TCIUS) in general. Particularly, a large increase in temperature was

observed from TCTOI to TCM. For the reference roof, similarly, the roof temperature increased vertically from top to bottom, with a prominent increase from TCTOI to TCM. Therefore, the heat was transmitted from the building to the atmosphere from both roofs. However, the roof temperature at TCTOI of the green roof was above 0°C and below 0°C for the reference roof. This reaffirms that the green roof reduced energy consumption to maintain the room temperature consistently throughout the day compared to the reference roof.

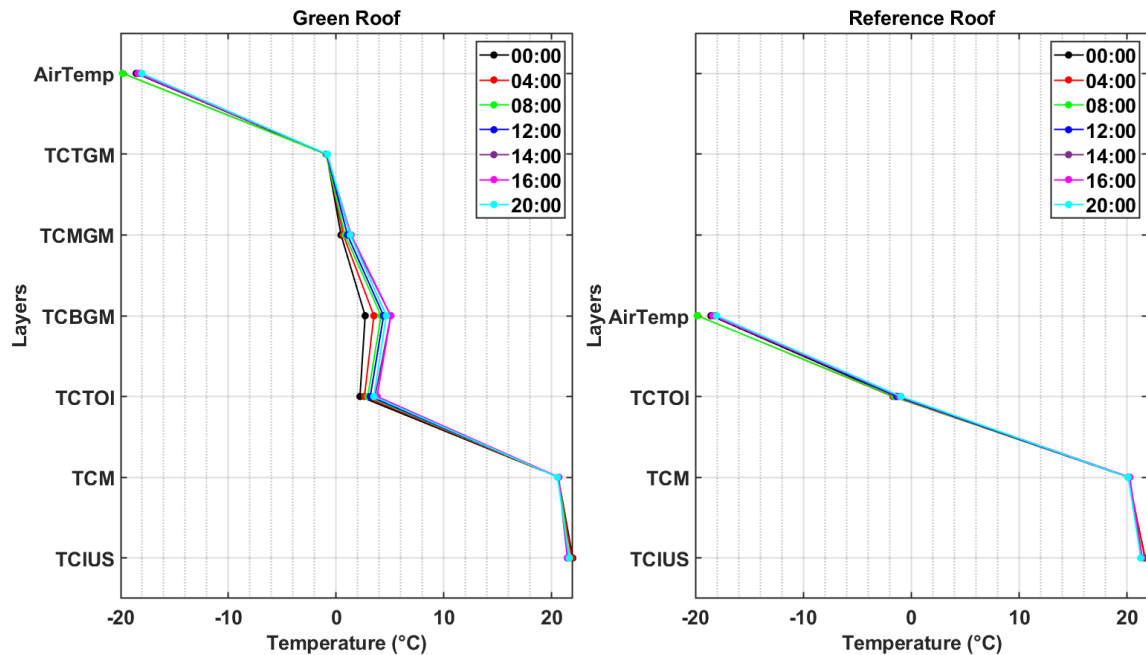


Figure 4.17 Vertical temperature profiles of the green roof and the reference roof on January 9th, 2017, an extremely cold day with a daily average air temperature of -20°C.

The vertical temperature profiles of both green and reference roofs are illustrated on another cold day (January 9th, 2018) (Figure 4.18). The daily average air temperature was approximately -10°C, and the air temperature varied in a large range (from -16°C to 2.5°C) diurnally, which is different from the cold day on January 9th, 2017. Consequently, differing from January 9th, 2017,

an apparent diurnal temperature variation was observed in the top layers of both the green roof and the reference roof (i.e., TCTGM and TCTOI, respectively). However, similar to January 9th, 2017, over the entire day, roof temperatures of both roofs increased vertically from the top to the bottom layers in general. Thus, for both roofs, heat was transferred from the building to the atmosphere throughout the day. Yet, the roof temperature at TCTOI of the green roof was above 4°C throughout the day, while that of the reference roof was consistently below 2°C and even dropped below 0°C at 20:00 hr. This demonstrates that similar to January 9th, 2017, the green roof increased the roof temperature at TCTOI, relative to the reference roof, and thus effectively reduced energy consumption for heating to maintain a desirable room temperature throughout the entire day. It is worth mentioning that the roof temperature at TCIUS of the green roof was evidently higher than that of the reference roof, implying that the room temperature under the green roof was higher than that under the reference roof. Given the same room temperature, the effect of the green roof in reducing energy might be more effective.

On both cold days, the vertical temperature profiles of both roofs demonstrate heat loss from the building to the atmosphere, but the green roof helped reduce heat loss from the building throughout the day. This is ascribed to the fact that the green roof retained more heat compared to the reference roof, resulting in maintaining higher temperatures at common layers of the roofs. Therefore, the green roof reduced energy consumption for heating on cold days.

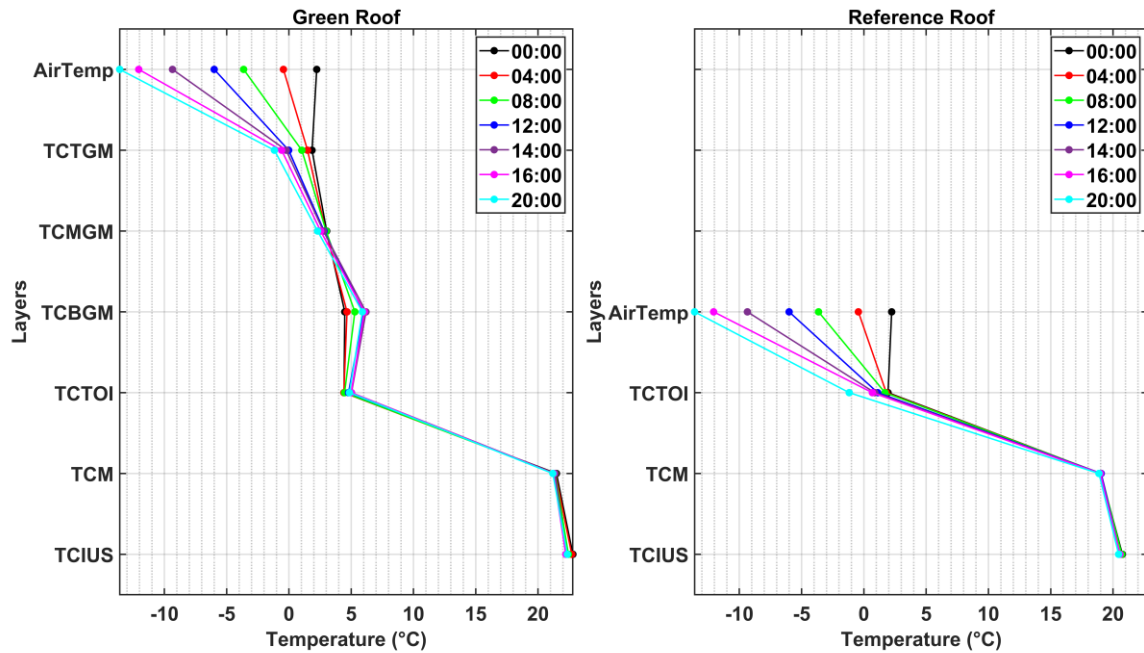


Figure 4.18 Vertical temperature profiles of the green roof and the reference roof on January 9th, 2018, a moderately cold day with a daily average air temperature of -10°C.

4.6.4 Vertical temperature profile on normal days

The vertical temperature profiles of the green roof and reference roof on normal days are shown on the selected day on May 3rd, 2017 (Figure 4.19). The average daily air temperature of the day is approximately 14°C, and the air temperature varied in a range of about 17.5°C. On this day, the vertical temperature profiles for both roofs were very close to those on April 28th, 2018 (hot day). However, at noon (12:00 hr) and 14:00 hr, the air temperatures were lower than the temperature at the TCTGM layer of the green roof, in contrast to April 28th, 2018. It is worth noting that the daily average air temperature on April 28th, 2018, was 6°C higher than the normal day (May 3rd, 2017). However, the diurnal temperature variation at the TCTGM layer of the green roof was largely different on this normal day compared to that of the hot day. Overall, on this normal day, the temperature at the TCTOI layer of the reference roof was consistently higher than the air

temperature, particularly during the daytime, while, in contrast, the temperature at the TCTGM layer of the green roof was lower (except at 12:00 and 14:00 hr). This clearly indicates that the green roof reduced energy consumption for cooling on a normal day by absorbing less heat, particularly during the daytime.

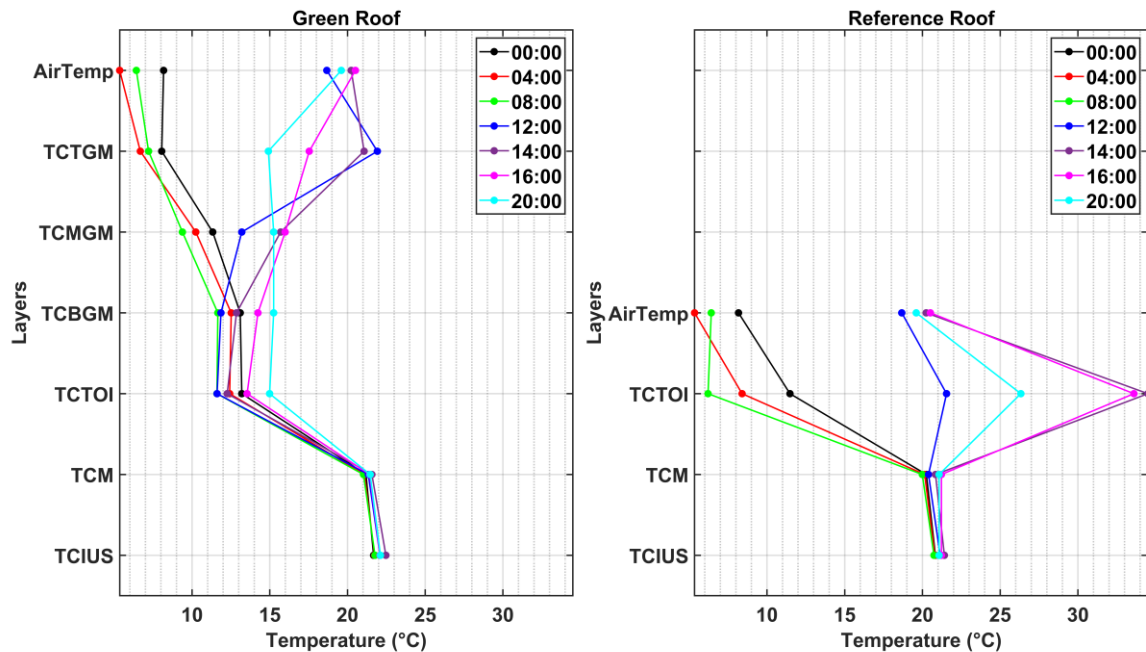


Figure 4.19 Vertical temperature profiles of the green roof and the reference roof on May 3rd, 2017, a normal day with a mean daily air temperature of 14°C.

Figure 4.20 depicts the vertical temperature profile on another normal day (June 29th, 2017). The average daily air temperature of this day (approximately 17°C) is higher than that on May 3rd, 2017, and has a narrower range of variation (about 11°C). The vertical temperature variations of the reference roof on this day were similar to those observed on the normal day on May 3rd, 2017. The vertical temperature profile for the green roof was also similar to those during nighttime but

slightly different during the daytime on May 3rd, 2017. During the daytime, as the air temperature began to rise, the TCTGM layer of the green roof experienced a drastic increase in temperature at 12:00 and 14:00 hr, which differed from May 3rd, 2017. Additionally, particularly from 12:00 to 14:00 hr, larger variations in both the air temperature and the temperature at the TCTGM layer of the green roof were observed than those observed on May 3rd, 2017. However, this drastic variation did not impact the pattern of heat transfer in the bottom layers, in general, thus remaining similar to that observed on May 3rd, 2017. Overall, during the daytime, the green roof was able to maintain a lower temperature at its top layer compared to the air temperature, in contrast to the reference roof, and reduce temperatures in the bottom layers. This reaffirms that the green roof absorbed and retained less heat in its top layer compared to the reference roof. It is worth noting that on this day, there was a lower variation in diurnal air temperature compared to the normal day on May 3rd, 2017. However, no major differences in the vertical temperature pattern were observed between both days.

In general, on both normal days, the green roof exhibited slightly different vertical temperature variations, especially during the daytime, with larger diurnal variations in the air temperature and the temperature at the top layer. However, it decreased the temperature at its top layer by preventing incoming heat transfer, especially during the daytime compared to the reference roof and also reduced the temperatures in the bottom layers, in general. This confirms that the green roof provided insulation to the building, thereby effectively reducing energy consumption for cooling when the air temperature was higher.

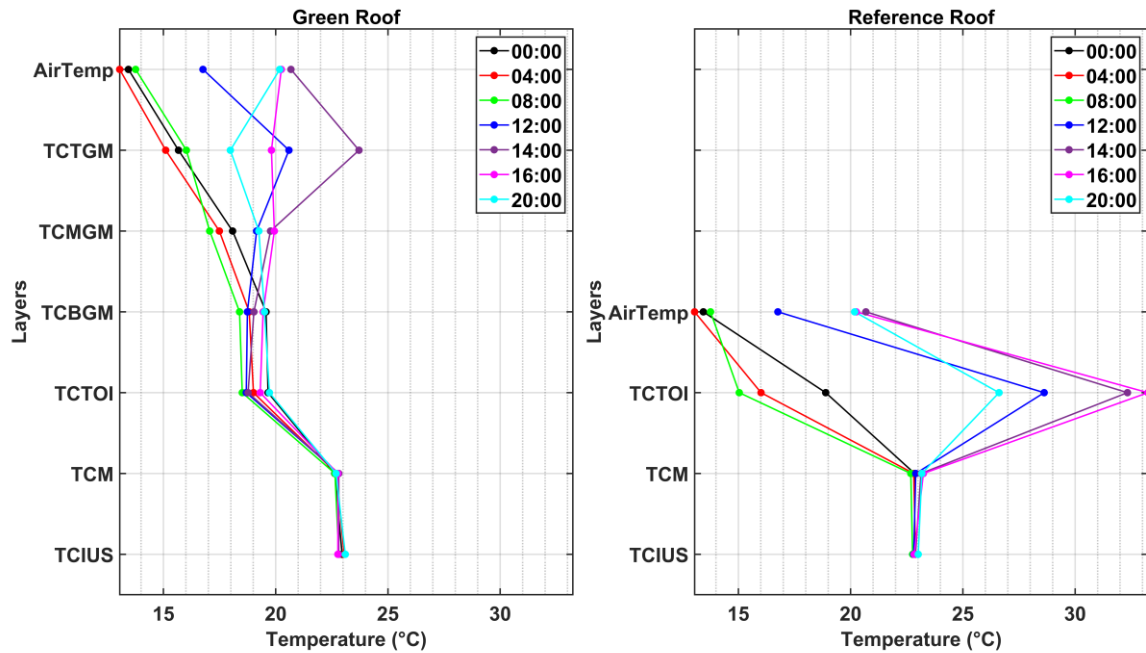


Figure 4.20 Vertical temperature profiles of the green roof and the reference roof on June 29th, 2017, a normal day with a mean daily air temperature of 17° C.

4.7 Impact of moisture on the thermal performance of growing media of the green roof

4.7.1 Impact of moisture on thermal performance of green roof on hot days

Figure 4.21 (a) displays the relationship between daily average moisture content and ΔT when heat was transferred from the atmosphere to the inside of the building on hot days in 2017. A significant positive Spearman's correlation coefficient between daily average moisture content and ΔT was calculated, indicating that the daily ΔT notably increased with increasing the daily average moisture content. This means that the higher moisture content in the soil helped to increase ΔT , namely decreasing the temperature at the media bottom compared to the top of the growing media

on hot days. This indicated that higher moisture content helped the soil/media store more heat energy, thereby increasing its thermal mass and reducing heat transfer (Al-kayssi et al., 1990).

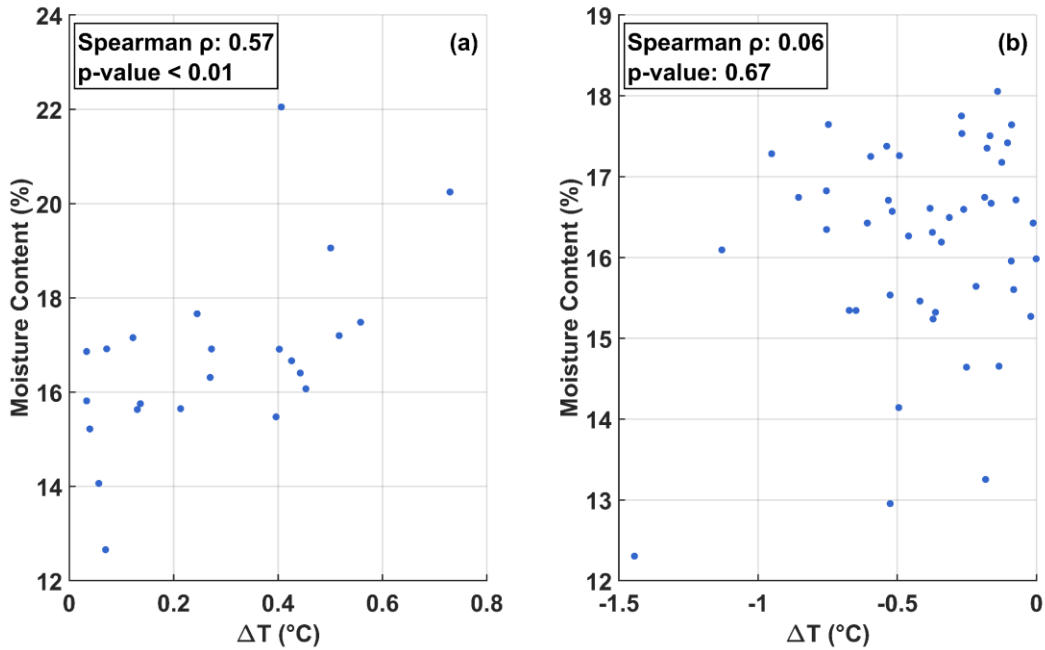


Figure 4.21 Scatter plot of daily average moisture content and temperature difference (ΔT) between TCTGM and TCBGM of the growing media (a) when heat was transmitted from the atmosphere to the building inside, and (b) when heat was transmitted from the building inside to the atmosphere on hot days in 2017.

Furthermore, the relationship between the daily average moisture content and ΔT is illustrated in Figure 4.21 (b), for the hot days when heat was transferred from the building inside to the atmosphere in 2017. The insignificant Spearman's correlation coefficient revealed the absence of significant relationship between moisture and ΔT . Further consideration of other factors associated with the thermal behavior of the growing media is necessary to understand the complex interactions affecting temperature distribution within the green roof.

In 2018, similar results were observed in both scenarios of heat transfer patterns as in 2017. The daily average ΔT increased with increasing moisture content on hot days when the air temperature was higher, and heat was transmitted into the building. Whereas on hot days when heat was transmitted into atmosphere from the building inside, no correlation was found between them. In general, on hot days in both years, higher moisture content was found to be beneficial in reducing temperatures at the bottom of growing media (relative to the top of growing media) when the ambient air temperature was higher (above 20°C). This helped to reduce the incoming heat absorbed by the green roof, thereby reducing the energy consumption needed for cooling. In contrast, there was no apparent dependency of ΔT on moisture content when the air temperature was lower (below 20°C). It is worth mentioning that the daily average air temperature threshold of 18°C was used to categorize hot days in this thesis. However, the observed relationship between moisture content and temperature reduction in the growing media, particularly when air temperature is above 20°C, suggests a possible slight discrepancy between the threshold utilized for data classification and the temperature threshold above which the influence of moisture on temperature is apparent. Furthermore, Spearman's correlation analysis was conducted to investigate the relationship between the daily average moisture content and the temperature measured at TCMGM, as well as between the daily air temperature and the temperature measured at TCMGM on all hot days in both 2017 and 2018. The analysis revealed a significant but not strong negative correlation between daily average moisture content and temperature at TCMGM in 2017, as shown in Figure 4.22. Namely, the temperature decreased along with the increase in moisture at TCMGM. On the other hand, it is not surprising that a significant positive correlation was found between daily air temperature and temperature at TCMGM. Similar results were observed in 2018, with findings mirroring those of 2017 for both relationships (data not shown).

These results further demonstrate that higher moisture content is beneficial in reducing the temperature of growing media on hot days, and consequently reducing the roof temperature and energy consumption for cooling.

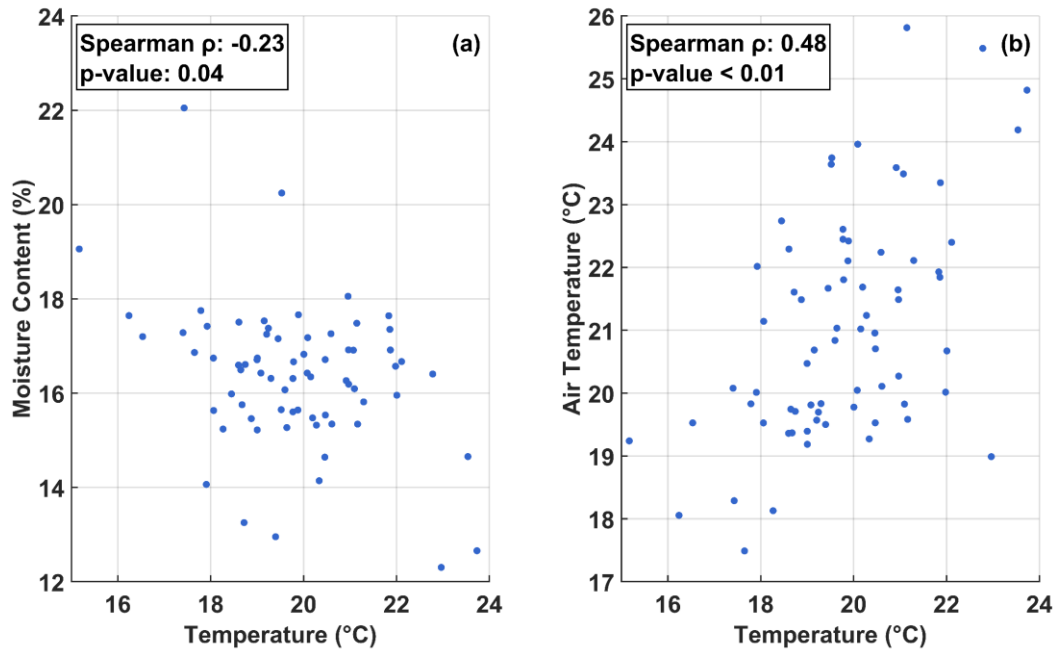


Figure 4.22 Scatter plot of (a) daily moisture content and temperature measured at the middle layer (TCMGM) of the growing media, and (b) daily air temperature and temperature measured at TCMGM of the growing media on hot days in 2017.

4.7.2 Impact of moisture on thermal performance of green roof on cold days

The growing media of the green roof was frozen from November to March in both years. Therefore, only cold days classified between April and October in 2017 and 2018 were used to examine the relationship between moisture content and media temperature. Figure 4.23 shows the relationship between daily average moisture content and ΔT on cold days in 2017 and 2018, respectively. It is worth mentioning that on all cold days in both years, the temperature at TCTGM

was lower than that at TCBGM (namely, ΔT is always negative), indicating that heat was consistently transferred from the building inside to the atmosphere. Different from hot days, the daily average ΔT decreased with the increase of the daily average moisture content on cold days in both years, as shown in Figure 4.23. This suggests that wet soil helped to maintain more stable temperatures within the growing media (by reducing the vertical temperature between TCTGM and TCBGM), thereby resulting in less heat escaping from the growing media compared to dry soil. As a result, the green roof retained more heat within the building, leading to a decrease in energy consumption for heating in both years.

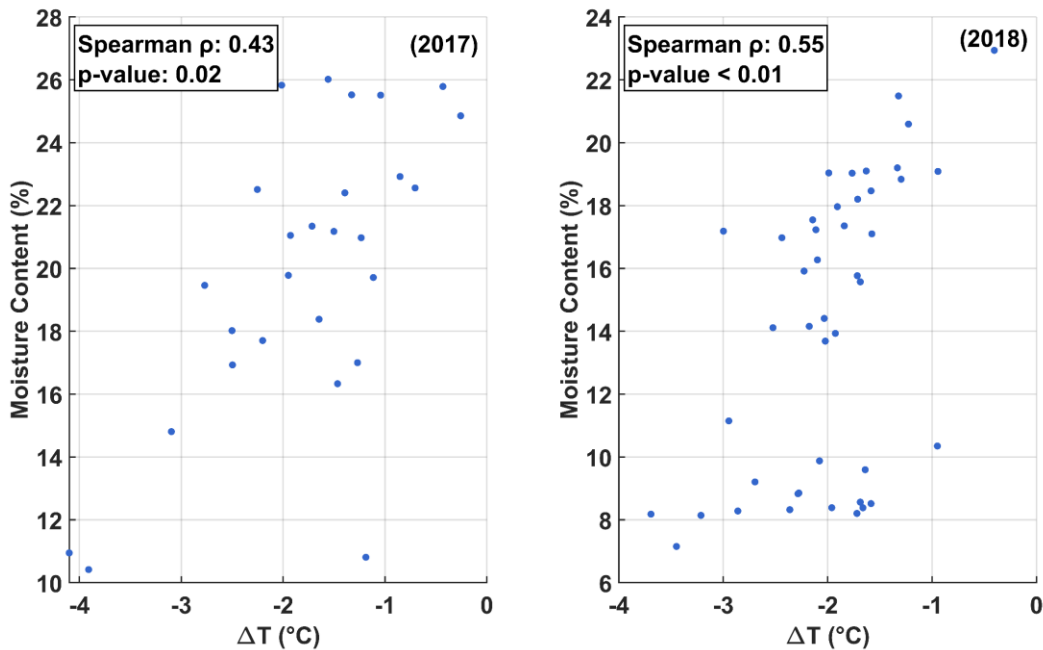


Figure 4.23 Scatter plot of daily average moisture content and temperature difference (ΔT) between TCTGM and TCBGM of the growing media on cold days in 2017 and 2018, respectively, when heat was transmitted from the building inside to atmosphere.

On cold days in 2017, at TCMGM the relationship between the daily moisture content and temperature was significant (Figure 4.24). The correlation coefficient indicates their negative correlation, with the temperature at TCMGM tending to decrease as the moisture content increased. In contrast, the temperature at TCMGM increased with the increasing air temperature. In addition, similar patterns were observed in 2018. These findings show that wet soil efficiently reduced the temperature of the growing media, irrespective of the direction of heat transfer.

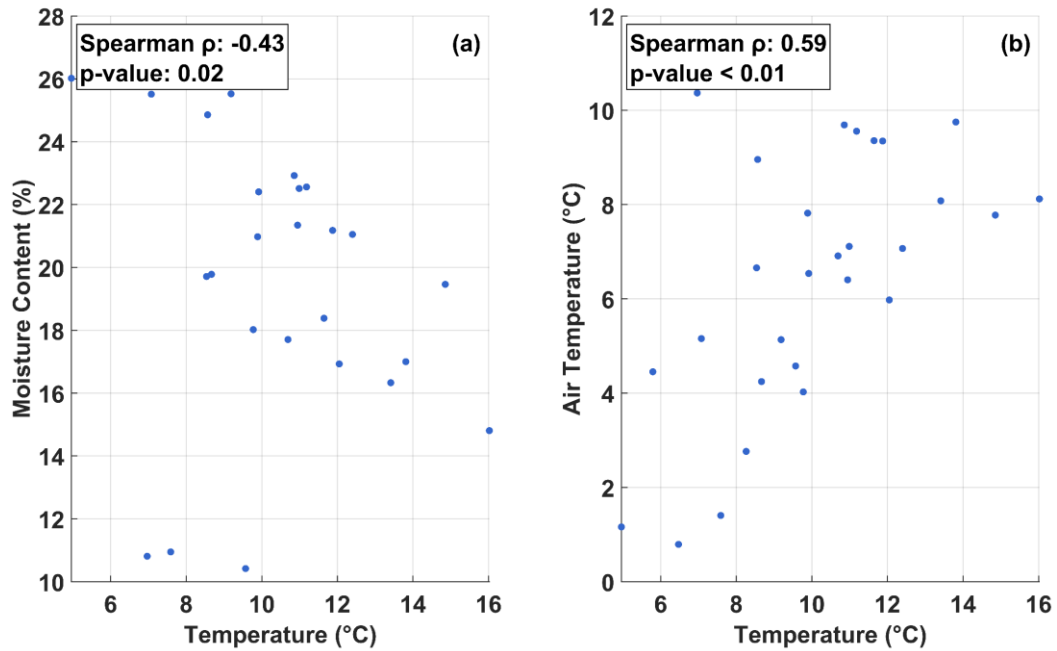


Figure 4.24 Scatter plot of (a) daily moisture content and temperature measured at the middle layer (TCMGM) of the growing media, and (b) daily air temperature and temperature measured at TCMGM of the growing media on cold days in 2017.

4.7.3 Impact of moisture on thermal performance of green roof on normal days

Similar to hot days, the daily average ΔT on normal days can be positive or negative. On normal days in both 2017 and 2018, the correlation analysis detected a significant positive

correlation between daily average moisture content and ΔT when the heat was transferred from the atmosphere to the building inside (data not shown), similar to the correlation observed on hot days (Figure 4.21 (a)). As moisture content increased, the ΔT also increased, leading to a reduction in temperature at the bottom of the growing media. Similarly, no significant correlation was found between them in 2017 when the heat was transferred from the building inside to the atmosphere. However, a different pattern was observed in 2018. Figure 4.25 displays the relationship between daily average moisture content and ΔT on normal days in 2018 when the heat was transmitted from the building inside to the atmosphere. As shown in the figure, different from hot days, the daily average ΔT tended to decrease with the increasing moisture content. This suggests that higher moisture content could maintain a more stable temperature within the growing media, and thus decrease the vertical temperature difference between TCTGM and TCBGM. However, this was not found in 2017. Furthermore, no significant correlation was observed between the daily average moisture content and temperature at TCMGM on normal days in both years. However, a significant positive correlation was detected between the daily average air temperature and the temperature at TCMGM in both years. This argues that apart from moisture content, the thermal performance of a green roof may also be affected by other factors, such as solar radiation, evapotranspiration, and vegetation, which intertwine with moisture content. Therefore, further research is desired to confirm the role of moisture content on the thermal performance of green roofs.

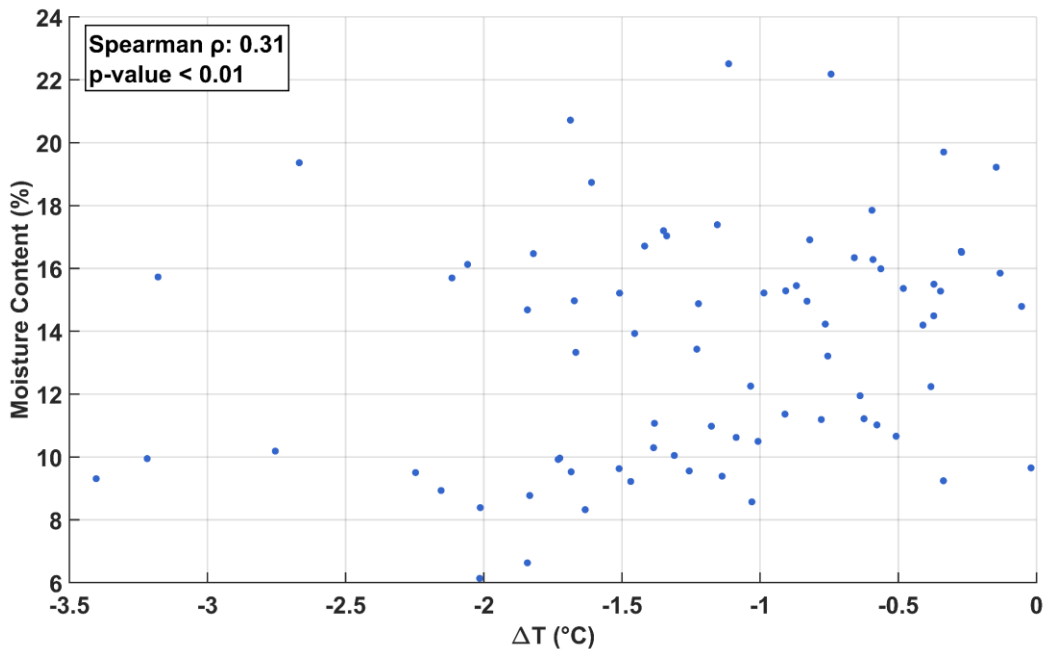


Figure 4.25 Scatter plot of daily average moisture content and temperature difference (ΔT) between TCTGM and TCBGM of the growing media on normal days in 2018 when heat was transmitted from the building inside to the atmosphere.

In general, these findings demonstrate that higher moisture content could mitigate the vertical temperature difference in the growing media on cold and normal days when heat is transferred from the building inside to the atmosphere. This helps the green roof retain more heat, thereby reducing the energy consumption needed for heating. In contrast, on hot and normal days when heat is transferred from the atmosphere to the building inside, higher moisture content reduces the temperature at the bottom of growing media and thus reduces the heat flux into the building through the roof. As a result, the green roof effectively mitigates the energy consumption needed for cooling.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Conclusions

The overall objective of this thesis was to enhance the knowledge and understanding of the thermal performance of green roofs in cold and semi-arid climate regions. To fulfill the objective, data collected from an extensive green roof and a reference roof in the City of Calgary were analyzed. Specifically, the data was used to examine the spatial variations (in both horizontal and vertical dimensions) in temperature and heat flux of the roofs, investigate and compare the thermal resistance index and surface temperature reduction of the roofs, and examine the impact of substrate moisture on the thermal performance of the green roof. The outcomes offer evidence-based knowledge for the potential large-scale implementation of green roofs in the City of Calgary to reduce building energy consumption. The primary conclusions are summarized as follows:

1. On the reference roof, significant spatial variations in daily average temperature among the four quadrants (SW, NW, NE, and SE) were observed at all roof layers and in daily average heat flux at TCM on hot, cold, and normal days. However, on the green roof, significant differences in the medians of daily average temperatures at all roof layers and heat flux among the four quadrants were detected on cold days, but not on hot and normal days (except temperature at TCM and TCIUS layers). Therefore, compared to the reference roof, the green roof appeared to mitigate the spatial variations in temperature and heat flux; namely, heat was distributed more evenly horizontally on hot and normal days.

2. No significant differences were detected in the medians and variances of daily average air temperature and relative humidity in the green roof and reference roof. Given that both roofs were exposed to the same ambient environment, the green roof did not improve the surrounding microclimate conditions. However, the observed lower daily average wind speed for the green roof, especially on cold days, could have been beneficial in retaining more heat within the building, thereby improving energy efficiency.

3. Relative to the reference roof, the green roof provided cooling effects on hot days and warming effects on cold and normal days, reducing energy consumption for cooling and heating, respectively. On hot days, the medians and variances of daily average temperatures and heat fluxes (from the ambient environment to the building inside) of the green roof were significantly lower than those of the reference roof at the TCTOI layer in 2017 and 2018. This fact is further supported by the reduced STR index (23%) of the green roof relative to the reference roof at the same layer in the study period. However, the higher temperatures at the TCM and TCIUS layers of the green roof may be influenced by the different indoor thermal settings/temperatures between the roofs. In contrast, on cold days, the roof temperature at all layers of the green roof was increased. This is evidenced by the higher medians in temperature and STR index (above one) of the green roof than the reference roof. Notably, the green roof increased the average temperatures at TCTOI, TCM, and TCIUS by 36%, 10%, and 9%, respectively, on cold days in the study period. While on normal days, the green roof generally maintained warmer temperatures at the TCM and TCIUS layers than the reference roof. Among the different layers, the highest reduction and increase in temperature were observed at the TCTOI compared to the other layers. In

addition, the green roof improved the average thermal resistance of the building by 22.27% and 14.4% compared to the reference roof on hot days in 2017 and 2018, respectively. The higher resistance to incoming heat from the ambient atmosphere to the building on hot days could be attributed to evaporative cooling through the moisture in the growing media and the higher albedo of the soil, which reduces solar radiation absorption. This further resulted in lowering the external roof temperature of the green roof compared to the inside roof temperature. The thermal resistance of the building improved by 10.4% in 2017 and 14% in 2018 on cold days, and by 14.4% in 2017 and 13% in 2018 on normal days. Consequently, the green roof maintained a warmer indoor roof temperature than the external roof temperature compared to the reference roof on cold and normal days. Overall, the increased resistance to incoming and outgoing heat reaffirms the green roof's potential to enhance the thermal insulation capacity of the building.

4. The green roof showed different patterns in the vertical temperature profile on hot and cold days at the daily temporal scale. On hot days, the green roof decreased roof temperatures vertically from the external roof surface layer (i.e., TCTGM) to the bottom layers when the ambient air temperature was higher during the daytime on hot days in general. This suggests that the green roof absorbed and retained heat through its growing media, which consequently led to reduced energy consumption during the daytime. During the nighttime, the green roof demonstrated a reverse pattern, with the roof temperature increasing vertically from the external surface layer to the bottom layers when the air temperature was lower, and thus, the heat transferred from the building inside to the atmosphere. In contrast, on cold days, the green roof showed consistent patterns in the vertical temperature profile

during daytime and nighttime, with roof temperatures increasing vertically from the external roof surface layer to the bottom layers. On cold days, the heat was transferred in only one direction (from the building inside to the atmosphere) in contrast to hot days as the air temperature consistently remained below the indoor room temperature during both nighttime and daytime. However, the green roof maintained warmer temperatures at the common layers compared to the reference roof, which resulted in retaining more heat within the building and thus reducing the energy required for heating.

5. The impact of media moisture on the thermal performance of the green roof was observed on hot and normal days, especially when heat was transferred from the atmosphere into the building. In general, higher moisture content was found to be beneficial in reducing the temperature of the growing media, especially at the bottom layer (TCBGM). This suggests that higher moisture in the growing media could reduce incoming heat, thereby reducing the energy needed for cooling. However, there was no apparent dependency of temperature differences on moisture content on hot days when the air temperature was lower, and the heat was transferred from the building inside to the atmosphere. In contrast, the higher moisture content decreased the temperature difference between the top (TCTGM) and bottom (TCBGM) layers of the growing media on cold and normal days in general when the heat was transferred from the building inside to atmosphere. This suggests that higher moisture content could decrease the vertical temperature difference in the growing media, thereby escaping less heat. This helps the green roof retain more heat, reducing the energy required for heating.

In conclusion, the green roof was able to enhance the roof thermal performance and thus reduce building energy consumption for cooling and heating in a cold and semi-arid climate. Compared to the reference roof, the results showed that the green roof (a) increased and decreased the roof temperatures at various layers on cold (and some normal) and hot days, respectively, (b) reduced temperature fluctuations of the roof, and (c) improves the thermal resistance of the roof. In addition, the media moisture affected the thermal performance of the green roof, and higher moisture in the growing media reduced both heat gain and heat loss. Therefore, to optimize the green roof's benefit in reducing building energy consumption, the consideration of irrigating green roofs would be relevant, as it, along with precipitation, would primarily affect media moisture.

5.2 Future recommendations

Based on this thesis's findings and broader considerations, the following research topics are recommended for future investigations:

1. In this thesis, differences in temperature at all layers and heat flux among the four quadrants were observed on the green roof. However, the average temperature and heat flux over the four quadrants at each layer were used to compare thermal performance between roofs. Future investigation on, for example, what provokes the spatial variations is desired.
2. The vertical temperature profiles of the green roof demonstrated their differences during daytime and nighttime, particularly on hot and normal days. As a result, the thermal behaviour of the green roofs in terms of heat transmission directions was different throughout the day. However, this thesis only examined the thermal performance of the

green roof at a daily temporal scale. This could potentially influence the comprehensive assessment of the thermal advantages of green roofs in terms of energy savings. In addition, a huge diurnal variation exists in the daily air temperature in this study region. Therefore, further quantification of the impact of the green roof on energy consumption at a finer temporal scale is necessary to investigate its energy savings potential in this region accurately.

3. In this thesis, it was found that moisture content could influence the temperature of the growing media, thereby enhancing the thermal performance of the green roof. This effect was observed on cold days when heat is transferred from the building to the atmosphere and on normal days when the heat is transferred from the building to the atmosphere and vice versa. However, on hot days, this impact was prominent only when heat was transferred from the atmosphere to the building interior. Therefore, further consideration of other factors besides moisture is necessary to understand the heat transfer from the building interior to the atmosphere, especially on hot days.
4. The literature widely acknowledged that the thickness of the growing media plays a crucial role in retaining water in the substrate and providing insulation to the building by reducing heat transmission. However, this thesis could not examine its effects on the thermal performance of green roofs. Therefore, it is recommended to further investigate the impact of varying thicknesses of growing media on the thermal behavior of green roofs.

5. In the context of the thermal performance of green roofs, vegetation is a key component. In this thesis, the effects of vegetation on the thermal performance of green roofs were not investigated. Therefore, it is recommended to conduct further investigation into the effects of vegetation, which might vary over seasons and time, on the thermal performance of green roofs, focusing on canopy temperature, plant species diversity, vegetation density, and the evapotranspiration process.
6. It is also well known that snow accumulation and melting on green roofs could potentially affect their thermal behaviour. In the Calgary region, snow accumulation, melting, and freeze-thaw of green roof media might play important roles in cold winters. Thus, it is strongly recommended to assess the impacts of snow processes.
7. This study did not directly focus on quantifying the amount of energy saved by the green roof, as heating and cooling systems for rooms beneath the green roof and the reference roof were not taken into consideration. Therefore, it is recommended to model the potential energy savings of green roofs in this region to estimate their cost-effectiveness.

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