Master's Thesis of Landscape Architecture

Variations in the cooling effect of a small urban river depending on urban canyon geometry

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February 2017

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Under the Direction of Adviser, Prof. Dong Kun Lee

Submitting a master's thesis of
Landscape Architecture

October, 2016

Graduate School of
Seoul National University
Department of Landscape Architecture and Rural Systems
Engineering, Landscape Architecture Major

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Confirming the master's thesis written by
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December, 2016

Chair _____(Seal)
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Examiner _____(Seal)

Abstract

Urbanization and climate change make urban temperature increase. Rapidly increasing urban temperature creates problems for the urban environment. Therefore, urban planning and design should consider heat mitigation strategies to reduce the temperature. Many researchers have studied urban cool islands as the heat mitigation strategies. Among them, urban river is an important design factor to reduce heat in the surrounding areas through evaporation and transfer of sensible heat, which is called the river cooling effect. In this study, river cooling effect includes its intensity and distance. River cooling intensity means the air temperature difference between river and urban, and river cooling distance means the diffusion distance of cool river air. Previous studies have found out river characteristics and climate influenced on river cooling effect. However, Urban canyon geometry near rivers, which is an important factor influencing the river cooling effect, has been overlooked so far. In this study, I evaluated the influence of urban canyon geometry on the river cooling effect. I measured the air temperature near Cheonggye stream

and calculated the river cooling effect for 8 streets with different urban canyon geometry at 2 p.m. and 10 p.m. Street width and building height were selected as the urban canyon geometry. Mobile survey used for measuring air temperature. This method could make densely measured points from river to urban area. The results show that the average river cooling intensity at 2 p.m. is 0.52 ℃ and larger than 10 p.m. the river cooling distance, however, is similar to 10 p.m. as 24 m. Also, the results indicate that street width and building height affect the river cooling intensity and the river cooling distance of Cheonggye stream. This relationship is shown in the daytime. During a day, the river cooling effect increases as streets get narrower and building heights get lower. This study is important to evaluate river cooling effect analysis in micro scale and find out basic characteristic of urban canyon geometry to make river cooling effect larger. Our finding can help urban planning and design near the river for mitigating urban warming.

Keyword : urban warming, mobile survey, microclimate, water cooling island, urban canyon geometry, cooling extent
Student Number : 2015-21747

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Study background

Urban areas have experienced serious warming. Temperature in urban areas has increased more rapidly than surrounding rural areas (Sugawara et al. 2015). Absorption of solar radiation by paved surfaces, multiple heat reflection from high-rise buildings and anthropogenic heat release contribute to urban warming (Mochida & Lun 2008). Urban warming has negative effects on both, humans and the natural environment. These damages are expected to increase in the future (Imhoff et al. 2010; O'Loughlin et al. 2012; Lin et al. 2015). Therefore, urban heat mitigation strategies should be developed right from the stage of urban planning. Reduction in solar radiation absorptivity by shading, high albedo elements and evaporative cooling with green or water surfaces have been known to be effective heat mitigation strategies (Rizwan et al. 2008; Vidrih & Medved 2013).

For reducing urban heat and developing heat mitigation strategies, many researchers have studied urban cool island

effect. A higher temperature or heat content called urban heat island (UHI) and a lower temperature called urban cool island (UCI) (Rizwan et al. 2008). According to the previous studies, urban green spaces and urban water bodies are verified as the UCIs (Sun et al. 2012; Feyisa et al. 2014; Kong, Yin, James, et al. 2014; Chen et al. 2014; Du et al. 2016). They reduce urban heat and have cooling effects by reducing sensible heat using conduction and providing latent heat using evapotranspiration.

Urban water cooling island haven't been researched widely, while urban green cooling island are well verified their effects (Du et al. 2016). Urban forests were verified that they provided cooling effects (Kong, Yin, James, et al. 2014; Sugawara et al. 2015; Jaganmohan et al. 2016). Also urban parks have been well studied by many researchers (Spronken-Smith & Oke 1998; Chang et al. 2007; Chow et al. 2011; Chen et al. 2012; Ren et al. 2013; Feyisa et al. 2014; Lin et al. 2015; Vaz Monteiro et al. 2016). In the aspect of water cooling effect, Sun et al. (2012) and Zhang et al. (2015) found urban wetlands had obvious cooling effect. Urban rivers or lakes are also known as UCIs (Murakawa et al. 1991;

Katayama et al. 1990; Hathway & Sharples 2012; Chen et al. 2014; Manteghi et al. 2015). However, studies about recent water cooling effect have just started (Du et al. 2016).

Among the water bodies, urban river is the most effective cooling elements which plays the role of an oasis in urban area (Chang et al. 2007; Costanza et al. 1997; Coutts et al. 2012; Du et al. 2016). Urban rivers have an obvious heat mitigation effect or a cooling effect (Du et al. 2016). River cooling effect (RCE) occurs in two ways on the river surface. One is latent heat generation by evaporation, while the other is sensible heat transfer between the river surface and the urban air (Webb & Zhang 1997). Moreover, rivers generate a cooling effect zone by diffusing cool air through the surrounding areas (Saaroni & Ziv, 2003; Kim, Cha, & Jung, 2014). Fig. 1 shows the cooling effect zone of an urban river. River cooling intensity (RCI) and river cooling distance (RCD) can be defined as the RCE (Honjo & Takakura 1990; Du et al. 2016; Jaganmohan et al. 2016).

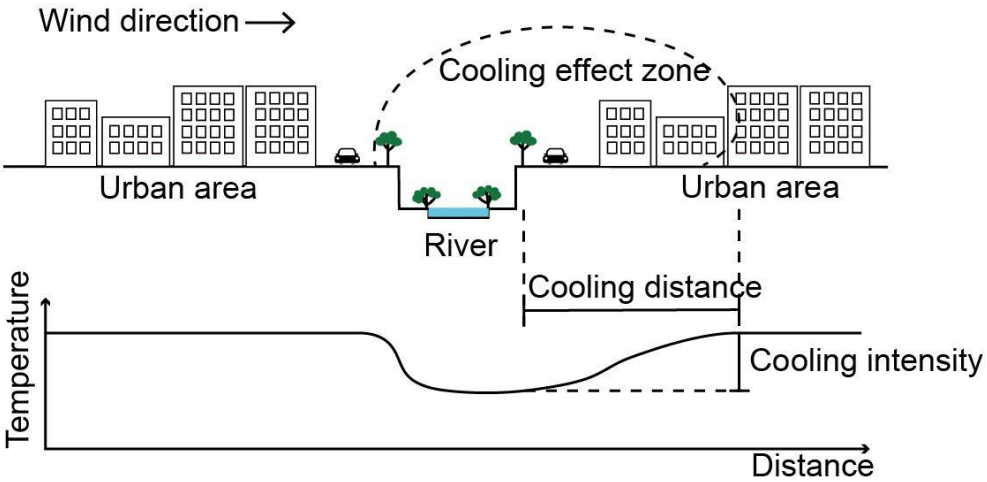


Figure 1. Concept diagram of the urban RCE
(image reproduced from Honjo & Takakura, 1990).

The RCE varies based on river characteristics and climate factors. It has been proved to be correlated to their geometry and shape index (Sun et al. 2012; Du et al. 2016). The proportion of vegetation and the height of the river bank were also found to have a positive impact on the cooling effect (Murakawa et al. 1991; Du et al. 2016). In addition, the impact of climate factors on RCE was studied. Wind speed is a particularly important factor influencing the cooling effect zone (Katayama et al. 1990; Tominaga et al. 2015). In addition, air temperature (or land surface temperature) and humidity have also been known to influence the RCE (Edinger et al. 1968; Webb & Zhang 1997; Du et al. 2016).

These studies, however, have not considered urban canyon geometry, even though many of them focused on urban areas as their study site. The cooling effect has already been found to vary depending on the surrounding area (Lin et al. 2015). The surrounding area are consisted of buildings and streets, the geometry component of urban canopy, and they change microclimate in urban canopy layer (UCL) (Lee 2011). UCL lies between the urban ground and urban boundary layer. And urban circumstances such as urban canyon geometry make UCL climate complicated (Mills 1997). Urban canyon geometry could control the amount of received radiation and airflow disperse in the UCL. Because of these controls, air temperature from the river boundary varied by urban canyon geometry (Lee et al., 2009). Therefore, urban canyon geometry could be a key factor affecting RCE with the air temperature.

Despite the importance of urban canyon geometry, only a few researchers have studied the impact of urban canyon geometry on the RCE. In Japan, three streets near a river were compared to determine whether the building density and the road width in the surrounding areas had an impact on RCE.

They determined that the RCE increases as the building density decreases or the roads become narrower (Murakawa et al. 1991). In U.K., closed and open street form along a river were studied, revealing that open streets have a greater cooling effect from the river than closed streets (Hathway & Sharples 2012). Building orientation is also an important aspect of urban canyon geometry, which was found to influence RCE (Manteghi et al. 2015). More studies on the relationship between the urban canyon geometry and RCE should be carried out to guide the design of urban areas to gain effective RCE (Hathway & Sharples 2012).

In order to understand RCE, I should recognize the horizontal temperature gradient from the river to the urban area. Some researchers studied the cooling effect using land surface temperature, acquired from remote sensing (Chen, Tan, Wei, & Su, 2014; Du et al., 2016; Sun et al., 2012). However, these researches were limited to a regional scale and dealt with a large river. However, a river representative of the ones near urban areas is small, which should be considered during researches (Hathway & Sharples 2012). In an attempt to study the effect of a small river, previous

studies used field measurement for acquiring screen level temperature data. However, measurement points were too sparse to determine the cooling distance accurately (Hathway & Sharples 2012; Kim et al. 2014). High spatial resolution is required for accurate RCE research.

1.2. Purpose of Research

Our goal in this study was to evaluate the relationship between urban canyon geometry and RCE from a small river, under summer conditions. The air temperature obtained from the mobile survey could increase the spatial air temperature resolution. Specifically, I measured the air temperature at 8 different points along the street for revealing the impact of urban canyon geometry on RCE. In this study, the indicators of urban canyon geometry were street width, mean of building height, and entrance building height. Identifying the variation in RCE with the urban canyon geometry may help in landscape and urban planning to reduce urban warming.

Chapter 2. Literature Review

2.1. Urban heat island (UHI)

Urban areas experience high temperature than surrounding areas, it is called the urban heat island effect. This phenomenon has become worldwide problem and many researchers have identified UHI intensity in many cities. UHI intensity is the temperature (air temperature or land surface temperature) difference between urban and surrounding area. Peng et al. (2012) calculated UHI intensity of 419 global big cities using remote sensing. Fig. 2 shows the spatial distribution of 419 surface UHI intensity. Daytime intensity was higher than nighttime. Tokyo and Nagoya (Japan), which had similar environment with Seoul, had the highest daytime surface UHI intensity following Medellin (Colombia). They argued nighttime UHI was positively influenced by albedo differences between urban and suburban area, while daytime UHI had negative correlation between vegetation activity differences. Park et al. (2016) calculated surface UHI intensity of 30 cities in South Korea, and found out the intensity of day and night were different (Fig. 3), same with

previous studies results. And they found that Seoul had 19℃, 4.5℃ surface UHI intensity at day and night time. On the other hand, Kim & Baik (2005) revealed UHI intensity in Seoul using AWSs. Seoul UHI intensity was over 2.2 ℃ over the 1 year period. They found out that nighttime UHI was higher than daytime. And this intensity decreased as wind speed and cloud cover increased. From the previous studies about the UHI intensity, I observed UHI phenomenon globally. Furthermore, the studies revealed that Seoul had high UHI intensity.

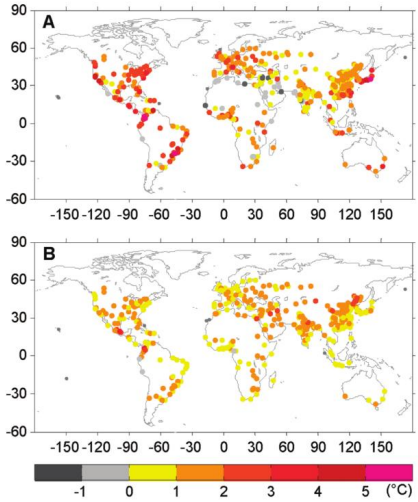


Figure 2. Spatial distribution of (A) annual mean daytime surface HIntensity and (B) annual mean nighttime surface UHI intensity.

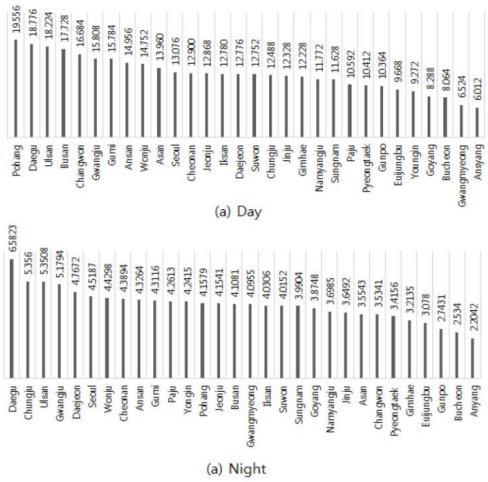


Figure 3. Surface UHI intensity of 30 cities in South Korea (Park et al., 2016)

2.2. Urban cool island (UCI)

UCI is the opposite concept of UHI. This phenomenon occurs when cool islands have lower air temperature than surrounding areas such as artificial area (Kim et al. 2016). UCIs can reduce urban heat, and many researchers have studied its cooling effect for mitigating urban warming and UHI effect. According to previous studies, green areas and water bodies such as rivers and wetlands were verified to have a cooling effect (Sun et al. 2012; Kong, Yin, James, et al. 2014; Chen et al. 2014; Sugawara et al. 2015; Jaganmohan et al. 2016; Lin et al. 2015). Green areas and water bodies absorb less radiation than impervious surfaces and reduce sensible heat using evapotranspiration. For these reasons, the green and water surfaces have lower air temperature. Furthermore, they can reduce the surrounding air temperature (Chang et al. 2007; Hathway & Sharples 2012).

Therefore, the air temperature distribution from the UCI boundary to its surrounding shows increasing curve (Fig. 4). Using this curve, some researchers calculated UCI cooling intensity and cooling distance (or cooling extent) (Lin et al. 2015; Vaz Monteiro et al. 2016; Jaganmohan et al. 2016).

Jaganmohan et al. (2016) found out urban forests had 0.8 ℃ cooling intensity and 469 m cooling distance, while urban parks had 0.5 ℃ cooling intensity and 391 m cooling distance in Leipzig, Germany. Adams et al. (1989) argued that rivers had 1~1.5 ℃ cooling effect, which was bigger than green areas. And these cooling effects of UCIs were larger in day time than night time (Hathway & Sharples 2012; Manteghi et al. 2015)

In East Asia cities that were consisted with high rise-high density buildings, UCI effects were verified. River's air temperature was 5 ℃ lower than urban area on fine warmer season in Hiroshima, Japan (Murakawa et al. 1991). In Hong Kong, Green area had 2 ℃ lower temperature than impervious roads (Ng et al. 2012).

There are some researches about UCI effects in Seoul. Lee et al. (2009) measured air temperature of Seolleeung and its surrounding commercial area. They found the difference of air temperature between park and subway station was 1.76 ℃ in average, and the biggest difference was observed in September. Because of the urban morphology and land use, the temperature was rapidly decreased from the park

boundary. When they used travers observation up to Tahn stream for determining the cooling intensity, they verified Seolleeung Park had over 4 ℃ and Tahn stream had 1.5 ℃ cooling intensity. Kim et al. (2008) studied cooling effect of Cheonggye stream by comparing before and after restoration. Entire stream dropped air temperature by 0.4 ℃ and some local area dropped by 0.9 ℃ than before. The biggest change was shown in the daytime. Unlike other previous study, this study compared same space's air temperature in different time. They also found that the air temperature of the north side of stream changed a bit. Since the Cheonggye stream were surrounded walls, cooling effect would not spread far from the river. However cooling effect could be varied by climate condition.

Finding out influencing factors is an important issue for developing UCI studies. Previous studies about green areas found out the spatial pattern of green areas had influence on cooling effects(Cheng et al. 2007; Kong, Yin, James, et al. 2014; Kong, Yin, Wang, et al. 2014). Also, specific green area characteristics such as tree species, sky view factor, and density were used in the studies (Cohen et al. 2012; Zhang et

al. 2013). In the river studies, like green area studies, almost studies focused on the river characteristics as the major factor affecting RCE. Landscape patterns, and geometry of rivers were verified to influence on RCE (Sun et al. 2012; Yang et al. 2015; Du et al. 2016). Some studies found out the portion and height of vegetation in rivers affected to the RCE (Du et al. 2016; Murakawa et al. 1991). Furthermore, climate factors such as wind speed, humidity, and temperature were known to control the RCE (Edinger et al. 1968; Edinger et al. 1968; Webb & Zhang 1997; Tominaga et al. 2015; x Du et al. 2016). Recently, researchers started to consider surrounding urban area of river. Kong et al. (2014) argued that future research should examine the influence of buildings and streets on cooling effects. However, just a few studies analyzed the effect of building or street canopy on RCE. Hathway & Sharples (2012) verified open streets near river had larger cooling effect than closed streets. And Manteghi et al. (2015) found that RCE varied by buildings' orientation.

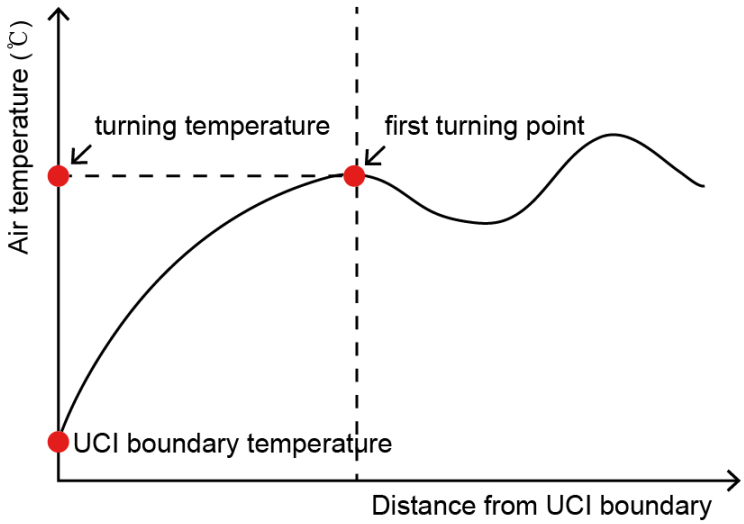


Figure 4. Curve line model from UCI boundary
to its surrounding
(image reproduced from Lin et al. 2015; Du et al. 2016)

2.3. Urban climate and scale

The urban atmosphere scale is classified into 4: micro, local, meso, macro (Oke 1987) (Fig. 5). Microscale extends from less than one meter to hundred meter. It deals with every interaction between surfaces. Local scale has one to several kilometers, and is used to identify landscape features and urban development except for microscale effect. Mesoscale is whole city scale, which extends to tens of kilometers. Macro scale is over tens of scale and show global influences.

Most previous studies used micro or local scale to identify

UHI and UCI (Guan 2011). They observed temperature with various methods depending on scale (Table 1). In micro scale, they used fixed station or mobile survey to collect air temperature in urban canopy layer (UCL) (Sun 2011; Middel et al. 2014; Sugawara et al. 2015). UCL locates between ground and roof level and includes air, and UCL climate is dominantly affected by urban microclimate (Guan 2011; Shashua-bar & Hoffman 2004). In local scale, fixed station like Automatic weather stations (AWS) measured air temperature in urban boundary layer (UBL) (Kim & Baik 2005). UBL is the layer above the UCL and represents local scale (Guan 2011).

Some studies revealed the UHI or UCI with land surface temperature (LST) (Ren et al. 2013; Maimaitiyiming et al. 2014; Y. Li et al. 2012; Imhoff et al. 2010; X. Li et al. 2012). They used remote sensing data such as Landsat or Moderate Resolution Imaging Spectroradiometer (MODIS) thermal band to achieve LST. Since LST has large correlation with air temperature, it is widely used for detecting urban heat from local to macro scale. On the other hand, some researchers argue land surface temperature is not the air temperature

which human exposed and related to heat wave events, and it is not suitable for identifying UHI or UCI.

Each scale has both advantages and disadvantages. For example, in local scale, comparing several areas is useful, however, identifying specific causes of the phenomenon is difficult (Y. Li et al. 2012). In micro scale, researchers can recommend specific landscape design guidelines related to building geometry or tree volume (Hathway & Sharples 2012; Kong et al. 2016). But there is difficulty in getting enough research samples for statistical analysis (Du et al. 2016).

Therefore, when I choose climate observation scale and method, I should consider the study scope. This study focused on a river and its surrounding urban canyon. In this case, micro scale observation method is suitable. In the next section, I reviewed this micro scale observation methods: field observation.

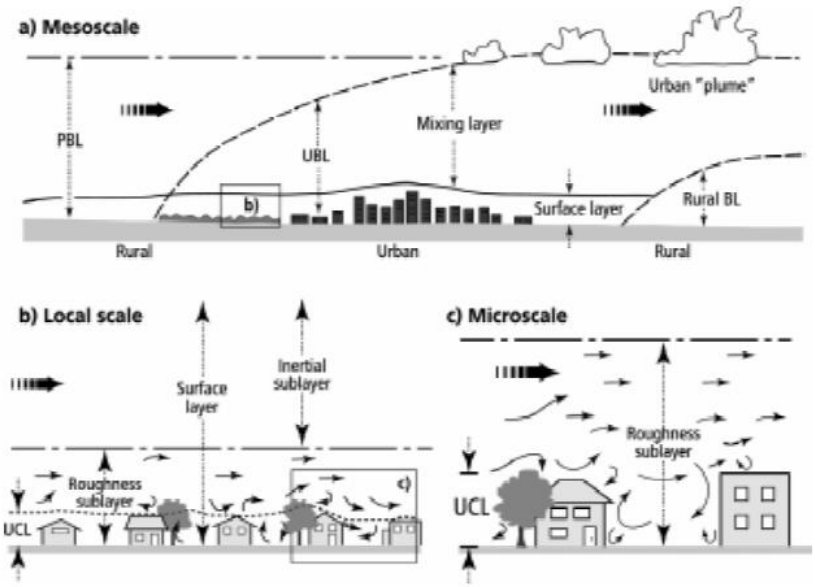


Figure 5. Schematic of climate scales PBL– planetary boundary layer, UBL– urban boundary layer, UCL– urban canopy layer (Oke, 2004)

Table 1. The classification of urban temperature observation

Object	Scale	Layer	Observation
Atmosphere	Micro scale	Urban canopy layer	Fixed weather station Mobile survey
	Local scale~	Urban boundary layer	Fixed weather station (AWS)
Surface	Local ~ maro scale	Land surface	Remote sensing (Lndsat, MODIS)

2.4. Field observation

Meteorological observation in urban area is differ from rural area. Buildings, impervious surfaces, and other urban components disturb airflow and transfer radiation, which makes difficulties in observing urban air temperature (Oke 2004).

Oke (2004) recommended to avoid wet patches in an otherwise dry area, individual buildings that jut up by more than half the average building height, big parking lot, irrigated gardens, and building roof. Especially building roof is sensitive to solar radiation and produces rapid climate change, and not adapt to observation site.

For observing UCL air temperature, most studies used screen level (1.25~2m from ground level) as a standard measuring height (Kim et al. 2016). The reason why researchers use screen level is they can avoid land surface influence and 1.25~ 2m is similar with human height. However it is not inflexible rule. Because the variation of temperature gradient in UCL is insignificant, more than 1 m from surface can be acceptable (Nakamura & Oke 1988).

There are two types of field observation: fixed weather

station, and mobile survey. Fixed weather station can collect air temperature every second or hour without human labor. However, it cannot provide sufficient spatial resolution to show the urban microclimate (Rajkovich & Larsen 2016). Therefore, researchers should put the stations on the several important places like Fig. 6.

If the study scope is larger than Fig. 6, mobile survey method would provide high spatial resolution. Mobile survey have many advantages. Firstly, it provide the high resolution in the large area (Rajkovich & Larsen 2016; Brandsma & Wolters 2012; Coseo & Larsen 2014). This method can cover up to 1 ~ 10 km. Brandsma and Wolters (2012) obtained 14 km long air temperature data for 3 years using micro data logger installed on a bicycle (Fig. 7). Secondly, it costs less than installing fixed weather station (Stewart 2011). In conclude, mobile survey is a good method to obtain microclimate of large area.

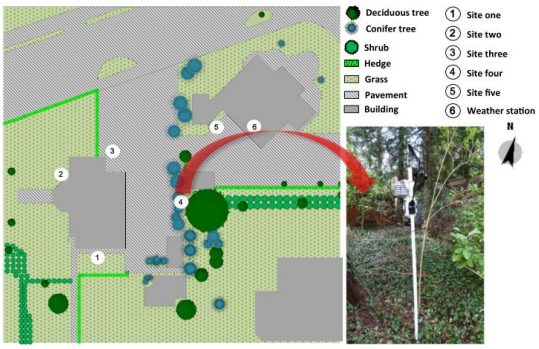


Figure 6. the location of observation sites in the study
(Wang et al. 2015)

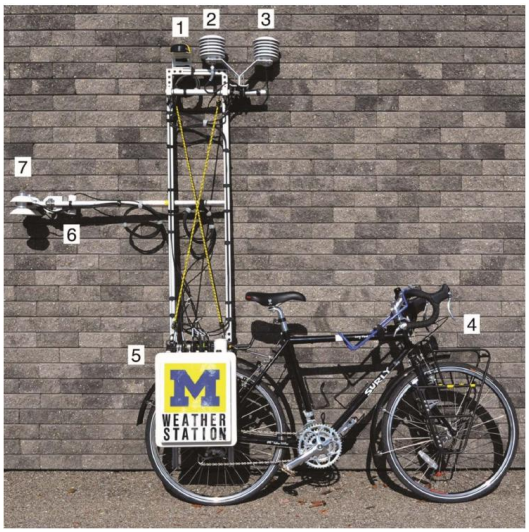


Figure 7. Image of bicycle-based mobile survey system
(Rajkovich and Larsen, 2016)

2.5. Literature review conclusion

Because of the rapid urbanization and global warming, urban air temperature have increased. UHI concept appeared for identifying this phenomenon. For reducing urban warming, researchers started to study UCI and its cooling effect. Until now, many green areas and water bodies were verified its cooling effect. However, the river cooling effect, especially in micro scale, should be more evaluated for suggesting detail design strategies. Furthermore, surrounding urban canyon geometry which can be defined as the morphology of buildings and streets should be examined to provide design guidelines for making effective RCE.

In micro scale, researchers used fixed weather stations or mobile surveys to observe air temperature. While fixed weather station has limit to cover large area with high spatial resolution, mobile survey is proper to obtain high spatial resolution temperature data. However, previous studies about river cooling effect tended to use fixed weather station (Hathway & Sharples 2012; Kim et al. 2014; Manteghi et al. 2015). In order to overcome this limitation, this study used mobile survey with sensitive thermometers.

Chapter 3. Materials and Methods

3.1. Study flow

This study included three steps: field measurement, calculating RCE and statistical analysis (Fig. 8). Before the field measurement, I reviewed field measurement in urban area, and designed new thermometers which were adapt to measure air temperature in urban canyon. With the designed thermometer, I used mobile survey to achieve dense air temperature points. Subsequently, I calculated RCE, including the river cooling intensity (RCI) and the river cooling distance (RCD), using air temperature gradients. Finally, I proceeded with statistical analysis to determine the correlation between RCE and the urban canyon geometry.

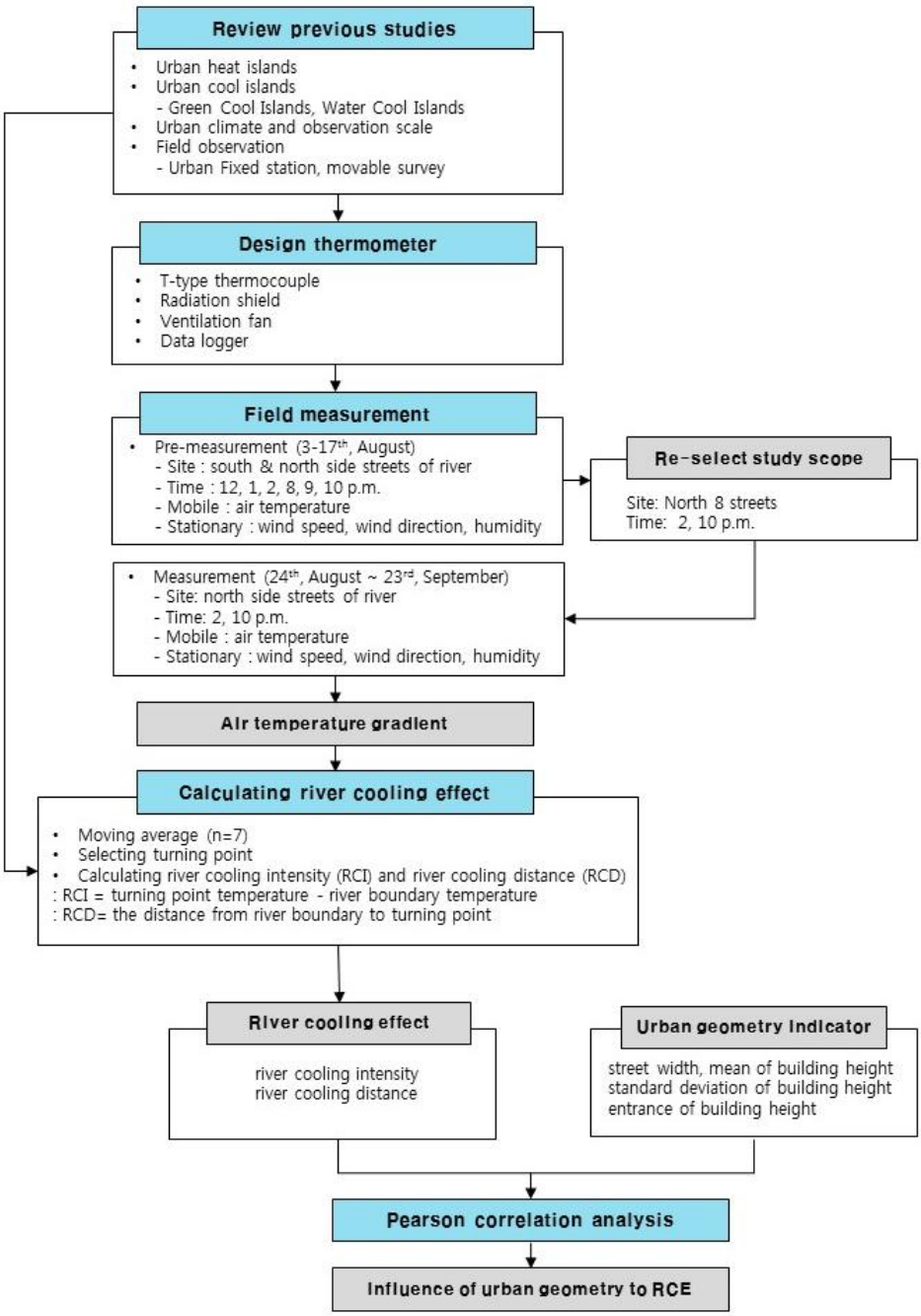


Figure 8. Study flow

3.2. Study scope

This study was aimed at a small urban river, the Cheonggye stream. It is located in the center of Seoul, in the interior region of the Korean Peninsula. Seoul suffers from hot and humid climate during summer, with heat waves being common in August. Before 2005, the study site was occupied by a highway. During 2003 to 2005, however, the Cheonggye stream was restored artificially. At present, it flows for 5.8 km in the central region of Seoul (Kim et al. 2008).

Restoration has changed lots of urban thermal environment of Cheonggye stream. Before the restoration, heavy traffic condition had a strong influence on the temperature in the highway. However, the land cover changed to water resulted in decreasing surface temperature and increasing wind speed. After restoration, the surface temperature of Cheonggye stream was 9.6 ℃ lower than center of car street, and average speed of wind increased to 2.2~7.1% compared with the original condition (Park & Choi 2005). Also, river vegetation and street trees were planted and they provided shades and evapotranspiration. Furthermore, river restoration had influenced on building use which resulted in anthropogenic

heat. Many restaurant and cafes have been located surrounding Cheonggye stream, and these influenced pedestrians. As a result, vehicle traffic decreased and the amount of pedestrian increased (Hoon et al. 2009). To conclude, Cheonggye stream restoration decreased impermeable surface, traffic volume and increased water and green surfaces (permeable surfaces), the amount of pedestrian, which resulted in increasing of temperature and wind speed.

The stream flows from west to east. The western part of the river is its upstream portion, which was our main study site (Fig. 9). Fig. 9 shows the 8 streets in the main study site. These streets are located in the north side of the Cheonggye stream, being about 200 m in length. The land uses in these areas are the same, although their urban canyon geometry such as the street width and the building height, vary.

In this study, I defined urban canyon geometry as the street width, mean of building height, standard deviation of building height, and entrance building height. Urban streets are composed of building walls and street, and it is called urban canyon. Urban canyon is a basic urban surface unit (Nunez &

Oke 1977). The heat balance of urban canyon is affected by the building and street geometry, component surfaces, and building orientation. Furthermore, street width, building height, and building orientation mainly affect urban specific thermal condition (Abreu-Harbich et al. 2014). Urban canyons in the study site have similar surfaces: buildings are composed of glass and tiles or bricks, and road are composed of asphalt, and have same building orientation: North-South. For these reasons, I focused on the urban canyon geometry than other heat affecting factors.

The field measurement was carried out on sunny days in August and September. Summer in South Korea is from June to September. Since it rains until July, I selected August and September as the study duration. I did pre-measurement before the major measurement. I measured air temperature of several streets located in the north and south side of the Cheonggye stream in 3-17th, August and calculated RCE. From the pre-measurement, there were two findings: 1) the main wind direction was WSW, which made the RCE more effective on the northern part than the southern part of the river. 2) 2 p.m. is the hottest time, when the difference

between the river and urban air temperature is the highest, while at 10 p.m., the weather is stable, with low artificial impact such as traffic. For these reasons, I selected the northern streets as the main study scope, as well as 2 p.m. and 10 p.m. as the representative time slots for evaluating RCE during the day and at night. The average air temperature based on the measuring time from the nearest Korea Automatic Weather Station was 26.6 ℃ at 2 p.m. and 21.7 ℃ at 10 p.m. (Table 2).

Table 2 Average air temperature based on the measuring date from AWS (unit: ℃)

Date \ Time	2 p.m.	10 p.m.
8/24	29.4	26.8
8/30	22.6	17.8
9/23	26.1	20.4
Average	26.6	21.7

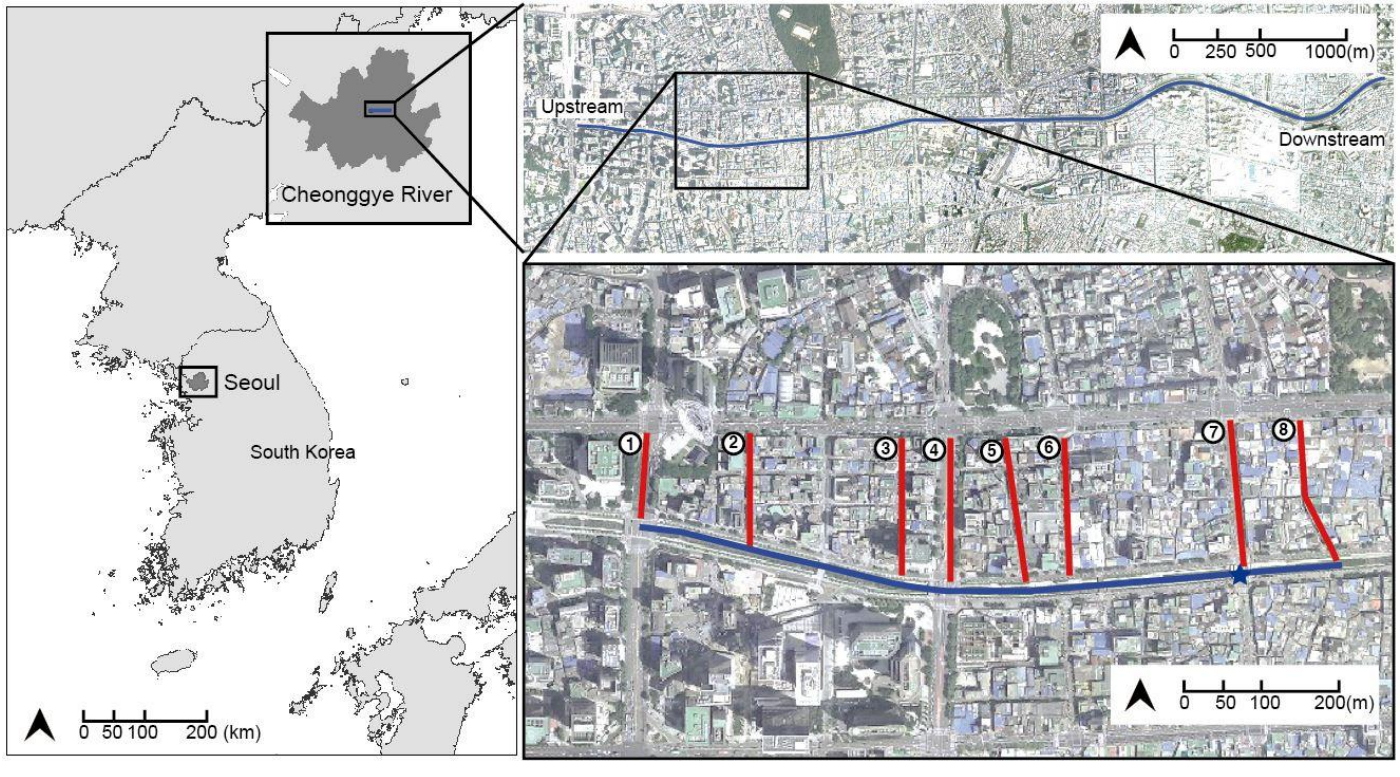


Figure 9. Monitoring sites of the Cheonggye stream: the blue line is the Cheonggye stream, the red line is the street mobile survey tracks (1–8) and the star is the stationary weather station

3.3. Urban canyon geometry

The survey sites, 8 streets near the Cheonggye stream, have different urban canyon geometry: street width (SW), mean of building height (MH), standard deviation of building height (SDH), entrance building height (EH). Street width is the distance between buildings on opposite sides of the street (Fig 10). While street width in each street is consistent, the building height is not. Therefore, I used three concepts of building height: mean, standard deviation, entrance (first) area. Equation 1 is calculation method of MH, SDH, EH. While MH considers the ratio of each building width, SDH is just simple variation of all buildings' height, and EH is average of two height of buildings that in front of the stream. Among them, MH, EH and SW would be used to correlation analysis with RCE, and SDH would be used to support data.

Equation 1

$$\mathrm{MH} = \sum_{j=1}^{n} \left(\frac{w_j}{\sum_{i=1}^{n} w_i} h_j\right)$$

$$\mathrm{SDH} = \sqrt{\frac{\sum(\bar{h} - h)^2}{n}}$$

$$\mathrm{EH} = \frac{h1 + h2}{2}$$

I collected building height information from Integrated Real Estate Information (Ministry of Land, Infrastructure and Transport) and building width and street width information from Korea National Spatial Data Infrastructure Portal.

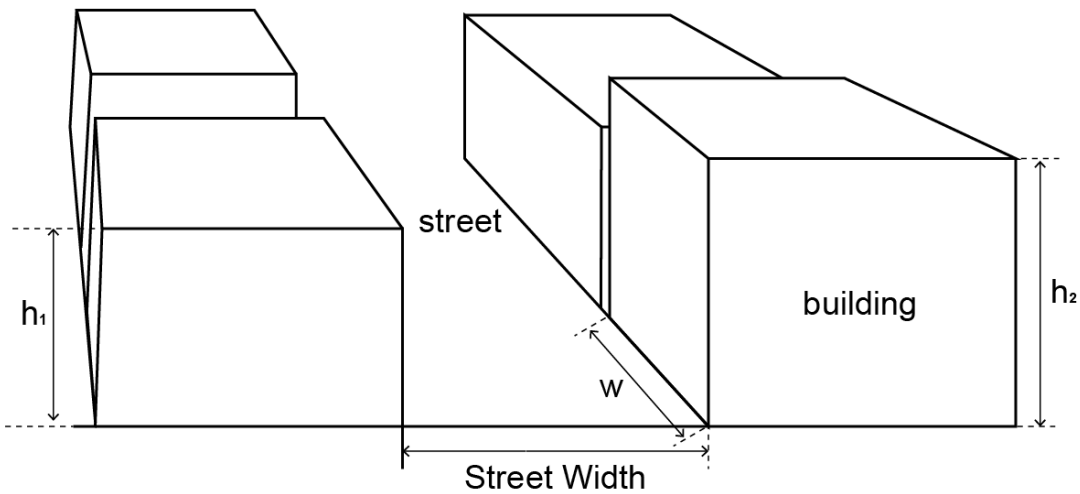


Figure 10. Schematic depiction of urban canyon
(image reproduced from Nunez & Oke, 1977)

3.4. Field measurement

In this study, the mobile survey method was used for field measurements. In order to study the urban micro climate, researchers should measure the air temperature at a

particular screen level (1–2 m above ground) of the UCL (Stewart 2011; Stewart & Oke 2012; Oke 2004). The urban micro climate is so complex that a fixed weather station cannot provide the spatial resolution required to study the urban micro climate (Rajkovich & Larsen 2016; Sugawara et al. 2015). On the other hand, mobile surveys provide high spatial resolution data at a lower price than installing a weather station (Stewart 2011). Previous studies have already proved the advantages of mobile survey for measuring the urban micro climate (Coseo & Larsen 2014; Brandsma & Wolters 2012).

Measuring the temperature at the screen level of the urban canopy has some difficulties: 1) The thermometer might receive radiation from outdoor materials; and 2) the urban canopy flow is blocked by several buildings. To overcome these difficulties, radiation shielding and ventilation are particularly recommended (Oke 2004). In this study, a T-type thermocouple, shielded by an aluminum double cylinder and a battery operated ventilator, was mounted on the bottom of a cylinder (He & Hoyano 2010; Jaganmohan et al. 2016). The T-type thermocouple used a 0.127 mm-diameter sensor

that is sensitive to outdoor air. The thermocouple was connected to a data logger (Oneset Computer Corporation, USA), which recorded the air temperature every 1 s, with an accuracy of ± 0.6 ℃ and a resolution of 0.02 ℃.

Fig. 11 shows the air temperature and wind speed measurement devices. In this study, a person walked on the streets, with two thermometers mounted on his shoulders, 1.5 m above the ground, which fits the screen level. The thermometers were verified with each other before taking measurements every day. I measured each survey track twice, with 2 thermometers, at 2 p.m. and 10 p.m.. Each point on the survey track had 4 air temperature data points, which were averaged as one. One stationary weather station, Vantage pro 2, was mounted on the bridge, which measured humidity with ±3 % accuracy and wind speed with ±0.4 m/s accuracy, every 5 minutes (Davis Instruments, USA). I averaged the humidity and wind speed per hour.

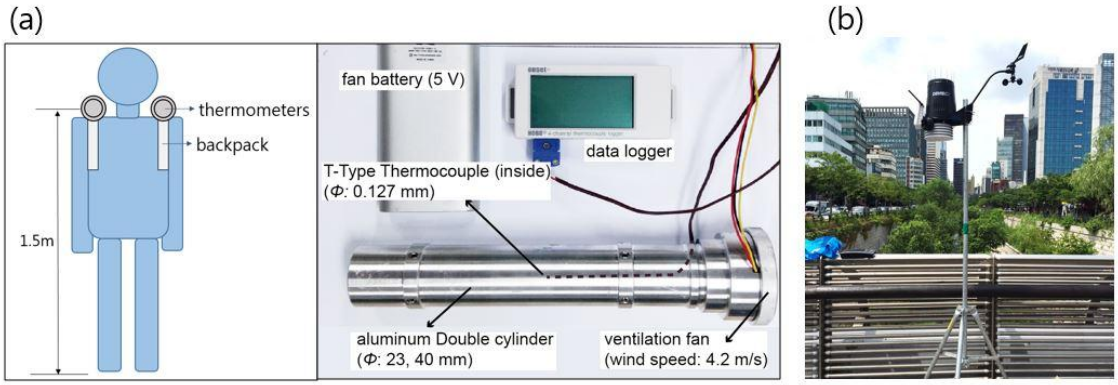


Figure 11. Measurement devices: (a) mobile survey thermometers, (b) stationary weather station

3.5. Calculating RCE

Many previous studies have researched calculating methods about cooling intensity and cooling distance (Chen et al. 2014; Kong, Yin, James, et al. 2014; Jaganmohan et al. 2016; Chen et al. 2012). The principle behind these methods is that the cooling effect decreases from the river or green area to the urban areas (Lin et al. 2015). Cooling distance is the distance to the turning point of temperature curve where the curve changed sharply or reached a flat level (Sun et al. 2012) and cooling intensity is the temperature difference between cool island and turning point. Therefore, most of studies focused on determining first turning point of the temperature graphs. Some of them used functions (models) as the trend

line of the temperature graphs. Chen et al. (2014) used sigmoid model for modeling a discontinuity at the origin of the surface temperature and found the flat points. Chen et al. (2012) and Jaganmohan et al (2016) fitted temperature into third-order polynomial and found the inflection points. Since the surface temperature data don't fluctuate, the functions methods could be useful for the local scale using the surface temperature data. In micro scale, however, measured temperature is easily influenced not only cool islands but also other factors such as wind and traffic heat. And temperature graphs cannot fit in a certain function.

In the microscale, calculating cooling effect method have not been developed. Hathway and Sharples (2012) and Kim et al. (2014), and Manteghi et al. (2015) calculated cooling intensity using several fixed points of air temperature in the river and in the reference points in its surrounding. Then, they focused on which point's temperature became lower than preceding ones. In this way, reference points were selected randomly, which could cause the overestimating or underestimating of RCI. Furthermore, the number of measuring fixed points were not sufficient to identify the

extent of cooling air. In this study, I used mobile survey and could collected very densely temperature points, 100~200 far from the river boundary, that could cover reference areas.

For selecting the first turning point, this study used simple moving average method. Method of moving average makes variation of points smooth and makes easy to understand the trends. As shown in Fig. 12, the measurement result of street 8 at 14h, 24th August, origin of the measured air temperature is hard to select turning point. However, moving averaged points help choosing cooling distance as 35 m. Equation 2 is the calculation method of moving average. In this study, I used 7 as n. It meant B_t represented air temperature of certain point that influenced by 10m around the point.

Equation 2

$$B_t = \frac{1}{n}\sum_{i=-(n-1)/2}^{n-1/2}(A_{t-i}) \quad (1)$$

$$B_t = \textit{moving average value}$$

$$A_t = \text{origin temperature value}$$

$$n = \textit{section of moving average (this study used 7)}$$

Using moving average result, I selected first turning point

manually considering the slopes of temperature curves change sharply or reach a relatively flat level (Du et al. 2016). RCI was calculated by subtract air temperature of river boundary from turning point, and RCD was determined as a distance to the turning point.

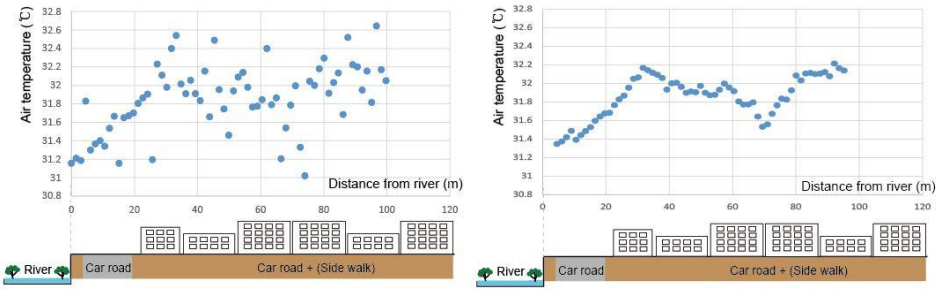


Figure 12. Measured temperature graph (left), moving average (n=7) of measured temperature (right) of street 8 at 14 p.m., 8/24

3.6. Statistical analysis

To examine the influence of urban canyon geometry, I used Pearson correlation analysis and one-way ANOVA analysis with SPSS statistics (IBM, USA). For one-way ANOVA analysis, the averages of RCE in each street were compared to verify difference with urban canyon geometry. For the Pearson correlation analysis, I used the RCI and RCD data over four days for the 8 streets (n=24) as RCE, street widths, mean of building height, and entrance building heights along

the 8 streets.

Chapter 4. Results

4.1. Urban canyon geometry

The study sites, 8 streets in the north side of Cheonggye stream, were composed of various type of urban canopy geometry (Fig. 13). Street 1 and 4 had wide width and tall mean height of buildings, but the variance of building height was larger in street 1. Street 2 and 3 had narrow width and tall buildings. Street 6 and 7 were composed of medium width and low buildings. Lastly, street 5 and 8 were composed of narrow street and low buildings. As the survey results, SW varied from 6 to 42 m. MH varied from 7.4 to 49.1 m, SDH varied from 0.5 to 17.3 m, and EH varied from 15 to 69 m (Table 3). Except for street 1, SDHs were not too high to be problem in using the MH.

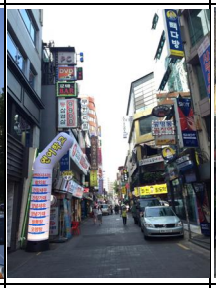
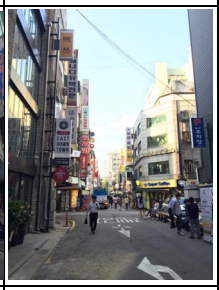
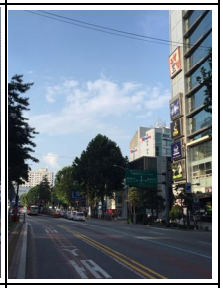
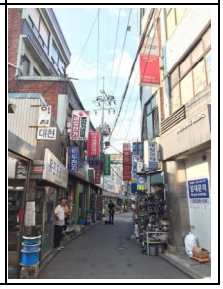
	street1	street2	street3	street4
photo				
	street5	street6	street7	street8
photo				

Figure 13. Photo of 8 streets

Table 3. Urban canyon geometry indicators of the 8 streets

Street / Variable	1	2	3	4	5	6	7	8
SW (m)	42	7	9	40	7	16	21	6
MH (m)	49.1	19.8	38.8	39.6	9.5	11.0	8.9	7.4
SDH (m)	17.3	1.7	7.7	5.2	0.5	0.6	0.4	0.5
EH (m)	15	21	52.5	69	18	14.5	10.5	15

4.2. Moving average of air temperature

The results of moving average analysis were air temperature curves for each days and each streets (Fig. 14). Since RCE was verified to extend less than 100 m and the shortest street was 120 m long, I drew air temperature graphs of 8 streets until 120 m. In the graphs, x axis meant the distance from the river boundary (meter) and y axis meant the air temperature (℃). The lines were moving average value curves of measured temperature (n=7). Among the 48 graphs, 14 showed there was no cooling effect. Except for that 14 results, I manually chose the turning points in the curves. The red lines meant the turning points. Before the turning point, air temperature steadily increased, as indicated by the fact that river cool breeze affected the air temperature dominantly in this sections. However, after the red line, air temperature fluctuated owing to radiation and anthropogenic heat on the street. The patterns of air temperature change were similar until turning point on all three days according to the streets.

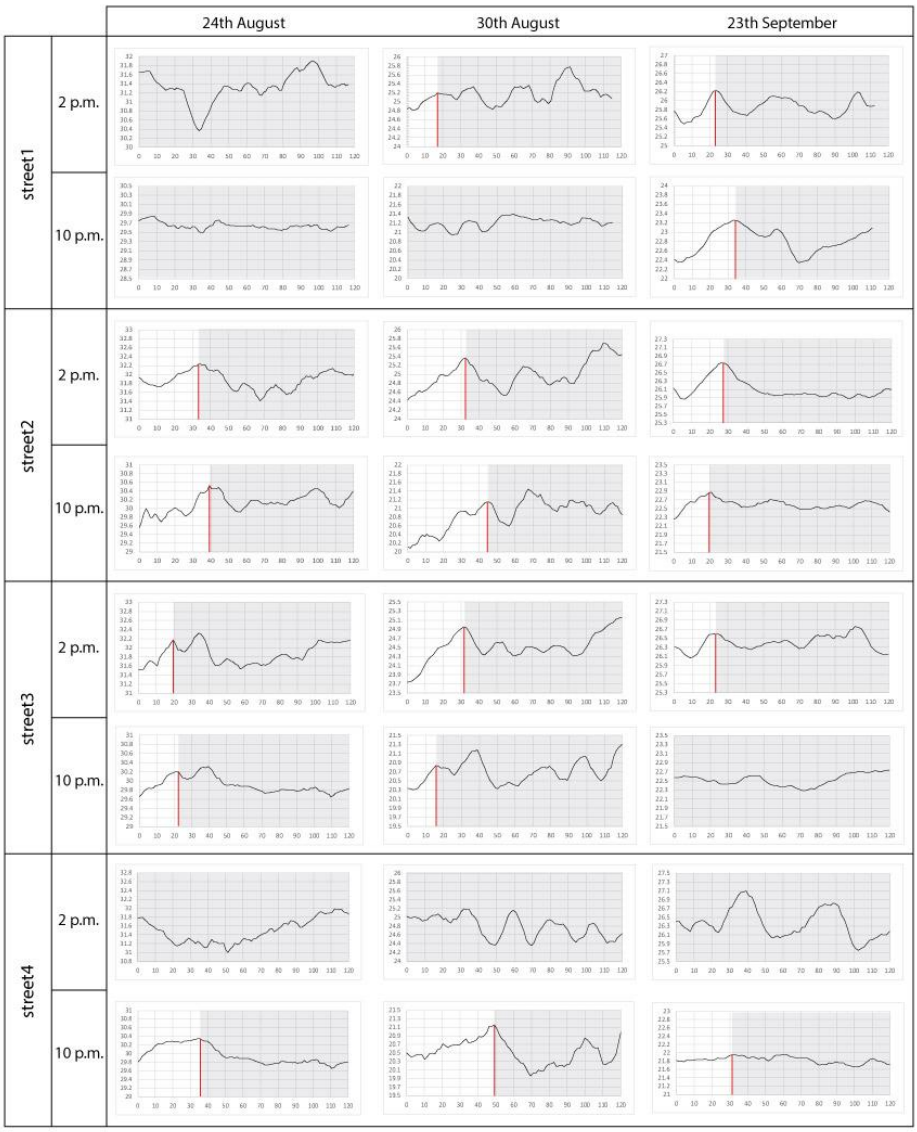


Figure 14. Moving average temperature curve of 8 streets

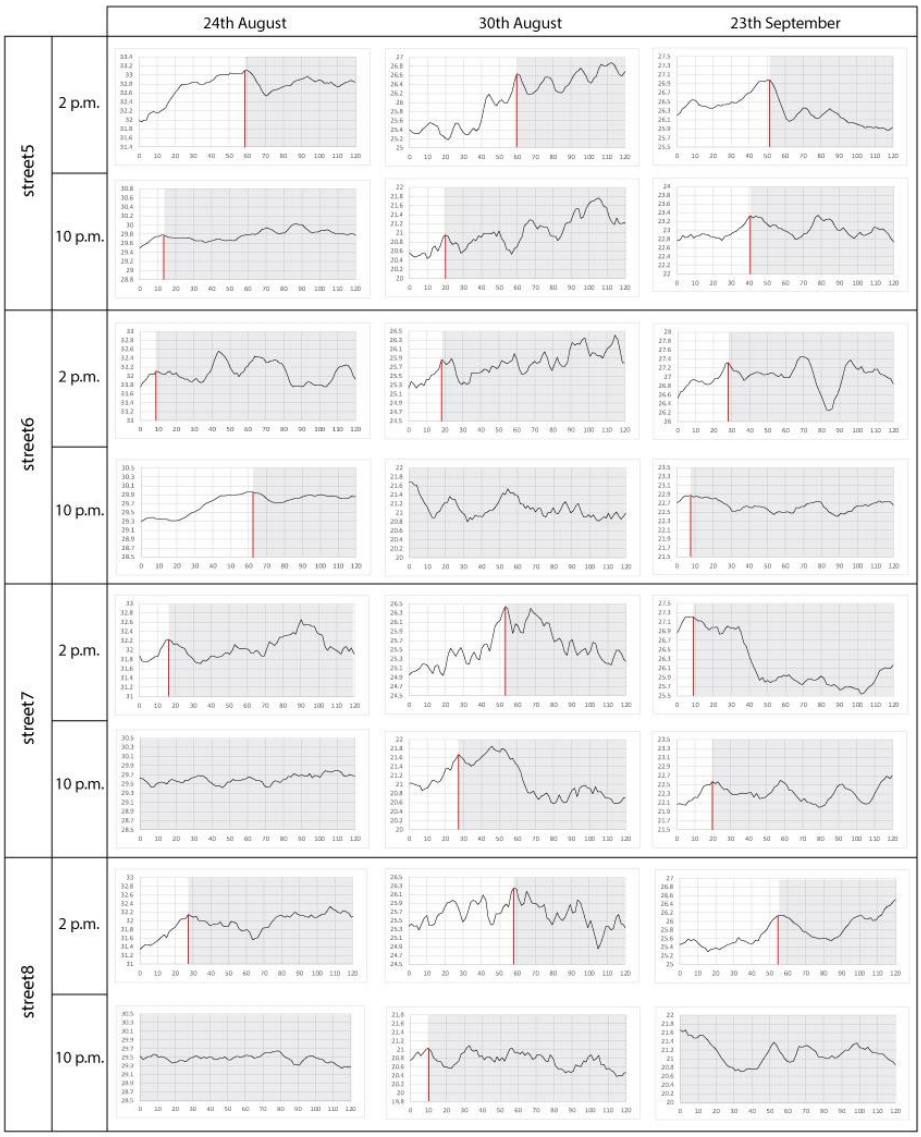


Figure 15 (Continued)

4.3. RCE of each street

Using moving average method, I calculated RCI and RCD in each streets and time. During the study period, the average RCI was 0.52 ℃ and 0.39 ℃, while the average RCD was 24.0 m and 20.3 m at 2 p.m. and 10 p.m., respectively (Fig. 15). RCI was higher at 2 p.m. than at 10 p.m.. At 2 p.m., the RCI reached up to a maximum of 1.22 ℃, while the minimum intensity was 0 ℃. The mean RCI was between 0 ℃ (street 4) and 0.79 ℃ (street 8). At 10 p.m., the RCI ranged from 0 to 0.97 ℃. The mean RCI of street 2 was the highest (0.86 ℃), while those of street 8 was the lowest (0.08 ℃). The RCD pattern was similar to RCI and most street had same order with RCI and RCD, indicating RCI and RCD had positive correlation at that time. RCD was slightly higher at 2 p.m. than at 10 p.m.. At 2 p.m., the RCD ranged from 0 to 68 m. Street 8 (46.7 m) had the highest mean RCD, while street 4 (0 m) had the lowest. At 10 p.m., RCD varied from 0 to 62 m. The mean RCD for street 4 (38.3 m) was the highest, while that for street 8 (3.3 m) was the lowest.

The variation by streets were verified using one-way ANOVA analysis. At 2 p.m., RCD differed significantly

between streets (p=0.011). RCI differed between streets, but not very significant (p=0.059). It inferred that RCD changed more sensitively by the urban canyon geometry in 2 p.m.. However, At 10 p.m., RCE didn't show significant differences between streets (p=0.198, 0.235).

(a) RCI, 2 p.m.

	8/24	8/30	9/23	Average (℃)
8	0.81	0.88	0.69	0.79
3	0.76	1.22	0.28	0.75
5	1.10	0.16	0.80	0.69
2	0.30	0.95	0.58	0.61
6	0.34	0.64	0.80	0.59
7	0.36	0.56	0.35	0.42
1	0.00	0.36	0.46	0.27
4	0.00	0.00	0.00	0
Avg	0.46	0.71	0.50	0.52

(b) RCD, 2 p.m.

	8/24	8/30	9/23	Average (m)
8	27	58	55	46.7
5	68	12	52	44.0
2	33	32	22	29.0
3	19	32	22	24.3
6	8	18	28	18.0
7	17	23	8	16.0
1	0	17	23	13.3
4	0	0	0	0
Avg	21.5	27.8	26.3	24.0

(c) RCI, 10 p.m.

	8/24	8/30	9/23	Average (℃)
2	0.97	1.04	0.58	0.86
4	0.52	0.66	0.13	0.44
5	0.28	0.39	0.58	0.42
7	0.00	0.64	0.50	0.38
3	0.54	0.50	0.00	0.35
6	0.66	0.00	0.18	0.28
1	0.00	0.00	0.88	0.28
8	0.00	0.00	0.24	0.08
Avg	0.37	0.40	0.38	0.39

(d) RCD, 10 p.m.

	8/24	8/30	9/23	Average (m)
4	35	49	31	38.3
2	37	44	20	34.3
5	13	20	41	24.7
6	62	0	8	23.3
7	0	27	19	15.3
3	21	16	0	12.3
1	0	0	33	11.0
8	0	0	10	3.3
Avg	21.5	19.5	20.3	20.3

Figure 16. Calculated RCI and RCD at 2 p.m. (a, b) and 10 p.m. (c, d). The yellow box indicates the same order with RCI and RCD.

4.4. Relationship between the urban canyon geometry indicators and RCE

The Pearson correlation results showed that the urban canyon geometry indicators had a negative correlation with RCE at 2 p.m. (Table 4). The Pearson correlation coefficient between street width and RCE is biggest. The coefficient was −0.672 ($p<0.01$) between street width and RCI, while it was −0.650 ($p<0.01$) between street width and RCD. This indicated that street width had strong relationship between RCE, and wide streets were less effective as cooling zones. Other indicators related building height also had negative correlation between RCE. The Pearson correlation coefficient was −0.403 ($p<0.05$) between the MH and RCI, while it was −0.565 ($p<0.01$) between the MH and RCD. Lastly, The Pearson correlation coefficient was −0.313 ($p>0.1$) between the EH and RCI, while it was −0.369 ($p<0.1$) between the EH and RCD. It inferred that high−rise buildings restricted the cooling effect on the streets. The building height located in the entrance had negative effect to RCE, but the correlation was only significant at $p=0.076$, 0.137. As shown in Fig. 16, regardless of the street width and building height, streets

sometimes did not experience a cooling effect. However, the maximum values and average values of RCD and RCI were varied by the road width and building height.

However, RCE and the urban canyon geometry were unrelated at 10 p.m.. The Pearson correlation coefficient was −0.056 ($p>0.1$) between the street width and RCI, while it was −0.102 ($p>0.1$) between the street width and RCD. The Pearson correlation coefficient was 0.053 ($p>0.1$) between the MH and RCI, while it was 0.060 ($p>0.1$) between the MH and RCD. And the Pearson correlation coefficient was 0.168 ($p>0.1$) and 0.335 ($p<0.1$) between the EH and RCI, and RCD.

Table 4. Pearson correlations between the urban canyon geometry indicators and RCE

		RCI	RCD
2 p.m.	SW	−0.672***	−0.656***
	MH	−0.403**	−0.484**
	EH	−0.313	−0.385*
10 p.m.	SW	−0.078	0.114
	MH	0.040	0.560
	EH	0.083	0.274

*p<0.1, **p<0.05, ***p<0.01

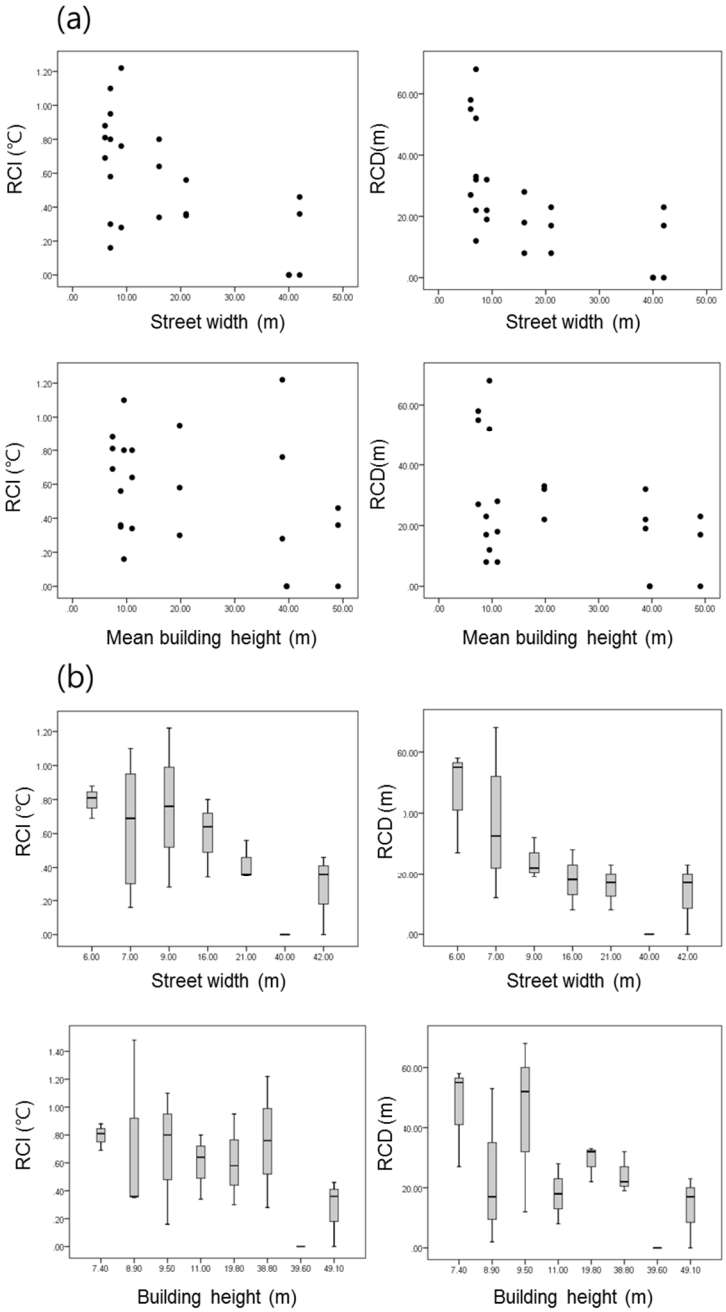


Figure 17. Scatter plots (a) and box plots (b) of RCI and RCD with

Street width and mean building height at 2 p.m.

Chapter 5. Discussions

I calculated the RCE of a small urban river and analyzed how the urban canyon geometry impacted on the RCE. I measured the horizontal air temperature gradient along the streets. The result showed significant correlation between RCE and streets during daytime. Streets that are narrow, with low-rise and low-roughness buildings, showed a higher RCE. The results of this study confirmed our hypothesis, which was that urban canyon geometry affected RCE.

5.1. River cooling effect

The results were comparable to those in previous researches using stationary measurement on a small scale. Hathway & Sharples (2012) reported that the cooling due to a small urban river was approximately 1 ℃ during an ambient temperature higher than 20 ℃, while Kim et al. (2014) found an effect of 0.7 ℃ at 2 p.m. in South Korea, which is slightly higher than our result. Some studies that dealt with larger rivers reported a maximum cooling intensity of 2–5 ℃ (Manteghi et al. 2015; Murakawa et al. 1991). The difference

in the results is probably because of the scale of the river and the climate. The result with regard to the cooling distance was very similar to that of Hathway & Sharples (2012). They concluded that the river had a cooling effect for approximately 30 m on an open street. Kim et al. (2014) reported that the cooling distance would be between 60 and 80 m. Previous studies provided an approximate distance based on the data from a few measurement stations to represent the overall river cooling distance. On the other hand, I presented accurate values with dense measurement points along the 8 streets.

5.2. Influence of the urban canyon geometry indicators on RCE

There were three findings regarding the influence of the urban canyon geometry on RCE during the daytime. Firstly, street width was the most important urban canyon geometry indicators regarding river cooling effect. This study revealed that narrow streets had a higher RCE. The RCE had a strong negative relation with solar radiation (Hathway & Sharples 2012). Wide streets receive more solar radiation than narrow streets. Narrow streets have a bigger impact from shade,

which reduces the solar radiation received (Xuan et al. 2016). Moreover, the narrow streets have interaction wind flow causing wind speed implication, while the wider streets have isolated wind flow (Blocken et al. 2007). It indicating that higher wind speed in narrow streets, which leads to a greater RCE. Murakawa et al. (1991) also supported these results. They argued that the difference in temperature between the streets and the river is inversely proportional to the width of the street.

Secondly, the height of the buildings is also negatively related to RCE. I used mean and entrance height of buildings as the indicators of street canyon height. MH significantly showed negative correlation between RCE. Streets 2, 5, and 8 had almost same width. However, the RCE of street 5 was significantly greater than that of street 2, and street 8 had greatest RCE. It resulted from the difference in building height. Taller buildings might receive more radiation on their surface, which increases the net radiation of the street. In addition, taller buildings lead to a larger cross-sectional area. Wind speed tends to decrease in a large area (Spirn & Whiston 1986). On the other hand, previous study argued high rise

buildings in front of river can block the cool air flow to the surroundings (Jamei et al. 2016). However, the result showed low correlation between entrance building height and RCE. To conclude, net radiation and wind speed lead to a greater cooling effect in streets with low-rise buildings.

Lastly, the influence of urban canyon geometry on RCE was different at 2 p.m. and 10 p.m.. Without considering cooling effect, the influence of urban canyon geometry on air temperature is diurnal. The effect of urban canyon geometry on air temperature could be seen during daytime. However, at nighttime, the effect of urban canyon geometry was not significant because the urban structure stores and traps heat (Middel et al. 2014). The results of this study confirmed the effect of urban canyon geometry on RCE only during daytime. At nighttime, the urban streets are probably influenced by the longwave radiation from the urban structure. Longwave radiation might negatively influence RCE just as solar radiation influences it during daytime. Furthermore, absolute RCI was too low to be effected by urban canyon geometry. The temperature difference between the water surface and the air temperature is lower at nighttime, which results in a

lower cooling effect. Moreover, the evaporation is known to increase until late afternoon, after which it decreases (Oke 1987). This result was corresponded with the previous studies (Chang et al. 2007; Hathway & Sharples 2012; Manteghi et al. 2015).

5.3. Proper urban canyon geometry for RCD

Since the average value of RCD is less than 25 m, starting point of urban canyon, it might seem urban canyon geometry doesn't influence on RCD. However, large range of RCD and correlation analysis results emphasizes that urban canyon geometry has great impact on RCD. There was a car road before starting point of urban canyon, and this road might have affected the RCD. However, since all the streets had the same car road at the starting point, it might not affected the RCD difference by streets. To conclude, proper urban canyon geometry is important for increasing RCD.

The RCD on the street 8 and 5 were 46.7 m and 44 m, respectively, which was much larger than the average. These two streets had many common things. Firstly, road width was less than 7 m. it was very narrow for cars to run smoothly.

Actually, most of the cars on these streets were cargo, and few were passing. Secondly, mean building height was less than 10 m, which meant urban canyons consisted of 2 or 3 story buildings. Lastly, there wasn't street trees. Trees reduced wind speed (Taha et al. 1991; Kubota et al. 2008). Taha et al. (1991) measured wind speed in the vegetation canopy and founded out that wind speed was reduced by 2 m/s inside the canopy. Although, street trees have not verified to reduce RCE, reduced wind speed could decrease RCD in the streets.

If there is a river to be restored like Cheonggye stream, I want to suggest some design proposals based on above discussions (Fig. 17). The nearest streets should be designed as narrow and low buildings. Also, car road and street trees should be avoided in front of the river. Traffic is the major anthropogenic heat generator and street trees reduce wind speed, which can reduce RCE. Therefore, restored river will be able to reduce air temperature to a far distance.

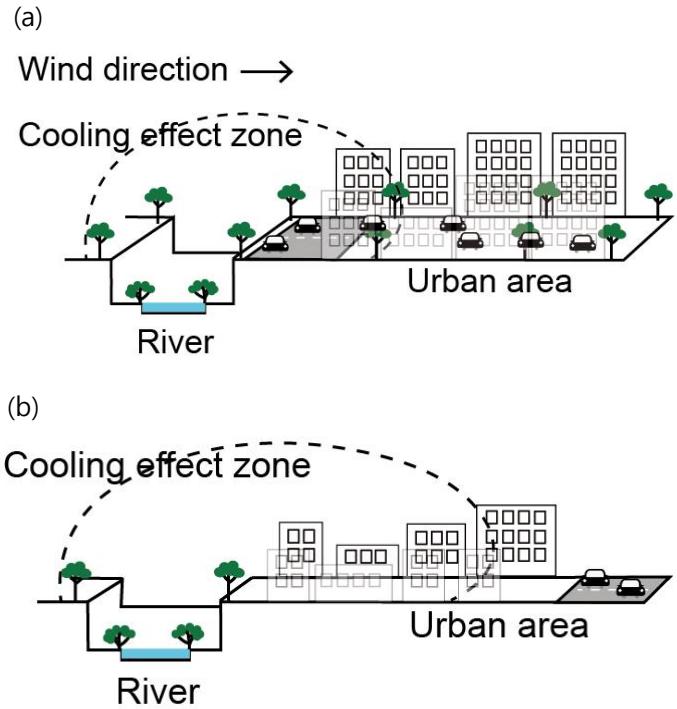


Figure 18. Improvement of urban canyon geometry around a river ((a)→ (b))

Chapter 6. Conclusions

This study analyzed the cooling effect of a small urban river on 8 streets in the surrounding areas, under summer conditions, to evaluate the relationship between RCE and the urban canyon geometry. I used mobile survey with sensitive thermometers composed of T-type thermocouples, radiation shield and ventilation fan. I measured the screen-level air temperature at intervals of 1 second for obtaining a high resolution horizontal temperature gradient, from which I calculated the RCI and RCD. The results obtained showed a mean cooling intensity of 0.52 ℃ and a mean cooling distance of 24 m at 2 p.m., along with a mean cooling intensity of 0.39 ℃ and a mean cooling distance of 20.3 m at 10 p.m.. The study revealed that a small river can have a cooling effect of over 20 m on the surrounding urban area, while the intensity of cooling is higher during daytime. Furthermore, the cooling effect on the surrounding areas varied depending on the urban canyon geometry, which includes street width and building height. As the width reduces and the height decreases, the

RCE increases, and especially width is more important indicators to impact on RCE. However, the entrance building height is much less important. I assumed that urban canyon geometry difference results from the wind speed and the amount of net radiation in the streets. Further studies are required to measure the wind speed and radiation for each urban canyon geometry to determine the reason for the influence of the urban canyon geometry on the cooling effect.

Our conclusion is that a small urban street canyon receive larger cooling effect by river. Since RCE depends on the street width and the building height, we should take urban canyon geometry into consideration when planning the development of a river and its surrounding areas. Our findings are the beginning to advanced knowledge about the effect of urban canyon geometry on the RCE, which can help to improve landscape and urban planning for mitigating serious urban warming.

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Abstract (Korean)

도시화와 기후변화로 인해 도심의 온도는 증가하고 있으며 급증한 도시 온도는 여러 문제를 야기한다. 따라서 도시 계획, 설계 측면에서 온도를 낮추기 위한 열 저감 전략을 고려해야 한다. 여러 연구자들은 열 저감 전략으로 냉섬효과를 연구해왔다. 냉섬효과를 갖는 것 중 도시하천은 증발과 현열 대류를 통해 주변지역의 열을 저감할 수 있는데 이것을 하천의 온도저감효과라고 한다. 본 연구에서는 하천의 온도저감효과로 강도와 거리를 온도저감효과로 정의하였다. 하천의 온도저감강도는 하천과 도심지역의 기온 차이를 의미하며, 온도저감거리는 하천으로부터 생성된 찬 공기가 영향을 미치는 범위를 의미한다. 기존의 연구에서는 하천의 온도저감효과에 영향을 끼치는 요소로 하천 자체의 특성이나 기후에 주목했었다. 그러나 하천 주위의 도시협곡구조 또한 온도저감효과에 영향을 미치는 주요한 인자로써 연구될 필요가 있다. 따라서 본 연구에서는 도시 형태가 하천 온도저감효과에 주는 영향을 분석하였다. 이를 위해 서울의 중심부에 위치하고 있는 청계천과 이와 인접한 도로의 온도를 2시와 10에 각각 측정하였다. 도시 협곡 구조를 설명하는 변수로 도로 너비와 건물의 평균 높이, 건물 높이의 표준편차, 입구에 위치한 건물 높이가 사용되었으며, 기온 측정을 위해서 이동식 측정방식이 사용되었다. 이동식 측정방식은 하천부터 도심까지 밀도 있는 측정 지점을 만들어준다. 본 연구의 결과로, 청계천의 평균적인 온도저감강도는 2시에 0.52℃로 10시보다 0.13℃높게 나타났으며 온도저감거리는 24m로 10시보다 3.7m 높게 나타났다. 또한 도로마다 서로 다른 온도저감효과를 갖는 것으로 나타났으며 도로 너비와 건물의 평균 높이, 건물높이의 표준편차는 하천 온도저감효과에 영향을 주는 것으로 나타났다. 이러한 영향은 낮에만 나타났으며, 도로가 좁고 건물이 낮을수록 강도와 거리가 크게 나타났다. 특히 건물의 표준편차도 커질수록 온도저감효과가 작게 나타났지만, 도시협곡 입구에 위치한 건물이 높다고 해서 효과를 크게 감소시키지는 않았다. 본 연구는 미시규

모에서 하천 온도저감효과를 평가했다는 것과 온도저감효과에 도움이 되는 기본적인 도시협곡구조 특성을 밝혔다는 것에 의의를 갖는다. 본 연구의 결과는 도시 온도를 낮추기 위해 도시하천과 그 주위의 도시를 계획하고 설계하는데 도움을 줄 수 있을 것으로 판단된다.

키워드 : 도시 열섬, 이동식 측정, 미기후, 냉섬효과, 도시협곡구조, 냉각거리
학번 : 2015-21747