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Influence of urban form on the cooling effect of a small urban river

Abstract: Urban warming due to increased urbanization is becoming a serious environmental problem, requiring urban planners to consider heat mitigation strategies that reduce urban air temperature. Urban rivers play an important role in reducing urban heat through evaporation and transfer of sensible heat, known as the river cooling effect (RCE). We used detailed field measurements to calculate the river cooling intensity (RCI) and river cooling distance (RCD) for the Cheonggye River in Seoul, Korea in order to determine the relationship between RCE and urban form at different times of day during summer. Our results showed that the Cheonggye River had a mean RCI of 0.46 °C and a mean RCD of 32.7 m at 2 p.m. and a mean RCI of 0.37 °C and a mean RCD of 37.2 m at 10 p.m. Spatial variations in RCE were negatively correlated with street width and mean building height at 2 p.m., indicating that narrower streets and lower buildings would improve the RCE. In addition, temporal variations in RCE were related to changes wind speed at similar humidity levels. Our results show that the urban form surrounding a river can affect the local RCE, suggesting that landscape and urban planners should consider urban form as a variable affecting urban heat and RCE.

Keywords: urban warming; mobile survey; cooling effect; street width; building height; wind speed

1 **1. Introduction**

2 Urban areas can experience intense warming events with temperatures increasing more

3 rapidly than in surrounding rural areas (Sugawara et al., 2015). Processes contributing to such urban warming include absorption of solar radiation by paved surfaces, heat reflection from 4 5 high-rise buildings, and anthropogenic heat release (Mochida & Lun, 2008). Urban warming 6 has negative effects on both humans and the natural environment that are expected to increase in the future (Imhoff, Zhang, Wolfe, & Bounoua, 2010; Lin, Yu, Chang, Wu, & Zhang, 2015; 7 8 O'Loughlin et al., 2012). Therefore, urban heat mitigation strategies should be developed at the urban planning stage. Effective heat mitigation strategies include reducing solar radiation 9 absorption through shading, increasing the albedo of urban elements, and encouraging 10 11 evaporative cooling by expanding green or water surfaces (Rizwan, Dennis, & Liu, 2008; Vidrih & Medved, 2013). 12

Water bodies are recognized as cooling islands in urban areas (Chang, Li, & Chang, 2007; 13 14 Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2012; Du et al., 2016); urban rivers in particular have clear heat mitigation and cooling effects (Du et al., 2016). The river cooling 15 effect (RCE) occurs in two ways: by generating latent heat via evaporation and by 16 transferring sensible heat between the river's surface and the urban air (Webb & Zhang, 17 1997). Moreover, rivers generate an effective cooling zone by diffusing cool air throughout 18 19 nearby areas (Kim, Cha, & Jung, 2014; Saaroni & Ziv, 2003). Fig. 1 shows the cooling effect 20 zone of an urban river, where the cooling effect is defined by its intensity and distance (Du et al., 2016; Honjo & Takakura, 1990; Jaganmohan, Knapp, Buchmann, & Schwarz, 2016). 21



Fig. 1. Conceptual diagram of the urban river cooling effect (RCE) (image reproduced from
Honjo & Takakura, 1990).

22

26 RCE varies with river characteristics such as geometry and shape index (Du et al., 2016; Sun, Chen, Chen, & Lü, 2012), vegetation cover and river bank height (Du et al., 2016; 27 Murakawa, Sekine, Narita, & Nishina, 1991), and climatic factors. Wind speed is a 28 particularly important factor determining the cooling effect zone (Katayama, Hayashi, 29 Shiotsuki, & Kitayama, 1990; Tominaga, Sato, & Sadohara, 2015), while air or land 30 31 temperature and humidity are also influential (Du et al., 2016; Edinger, Dutterweiler, & Geyer, 1968; Webb & Zhang, 1997). 32 However, the studies cited above did not consider urban characteristics despite their focus 33 on urban areas. Each urban area has a specific infrastructure layout, or form, that alters the 34 microclimate in the urban canopy layer (UCL) lying between the ground and the boundary 35 layer (Lee, 2011; Mills, 1997). Urban form can affect radiation transfer or airflow dispersal in 36 the UCL, driving variations in RCE within the surrounding area (Lin et al., 2015). 37 Despite the importance of urban form, only a few studies have analyzed its impact on the 38

39 RCE. Murakawa et al. (1991) compared three streets near a river in Japan to determine the

impact of building density and street width on RCE, finding that the RCE increased as
building density decreased or streets became narrower. Hathway & Sharples (2012) compared
open and closed street forms along a river in the U.K., revealing that open streets experienced
a greater cooling effect from the river. Manteghi, Lamit, & Ossen (2015) determined that
building orientation also influences RCE. However, more studies on the relationship between
urban form and RCE are required to better guide the design of urban areas with respect to
developing and maintaining an effective RCE.

One aspect of this process involves determining the horizontal temperature gradient from 47 the river to the nearby urban area. Some researchers have studied the cooling effect using 48 49 land surface temperature as acquired from remote sensing (Chen, Tan, Wei, & Su, 2014; Du et al., 2016; Sun et al., 2012). However, these studies were limited to a regional scale and 50 51 only dealt with large rivers, whereas urban rivers are typically small. Although some previous 52 studies have attempted to analyze the effect of small rivers using field measurements to acquire screen level temperature data, their measurements were too sparsely distributed to 53 accurately measure the cooling distance (Hathway & Sharples, 2012; Kim et al., 2014). 54 Accurate RCE research requires data with high spatial resolution. 55

In order to fill these gaps in previous research, in this study we considered the effect of urban form on the RCE of a small urban river under summer conditions. We defined the urban form using street width and building height along with high-resolution temperature data with a temporal range of 4 days. Our main research questions were:

- 60 1) What is the most effective field measurement method for analyzing RCE?
- 61 2) What are the quantitative effects of each urban form characteristic on RCE?
- 62 3) How and why does the impact of urban form on RCE vary temporally?

63	Our results have two main applications: 1) to better inform future studies of RCE,
64	particularly field measurements of high-resolution air temperature and 2) to improve design
65	guidelines for urban rivers and nearby areas in order to mitigate urban warming and
66	improve thermal comfort.
67	
68	2. Materials and Methods
69	2.1. Study overview
70	This study was composed of three steps: field measurements, RCE calculations, and
71	statistical analysis. For the field measurements, we used a mobile survey to increase the
72	number of measurement points. We subsequently calculated RCE, including the river cooling
73	intensity (RCI) and the river cooling distance (RCD), using air temperature gradients and
74	their trend lines. Finally, we performed a correlation analysis to determine the effects of
75	urban form on RCE and to examine the causes of RCE variations. A complete flow chart of
76	our methodology is presented in Fig. 2.



79 **Fig. 2.** Flow chart showing the analysis procedures used in this study.

81 2.2. Scope of study

We focused on the Cheonggye River, a small urban waterway located in the center of 82 Seoul, South Korea. This area has a hot and humid summer lasting from June to September, 83 with heat waves common in August. As frequent rains are common until July, sunny days in 84 August and September were selected for field measurements. The study site was occupied by 85 a highway until 2003, but the Cheonggye River was artificially restored over the next two 86 years, now flowing from west to east across the central region of Seoul for 5.8 km (Kim et 87 al., 2008). The main study site was located in an upstream (western) portion of the river 88 where eight streets were selected for analysis, each approximately 200 m in length (Fig. 3). 89

Fig. 3. Monitoring sites on the Cheonggye River (blue line). Red lines indicate the tracks of
eight mobile street surveys; the blue star marks a fixed-location weather station.

We conducted pre-measurement analysis from August 3–17th to determine the optimum study conditions. The dominant wind direction, which has a major influence on the formation of the cooling effect zone (Fig. 1), was WSW, meaning that the RCE would be more effective on the north bank than the south bank of the river. Furthermore, metro station entrances were located at the end of southern streets near the river, which could affect air temperature measurements. Therefore, we selected eight streets on the north bank of the Cheonggye River.

We further selected 2 p.m. and 10 p.m. as representative time slots for evaluating RCE during day and night because the former was the hottest time of the day with the biggest difference between river surface temperature and urban air temperature while the latter had the most stable weather of the day with minimal artificial impacts (such as traffic). Four days were selected to represent an average RCE; these were all clear and cloudless, except for one day and one night, and humidity was almost constant so that the influence of humidity on

107 RCE could be controlled. The average air temperature, based on measurements from the
108 nearest Automatic Weather Station (AWS), was 27.7 °C at 2 p.m. and 23.8 °C at 10 p.m.
109 (Table 1).

The land use pattern in the study area was uniformly commercial although the urban form 110 varied in terms of street width and building height. The basic structure consisted of an urban 111 canvon formed by building walls and streets (Nunez & Oke, 1977) (Fig. 4), in which the 112 main factors influencing specific urban thermal conditions are street width, building height, 113 and building orientation (Abreu-Harbich, Labaki, & Matzarakis, 2014). In this study, building 114 115 orientations in all eight streets were the same, so only street width and building height were used for analysis. Street width (SW) was defined as the distance between buildings on each 116 side of the street, which remained constant within each street. However, as building height 117 118 varied within a street, we used two building height descriptors: mean building height (MH) and frontage building height (FH, that of buildings facing the river). The latter is an important 119 descriptor because high-rise buildings facing the river can prevent the outwards spread of 120 cool air (Jamei, Rajagopalan, Seyedmahmoudian, & Jamei, 2016). These parameters were 121 calculated as: 122

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

124
$$FH = \frac{h1+h2}{2}$$
(2)

123

where w is the width of each building, h is height of each building, and h1 and h2 are the height of buildings facing the river. MH is weighted based on building width and FH is the average height of the two buildings facing the river (on either side of the street). Building height and street width data were obtained from the Integrated Real Estate Information

- 129 dataset (Ministry of Land, Infrastructure and Transport of Korea) and the Korea National
- 130 Spatial Data Infrastructure Portal, respectively. SW varied from 6-42 m, MH varied from
- 131 7.4–49.1 m, and FH varied from 14.5–69 m (Table 2).
- 132

Fig. 4. Schematic depiction of an urban canyon (image reproduced from Nunez & Oke,1997).

137

139 Urban microclimates are so complex that a fixed weather station cannot provide sufficient spatial resolution (Rajkovich & Larsen, 2016; Sugawara et al., 2015). Thus, we used mobile 140 surveys for field measurements, which provide higher spatial resolution data at a lower cost 141 than a fixed weather station (Stewart, 2011) and have additional advantages for measuring 142 urban microclimates; catching micro heat wave, covering large study sites, measuring in 143 narrow spaces (Brandsma & Wolters, 2012; Coseo & Larsen, 2014). When studying urban 144 microclimates, air temperature should be measured at a screen level (1-2 m above ground) of 145 the UCL (Oke, 2004; Stewart & Oke, 2012; Stewart, 2011). This presents some difficulties, 146

147 however, in that the thermometer can receive radiation from outdoor materials and the air flow can be stagnant because of many obstacles. To overcome these difficulties, radiation 148 shielding and ventilation are recommended for the thermometer (Oke, 2004). In this study, a 149 150 T-type thermocouple was 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., 151 2016). This thermocouple used a 0.127 mm diameter sensor that was sensitive to outdoor air 152 and was connected to a data logger (Oneset Computer Corporation, USA) that recorded the 153 air temperature in 1 sec intervals with an accuracy of ± 0.6 °C and a resolution of 0.02 °C 154 155 (Fig. 5a).

Two people walked the streets at the same speed (about 1.4 m/s). Each walked four streets 156 for 30 minutes, with two thermometers mounted on their shoulders 1.5 m above the ground. 157 158 The thermometers were verified against each other every day prior to measurement. Survey tracks were measured twice, at 2 p.m. and 10 p.m. Each point on the survey track therefore 159 had four air temperature data points, which were then averaged. A fixed-location weather 160 station (Vantage Pro 2, Davis Instruments, USA) was mounted on a nearby bridge; this took 161 measurements every 5 minutes of humidity (\pm 3% accuracy) and wind speed (\pm 0.4 m/s 162 163 accuracy) (Fig. 5b). The humidity and wind speed values were averaged per hour.

Fig. 5. Measurement devices used in this study: (a) moving survey thermometers and (b)
 fixed-location weather station.

165

169 2.4. Calculating RCE

170 We calculated RCE using a third-order polynomial method developed by Lin et al. (2015) after noting that the further an area was from a river, the smaller the cooling effect was. 171 Cooling intensity is defined as the difference in air temperature between a river and an urban 172 area (Feyisa, Dons, & Meilby, 2014) and the cooling distance is the distance from a river to 173 the point in the temperature curve where temperature abruptly changes or flattens out (Sun et 174 al., 2012), as shown in Fig. 6. Over this distance, air temperature increases until an inflection 175 point and then decreases due to another thermal influence from buildings, cars, and roads. 176 The trend line of this phenomena fits a third-order polynomial, f(x), in which the x-axis 177 denotes the distance from the river while the y-axis denotes the air temperature. If we set the 178 inflection x-value as x_1 , then RCD is x_1 and RCI is $f(x_1) - d$, as shown in the third-order 179

polynomial equations first proposed by Chen et al. (2012) and developed by Jaganmohan et
al. (2016):

182
$$\operatorname{RCD} = x_1 = \frac{-2b - \sqrt{4b^2 - 12ac}}{6a}$$
 (3)

183
$$\operatorname{RCI} = f(x_1) - d = ax_1^3 + bx_1^2 + cx_1$$
(4)

When the air temperature data do not fit a third-order polynomial (negative polynomial or flat), the values of RCI and RCD are zero. Based on the results of previous studies, we restricted the maximum RCD to 100 m to reduce other cooling influences (except for two instances: street5 at 2 p.m. and 10 p.m. on August 30th).

188

191 2.5. Statistical analysis

To examine the influence of urban form, we used SPSS statistics software (IBM, USA) to conduct Pearson correlation analysis with the RCI and RCD data from all four days and eight streets (n=32) along with the SW, MH, and FH values along all eight streets. As the RCE can vary with measurement date because of climate factors such as humidity and wind speed, we standardized RCE for each day before performing the correlation analysis in order to compare values from different dates. However, to examine the influence of climate on RCE
and determine the temporal variations due to wind speed, we used non-standardized RCE for
the relevant analysis.

200

3. Results

202 3.1. Air temperature gradient

The horizontal air temperature gradient results showed two trends. For example, Fig. 7 203 shows the air temperature gradient at 2 p.m. on August 24th. Six streets (2, 3, 5, 6, 7, and 8) 204 had explicit polynomial functions with third-order polynomial trend lines, indicating a clear 205 RCE where air temperature gradually increased with distance from the river, following the 206 exponential curve until the inflection point (Murakawa et al., 1991). Two streets (1 and 4) had 207 flat or implicit functions, indicating zero RCE; thus RCE could not be determined. These 208 streets' width and building height were longer than the others' and included a vehicular 209 bridge over the river, resulting in high traffic and no RCE. The distance to the inflection point 210 211 varied, along with the difference in air temperature between the river and the inflection point, 212 indicating that RCD and RCI varied from street to street.

214

215

Fig. 7. Horizontal air temperature gradients at 2 p.m. on August 24th, 2016. (a) Explicit function: air temperature initially increases with distance from the river and streets show positive RCE values. (b) Implicit function: air temperature initially decreases with distance from the river and streets show zero RCE.

- 220
- 221 3.2. RCE (RCI and RCD)
- 222 During the study period, the average RCI and RCD at 2 p.m. and 10 p.m. was 0.46 °C and
- 223 0.37 °C and 32.7 m and 37.2 m, respectively (Fig. 8). The RCI was therefore higher at 2 p.m.

- than at 10 p.m., while the reverse was true for RCD. Both patterns were similar, especially at
- 225 2 p.m., indicating that RCI and RCD were positively correlated.

Fig. 8. RCI and RCD for each street calculated at (a) 2 p.m. and (b) 10 p.m. Dotted lines
show the range of values.

3.3. Relationship between urban form descriptors and standardized RCE

233 The correlation results show that the urban form descriptors were negatively correlated

- with standardized RCE at 2 p.m. (Table 3). The correlation coefficients between SW and
- standardized RCI and RCD indicated a lower cooling effect in wide streets. The correlation
- 236 coefficients between MH and standardized RCI and RCD indicated that high-rise buildings

Fig. 9. Box plots of RCI with (a) street width and (c) mean building height and RCD with (b) street width and (d) building height at 2 p.m.

249 3.4. Relationship between wind speed and RCE

250 During the study, humidity did not change sufficiently to have a significant impact on RCE,

- except for one day (43.8 % at 2 p.m., 78 % at 10 p.m.). For three days, the humidity ranged
- 252 from 53.9–54.3% at 2 p.m. and 60.2–66.0% at 10 p.m. However, the wind speed varied from
- 253 1.15–2.03 m/s at 2 p.m. and 0.03–1.60 m/s at 10 p.m., which did influence the RCE. During
- 254 daytimes with similar humidity, the Pearson correlation coefficient between wind speed and
- RCI at 2 p.m. was 0.454 (p<0.05) and that between wind speed and RCD was 0.609
- 256 (p<0.001). There was a positive relationship between wind speed and RCE at 2 p.m.,
- especially for RCD (Fig. 10). At 10 p.m., the Pearson correlation coefficient between wind
- speed and RCI was 0.151 (p>0.05) and that between wind speed and RCD 0.045 (p>0.05).
- Although the correlation at 10 p.m. was smaller than that at 2 p.m., the average RCI and RCD
- still increased with wind speed.

261

Fig. 10. Correlation at 2 p.m. between wind speed and RCI (a) and RCD (b) and at 10 p.m.
between wind speed and RCI (c) and RCD (d) for (from left to right) August 24th, August 30th, and September 23rd.

266 **4. Discussion**

267 Our results showed a higher RCE for narrow streets with low-rise buildings, confirming

268 our hypothesis regarding the influence of urban form on RCE. Our results also showed that

269 variations in RCE are due to both urban form and date/time.

270

271 4.1. River cooling effect

272 Our results are comparable to those of previous research using small-scale fixed location measurements. Hathway & Sharples (2012) reported that the cooling effect of a small urban 273 river was approximately 1 °C when the ambient temperature was over 20 °C, while Kim et al. 274 (2014) reported a cooling effect of 0.7 °C at 2 p.m. in South Korea, which was slightly higher 275 than our result. Some studies of larger rivers reported a maximum cooling intensity of 2–5 °C 276 (Manteghi et al., 2015; Murakawa et al., 1991), a difference most likely due to the different 277 river scale and climate, as large rivers in dry climate with high wind speed have higher a 278 cooling intensity. 279

Our cooling distances were also very similar to those of Hathway & Sharples (2012), who reported a cooling effect for a distance of approximately 30 m on an open street, while Kim et al. (2014) reported a cooling distance of 60–80 m. Although other studies provided approximate cooling distances based on data from a few measurement stations to represent an overall river cooling distance, our results provide accurate values from close measurement points along eight streets.

286

287 4.2.	Influence	of urban	form	on RCE
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Our results documented the effects of two major urban forms on RCE. First, narrow streets had a higher RCE because this has a strong negative relationship with solar radiation (Hathway & Sharples, 2012) such that wide streets receive more solar radiation than narrow streets. Furthermore, shade has a greater impact on narrow streets, reducing the amount of solar radiation received (Xuan, Yang, Li, & Mochida, 2016). Narrow streets also experience greater wind flow interactions while wider streets exhibit isolated wind flows (Blocken, Carmeliet, & Stathopoulos, 2007), leading to a higher wind speed in narrower streets and thus

a larger RCE. Murakawa et al. (1991) argued that the temperature difference between streets
and rivers was inversely proportional to the width of the street, in agreement with our results.

Second, building height was negatively correlated with RCE (Fig. 9). Although streets 2 297 and 5 had the same width, the RCE of street 5 was significantly greater than that of street 2 298 because of the difference in building height. Taller buildings can receive more radiation on 299 300 their surfaces and so increase the net radiation toward the street. In addition, taller buildings 301 lead to a larger cross-sectional area of the urban canyon, and wind speeds tend to be lower in large areas (Spirn & Whiston, 1986). On the other hand, although a previous study argued 302 303 that high-rise buildings facing the river could block the flow of cool air to their surroundings (Jamei et al., 2016), our results showed an insignificant correlation between FH and RCE. 304 The average building height, rather than the building height facing the river, had a greater 305 306 effect on RCE. In other words, net radiation and wind speed led to a greater cooling effect in streets with low-rise buildings. 307

The influence of urban form on RCE was different at 2 p.m. and 10 p.m., suggesting a diurnal effect. The effect of urban form on air temperature was clear during the daytime, but at night there was no significant effect because urban structures stored heat (Middel, Häb, Brazel, Martin, & Guhathakurta, 2014) that was released and trapped inside the urban canyon (Ryu et al., 2011; Zoulia et al., 2009). Thus trapped heat can negatively influence RCE during the nighttime just as solar radiation does during the daytime.

Although urban microclimates can be significantly affected by urban envelope materials (Alchapar, Correa, & Cantón, 2014), our study sites were selected to compare only urban forms and therefore consisted of very similar materials. The streets were all asphalt concrete and the buildings were glass, tile, and brick. Although the microclimate could change with

these materials along the street, it was difficult to accurately distinguish any such variations,so we did not consider envelope materials as a factor.

320

321 4.3. Temporal variation in the RCE

The RCE varied in both time and space, diurnally and between different days. The RCI and 322 RCD had relatively large daily variations (approximately 50% of their mean value). The main 323 heat mitigation from the river was due to evaporation, which can be influenced by climate, 324 especially wind speed and humidity (Edinger et al., 1968; Hathway & Sharples, 2012; 325 Tominaga et al., 2015; Webb & Zhang, 1997). While humidity was relatively constant in our 326 study, wind speed variability affected the RCE (Fig. 10), suggesting that wind speed 327 328 increased evaporation by stimulating the movement of water molecules between the river surface and the air, resulting in a higher RCI. Moreover, wind speed allowed these effects to 329 travel a greater distance from the river, increasing the RCD. 330

Regarding the diurnal difference, our results showed that daytime cooling intensity was higher than nighttime cooling intensity, in agreement with previous studies (Chang et al., 2007; Hathway & Sharples, 2012; Manteghi et al., 2015). The temperature difference between the water surface and the air is lower at nighttime, resulting in a reduced cooling effect. Moreover, evaporation is known to increase during daytime until late afternoon, when it begins to decrease again (Oke, 1987).

The cooling distance showed a smaller difference between daytime and nighttime, in agreement with the findings of Hathway & Sharples (2012). Furthermore, the RCE at 10 p.m. showed no correlation with wind speed and urban form. However, we did not evaluate the reasons for diurnal changes in the river cooling distance in detail, and further research is 341 necessary to identify which factors influence river cooling distance at night.

342

343 4.4. Future research

Although our research presented improved measurement methods and revealed the 344 relationship between RCE and urban form, some limitations should be discussed. First, a 345 large number of samples are required to accurately determine urban climate dynamics while a 346 small number of samples results in a limited spatial and temporal scale. Our data focused on a 347 348 commercial urban form during the summer season, but it cannot be assumed that every urban area will experience the same effect on the RCE as shown in this study. Moreover, building 349 350 orientation and envelope material are important urban descriptors affecting the urban 351 microclimate, but we did not consider these as variables. In addition, we used four representative days and two representative times of day, but our results cannot necessarily be 352 extrapolated to all days and times of day. 353

Future research should measure RCE for other diverse cases to provide proper guidelines 354 for street planning surrounding rivers in urban areas, using the mobile survey methods 355 356 presented in this study to better define RCE at smaller scales. Such research could choose rivers in diverse climate zones, explore diverse urban forms including street orientation, or 357 compare materials' effects on the RCE such as those from radiation transfer. We also suggest 358 359 that future research explore diurnal changes, as no study has yet defined why RCD varies at night. As more data are accumulated through such measurements, the cooling effect of rivers 360 can be used effectively in urban planning. 361

Also, the correlation analysis method is limited regarding improving urban planning and policy strategies. During the process of city planning and landscape design, knowledge of

threshold values might be as important as understanding the effects of different urban forms. For example, we found that building height and RCE were negatively correlated, but an urban planner or designer would need to know the exact building height value that would result in negative effects on the RCE. Therefore, future studies are required to discover such threshold values using simulations or sufficient data collection.

369

5. Conclusions

371 We analyzed the cooling effect of a small urban river in summer on eight streets in the surrounding area to examine the relationship between the RCE and urban form. We used a 372 373 mobile survey method with sensitive thermometers composed of T-type thermocouples, 374 radiation shields, and a ventilation fan. We measured the air temperature at 1.5 m height at 1 s intervals to obtain a high-resolution horizontal temperature gradient from which we 375 calculated the RCI and RCD. We fitted the measured air temperature gradients with a third-376 order polynomial function and confirmed that this method could also be applied to a micro 377 scale. The results showed a mean cooling intensity of 0.46 °C and a mean cooling distance of 378 32.7 m at 2 p.m., and a mean cooling intensity of 0.37 °C and a mean cooling distance of 37.2 379 m at 10 p.m. 380

We found that the mobile survey method was effective for RCE calculations on a micro scale. Our results also revealed that even a small river could have a cooling distance of over 30 m on the surrounding urban area, while the intensity of cooling was higher during the daytime than nighttime. Furthermore, the cooling effect on the surrounding areas varied with the urban form, especially street width and mean building height: narrower streets and taller buildings resulted in a larger RCE. We assume that this difference resulted from wind speed

and radiation flux variations. Furthermore, we found that RCE varied with the measurement time and date because of the wind speed. However, the number of samples used in this study was limited, and the correlation analysis results are insufficient to provide specific guidelines for urban planning. Further studies are required to measure wind speed and radiation for each urban form to determine their specific influence on the river cooling effect. The above limitations can be overcome through a combination of multiple field measurements in various regions and detailed simulation analyses.

In conclusion, we confirmed that RCE is influenced by urban form as well as river 394 characteristics. Until now, urban planning did not consider the urban form near rivers with 395 respect to the potential for enhancing the nearby RCE, only considering river size and bank 396 vegetation. Our findings enhance the understanding of RCE by showing that building height 397 398 and street width correlated to RCE during daytime near a small urban river. However, this result should be carefully applied to urban planning because our limited case study does not 399 necessarily apply to all situations. Further diverse results using the mobile survey methods 400 evaluated in this study are needed to enable urban planners to design more effective urban 401 402 rivers and mitigate urban warming.

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- **Table 1** Average air temperature based on the measuring date from AWS (°C).
- **Table 2** Urban form descriptors of the 8 streets, including street width (SW), mean building
- 548 height (MH), and average height of buildings fronting the river (FH).
- **Table 3** Pearson correlation between the urban form descriptors and RCE.

Time	2 p.m.	10 p.m.
Date		
8/24	29.4	26.8
8/30	22.6	17.8
9/09	27.3	21.4
9/23	26.1	20.4
Average	27.7	23.8

Table 1 Average air temperature based on the measuring date from AWS (°C).

Table 2 Urban form descriptors of the 8 streets, including street width (SW), mean building

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
FH (m)	15	21	52.5	69	18	14.5	10.5	15
Building orientation	N-S	N-S	N-S	N-S	N-S	N-S	N-S	N-S

bight (MH), and average height of buildings fronting the river (FH).

		Standardized RCI	Standardized RCD
	SW	-0.554**	-0.567**
2 p.m.	МН	-0.466**	-0.458**
	FH	-0.266	-0.346
10	SW	-0.023	-0.182
10 n m	МН	-0.001	-0.115
p.m.	FH	-0.023	0.061
**p<0.0	01	I	I

Table 3 Pearson correlation between the urban form descriptors and RCE.

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- Fig. 3. Conceptual diagram of the urban river cooling effect (RCE) (image reproduced from
 Honjo & Takakura, 1990).
- 566 **Fig. 4.** Flow chart showing the analysis procedures used in this study.
- **Fig. 3.** Monitoring sites on the Cheonggye River (blue line). Red lines indicate the tracks of eight mobile street surveys; the blue star marks a fixed-location automatic weather station.
- Fig. 4. Schematic depiction of an urban canyon (image reproduced from Nunez & Oke,1997).
- 571 **Fig. 5.** Measurement devices used in this study: (a) moving survey thermometers and (b) 572 fixed-location weather station.
- 573 **Fig. 6.** Schematic diagram of river cooling intensity (RCI) and river cooling distance (RCD).
- 574 **Fig. 7.** Horizontal air temperature gradients at 2 p.m. on August 24th, 2016. (a) Explicit
- 575 function: air temperature initially increases with distance from the river and streets show

positive RCE values. (b) Implicit function: air temperature initially decreases with distance

- 577 from the river and streets show zero.
- 578 **Fig. 8.** RCI and RCD for each street calculated at (a) 2 p.m. and (b) 10 p.m. Dotted lines 579 show the range of values.
- Fig. 9. Box plots of RCI with (a) street width and (c) mean building height and RCD with (b)
 street width and (d) building height at 2 p.m.
- 582 Fig. 10. Correlation at 2 p.m. between wind speed and RCI (a) and RCD (b) and at 10 p.m.
- between wind speed and RCI (c) and RCD (d) for (from left to right) August 24th, August 30th, and September 23rd.
- 585
- 586
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588 Appendix 1. Supplementary data

- 589 Measured air temperature (grey dots) and fitted third-order polynomial graphs (black lines)
- of 8 streets and 4 days. X-axis denotes air temperature (°C) and y-axis denotes the distance
- 591 from the river.

		August 24th	August 30th	September 9th	September 23th
street5	2 p.m.	133 131 132 132 132 133 133 133 133 133	27 26 26 25 25 25 25 25 25 25 25 25 25 25 25 25	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	
	10 p.m.		13 -	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
set6	2 p.m.	31	25 25 25 25 25 25 25 25 25 25	13 25 25 25 26 27 28 26 27 28 26 27 28 29 20 21 22 23 24 25 26 27 28 29 20 21 22 23 24 25 26 27 28 29 20 21 22 23 24 25 26 27 28 29 20 21 224 23 24 25 26 27	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$
stree	10 p.m.	1 1 1 1 1 1 1 1 1 1 1 1 1 1	224 24 14 14 14 15 16 16 16 16 16 16 16 16 16 16 16 16 16	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
streel7	2 p.m.		$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	226 234 24 25 26 26 25 26 25 25 25 25 25 25 25 25 25 25	233 234 245 245 245 245 245 245 245 245 245 24
	10 p.m.	385 364 364 364 36 36 36 36 36 36 36 36 36 36		$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$
street8	2 p.m.		$ \begin{bmatrix} 36.8 \\ 26.6$	$\begin{array}{c} 23\\ 39\\ 4\\ 32\\ 4$	$ \begin{bmatrix} 364\\ 46\\ 46\\ 36\\ 36\\ 36\\ 36\\ 36\\ 36\\ 36\\ 36\\ 36\\ 3$
	10 p.m.		$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		$\begin{array}{c ccccccccccccccccccccccccccccccccccc$