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Research on the cooling island effects of water body: A case study of Shanghai, China

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ABSTRACT

The water cooling island (WCI) is important to the mitigation of urban heat island (UHI) effects. In this study, the three aspects: WCI range (L_{max}), amplitude of temperature drop (ΔT_{max}) and temperature gradient (G_{temp}) are used to investigate the WCI effects of the water bodies in Shanghai, China based on the high resolution Google Earth and Landsat-8 satellite image data of the eighteen lakes and three rivers within the outer ring road of the city. The results show that the water bodies have mean L_{max} of 0.74 km, ΔT_{max} of 3.32 °C and G_{temp} of 5.15 °C/km. The WCI effects of the lakes are significantly stronger than that of rivers. In addition, geometry, proportion of vegetation and impervious surfaces are important impact factors on the WCI effects of water bodies. In particular, L_{max} and ΔT_{max} of water bodies are negatively correlated to their geometry and the proportion of impervious surfaces, but positively correlated to the proportion of vegetation around them. The results suggest that with a fixed area of water body, the geometry of the water body should be relatively simple, the proportion of vegetation should be increased and the proportion of impervious surfaces should be reduced to realize good WCI effects. This provides useful implications for urban planners and designers to mitigate UHI effects.

1. Introduction

The theory of urban cooling island (UCI) effects is developed along with the in depth research of urban heat island (UHI) effects. It can reduce UHI by efficient landscape planning. According to the World Urbanization Prospects released by the United Nations in 2014, more than half (54%) of the world's population lives in urban areas and the number is expected to increase, reaching 66 per cent by 2050 (United Nations 2014). The rapid urbanization process changes the type of land use radically, which increases the number of motors, high-rise buildings and artificial heat sources. These factors lead to serious UHI effects which indicate higher temperature in urban areas than its surrounding regions (Oke, 1973; Carlson et al., 1994; Lo et al., 1997; Wilson et al., 2003). The increased temperature contributes to worse air quality, more energy consumption and impaired human health (Vitousek et al., 1997; Owen et al., 1998; Luck and Wu, 2002; Patz et al., 2005; Rizwan et al., 2008; Vanos et al., 2010). So the research of UHI mitigation, especially UCI arouses great interest.

According to the previous researches, it is now well verified that park, greenspace and water body can provide UCI effects (Chang et al., 2007; Cao et al., 2010). The UCI effects of park and urban greenspace have been researched widely already.

Chang et al. (2007) and Cao et al. (2010) defined the UCI of park as park cooling island effects. By meta-analysis, Bowler et al. (2010) found obvious park cooling island effects (0.94 °C temperature drop in average). In the research of Chang et al. (2007), the authors thought that park size, park shape and vegetation could influence the park cooling island effects and parks with complex shapes provided stronger park cooling island effects. However, Lu et al. (2012) concluded that the park cooling island efficiency was negatively correlated to the geometry of the park.

Also, Kong et al. (2014) defined the UCI of greenspace as greenspace cooling island. Chen and Wong (2006) and Oliveria et al. (2011) indicated that urban greenspace was able to mitigate UHI effects. Its UCI effects were influenced by the area and type of the greenspace, feature of plant structure and spatial configuration characteristic (Chen et al., 2014; Kong et al., 2014).

Abbreviations: WCI, water cooling island; UHI, urban heat island; L_{max}, WCI range; ΔT_{max}, amplitude of temperature drop; G_{temp}, temperature gradient; UCI, urban cooling island; WA, water area; PI, proportion impervious surfaces; PG, proportion green land; LST, land surface temperature; RTE, radiative transfer equation; LSI, landscape shape index.

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As to the water cooling island (WCI), Costanza et al. (1998), Chang et al. (2007) and Cao et al. (2010) found water body had obvious WCI. Water body has high thermal inertia and capacity, low thermal conductivity and radiance (Wilson et al., 2003). In addition, it absorbs less heat than impervious surfaces and buildings as it has fewer surfaces that absorb and store energies under solar radiation (Zhou and Shu, 1994). So, according to the theory of ground surface heat balance, water body not only corresponds to relatively lower surface temperature, but also influences the ambient temperature of the surrounding environment. Adams and Dove (1989) found a 35 m wide river caused an ambient temperature drop of 1–1.5 °C. More temperature drop could be achieved if the river was companioned with greenspace. Sun et al. (2012) concluded that WCI effects correlated to the position and landscape shape index.

However, unlike the widely researched park and greenspace cooling island, studies on WCI have just started. Plenty of problems are yet to be solved. What is the range of WCI effects, what is the amplitude of temperature drop and what factors impact the actual WCI effects? Large water bodies can bring good WCI effects. However, in practice, the water area (WA) is limited. So, researches on these problems can provide good directions to urban landscape planning by efficient distribution and design of water bodies to maintain their maximum value of micro climate adjustment.

To research the relation between environment temperature and the range of WCI, the previous method is to get the real test data at fixed points besides the water bodies (Chang et al., 2007). However, this method requires distributing intensive test points around the water bodies to guarantee the precision of spatial interpolation. The explicit range of appropriate test point distribution is difficult to estimate. Besides, test points also have to be set around all types of different water bodies simultaneously to get enough research samples for statistical analysis. The method will require massive labor and cost.

In recent years, remote sensing technology provides a good method for WCI research at a reasonable precision (Sun et al., 2012). The statistical analysis of the retrieved temperature data from satellite images could well indicate the trend of temperature change. This is especially suitable to search for the range of WCI effects. Meanwhile, the remote sensing images of large numbers of water bodies can be easily approached to replace the huge numbers of test points required in the previous method.

So in this study, based on the high resolution Google Earth and Landsat-8 satellite imagery data of the eighteen lakes and three rivers within the outer ring road of Shanghai, China, we aim to (1) quantify the range of WCI effects (L_{max}), temperature drop amplitude (ΔT_{max}) and gradient (G_{temp}), (2) assess the factors that impact the effects of WCI, including WA, geometry of water body and the proportion of the impervious surfaces (PI) and green land (PG) in the surroundings, (3) discuss the implications for water landscape design in urban regions.

2. Materials and methods

2.1. Study area

Shanghai is the economic center of China. It locates on the coast of East China Sea, ranging from 31°40′ N to 31°53′ N and 120°51 E′ to 122°12′ E (Fig. 1). By the end of 2014, the permanent resident population of Shanghai is 24.2568 million. It is one of the most urbanized cities in China. Among the total area of 6340.5 km^2, the area of water bodies is 642.7 km^2 (Shanghai Municipal Statistics Bureau, 2011). Restricted by limited land resources, adverse conditions, such as artificial invasion of water areas are relatively common to satisfy the demand of rapid urbanization and economic development. The total area of water has decreased by 25% during the last 20 years (Wang and Ruan, 2001). The water surface ratio of the central urban area is now less than 2%, which directly influences the ability of micro climate adjustment and residential environment improvement (Wang and Ruan, 2001). Our study focuses on the areas within the outer ring road of the city. The area is about 665.5 km^2 (Fig. 1). As the spatial resolution of thermal remote sensing image is 100 m, we select the 18 lakes (1–18) whose areas are larger than 1 ha and the 3 main rivers (R1–R3) in the area as the research objects (Fig. 2).

Table 1
Values of K_1 and K_2 [a].

	TIRS 1	TIRS 2
K_1	774.89	480.89
K_2	1321.08	1201.14

[a] The data is from the NASA Landsat8 science data user's handbook [EB/OL], http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_htmls/chapter11/chapter11.html#temperature.

2.2. Land surface temperature and land cover

The land surface temperature (LST) of Shanghai in August 29th, 2013 is estimated by radiative transfer equation (RTE). By radiative RTE according to atmospheric profile measurement, the retrieved LST could reach an accuracy of 0.6 °C (Sobrino et al., 2004). The data come from thermal infrared sensor (TIRS) carried by the Satellite Landsat-8 launched in February, 2013.

First, ENVI5.1 is used to preprocess the raw images, including radiometric calibration, atmospheric correction, cutting, splicing, et al. For atmospheric correction, atmospheric radiation process is simulated with the help of atmospheric correction software MODTRAN4.0 model, which is based on RTE. By the simulation, atmospheric downward radiance $L_{atm,i}\downarrow$, upward radiance $L_{atm,i}\uparrow$, and transmissivity τ can be estimated. Then, with the given land surface emissivity ε, the $B(T_s)$ in (1) can be calculated. And the LST can be approached by Eq. (2):

$$L_{sensor,i} = \tau_i \varepsilon_i B(T_s) + (1-\varepsilon_i)\tau_i L_{atm,i}\downarrow + L_{atm,i}\uparrow, \quad (1)$$

$$B(T_s) = \frac{c_1}{\lambda^5 (e^{(c_2/\lambda T_s)} - 1)}, \quad (2)$$

$L_{sensor,i}$ in the RTE is radiation intensity (W m^{-2} sr^{-1} μm^{-1}) of wave band i measured by satellite sensor. It can be obtained by the gray value of raw images according to Eq. (3)

$$L_{sensor,i} = gain \times QCAL + offset, \quad (3)$$

QCAL is the gray value, *gain* is the gain value in wave band i and *offset* is the deviation value in wave band i. For the two thermal infrared bands of Landsat-8, both *gains* are identical (0.0003342), so are the *offsets* (0.1).

In Eq. (2), $B(T_s)$ is black body radiation intensity gained by Plank radiation function, c_1 and c_2 are radiation constants, whose values are 1.19104356×10^8 W m^{-2} sr^{-1} μm^4 and 1.4387685×10^4 μm K, respectively, and λ is wave length (μm). Eq. (2) can be transferred to Eq. (4),

$$T_s = \frac{K_2}{\ln(1 + (K_1/B(T_s)))}, \quad (4)$$

K_1 (mW m^{-2} sr^{-1} μm^{-1}) and K_2 are preset constants before launch. For TIRS data of Landsat-8, values of K_1 and K_2 are shown in Table 1.

High-resolution Google Earth 2013 is used to identify the types of land cover. Four types of land cover are mapped visually: green land (based on trees and shrubs, and other vegetation are more than 10%), grassland (based on lawn, and other vegetation are