Simulating the influence of microclimatic design on mitigating the Urban Heat Island effect in the Hangzhou Metropolitan Area of China

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Abstract

There are many indications that Urban Heat Island (UHI) is a significant contributor to the increased emission of greenhouse gases due to the increase in energy consumption for cooling during summer. Hangzhou is currently the second hottest city in China, and this paper investigates how the West Lake and the Xixi Wetland areas in the city act as passive thermal comfort systems in improving the outdoor built environment and mitigating UHI effect. Through using ENVI-met, this research evaluates the most effective development scenarios of West Lake and Xixi Wetland area for reliving UHI effect. The energy consumptions for cooling in a typical office building located close to the West Lake and Xixi Wetland under different development scenarios of these two ecological resources are then also compared. It was shown that the average atmosphere temperature and urban heat intensity in urban area increased by more than 0.5°C if the West Lake and Xixi Wetland are both transformed to building construction areas. Moreover, the cooling demand of a typical office building in summer would increase by 10.8% due to ambient temperature increasing by 0.5°C.

Keywords: Urban Heat Island; West Lake; Xixi Wetland; Cooling demand; Hangzhou

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1 INTRODUCTION

Urbanization is defined as a growth in the proportion of a population living in urban areas, and it is affecting many developing countries as they grow and develop economically. According to the latest estimation and projection released by the Population Division, United Nations, since urban agglomerations emerge, 3 billion people or ~48% of the world's population became urban dwellers by 2003 [1]. Although China is still under a comparatively low urbanization level, predictions suggest that the number of Chinese citizens living in urban areas will reach 50% by 2020 [2]. Despite numerous benefits originating from urbanization, rapid urbanization in China is also posing huge pressures on the urban thermal environment.

The phenomenon relating to the atmospheric temperature rise occurring in urbanized area is known as the Urban Heat Island (UHI) effect. This is commonly associated with cities, since surfaces of the built environment are characterized by low albedo, high impermeability and high thermal energy storage capacity. Additionally, urban canyons with reduced sky view factors (SVFs) tend to absorb and re-emit the radiated energy from their surfaces [3]. If UHI countermeasures are incorporated in cities going through urbanization or urban renewal, then the increased population can still be accommodated and the increase in building energy consumptions, especially air-conditioning demand in summer, will be minimized as the decrease in air temperature is minimized.

It is generally agreed that urban expansion reduces the natural underlying surfaces and weakens the curb of the natural ecology on the heat island. Based on the adaptive use of a climate modeling software, ENVI-met (with LEONARDO), developed by Michael Bruse from the University of Bochum, Germany [4], this study selects Hangzhou as a case study to identify how natural ecological resources, such as water space and wetland, play positive roles to improving outdoor built environment and relieving the UHI intensity. This study will compare the consequences of

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different development scenarios referring to the Xixi Wetland and the West Lake on Hangzhou's urban climate. The paper then uses building energy modeling software, Ecotect, to compare the cooling energy consumption results of a typical office placed close to the West Lake and the Xixi Wetland under different development scenarios of these two ecological resources.

2 STUDY AREA

Hangzhou, the capital of Zhejiang Province, lies 180 km southwest of Shanghai (Figure 1). It has a total area of 16 596 km^{2}and forms part of Yangtze River Delta region, one of the most dynamically developed, densely populated and concentrated urbanized areas situated on the east coast of China [5]. In 2011, the population of the Hangzhou Municipality was 8.7 million, of which ∼5.38 million was in the administratively defined urban core [6]. Hangzhou focused on strengthening its central position through developing its technological innovations, distribution of commodities and tourism. In 2011, the GDP of Hangzhou reached US$ 11.3 billion, a rise of 10.1% over the previous year [6]. The city has enjoyed a double-digit GDP growth rate for 21 years in a run. Rapid urbanization process contributes to the formation of UHI and urban climate change in Hangzhou. The past 20 years has witnessed a significant rising of the average temperature in Hangzhou city. Since 2003, up to 40–50 days of continuous high temperature were recorded in the summer of Hangzhou, which made it the second hottest city in China. The reason for choosing Hangzhou as the research area is that even though Hangzhou is a relatively well-developed city in China, there is still plenty of potential for growth. Also from an urban planning perspective, Hangzhou has a large West Lake and Xixi Wetland, which may help mitigate UHI effects.

Figure 1. *The geographic location of Hangzhou.*

Figure 2 shows the land surface temperature of Hangzhou, measured by satellite-based thermal infrared remote sensing technology in 1991, 2000 and 2007. Even in 1991, the UHI situation in Hangzhou can be clearly seen, and the size of UHI area has been expanding rapidly since 1991. According to a previous research, the difference between highest and lowest surface temperatures that occurred in Hangzhou was as high as 15°C [7]. Although it has also been verified by other researchers that the urban green space system in Hangzhou has played a significant role in reducing the air temperature and remitting the UHI effect [8], this study would evaluate the exact temperature reduction effect of its two main ecological resources, the Xixi Wetland and West Lake, in summer in detail. Referring to a previous research, an urban wetland area, such as the Xixi Wetland, is a good regulator of the urban temperature, and the closer it is to the urban wetland, the more effective its regulation of temperature [9].

3 METHODOLOGY

3.1 ENVI-met

In order to understand and solve problems in complex environmental settings effectively, environmental modeling has been used more frequently in scientific research in this area. For this research, the ENVI-met climate model (Version 3.1 Beta 5) developed by the Research Group Climatology at Ruhr-University Bochum in Germany for the microclimate modeling [10] was selected to simulate urban climate parameters, such as air temperature, relative humidity and wind velocity. Mirzaei and Haghighat [11] commented that there are several limitations referring to the field measurement approach to UHI research. These include expensive costs and time-consuming of taking field measurements; making it difficult to achieve an overall picture of UHI pattern and obtaining consistent results. Therefore, this initial study is conducted using the three-dimensional numerical model ENVI-met, which is mainly applied to simulate the surface–plant–air interactions in the urban environment. ENVI-met is based on several principles of fluid dynamics, thermo-dynamics and atmospheric physics and has been widely applied in urban climatology, building design and planning research. The quantitative evaluation has shown that the ENVI-met model is capable of predicting the thermal behavior of different ground surfaces with good accuracy [12–14].

3.2 Ecotect

Autodesk Ecotect is a comprehensive building design software that offers a wide range of simulation and building energy

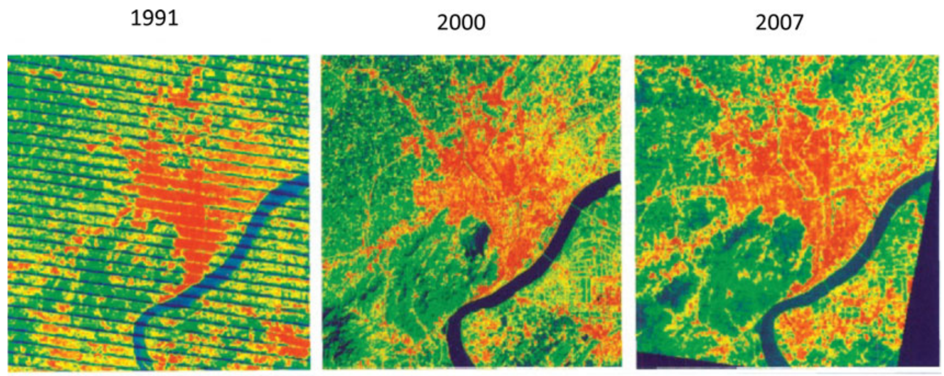

Figure 2. *Land surface temperature of Hangzhou in 1991, 2000 and 2007 [8].*

consumption analysis. It is one of the few tools in which thermal performance analysis is fairly accurate, simple and visually responsive. Its code follows the methodology proposed by Chartered Institute of Building Services Engineers [15]. A previous research compared several different simplified methodologies for building energy performance assessment, and when compared with the results from more detailed tools, the results from Ecotect gave reliable result [16]. Ecotect has been applied in the simulation of building energy performance in much previous research [17, 18] and offers a fast and reliable way to compare the differences in energy consumption for various options. Accordingly, thermal evaluation of a building model was conducted for two different conditions: keeping the West Lake and Xixi Wetland in this current form and converting the West Lake and Xixi Wetland into building construction areas. Ecotect simulation program was used to determine the difference between cooling demands of a typical urban building under these two scenarios.

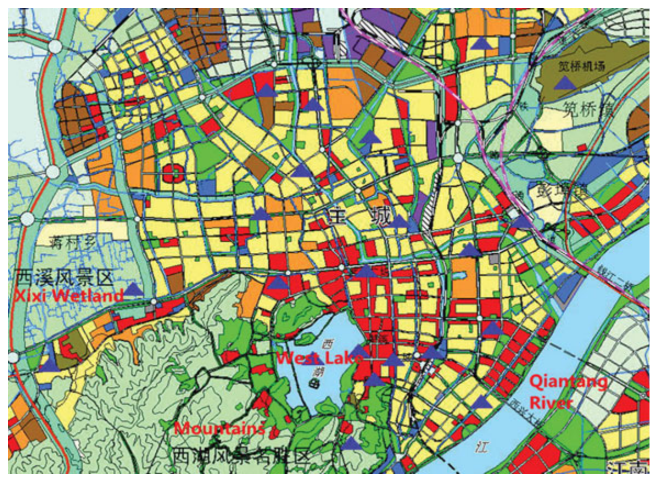

Figure 3. *The General Layout of Hangzhou City.*

4 CASE STUDY

West Lake is a famous tourist lake, locating west of the city center of Hangzhou, with a latitude of 30°15′N and a longitude of 120°10′E. West Lake is a small shallow lake with an average depth of only 1.56 m, and its area is 5.66 km^2. Xixi National Wetland Park is also located in the west part of Hangzhou, only 6 km from the city center and 5 km from the West Lake. Historically, Xixi Wetland covered an area of ~60 km^2 and currently, the overall area of the protected Xixi Wetland is ~11.5 km^2. West Lake and Xixi Wetland are both rare urban ecological resources in Hangzhou. They serve similar functions and complement each other in improving the urban environment. The effects of the West Lake and Xixi Wetland on the urban microclimate in Hangzhou city are investigated in this research. Figure 3 shows the general layout of Hangzhou city and locations of West Lake and Xixi Wetland.

The software simulates the model for a 24-h period, with updated surface data every 60 s, starting from 1200 h, 23 June 2011, designated as the start of summer. The settings to run the simulation are shown in Table 1. The thermal performance of the building system is defined by the indoor temperature and the heat transmission through the walls and roofs. In addition, the albedo of walls and roofs are set. The most important part of simulation conditions are the environmental parameters, such as initial outdoor temperature, wind speed and relative humidity. A user-specified area input file defining the three-dimensional geometry of the study area is required for the simulation. The file would include geo-coded building dimensions (e.g. width and height), soil (e.g. type and texture), surface (e.g. concrete or water) and vegetation types. However, since ENVI-met is limited to simulate at micro-scale, the whole area of Hangzhou is perhaps too large for it to model completely. Thus, the model used in this study focuses on an area of Hangzhou around the West Lake and Xixi Wetland.

5 RESULTS

5.1 Temperature

According to the input conditions listed in Table 1, Figure 4 reveals an obvious heat island in Hangzhou urban area. The maximum UHI intensity in Hangzhou city center is up to 4.0~4.5°C and gradually weakened from the city center to the

Table 1. *Selected input parameters for ENVI-met base simulation.*

Category	User input during simulation
Wind speed in 10 m above ground	2 m/s
Wind direction (0 = N; 90 = E; 180 = S; 270 = W)	135
Mean roughness length of study area	0.2
Specific humidity in 2500 m	9 g water/kg air
Relative humidity in 2 m	40%
Initial atmospheric temperature	308 K
Fraction of low clouds (x/8)	2
Fraction of medium clouds (x/8)	4
Fraction of high clouds (x/8)	2
Soil inputs	
Initial soil temperature at upper layer (1–20 cm)	313 K
Initial soil temperature at middle layer (20–50 cm)	315 K
Initial soil temperature at lower layer (below 50 cm)	317 K
Relative humidity upper layer	40%
Relative humidity middle layer	45%
Relative humidity lower layer	50%
Building inputs	
Building interior temperature	298 K
Mean heat transmission of walls	1.94 W/m^{2}K
Mean heat transmission of roofs	6 W/m^{2}K
Mean wall albedo	0.2
Mean roof albedo	0.3

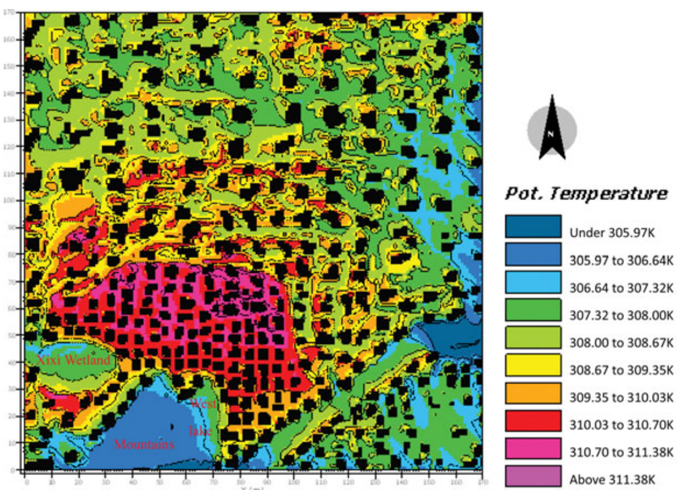

Figure 4. *Simulated temperature distribution in Hangzhou city centre at 13:00 23rd June 2011.*

surrounding areas. It can also be seen that the greater the building density, the more easily the heat gathers and the greater the intensity. Temperatures are relatively lower in areas concentrated with vegetation and water surfaces, such as the XIxi Wetland, West Lake and Qiantang River. Moreover, wind flow is bound to spread the cold air in these areas, producing cooling effect on their surroundings.

5.2 Relative humidity

Figure 5 shows the relative humidity distribution in Hangzhou city center; there is a phenomenon that the relative humidity in urban area is ∼20% lower than rural places, which is normally called the Urban Dry Island (UDI) effect. It can be generally agreed that the UDI effect is commonly accompanied by UHI situation due to the rapid urbanization process. The lower urban humidity can be ascribed to reduced urban evapotranspiration and enhanced urban turbulence, which results in the efficient upward diffusion of near-surface moisture and the entrainment of drier air from higher areas.

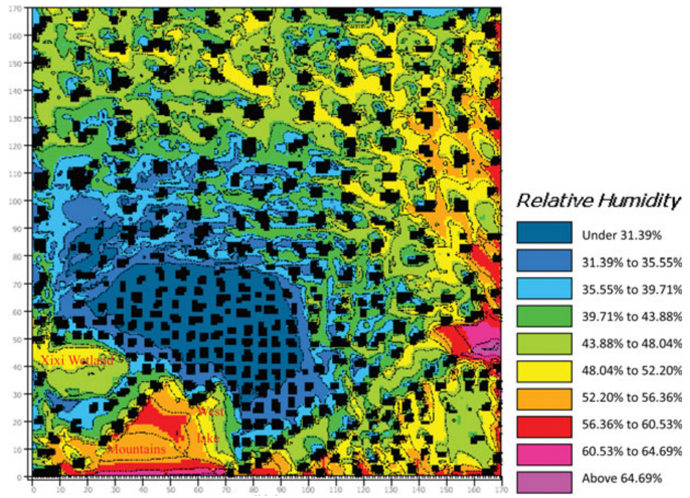

Figure 5. *Relative humidity distribution in Hangzhou city centre at 13:00 23rd June 2011.*

5.3 Wind speed

As Figuerola and Mazzo [19], and Kidder and Essenwanger [20] demonstrated, wind speed is one of the most significant meteorological parameter that influence the development and the intensity of the UHI effect. Figure 6 shows the wind speed distribution at 0, 10 and 30 m height in Hangzhou city at 13:00 on 23 June 2011. The prevailing wind direction is southeast in Hangzhou during summer period. On the basis of the comparison in Figure 6a–c, it is obvious that the wind speed increases with height as building constructions cause obstructions to the flow of wind and modifies the encompassing wind environment. In general, mean urban wind speeds are consistently 20–30% lower than rural places, especially during the day [21]. In this model, the wind speed in urban center area is roughly 25% lower than surrounding area.

5.4 Temperature comparison

West Lake and Xixi Wetland, as two natural underlying surface, are both full of water and vegetation. Apart from the ability of vegetation to lower surface temperatures by releasing water to the environment through evapotranspiration process, water space with great albedo can reflect the solar radiation effectively to relieve the UHI effect. In order to find out the impact of West Lake and Xixi Wetland on UHI situation in Hangzhou city center, the research evaluates the scenarios if they are transformed into building construction areas. Figure 7a shows the situation of West Lake

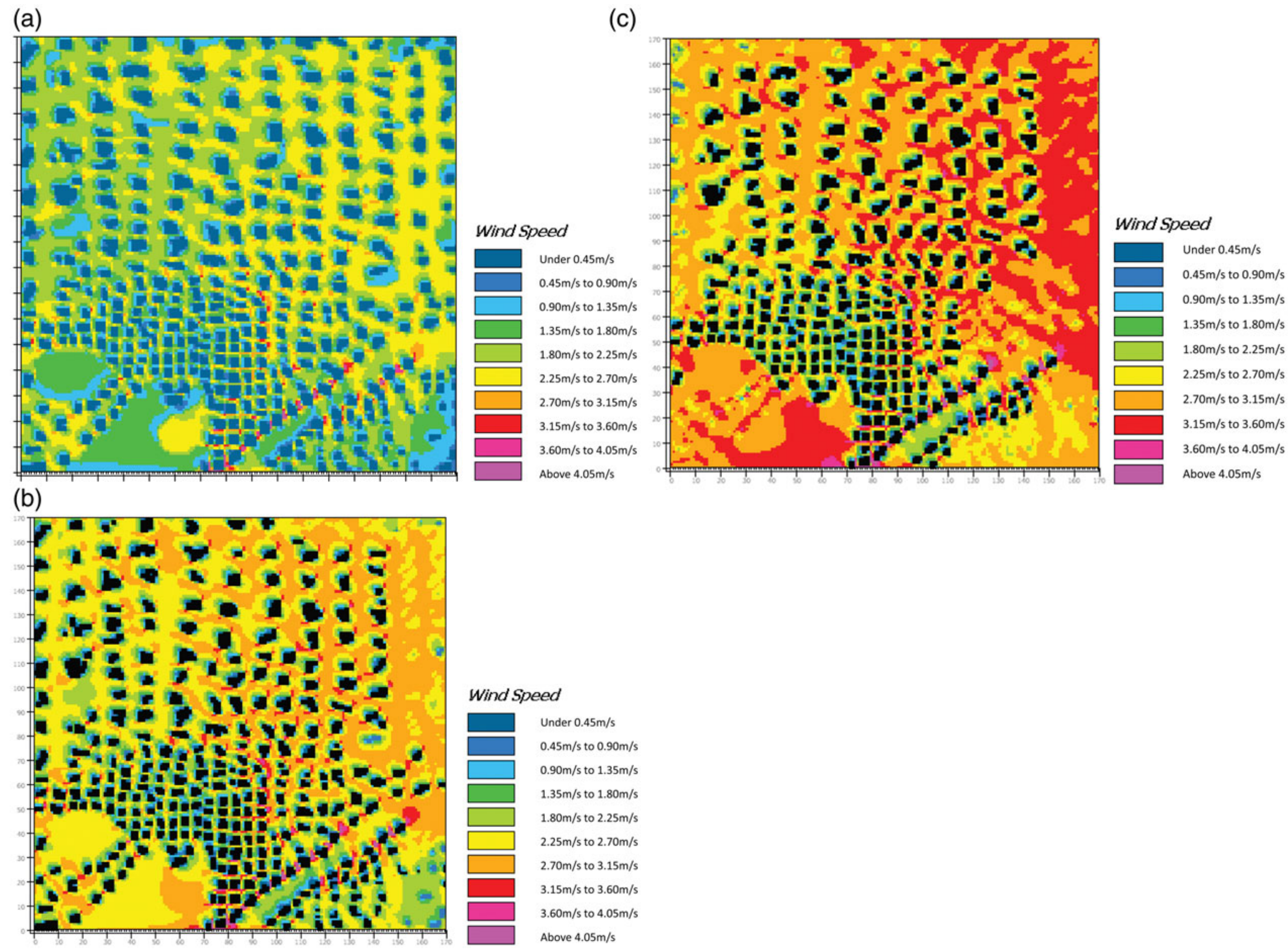

Figure 6. *Wind speed distribution at (**a**) 0m, (**b**) 10m and (**c**) 30m height in Hangzhou city centre at 13:00 23rd June 2011.*

and Xixi Wetland as they are; Figure 7b shows the situation that the West Lake is transformed into building construction area; Figure 7c shows the situation that Xixi wetland is transformed into building construction area and Figure 7d shows both West Lake and Xixi Wetland transforming into building construction area.

According to the comparison, it can be seen that the average atmospheric temperature or the UHI intensity in general urban area will be increased by ~0.5°C roughly if West Lake and Xixi Wetland are transformed into building areas. It seems that these urban natural ecological sources do not relieve the UHI intensity in the whole city significantly but mainly affect the area where close to natural ecological sources.

6 DISCUSSION

6.1 Impacts of West Lake and Xixi Wetland on UHI

Urban expansion reduces the natural underlying surface and weakens the curb of the natural ecology on the heat island. West Lake and Xixi Wetland are two types of underlying surfaces containing a large amount of water by nature. The radiation process between the atmosphere, vegetation and soil surface, exchange of sensible and latent heat, and heat transfer of thermal conduction between soil and soil pore space occurring in the energy conversion may all directly or indirectly affect the climate. Amongst these radiation processes, their cooling effect directly or indirectly affects the surrounding climate, which is conducive to improving the microclimate of local urban areas and weakening the UHI effect.

However, in this case even with the effect of West Lake and Xixi Wetland, the average UHI intensity is only reduced by 0.5°C, which is far below expectation. The most significant reason for the reduced effect of these two natural ecological sources is the reduced wind-induced convective heat transfer between natural sources and urban construction area. Notably, according to Memon and Leung, 1 m/s increase in wind speed could decrease the UHI intensity by 1.9 K [22]. As Figure 6a–c displays, the wind speed in urban area is relatively lower so that the convective heat transfer in building constructions is less effective. The wind speed at 10 meter above the ground in the

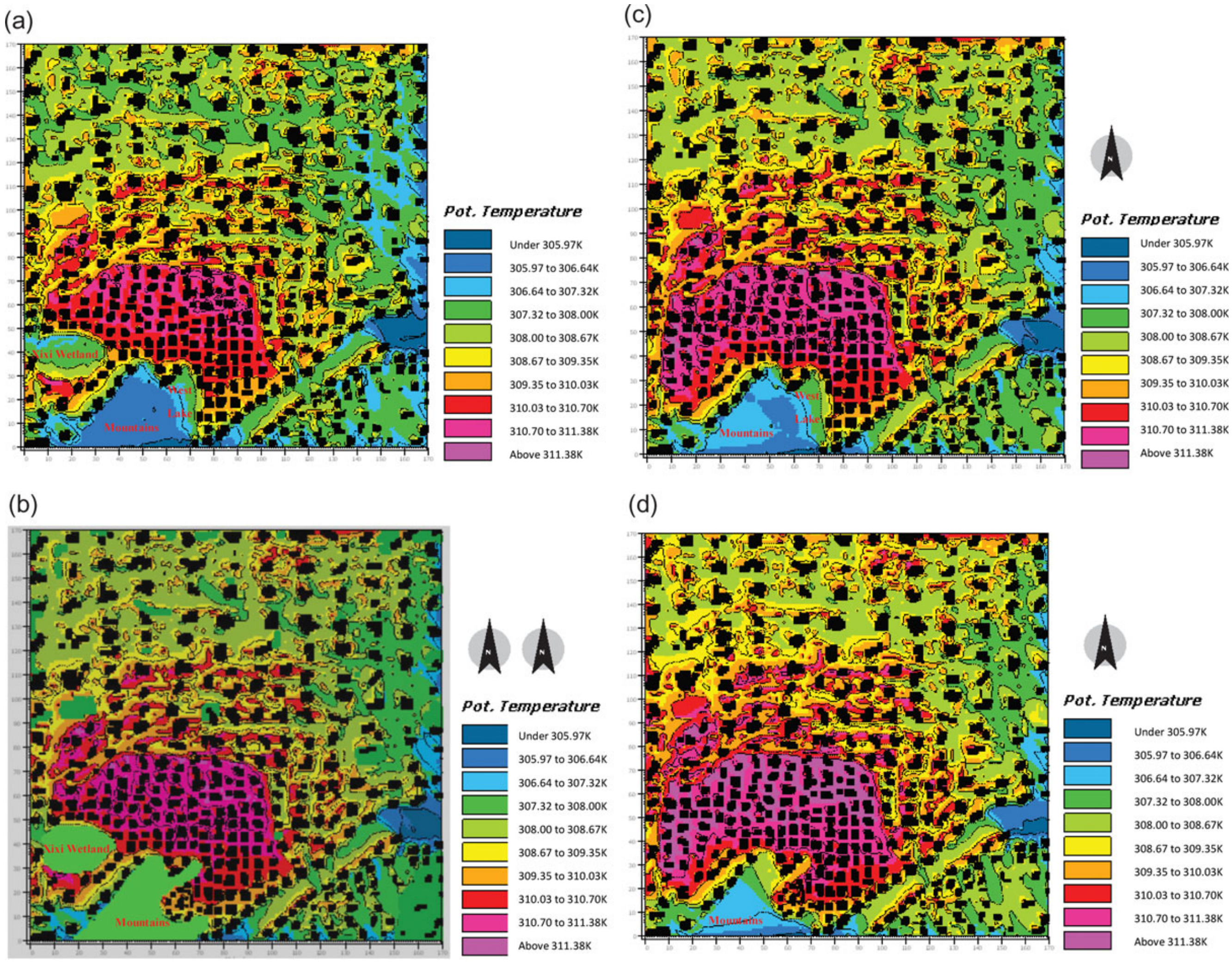

Figure 7. *(**a**) Xixi Wetland and West Lake before transformation. (**b**) After transformation of West Lake into building construction area. (**c**) After transformation of Xixi Wetland into building construction area. (**d**) West Lake and Xixi Wetland transformed into building construction area.*

prime model is set as 2m/s. If the wind speed increases to 4m/s, the average air temperature appears to decrease by $\sim$1.5°C and the UHI situation is also relieved more significantly, as Figure 8a and b displays.

The impact of wind speed on UHI can be also shown by the vertical variation of the UHI intensities. As Figure 6a–c shows, the wind speed at 30 m height is about twice greater that that on the ground. As a result, the UHI intensity at the bottom of the urban canopy was significantly higher than that on the top of the urban canopy, as Figure 9a and b displays.

According to the comparisons mentioned above, it is clear that there is a gradual decrease of UHII with increasing wind speed in urban area. Many studies have shown that wind flow characteristics are greatly affected by the building configurations and ambient wind directions [23]. Furthermore, urban planners and designers should consider gaps between adjacent buildings and arrangement of buildings, because for a given building height, larger gaps and identical arrangement induce more wind in urban canyons, thus improving ventilation process and relieving UHI effect.

The prevailing wind direction is southeast in Hangzhou during summer days; nevertheless, both West Lake and Xixi Wetland are in the southwest part Hangzhou urban area. The southeast wind is not effective in transporting the cool air generated in these natural sources, especially the West Lake, to the urban area. Furthermore, the cooler air from the Qiantang River also cannot be blown to the urban area either, because the buildings on the northeast side of the river are highest and block the cool wind into the urban area. Figure 10a and b shows the case where the wind direction changes to southwest and the comparison with the prime case. It is clear that the shape of UHI changes. Although the general situation of UHI has not been mitigated, the building area at the northeast side of West Lake is cooled significantly by the wind from West Lake. As the southeast prevailing wind direction cannot be easily altered, one possibility to mitigate the effects of UHI is to

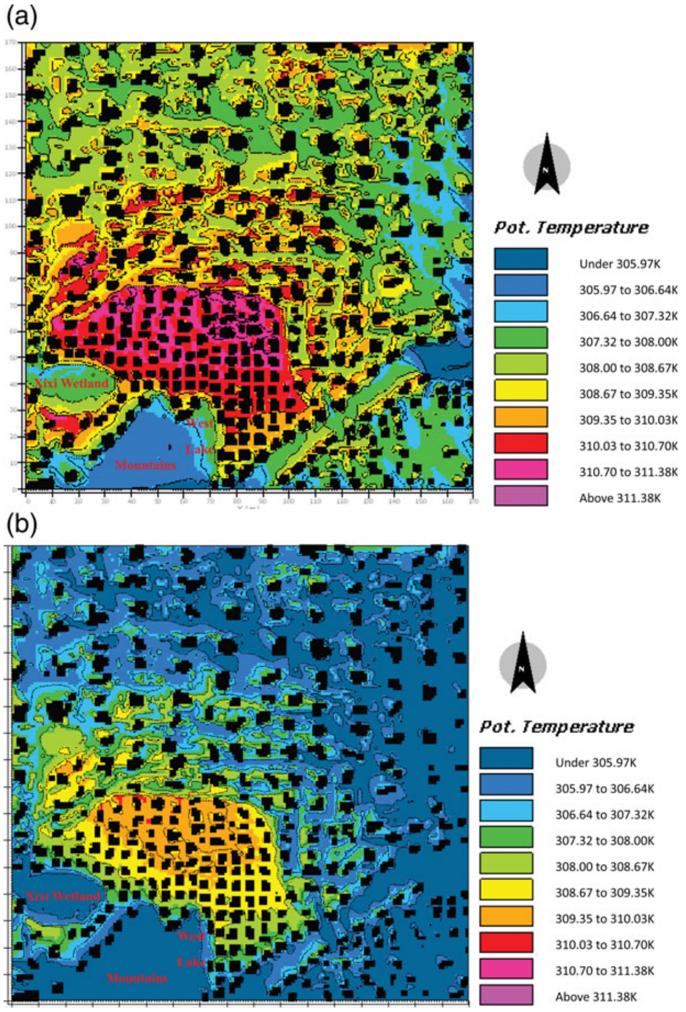

Figure 8. *Temperature distributions when wind speed is (**a**) 2m/s and (**b**) 4m/s at 13:00 23rd June 2011.*

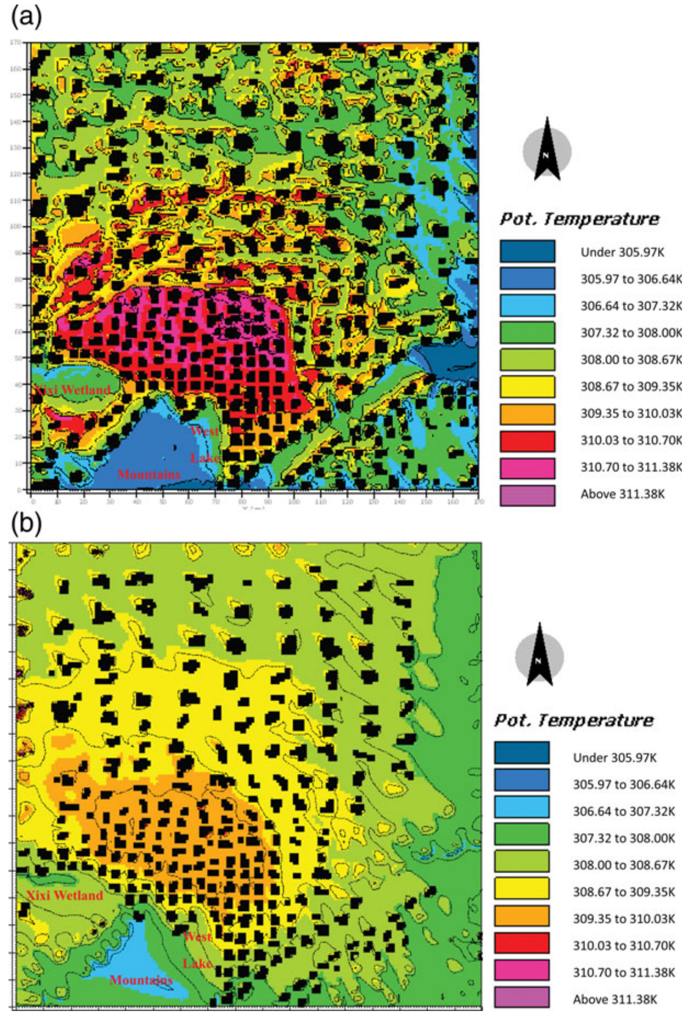

Figure 9. *Temperature distributions at (**a**) 0m and (**b**) 30m height in Hangzhou city centre at 13:00 23rd June 2011.*

build in some water spaces at the southeast part of dense urban area in Hangzhou.

However, the gap between buildings also relates to another variable, the SVF, which is an important indicator of the magnitude of urbanization of a city. Figure 11 shows that an area with low SVF can be normally recognized as urban area where UHI effect is significant. Nevertheless, the impact of SVF on UHI is quite complicated. In principle, during nocturnal periods, reductions in SVF lead to an increase in UHI. This is because dense infrastructure in some developed areas with low SVF cannot easily release long-wave radiation into the open sky, and this trapped heat contributes to the UHI effect. During daytime, especially during peak summer clear sky days, increases in SVF will most likely lead to an increase in UHI, due to the strong solar radiation reaching on the urban construction surface. However, during cloudy days in late summer when the intensity of solar radiation is fairly low, UHI may tend to decrease despite increases in SVF. It is because the long-wave radiation cannot be trapped in large open area where the heat can be dispersed quickly by strong wind in late summer. As a result, larger SVF is widely recommended for urban planning process to relieve the UHI effect.

6.2 The change of cooling demand of the typical urban building in summer

According to the ENVI-met simulation result, the average ambient air temperature of urban area would increase by 0.5°C if West Lake and Xixi Wetland are transformed into building construction areas. Ecotect software was applied to evaluate the impact of the air temperature increase on the cooling demand of the designed building in summer days. The reference weather data file of Hangzhou is downloaded from Energy Plus webpage. Figure 12 shows the appearance of the urban building model designed in Ecotect. Table 2 displays the material descriptions of the simulated urban building and Table 3 lists the average monthly temperature value in reference and the modified weather data files. Other weather data parameters were kept same as the reference values.

In this case study, cooling demand of urban building in summer is simulated to evaluate the impact of the temperature

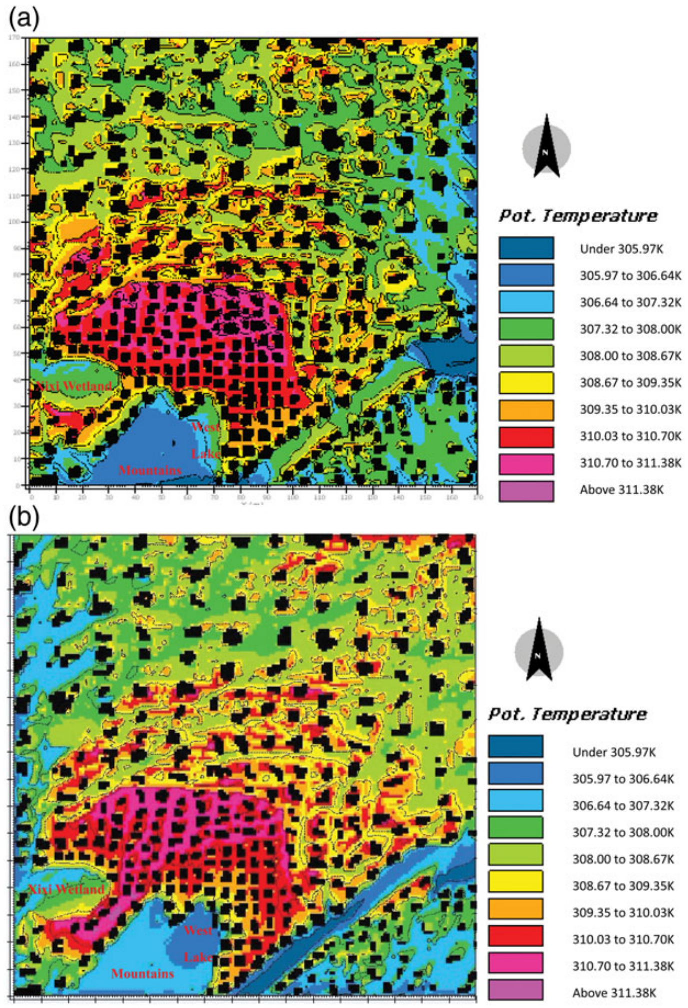

Figure 10. *Temperature distributions when wind direction is (**a**) southeast and (**b**) southwest at 13:00 23rd June 2011.*

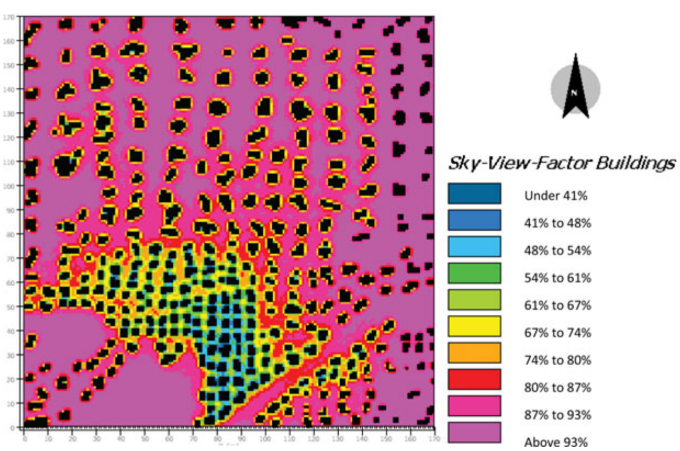

Figure 11. *Sky view factor distribution in Hangzhou city centre.*

increase of 0.5°C on the cooling energy consumption of the designed urban building, as Figure 13 illustrates. If the ambient temperature increases 0.5°C, the total cooling demand of the urban building is ∼41 KWh/m^2, which is 10.8% higher than the value that is based on the reference weather data file. During the two hottest months, July and August, the increase in cooling demand of this specific house building is ∼2500 KWh, which is much higher than the value in other months. Moreover, it is generally agreed that the actual UHI intensity of Hangzhou city center is higher than 0.5°C in summer hot weather [24]. For urban buildings in Hangzhou where the cooling load dominates, the higher air temperature that is associated with urban areas will result in higher energy consumption. The minimum total

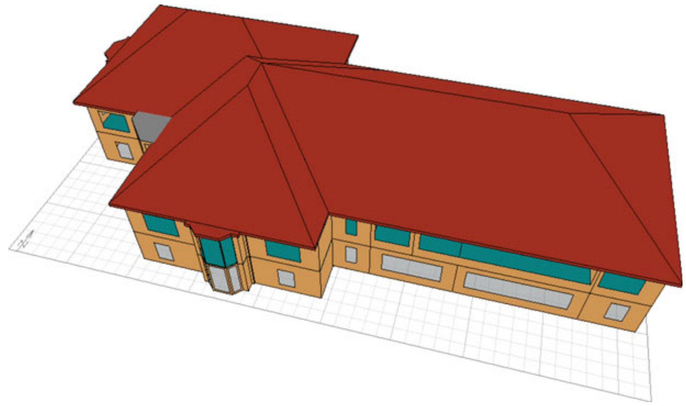

Figure 12. *The model of designed urban building.*

Table 2. *Material description for the case study building.*

Material description	U-value (W/m^2 K)	Admittance (W/m^2 K)
Brick plastered wall	2.23	4.87
Window: 6-mm clear float glass metal frame	6.0	6.0
132-mm clay tiled roof	3.1	3.1
162-mm tiled floor	0.8	6
Wooden door	2.36	3.9

Table 3. *Average monthly temperature value in reference and altered weather data files.*

Months	Average temperature Reference weather data (°C)	Altered weather data (°C)
January	5.2	5.7
February	6.6	7.1
March	10.7	11.2
April	16.3	16.8
May	21.2	21.7
June	24.8	25.3
July	27.5	28.0
August	28.2	28.7
September	24.1	24.6
October	19.1	19.6
November	12.6	13.1
December	6.5	7.0

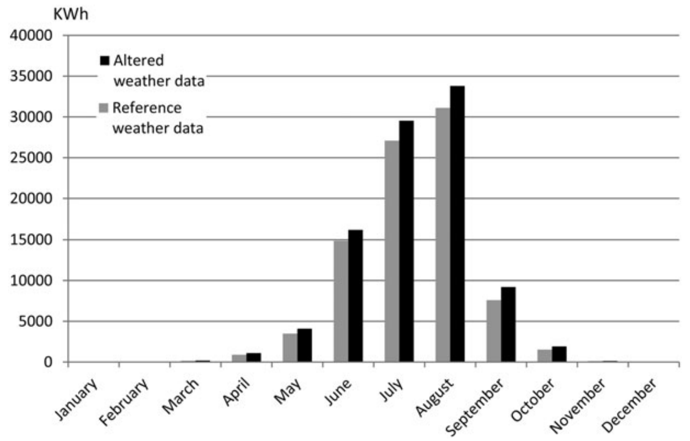

Figure 13. *The comparison of cooling demands of the designed urban building based on reference and altered weather data files.*

energy demand and CO_2 generation is therefore always found when the building is positioned away from the heat island or near natural ecological sources.

6.3 Limitations of ENVI-met software for this study

The ENVI-met simulation case study shows the UHI situation in Hangzhou city center. In addition to that, it also evaluates the impacts of natural ecological sources and wind speed on UHI intensity. However, after using ENVI-met software, five main limitations of ENVI-met for this study are concluded as follows:

(1) The simplified 1-d atmospheric inflow model restricts the ability to dynamically simulate meso-scale thermal and turbulence exchanges that potentially effect microclimate. It would be problematic if regional weather conditions vary greatly over the model simulation period, but the simulated result from ENVI-met is probably very stable and this is unconvincing,
(2) Building facades throughout the model environment are parameterized with a single mean heat transmission value, which oversimplifies the heterogeneity of the urban environment.
(3) The software is suitable for micro-scale model, but not for macro-scale model.
(4) The lack of horizontal soil transfer within the model potentially affects accurate calculations of soil heat storage.
(5) The weather data file of ENVI-met could not be changed or refined.

Hence, if the ENVI-met software is used for detailed simulation case study, it would be more beneficial to apply other research methods, such as experimental measurement and other simulation software, to reinforce the output of ENVI-met.

7 CONCLUSION

Previous research has shown that with the outward expansion of built-up urban area and the net increase in bare land, both of which have low ecosystem service functions, sustainable development must address the impact of the loss of natural ecological resources due to drastic urbanization in Hangzhou [25]. From this research, it has been demonstrated that protecting and expanding the natural ecological sources is a potential option for lowering urban temperatures. It also shows that the closer to urban natural ecological sources, the more remarkable the regulation on temperature. According to the case study simulation results, if the West Lake and Xixi Wetland are replaced by building constructions, the urban air temperature would increase by 0.5°C. Regarding the urban geometry, the larger gap between adjacent buildings and identical arrangement of buildings is recommended during the urban planning process to increase the wind speed and SVF in urban area, which can lower the urban temperature effectively.

Referring to the impact of UHI situation on cooling energy consumption of buildings in summer, the Ecotect model simulation has shown that for a typical urban building, the cooling demand would increase by 10.8% if the ambient air temperature increases by 0.5°C. As a result, for sustainable urban futures, government in the city-planning process has to make accurate decisions about land-use choices and development patterns.

The main limitation of this research is that the outputs presented in the paper completely rely on simulation software. In order to evaluate the more accurate impact of UHI on the energy consumption of urban buildings, filed measurement of air temperature and other environmental parameters in Hangzhou city is proposed to be used to reinforce the initial findings from this research. Also, the increase of 0.5°C for all 24 h in the weather file for simulation is very crude. More simulation runs could be conducted to see the possible differences for the different hours in a typical summer day.

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