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Urban features at neighbourhood scale to assess and mitigate the heat island in arid Mendoza, Argentina

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ABSTRACT

In arid and hot climate cities, urban heat island (UHI) phenomenon reductions represent a major challenge. Nowadays, climate-sensitive urban planning strategies are useful in order to reduce the UHI in arid cities. The presented study was carried out in the arid Metropolitan Mendoza Area (MMA), Argentina. The study measures the thermal improvement of apply high-albedo's roof materials and analyses its effectiveness in different neighbourhood´s layouts forms. To carry out the study, three low-density neighbourhoods that have analogous urban features but different layouts forms (multi-azimuthal, rectangular and Cul-de-Sac) were selected. Also, the downtown and four MMA´s boundaries points were assessed. The study cases were micro-climate monitored, and the three neighbourhoods were modelled and adjusted with ENVI-met software. The results show that reductions in diurnal air temperatures could be achieved by using cool roofs strategy. These findings validate the researches that indicate that this UHI mitigation strategy has a higher diurnal cooling impact. Regarding the neighbourhood form, the rectangular and multi-azimuthal layouts forms remain cooler. This highlights that suitable urban planning decisions in arid cities could helps reduce the UHI phenomenon and improves the liveability of outdoor and indoor spaces.

Introduction

Global warming and urban development are generating several environmental impacts at different climatic scales. At city scale, urban heat island (UHI) is the most noticeable phenomenon, worldwide observed and measured (Suman et al. 2018; Leal Filho et al. 2017; Tsoka Tsikaloudaki and Theodosiou 2017; Yan and Dong 2015; Mills et al. 2010; Jusuf, Wong and Hagen 2007; Collier 2006; Oke 1982). UHI impacts on outdoor and indoor thermal conditions decreasing thermal comfort and increasing the energy consumption for air condition demand (Salamanca et al. 2014; Lin, Matzarakis and Hwand 2011; Kovats and Akhtar 2008).

Particularly in arid and hot climate cities, reduce the UHI represents a major challenge because of the extreme weather conditions during summertime. In addition, hot climates areas have higher urbanization rates and population growth compared to other climates (United

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Nations 2015). According to *Keitsch (2012)* an unfavourable outdoor and indoor climate can be prevented or mitigated through the application of climate-sensitive urban and building design, which refers to measures that adapt the urban landscape to the site, the region, and the climate. In relating to this, there exists a wide range of strategies to reduce and mitigate the UHI that urban planners could implement. *Kleerekoper, Van Esch and Salcedo (2012)* summarize and cluster the strategies in four categories: (i) built form, (ii) material, (iii) vegetation, and (iv) water.

Regarding the built form many studies suggest that a well-planned neighbourhood, which considers the layout, street and block proportions and orientations can reduce the impacts on the micro-climate (Hu, White and Ding 2016; Jusuf, Wong and Hagen 2007). In this sense, *Middel et al. (2014)* have demonstrated, at neighbourhood scale, that the urban form has a larger impact on daytime temperatures than urban greening. Taking into account the materials, high-albedo urban surfaces are an effective strategy to counterbalance the UHI impacts, particularly in cities with sunny climates, high solar radiation and external air temperature (Baniassadi et al. 2018; Kolokotroni et al. 2018; Santamouris 2014). High-albedo roofs in the southwest U.S. reported a 0.3°C decrease in summertime average ambient temperature in urban areas per 0.1 increases of average albedo of urban surfaces (Santamouris 2014). Also, *Sproul et al. (2014)* reported that cool roofs are the most cost-effective energy saving strategy when it comes to rooftops. According to incorporate vegetation, *Declet-Barreto et al. (2013)*, showed that increasing vegetation have the potential to cool the air by as much as 1.9 °C by modelled air temperatures through the creation of park cool islands in inner-city neighbourhoods in Phoenix. Finally, the incorporation of water bodies and fountains into cities with arid climates is not considered a sustainable planning policy, because of this resource scarcity. *Jenerette et al. (2011)* underscores the paradox of water conservation and UHI mitigation through evapotranspirational cooling in arid regions. The implementation of these strategies depends on the availability for that purpose of natural, economic, industrial, and social resources in each city.

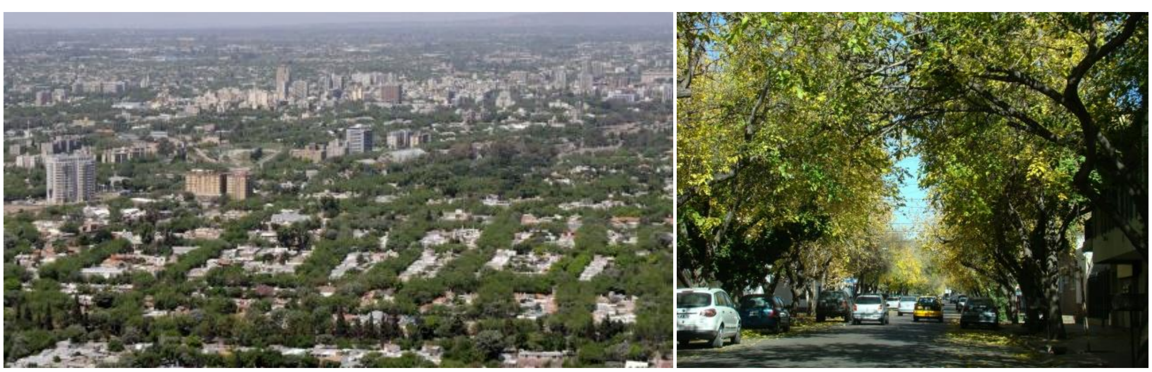

Figure 1. Mendoza Metropolitan Area - Argentina

The presented study was carried out in the Metropolitan Mendoza Area (MMA), Argentina 32º53'S latitude, 68º51'W longitude, 750m.a.s.l. The MMA has most of its streets forested, being this a particular characteristic regarding it arid climate context, see Figure 1. As the street trees are already considered an effective UHI mitigation strategy, evaluate the outdoor air temperatures improvement by taking into account others features at neighbourhood scale is considered a suitable urban planning recommendation. For the exposed, the study aims to analyse the thermal performance by applying high-albedo roofs in three low-density neighbourhoods, which are forested and have different layouts form. Also, analyse if the effectiveness of the strategy dependent on the urban grid form.

Methodology

The method implemented for the present work consists of three main stages.

Study cases

The selected three neighbourhoods have different layout grids —multi-azimuthal, rectangular and Cul-de-Sac— but similar features —houses typology, materials, street trees and LCZ class— that allows contrasting their thermal behaviour. The selection criteria and characterization was described in *Sosa, Correa and Cantón (2017)*. The three neighbourhoods have their streets forested with second magnitude trees, streets widths of 16 and 20m, houses height of 3m, albedo's of 0.2 in roofs, 0.3 in façades, 0.5 as a combined average value between side-walks and streets materials, and LCZ class 6_b (open-low rise class with scattered trees subclass). Also, these neighbourhoods are located in different areas of the MMA around 6.5 and 4.8km distance to the downtown.

In order to analyse the UHI impact in the MMA, four boundaries points (North, South, East and West sectors) and a point in the MMA downtown were monitored. The selected boundaries points are coincident with the MMA urbanization limits, sparsely built areas (LCZ class 9). The study cases are show in Figure 2.

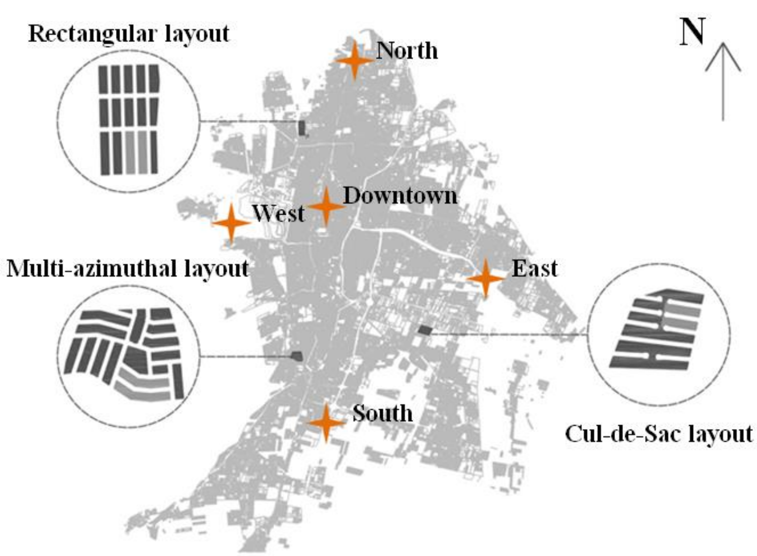

Figure 2. Study cases located in the MMA

Micro-climatic data monitoring

The thermal behaviours were monitored with HOBO® data-loggers (model H08-003-02; measure range -20°C to +70°C; accuracy ±0.7°C at +21°C; resolution 0.4°C at +21°C) set up every 15 minutes. They were installed into a solar radiation shield at 2m height, a total of eight fix-sensors were used simultaneously during the summer period from January 8th to February 6th 2014. The monitored points are presented in Figure 2.

Micro-climate simulation

In a second stage, three urban scenarios were numerically simulated in order to analysed the cool roof´s effectiveness at neighbourhood scale. ENVI-met software version 3.1 (Bruse 2004) was used. ENVI-met requires two main input files: the area input file (.IN file), and the configuration file (.CF file). The .IN file specifies the geometry of the model environment such as buildings, plants or soils in detail. In this study the scenarios were modelled within a horizontal area of 258 × 258m that comprised of 86 × 86 cell grids of 3 × 3m. Each cell grid was 3m in height, and there were 30 such grids (i.e., the spatial height of each model is 90m).

Table 1. ENVI-met input parameters after model adjustment

Meteorological	
Mean wind speed 10 m from the ground (m/s, Airport meteorological station)	2.5
Prevailing wind direction (Airport meteorological station)	140º
Roughness length	0.1
Solar adjustment factor	1.3
Initial atmospheric temperature (K) (University of Wyoming, station 87418 Mendoza)	300
Specific humidity at 2500 m (g/kg-1)	2.8
Relative humidity at 2 m (%)	37
Building	
Indoor temperature (K)	297
Heat Transmission Walls (W/m^{2}K)	2
Heat Transmission Roofs (W/m^{2}K)	0.78
Walls albedo	0.3
Roofs albedo	0.2
Soil	
Initial upper soil layer (0-20 cm) temperature (K)	292
Initial upper soil layer (20-50 cm) temperature (K)	292
Initial deeper soil layer (below 50 cm) temperature (K)	290
Upper soil layer (0-20 cm) moisture content (%)*	20
Upper soil layer (20-50 cm) moisture content (%)*	35
Deeper soil layer (below 50 cm) moisture content (%)*	60

To represent street trees, the "Tb" model was selected from the ENVI-met PLANTS database, which was based on a field survey and observation of the vertical configurations of trees (a height of 10m and LAD between 0.80 and 2.00m²/m³ were used for calculation). Also, the SVF values of each urban canyon where the data-logger was installed were adjusted with those generated by the ENVI-met model. The soils data represent the real condition of the study cases that have concrete streets, side-walks with tiles and grass areas in the patios of the houses. Also, the positions of receptors were designed in this file. To ensure numerical stability and minimize boundary effects that may affect the output data, three (9m) nesting grids were set around the main model area (Morakinyo et al. 2017). The .CF file defines the settings for the simulation to run, for example, the name for the area .IN file, the meteorological settings or the name of the output files. Table 1 shows the .CF ENVI-met input parameters that were used.

Validation of the models and data calibration

A calibration procedure was made for each neighbourhood layout, by comparing the series of air temperature measurements from January 18th with the corresponding simulated values. Then the three scenarios were statistically evaluated using a set of indices that describe the magnitude of the difference between the observation and prediction (R^2, RMSE, MAE and MBE). After made several simulations adjustments the scenarios achieved a good statically accuracy. Based on statistical index values that were accepted in previous ENVI-met evaluation studies, the models can reliably simulate micro-climates (Tsoka, Tsikaloudaki and Theodosiou 2017). The adjustment values for the three models are shown in Table 2.

Table 2. Models adjustment and statistical indicators for validation

	Rectangular	Multi-azimuthal	Cul-de-Sac
MAE	0.5	0.6	0.5
RSME	1.7	0.4	1.1
MBE	-1.0	-0.2	-0.3
R^2	0.91	0.99	0.95

Cool roofs scenarios modelling

With the three adjusted models, the high-albedo material where apply at roofs scale (original value 0.2, improved value 0.7). This albedo material value has a strong reflective capability and potentials to lower surface temperature, so its colour tends to be light (Santamouris 2013; Synnefa et al. 2011). The high-albedo value used follows the recommendations of a previous study conducted in the MMA (Alchapar and Correa 2015). The albedo values of walls and pavements were maintained at same from the original neighbourhood materials (walls 0.3, pavements 0.5).

Results

Figure 3 shows the thermal performance of the four boundaries points (North, South, East and West) and the MMA downtown. The North sector registered the lowest minimum air temperature (21.5 °C). The downtown point registered the coolest maximum air temperature (36.8 °C) and the highest minimum (26.3 °C). These behavioural differences between the boundaries and downtown are a result of several factors, including but not limited to the amount of built-up areas and the anthropogenic heat generation (e.g., transportation and air conditioning use) that exists within a city (Ahmed et al. 2013). In terms of habitability, the downtown behaviour is positive. However, at night, this area suffers from the worst scenario of UHI.

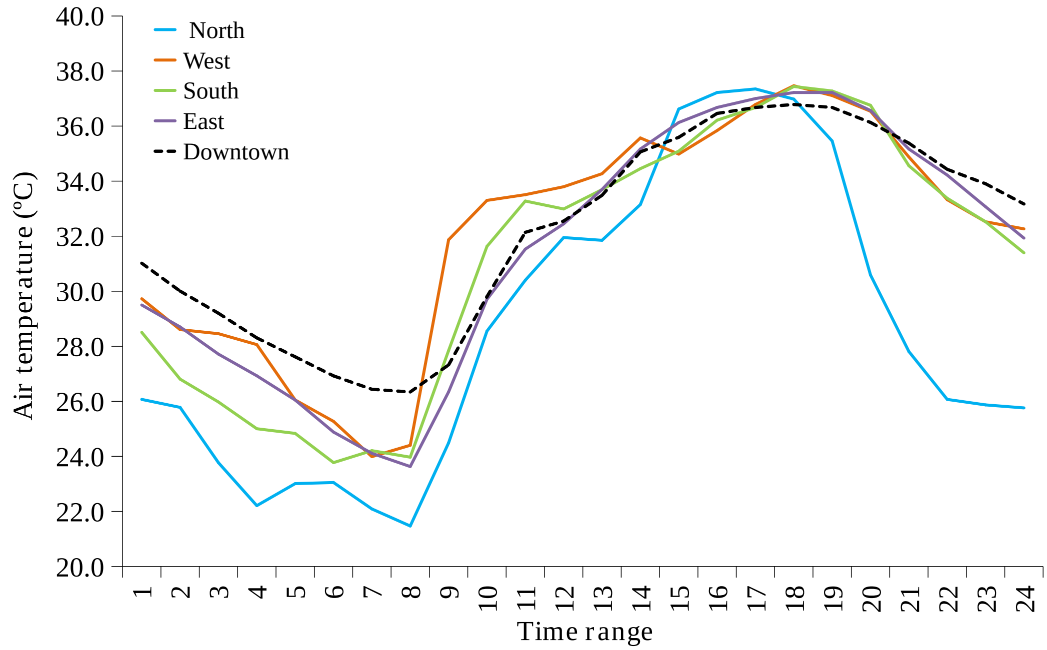

Figure 3. Thermal performance of each monitored point

The monitoring data were used the calibrate the model. Figure 4 and Table 3 shows the thermal performance by applying high-albedos roof in the three neighbourhood layouts. By analysing the impact in each neighbourhood layout we can see that:

- The rectangular layout neighbourhood achieved the lowest maximum and average air temperatures (37.5ºC and 30.6ºC), but the highest minimum temperature (25.1ºC).
- The multi-azimuthal layout neighbourhood achieved the lowest minimum air temperature (23.2ºC), and similar maximum and average air temperatures with the rectangular layout (37.8ºC and 30.9ºC).
- The Cul-de-Sac layout neighbourhood achieved the highest maximum and average air temperatures (38.4ºC and 31.1ºC), and similar minimum air temperature with the multi-azimuthal layout (23.5ºC).
- These observations follow the thermal performance trend of the original neighbourhood, where the rectangular and multi-azimuthal layouts forms remains cooler. Also, the maximum and average air temperatures decrease in all the neighbourhoods but the minimum air temperatures have not significant reductions. These findings are in concordance with researches that have been demonstrating a higher diurnal cooling

performance than the nocturnal cooling performance (Qi et al. 2019; Li and Norford 2016).

Table 3. Thermal performance of the study cases

Study cases	T° maximum (°C)	T° minimum (°C)	T° average (°C)
R.O	38.6	25.4	33.0
R.I	37.5	25.1	30.6
Δ	1.1	0.3	2.4
M.O	39.5	23.2	31.9
M.I	37.8	23.2	30.9
Δ	1.7	0	1.0
C.O	40.8	24.1	32.8
C.I	38.4	23.5	31.1
Δ	2.4	0.6	1.7

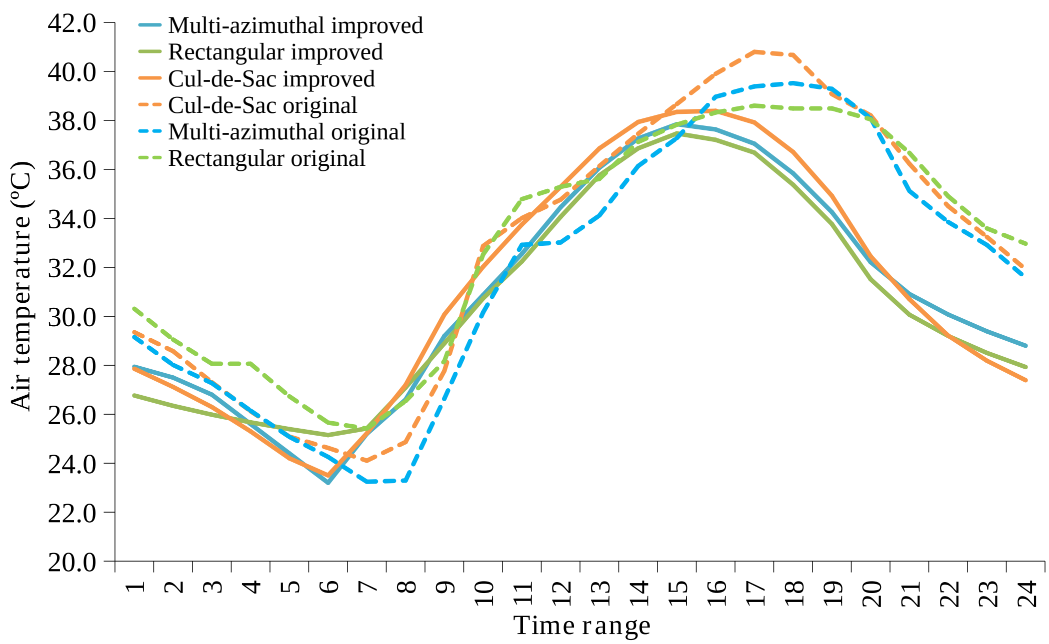

Figure 4. Ambient temperature profile of the study cases

Regarding the relationship between the layout form and the thermal performance, the rectangular neighbourhood achieved the lowest maximum air temperature by the North-South streets orientation (south hemisphere). On the other hand, the minimum air temperature is the highest. This could be because the distribution of the street trees in the canyon.

Conclusions

The study presents and analysed the outdoor air temperature performance of three MMA`s low-density neighbourhoods by applying high-albedo materials at roof scale. Each study case has different layout form but maintain similar other urban features. The study cases were modelled in ENVI-met in order to measure the thermal impact of the application of the cool roof as an UHI mitigation strategy. The results show that air temperatures reductions could be achieved in the daytime. These findings validate the researches that indicate that this UHI mitigation strategy has a higher diurnal cooling impact. Regarding the neighbourhood form, the rectangular and multi-azimuthal layouts remain cooler in both stages, original and improved.

These findings highlight that suitable neighbourhood layouts, that incorporates cool materials, could help to decrease the UHI phenomenon in arid cities. Also in order to avoid this phenomenon extension, cool surfaces should be used in entire city districts. For that, the cool roof application needs to be further analysed in a bigger area of intervention in order to measure the expected temperature improvements. This strategy is feasible to apply in climate-sensitive planning regulations and policies at neighbourhood scale by promoting mitigation measures into new developments as well as during retrofitting and maintenance.

Acknowledgments

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Development and Application of “Shadow Ratio” for Evaluating Urban Thermal and Wind Environment - Take a Site of Xi 'an West Street as an Example

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ABSTRACT

The development of urban economy and society, especially the advancement of urbanization greatly facilitates human life, and also deteriorates the living environment of cities to a certain extent. The urban environment is closely related to citizens’ well-being. Therefore, the continuous improvement of living standards, creating a livable city space environment is particularly important. Urban wind environment and thermal environment are elements of urban microclimate and are playing an important role in optimizing urban living environment. Shadow from the buildings have an important influence on urban microclimate, because it affects the heat and wind environment to a great extent.

This paper proposed the concept of “Shadow Ratio” and its derivative concept of “Continuous Shadow Ratio”, which could be used to indicate the spatial morphology of urban thermal environment and wind environment. The importance of using sunlight shadow to prevent heat in buildings in cold region is analyzed, and the relationship between sunlight shadow and building thermal environment and wind environment is indicated. ENVI-met software is used to simulate and evaluate the urban environment in a 300m×300m scale in the central area of Xi 'an city, calculated the shadow ratio of the site at 7 time points in the day and compares the calculated results with the environmental simulation data, and carried out coupling analysis. This paper developed and demonstrated the application value of “Shadow Ratio” for urban building environment evaluation.

1.Introduction

Cities in cold regions like Xi’an should try to improve the thermal comfort of the urban environment as much as possible in winter and should consider heat prevention in summer. Increasing solar radiation in winter can improve thermal comfort. In summer, shade can be used to reduce the heat at human level. Therefore, the use of shadows in cold regions like Xi’an is of great significance for heat mitigation in summer. Related researches have demonstrated that Shadows are formed when opaque objects block direct sunlight. And shadow in a city may come from (1): the shadow of topography; (2): architectural shadow; (3): the shadow of the vegetation. Shadow has an important influence on the thermal environment and wind environment around the buildings. Cities that are hot in summer can alleviate the heat caused by solar radiation by shading, while cities that are cold in winter can improve the thermal comfort by increasing the sunshine radiation. Shadow plays an important role in improving the urban thermal and wind environment and improving the comfort in summers.

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In the 1990s, Arnfield (A.J) proposed the solar energy utilization coefficient, which represents the potential use of solar energy by a certain urban ground. Givoni.b proposed the shadow coefficient in the microclimate of seville, Spain.

Sunlight shadow and the thermal environment of residential area have a close relationship, which is one of the important factors to deal with the microclimate environment of residential area. Cities in hot-summer and cold-winter zone are sunny and have strong radiation, causing the outdoor temperature is higher. If we can make full use of the shadows generated by buildings in the planning and design process of residential districts to reduce the direct sunlight on the ground and external walls of buildings, it will be conducive to improve the thermal environment and save the energy consumption of air conditioning buildings.

The purpose of this paper is to propose a concept of “Shadow Ratio” to describe space environment. Numerical simulation is used for demonstrating this concept and proving the relationship between shadow ratio and urban environment such like thermal environment and wind environment. Considering that the concept of shadow ratio lacks time universality as an indicator of urban morphology, in order to better apply this concept to the study of urban microenvironment, the concept of "Continuous Shadow Ratio" is further proposed. The main research method used in this paper is to simulate the 24-hour climate of summer solstice day (June 21) in an area near the central area of Xi’an city with ENVI-met software then put the results, such as temperature, wind speed together with the shadow ratio to make a coupling calculation to prove that the shadow ratio is valuable for the study of urban thermal and wind environment.

2. Research Methodology

The area of 300m×300m in the central district of Xi'an is selected for simulation and analysis. Summer solstice day of 2017 (June 21) is selected, and the 24-hour thermal environment and wind environment simulation results are carried out by using the environment simulation software which is called ENVI-met to complete the 24 hours simulation. A site and building model were built in Sketchup software to simulate and calculate the shadow ratio of 7 time points in the day on 21 June. The data of temperature, wind speed and shadow ratio in the simulation results were analyzed by linear regression, and then the conclusion was drawn.

In order to better apply this concept as an indicator in the study of urban morphology, the author calculated the "Continuous Shadow Ratio" of the region. According to the regulations of Japanese building standards on building shadow, the author uses Tianzheng software to analyze the sunshine in this area from 8:00 a.m. to 4:00 p.m. on the winter solstice day. The area of continuous shadow area exceeding 4 hours is regarded as "continuous shadow area". The result of "continuous shadow area" is obtained by calculating the data of "continuous shadow area" and the floor area of the building, the total area of the study area, etc.

ENVI-met is a software for microclimate simulation of the scale of city blocks, which can be used to build an overall three-dimensional and non-static model, so as to simulate the interaction of surface-plant-air. Therefore, it is often used to simulate the environment of the city. It is designed to have a typical horizontal resolution of 0.5 to 5 meters and a microscale simulation of typical time frames of 24 to 48 hours with a time step of 1 to 5 seconds.

3. Definition and Calculation of the Shadow Ratio (SR) and Continuous Shadow Ratio (CSR)

3.1 Definition of Shadow Ratio (SR)

The ratio of the total area shaded by buildings or other obstructions in the area and the floor area of the building to the total area of the site is called the shadow ratio. And the calculation formula is shown as follows:

$$\mathrm{SR} = \frac{A_S + A_B}{A}$$

Where SR represents the shadow ratio, A_S represents the shadow area, A_B represents the floor area of the building, A represents the total area of the study area.

3.2 Definition of Continuous Shadow Ratio (CSR)

Because the concept of shadow ratio varies with time and in many cases a universal indicator is needed to evaluate urban morphology. In order to better apply this concept as an indicator to the study of urban microclimate, the author proposed a derivative concept of "Shadow Ratio": "Continuous Shadow Ratio". According to Article 56 of the Building Standard Law of Japan, the allowable hours of shadows in different land-use zones are indicated by shadow restrictions, to restrict the building heights for different neighborhoods. The standard time for environmental shadow evaluation is on the winter solstice, from 8 am to 4 pm. On average, 2-hour shadows are restricted 10 m away from buildings, and 4-hour shadows are restricted 5 m away from buildings. In this paper, 4-hour shadows are taken as the calculation criteria. Taking 8 am to 4 pm. on the winter solstice as the calculation range of shadow area, the ratio of the total area shaded by buildings or other obstructions in the area for more than 4 hours and the floor area of the building to the total area of the site is called the continuous shadow ratio. And the calculation formula is shown as follows:

$$\mathrm{CSR} = \frac{A_{CS} + A_B}{A}$$

Where CSR represents the continuous shadow ratio, A_{CS} represents the shadowed area lasting more than 4 hours from 8 am to 4 pm on winter solstice, A_B represents the floor area of the building, A represents the total area of the study area.

3.3 Study Area and the Model

The central area of Xi'an city was selected as the research area, and the map is shown in Figure 1. Xi'an is located in the cold region of China with cold and dry winters and the summers are hot with large daily temperature range of which the sunshine is relatively abundant. Therefore, the study of urban building shadow plays an important role in summer cooling and improving human comfort. And as shown in Figure 1, according to the Baidu map information, a simplified site and building model is established in Sketchup software to facilitate calculation and environmental simulation. The highest building in the area is 64m, and the lowest building height is 4m. Moreover, the plane form is diversified, including enclosed, semi-enclosed and open space.

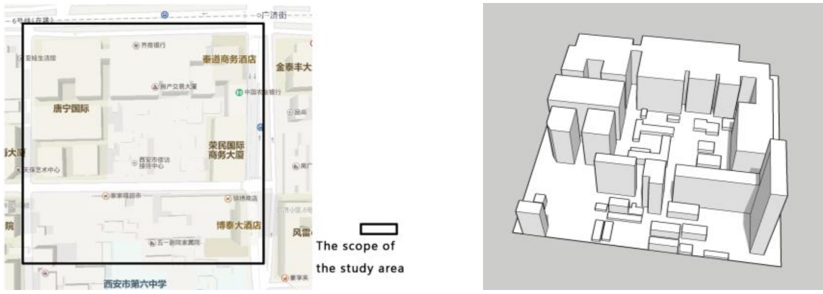
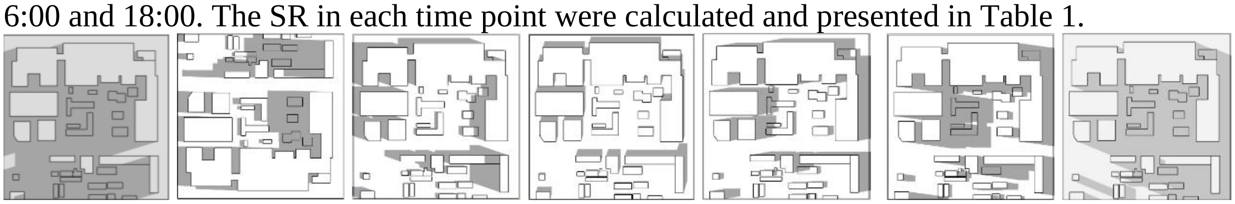


FIG 1. The Baidu map (left side) and the simulation model (right side) of the study area

3.4 Calculation of the Shadow Ratio (SR) and the Continuous Shadow Ratio (CSR)

The effect of shadow on urban environment is mainly reflected in the cooling effect during the summer heat period. Therefore, the summer solstice day (June 21, 2017) was selected as a typical example for the study in this paper. In order to make a comprehensive analysis of the whole summer day, SR in every two hours from 6:00 (7 time points) were calculated using Sketchup software. Then the plane graphs were exported separately to obtain the shadow distribution results as shown in Figure 2. As shown in the shadow simulation results, the minimum shadow area was observed at 12:00, and the largest shadow areas were observed at 6:00 and 18:00. The SR in each time point were calculated and presented in Table 1.



6:00 8:00 10:00 12:00 14:00 16:00 18:00

FIG 2. Shadow simulation results

Table 1. SR in 7 time points in June 21, 2017

Time	**6:00**	**8:00**	**10:00**	**12:00**	**14:00**	**16:00**	**18:00**
SR	0.85	0.68	0.62	0.54	0.60	0.69	0.82

The sunshine from 8 am to 4 pm on the winter solstice of 2017 was simulated by Tianzheng software. As shown in Figure 3, the area with less than 4 hours of sunshine in the figure can be considered as the area covered by shadows for more than 4 hours, thus selecting elements in Photoshop and calculating the shadowed area lasting more than 4 hours from 8 am to 4 pm on winter solstice day, floor area and the total area of the study area , so as to calculate the continuous shadow ratio (CSR). Therefore after calculation the CSR in this area is 0.87.

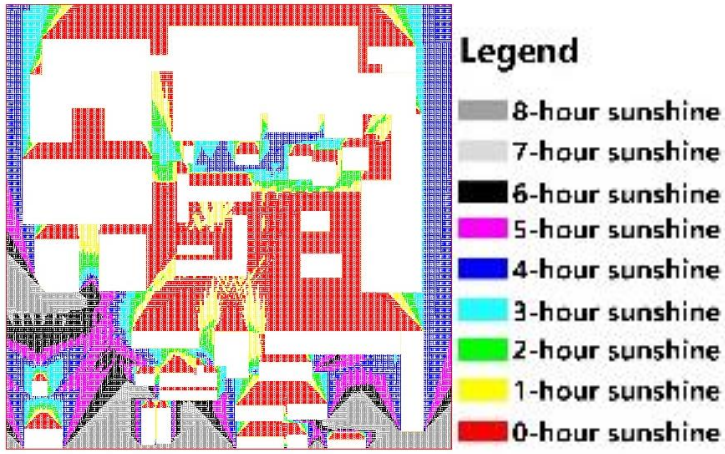


FIG 3. Shadow simulation results

3.5 Modeling and Setting of Boundary Conditions

The basic setting of ENVI-met model : x-grids of 60, y-grids of 60, z-grids of 30, the grid size of X and Y axes are 5m and the Z axes is 7m. The actual height of the buildings and the distribution of vegetation are measured by Baidu map street view and used in this simulation model. The simulation started from 18:00 at June 20, 2017, reserved six hours for the "preheating" of model, the total simulation time is 30 hours. Practical and effective data is from 0:00 to 24:00 of June 21, 2017. Initial temperature and humidity values for simulation was set according to the actual conditions from the Shaanxi provincial meteorological station. The highest temperature was 32 ℃ occurred at 15:00 and the lowest temperature was 23 ℃ occurred at 5:00. The highest humidity was 75% at 19:00, and the lowest humidity is 35% at 17:00.

In order to carry out the analysis more accurately, 3 measuring points in the study area were selected. The 3 location points are presenting enclosed urban form that is surrounded by buildings (A), semi-enclosed urban form with buildings in the north and south side (B) and open urban form with no buildings close by (C). (FIG. 4)

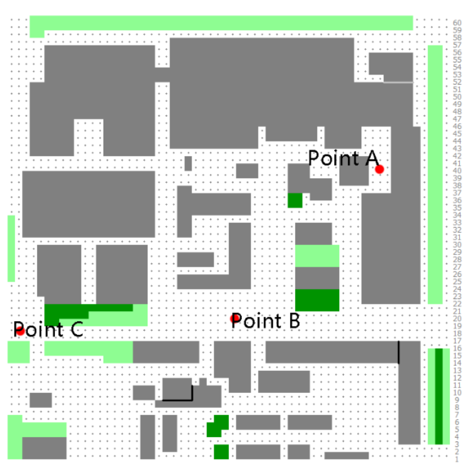


FIG 4. Image of simulation model and the location of measuring points

4. Research Results

4.1 Environmental Simulation

The simulation results of the temperature distribution are shown in Figure 5. Simulation results show that the whole day's temperatures range from 23.04 ℃ to 32.38 ℃. The lowest temperature appears at 6:00 while the highest temperature appears at 16:00. The whole day's temperature changes from 6:00 to 16:00 showed an upward trend, and after 16:00 the temperature began to decrease.

The simulation results of wind speed distribution are shown in Figure 6. The simulation results show that the wind speed ranges from 0.41m/s to 4.41m/s. The lowest wind speed is below 0.39m/s occurring from 12:00 to 18:00. And the highest wind speed is 3.86m/s appearing at 6:00. The whole day's wind speed changes from 6:00 to 16:00 showed a downward trend and increased from 16:00 to 18:00.

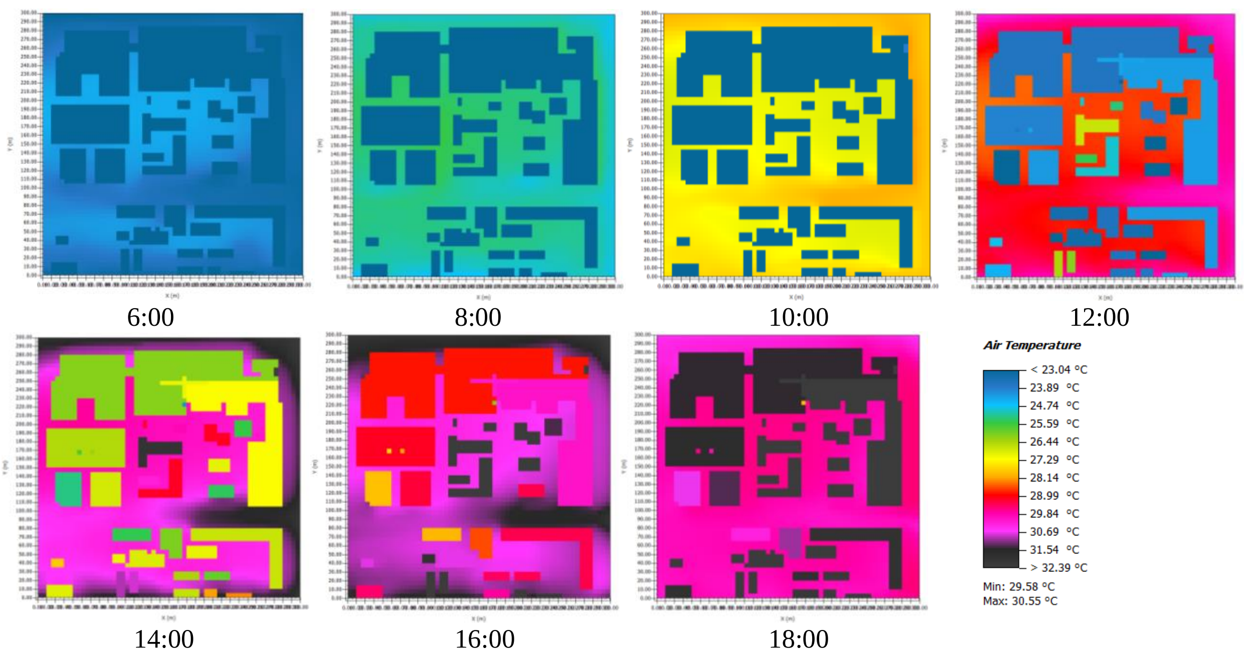
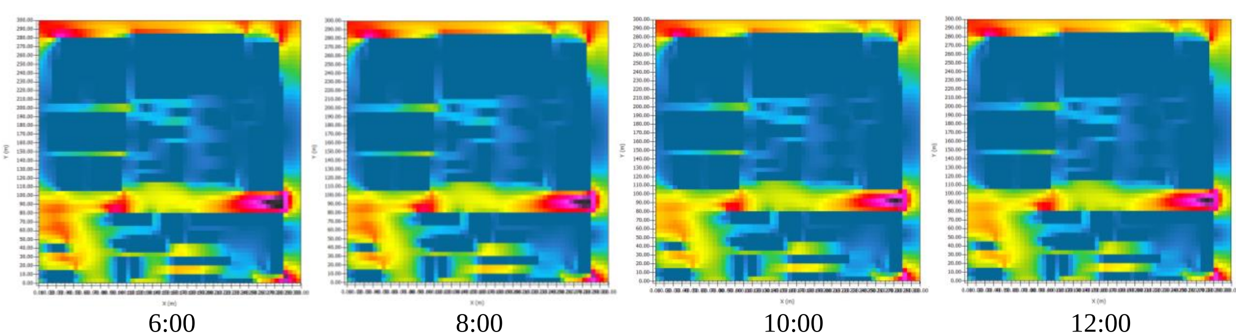


FIG 5. Temperature distribution at 1.5m height in June 21, 2017



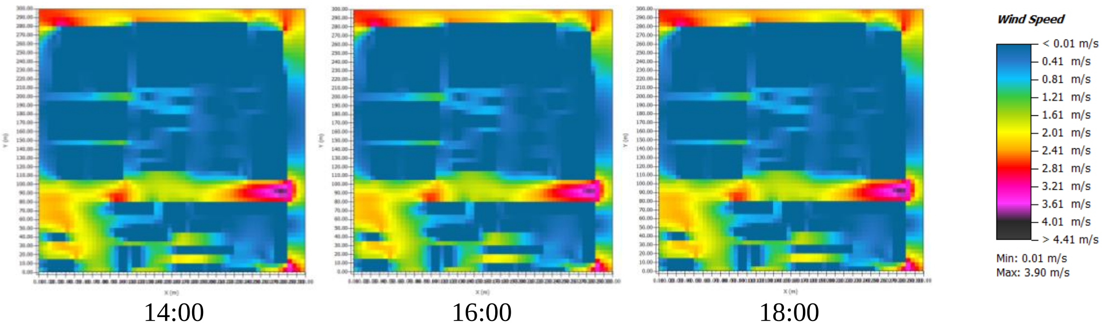


FIG 6. Wind speed distribution at 1.5m height in June 21, 2017

4.2 Linear Regression Analysis of SR and Urban Environments

As shown in Figure 7, the three measuring points all reached the maximum shadow ratio at 6:00 and 18:00 and 6:00 was also the lowest temperature. The lowest shadow ratio occurs at 12:00, the highest temperature appears at 16:00. The lowest shadow ratio does not exactly match the highest temperature but it can be seen that the shadow ratio and temperature does exist a certain negative correlation. The correlation between SR and temperature need further correlation analysis to prove.

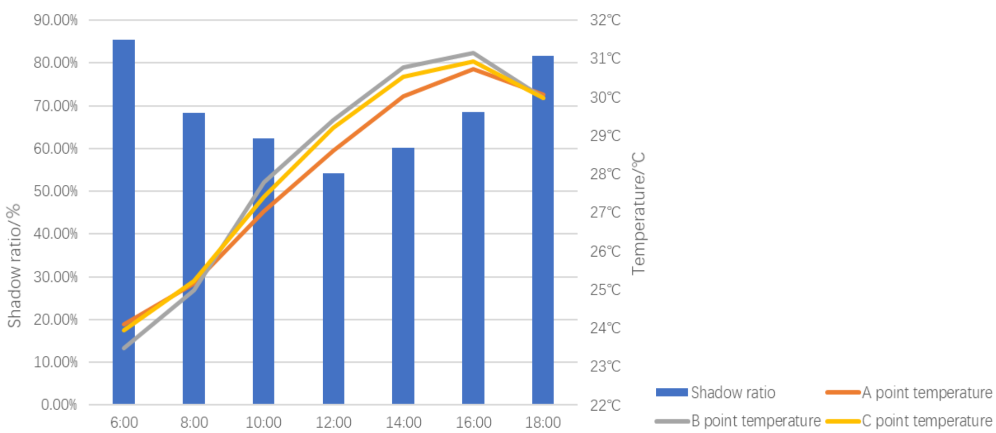
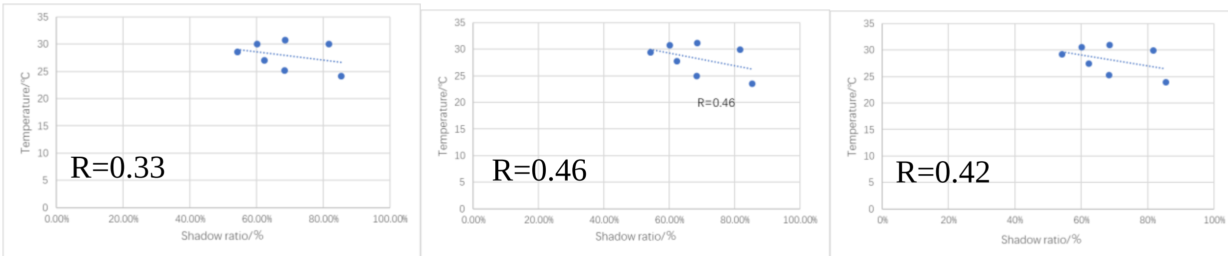


FIG 7. Statistic chart of measurement point temperature and shadow ratio

Figure 8 shows the correlation analysis between the temperature and SR in the three measurement points at each time point. The temperature and shadow ratio data of three measuring points at each time point were input into Excel software to generate scatter plots, then trend lines are generated, and then the correlation coefficients were calculated by a linear regression method. The coefficient of correlation between temperature and shadow ratio of the three measuring points are 0.33 (point A), 0.46 (point B) and 0.42 (point C). The average correlation coefficient is 0.40 in these 3 points. This is to say the temperature is related to the SR in each measuring point.



(a) Point A (b) Point B (c) Point C

FIG 8. Regression analysis of measuring point temperature and shadow ratio

Figure 9 shows the wind speed and shadow ratio of the three measuring points at 7 time points in a day. The three measuring points all reached the maximum shadow ratio at 6:00 and 18:00, while the maximum wind speed appeared at 6:00 in the morning. From 6:00 to 12:00 the proportion of shadow is decreasing and the wind speed is decreasing. Except point A, the shadow ratio between 16:00 and 18:00 showed an upward trend, and the wind speed also showed an upward trend. There may be a correlation between SR and wind speed, which needs further correlation analysis to prove.

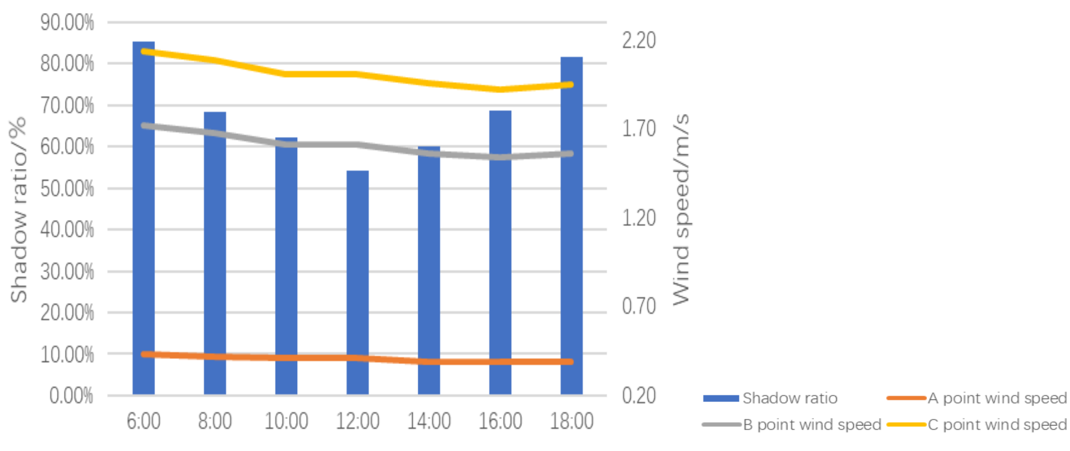
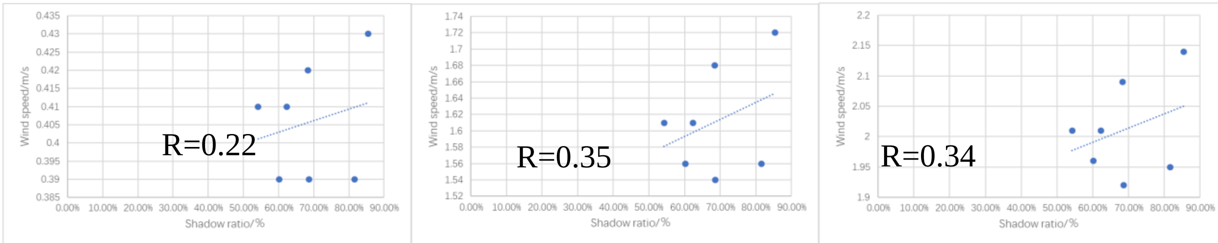


FIG 9. Statistics of wind speed and shadow ratio at measurement points

Figure 10 shows correlations between wind speed and shadow ratio of the three measurement points at each time point. The coefficient of correlation between temperature and shadow ratio of the three measuring points are 0.22 (point A), 0.35 (point B) and 0.34 (point C). The average coefficient of correlation is 0.30. The reason why point A has a low correlation may be that point A is a completely enclosed measurement point and buildings on the east and south sides are relatively high and urban wind is largely blocked here. The point A is likely to be insensitive to changes in wind speed. It can be concluded that the wind speed of the measurement point is related to SR, when the influence of the measurement point A is weakened.



(a) Point A (b) Point B (c) Point C

FIG 10. Regression analysis of wind speed and shadow ratio at measurement points

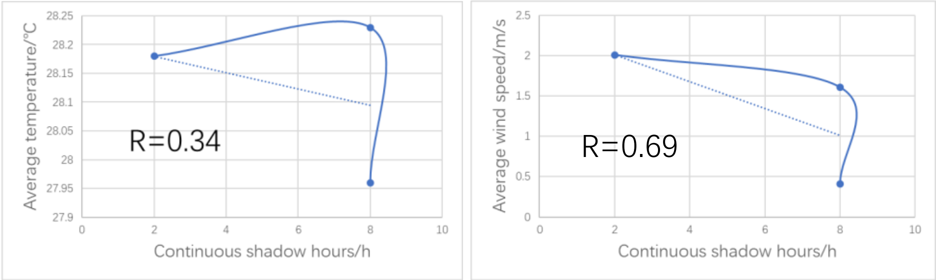
4.3 Analysis of the Relation between CSR and Urban Environment

CSR is a concept with time universality, so it is difficult to make a regression analysis of CSR at multiple time points with its corresponding temperature or wind speed like SR. Since continuous shadow hour is an important factor in CSR, we can study the relationship between CSR and environment by analyzing the relationship between continuous shadow hour and urban environment. Table 2 shows the continuous shadow hours at three measuring points and the average temperature and wind speed at each point. We will continue to study the correlation between continuous shadow hours and urban environment by regression analysis.

Table 2. Continuous shadow hours, average temperature and wind speed of 3 measuring points

Measuring points	**Point A**	**Point B**	**Point C**
Continuous shadow hours	8	8	2
Average temperature	27.96	28.23	28.18
Average wind speed	0.41	1.61	2.01

Figure 11 shows the linear regression relationship between the average temperature of summer solstice day and the continuous shadow hours of 8 am to 4 pm on winter solstice day at each point and the linear regression relationship between the average wind speed and the continuous shadow hours. The coefficient of correlation between the average temperature and the continuous shadow hours is 0.34 while the coefficient of correlation between the average wind speed and the continuous shadow hours is 0.69. This is to say that there is a correlation between continuous shadow hours and the average temperature and between continuous shadow hours and the average wind speed. Since continuous shadow hour is an important factor in CSR, we can conclude that there is a certain correlation between CSR and urban temperature. Similarly, there is a certain correlation between CSR and urban wind speed



(a) (b)

FIG 11. Regression analysis of continuous shadow hours and average temperature (a) and Regression analysis of continuous shadow hours and average wind speed (b)

4.4 Application of SR and CSR

The difference between SR and CSR is that SR is a time-varying indicator, while CSR is a fixed indicator. Generally speaking, CSR is used to compare the shadow condition in different sites, while SR is used to compare the shadow condition at different moment in a site. SR and CSR are mainly used to quantify the shadows of an area. Controlling SR or CSR in a reasonable range can improve the thermal comfort of buildings in the process of Architectural design. At the same time, SR and CSR can also be used as reference indicators for evaluating the quality of architectural design. There is also a correlation between the overall urban shadow and the urban heat island effect. The relationship between SR and CSR can be used to guide urban design in order to reduce urban heat island effect if they are applied to larger scale, such as urban scale.

5. Conclusion

As an important factor of urban spatial environment, shadow has an important influence on microclimate of city. This paper proposed the concept of SR and its derivative concept of CSR and simulated the environmental simulation data of a 300m*300m site in the near central area of Xi 'an city on June 21, 2017 using ENVI-met software. By coupling the data of thermal environment and wind environment with the SR data calculated by Skectup software, the correlation between this concept and thermal and wind environment of city has been proved. Compared with other spatial morphological indicators, the concept of SR proposed in this paper has the following characteristics: (1) Calculation of SR is different from that of traditional index of space such as intensity, height, maintenance coefficient factor, street height to width ratio, etc. After completion of the planning and design of city, intensity and height values are fixed and unique. But for buildings and the surrounding environment, the SR varies with the seasons and different times of the day, so that the shadow ratio has a characteristic that changes with date and time. At the same time, the CSR has the universality of time, which is convenient for quantitative research as an indicator of urban morphology. (2) SR can be used as an indicator to describe the spatial form. Through simulation and regression analysis, this paper proved the thermal environment and wind environment in the city are correlated to SR, especially with thermal environment, which can be described as a spatial morphological index for studying thermal environment and wind environment of city. (3) SR is easy to quantitative research. It is simple to calculate SR, and there is a situation that can directly characterize the distribution of shadow in the research site and it is suitable for using in the quantitative description of the spatial morphology to facilitate further research and analysis.

And the concept has the following advantages: (1) The concept of SR has been proposed to reflect the sunshine and shadow of the city in the cold region better so as to optimize the thermal environment and wind environment design of the city better and to improve the living environment. Evaluating the spatial shape of the region by SR will be conducive to improve the urban environmental quality. (2) SR is closely related to the thermal and wind environment of the area. In the area where is hot in summer, if the shadow of the building can be fully utilized to reduce the direct sunlight, the thermal environment will be improved.

In general, the paper proved that SR has a strong correlation with thermal environment and the wind environment. And it proved that the concept is very valuable to the study of thermal and wind environment of city, which can be used in the study of urban thermal and wind environment. In the cold areas represented by Xi 'an, there is a need to utilize the solar radiation rationally in winter to improve the thermal comfortableness of the human body and to use the shadow to cool down and prevent heat in the summer. The shadow is of great significance for optimizing the thermal and wind environment of the city. The concept of SR for the quantitative study of the microclimate in the cold regions is of great value.

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