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Research article

A field research on the impact of underlying surface configuration on street thermal environment in Lhasa

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Abstract: Commercial street is an important place for outdoor activities of urban residents. The quality of its thermal environment directly affects the comfort of pedestrians and the energy consumption of surrounding buildings. Block-scale microclimate studies have already been conducted in the context of different climates, while limited attention has been paid to the microclimate within high-altitude cold climate. Tibet, as the main body of the Qinghai-Tibet Plateau, presents typical plateau climate characteristics, and its unique natural climate conditions will certainly give birth to special urban environmental problems. Therefore, taking Lhasa as an example, this paper focuses on the impact of street thermal environment under different underlying surface configurations under unique plateau climate conditions. Based on the field measurement of the thermal environment of three streets in Lhasa City, namely, Yutuo Road, Duosen Road and Hongqi Road, the influence of different underlying surface design elements, namely, greening and water area, on the near ground microclimate and pedestrian comfort of the streets were analyzed. The analysis results of the measured datas show that: there are obvious temperature differences in the streets of different directions. Trees have a more significant cooling effect on East-West streets. The leaf area index (LAI) of trees will affect the improvement of thermal environment. Fountain has cooling effect in summer, but it is lower than that of trees. The research contents of this paper provides data basis for further research on the thermal environment and the optimization design of the underlying surface of the streets in the high altitude cold climate area.

Keywords: underlying surface properties; street thermal environment; greening; fountain body; field measurement

1. Introduction

Architecture, urban planning and design, and the behavior of residents will affect the urban environment and climate. The large-scale and rapid development of cities and the rapid growth of urban population bring about the unreasonable distribution of resources, which makes the urban climate and environment of our country change greatly. These changes affect the energy consumption of urban buildings and the physical and mental health of residents in all aspects. The key of building and urban design is to create a suitable living environment. As an important place for outdoor activities of urban residents, the quality of thermal environment of commercial street directly affects the quality of life of residents, and plays a very important role in regulating regional microclimate. In recent years, people continue to pay attention to the concept of sustainable development, and the research on urban microclimate is more and more extensive, among which the research on urban street space and ecological environment is also gradually deepened.

The study of outdoor microclimate started early, and has formed a theoretical system related to urban design and microclimate, especially how to consider the impact of climate factors in the design process, and has carried out a lot of research in different climate regions, and has made rich achievements. Among them, the research elements of outdoor microclimate mainly include the height width ratio of street, street trend, greening and the characteristics of underlying surface. For example, shashua-bar [1] and others have carried out a series of studies on the street valley with trees based on the CTTC model. The results show that the addition of trees is very effective to improve the microclimate and thermal comfort. In the street valley with trees, the canopy plays a major role in shading, the addition of trees increases the CTTC value, and the daily change of temperature slows down. The cooling effect of trees mainly depends on the shadow coverage, and the tree coverage also affects the Improving the thermal environment of streets plays a key role. Andrew M. Coutts [2] et al. Studied the thermal environment of different street valleys through field measurement, and proposed that the impact of trees in street valleys on air temperature and human thermal comfort is different, which depends on tree coverage, geometry and relevant climatic conditions. When the height width ratio of the street is small, the cooling effect of the tree canopy is more obvious, so choosing appropriate tree planting density and tree species can be used as the strategy to improve the microclimate of the street. Toudertr [3] points out that the shading effect of trees on solar radiation is affected by leaf area index and solar radiation through light path, which in turn affects the effect of trees on reducing Street thermal effect. The improvement depends largely on LAD, LAI and geometry. Low density trees produce less shadows but allow more air flow. Morakinyor [4] simulated the thermal environment of LAI and LAD under different wind speeds through Envi-met, and proposed that in addition to the LAI and LAD of trees, the arrangement form of trees is also an important factor, and the trees arranged in two rows have a greater impact than those arranged in the center of a single row. Oke [5] pointed out that the air temperature in the park is nearly 3K lower than that of the surrounding urban canopy, and the influence range is extensible; Stella Tsokar [6] measured and simulated the influence of different underlying surfaces on the microclimate and physiological equivalent temperature (PET) of the urban climate space, and the research shows that the influence of different underlying materials on the solar reflection coefficient is different, and the greening can effectively reduce the solar reflection coefficient in the street valley space. Kubota T [7] put forward the method of using building coverage to achieve acceptable wind environment index of residential quarters by analyzing the wind tunnel test results of 22 residential quarters in Japan.

The research on outdoor microclimate started late in China. Jingyuan Zhao [8] of Chang'an University in Xi'an studied the improvement effect of trees on the thermal environment with WBGT and set as indicators. He pointed out that the improvement of trees on the thermal environment was mainly caused by the shade of canopy on the solar radiation, and the effect of trees on the improvement of the thermal environment of street valley was the most significant, followed by lawn, and shrub. Zhen Wang [9] put forward the greening design of the underlying surface of the block gap, which is conducive to improving the microclimate of the gap in summer. Increasing the area of green space appropriately can also improve the microclimate of the block gap. Haiping Liu [10] studied the influence of different greening types on the thermal environment of Shanghai residential area by simulation, and concluded that under the premise of the same greening coverage rate, the combination of trees, shrubs and grass bottom has a more obvious cooling effect on the residential area. Tobi Eniolu Morakinyo [11] studied the influence of greening species and greening rate on microclimate in Mongkok area of Kowloon Peninsula, Hong Kong. It is recommended to plant high trees with low canopy in the street valley of Hong Kong. Yingsheng Zheng [12] selected three types of areas in the research area of Tai Pu ruins, namely, multi-layer high-density area, high-rise medium density area, and open area, to analyze the wind environment of pedestrian floor height, and then, on the premise of high-density construction, established new models to simulate and verify the feasibility of improving regional summer ventilation by optimizing the urban morphology.

Based on the summary of the research status at home and abroad, it is found that although a large number of urban microclimate studies have been carried out under different climate conditions at home and abroad, and very rich research results have been achieved, but the research on urban microclimate in high-altitude and cold areas is less, especially for the research on microclimate in high-altitude and cold areas. The research mainly focuses on the microclimate related research at the architectural scale, for example, Xinrong Zhu [13] has made some research achievements in the construction system of Tibet Plateau, Ya Feng [14] studied heating system and natural energy utilization, Quan He [15] studied ecological attribute in residential buildings, and Songtao Hu [16] experimental research on thermal comfort in high altitude areas. Although there have been a lot of research results on single building, however the research on urban block scale is still lacking in Tibet. Therefore, the purpose of this paper is to study the impact of the layout of the underlying surface of the street on the thermal environment of the street in Lhasa, hoping to provide reference for the future urban planning and design in Lhasa through the analysis and consideration of the test data.

2. Methods and objects

2.1. Case of study area

2.1.1. Study area

Lhasa, 29°36′ north latitude and 91°13′ east longitude, is located on the Qinghai-Tibet Plateau with an altitude of about 3648 m. It is one of the highest cities in the world, which belongs to the cold climate zone according to the zoning of China's architectural climate region. It also belongs to plateau temperate semi-arid monsoon climate zone. Lhasa area has a cold and dry climate, less annual precipitation, low relative humidity in spring and winter, and southwest gale in winter. The vertical climate changes obviously. The annual sunshine hours can reach more than 3000 hours, and the solar radiation is very strong. So, it is known as “Sunshine City”.

2.1.2. Basic characteristics of modern commercial streets

(1) Basic characteristics of streets

The buildings on both sides of the street surveyed are mostly low-rise buildings and multi-storey buildings, dominated by multi-storey without high-rise buildings. The main types of buildings are commercial buildings and public buildings, dominated by commercial buildings with the first floor mainly for business use and the second floor for living. Most of the building materials are light-colored tiles, dominated by red, white and gray. The street direction is mainly east-west and north-south. Due to the urban planning control in Lhasa, the Height-width ratio (H/W) of Lhasa street is generally less than 1, and mainly between 0.2 and 0.5. It is impossible to form the deep street canyon space just as other cities. The pedestrian road is mainly paved with gray tiles.

(2) Arrangement of greening

The street trees in the surveyed pedestrian space are basically arranged in the form of interval and the combination of trees and shrubs. The distance between the trees is not equal, ranging from 4 to 8 m. The trees are mainly willow, poplar and elm, but there is no uniform standard for tree selection for Lhasa streets. Thus, some trees are unable to ease the thermal discomfort of pedestrians in the summer.

(3) Arrangement of water area

In terms of water area, there is only one form of fountain in the surveyed area with two fountains on the north side of Yutuo Road and one fountain on the south side of Bakuo Street. The fountain opens during daytime in summer, creating a local cool microclimate to attract people to stay around.

2.2. Field measurement

2.2.1. Selection of measurement site

Through the large-scale investigation of Lhasa streets in the early stage, three streets in the same area, east-west, and north-south direction were selected for actual measurement. The principle of selecting measurement sites is that there are different underlying surface elements for preliminary comparative analysis. Secondly, considering the influence of artificial heat sources and vehicle emission heat sources, three commercial streets are selected, namely Yutuo Road, Duosen road and Hongqi Road. The characteristics of each street are shown in Table 1.

Table 1. Description of the street property (Data source: field survey).

Name of street	Yutuo road	South Duosen road	Hongqi road
Street direction	E-W	N-S	E-W
The number of measuring point	5	4	2
Minimum building height (m)	12	12	7
Maximum building height (m)	17	7	14
Average building eeight (m)	15	9	11
Street width (m)	45	34	23
Average height-width ratio	0.3	0.26	0.47

2.2.2. Layout principle of measuring points

In order to avoid the influence of external factors on the experimental results and ensure the accuracy and effectiveness of the measurement results, the selection and arrangement of measurement points shall follow the following principles:

(1) Minimize the Interference of People and Vehicles on the Experimental Results

Crowd movement and vehicle exhaust emissions will affect the surrounding environment. Therefore, in the selection and layout of measurement points, we choose the location with less pedestrian volumes and traffic volumes to ensure the accuracy of measurement results.

(2) Ensure the Unity of the External Environment

In microclimate measurement, the differences of underlying surface, height-width ratio (H/W) of surrounding buildings, street orientation, greening and other factors will affect the experimental results. Therefore, we try our best to ensure the unity of the external environment, and reduce the impact and error caused by the difference of the external environment in the same experimental scheme.

2.2.3. Selection of measuring points

(1) Layout of measuring points on Yutuo Road: measuring point 1 was arranged next to the fountain on the north side of Yutuo Road, measuring point 2 was arranged under the tree shade of the north side of Yutuo Road, measuring point 3 was arranged in the shadeless area, measuring point 4 was arranged under the tree shade of the south side of Yutuo Road, and the measuring point 5 was arranged outside the tree.

(2) Layout of the measuring points on Duosen Road: The measuring point 6 was arranged in the area without tree shade on the west side of the Duosen Road, the measuring point 7 was arranged in the tree shade which is not far from the measuring point 6, the measuring point 8 was arranged under the shade on the east side of the South Duosen Road, and the measuring point 9 was arranged in a shadeless area.

(3) Layout of measuring points on Hongqi Road: The measuring point 11 was arranged under the shade of the south side of Hongqi Road, and the leaf area index of the trees is small. The measuring point 10 was arranged in the area without tree shade on the south side of the Hongqi Road.

Figure 1. The arrangement of measuring points (Left is Yutuo road-Duosen road, right is Hongqi road).

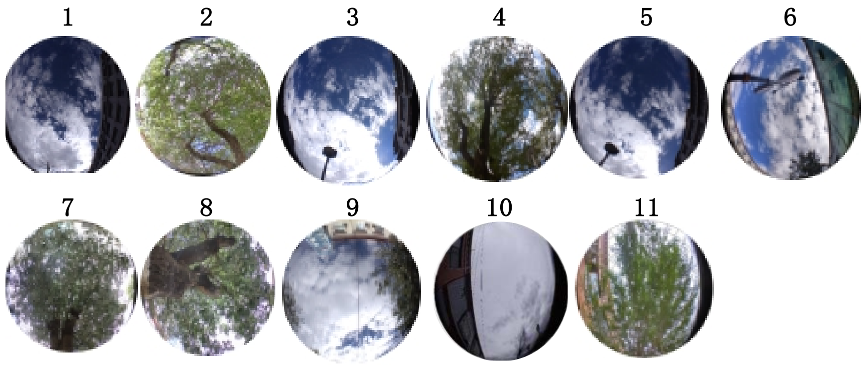

Figure 2. Fisheye photographs of each measuring.

Table 2. Measuring point information.

	H/W	SVF	Tree species	Details
1	0.45	0.802	——	Fountain
2	0.45	0.42	Elm	Below tree
3	0.45	0.79	——	Outside tree
4	0.45	0.49	Elm	Below tree
5	0.45	0.77	——	Outside tree
6	0.31	0.73	——	Outside tree
7	0.31	0.42	Poplar	Below tree
8	0.31	0.44	Poplar	Below tree
9	0.31	0.74	——	Outside tree

2.3. Test contents and test methods

In this field measurement, the measurement points of different underlying surface structures of pedestrian street are tested for 4 consecutive days in winter and summer. According to the hourly meteorological data provided by Lhasa Meteorological Bureau, one day with similar meteorological conditions was selected as the effective date. The final test date was June 26, 2017 and December 7, 2017. The measurement time during the test was 10:00–20:00. The test contents include air temperature, relative humidity, wind speed, black ball temperature and solar radiation at the pedestrian height (1.5 m above the ground) of each measuring point. The instruments used for the test are shown in Figure 3, and the parameters of each instruments are shown in Table 3.

Figure 3. Test instruments.

Table 3. Test instruments and accuracy.

Measurement parameters	Instrument	Instrument parameters	Acquisition time
Air temperature relative humidity	Temperature and humidity recorder model: GSP958	Temperature Measurement Range: − 40–85 °C; Accuracy: − 20–40 °C, ± 0.5 °C; Humidity Measurement Range: 0–99.9% RH; Accuracy: ± 3% RH;	5 mins
Wind speed	Portable anemometer model: WFWZY-1	Instrument range: 0.05–30 m/s Accuracy: 5% ± 0.05m/s (0.05–30 m/s)	15 mins
Black sphere temperature	Black sphere thermometer model: HQZY-1	Measurement range: − 20–80 °C; Accuracy: ± 0.3 °C (−40–60 °C)	5 mins
Solar radiation	Solar radiometer model: SPN1	Overall accuracy: total radiation and scattering ± 5% (daily integration); ± 5% ± 10W/m^2 (hourly average)	15 mins
	Thermal comfort instrument Model: JI-IAQ	Wind speed measurement range: 0.05–5 m/s, Accuracy: ± (0.03m/S + 2 & reading), Humidity measurement range: 0–100% RH, Accuracy: ± 1.5% RH, Black sphere temperature range: 5–120 °C, Accuracy: ± 0.5 °C (5–50 °C)	5 mins

2.4. Concept and calculation of relevant indexes

(1) Street height-width ratio (H/W)

The height-width ratio (H / W) of street valley refers to the ratio of the average width of buildings on both sides of street valley (the elevation of adjacent vertical buildings) to the width of street valley (the width from wall to wall across the street), which reflects the compactness and opening degree of Street [9] (Figure 4). In addition to the direct psychological feeling, the aspect ratio has a direct impact on the microclimate index of the street valley, such as the solar radiation area of the street valley.

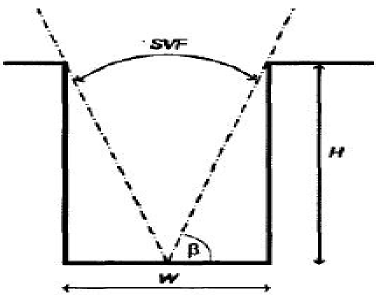

Figure 4. H/W.

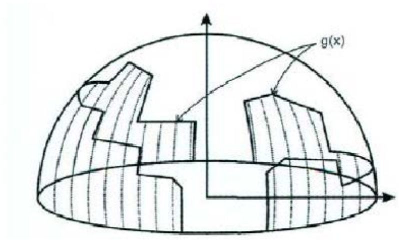

Figure 5. Sky view factor.

(2) Sky view factor (SVF)

In the field of architecture and urban design, the definition based on geometric form is the ratio of visible sky to all day sky for a given point; from the perspective of climate, the definition based on sky is the ratio of the ratio of blessing flux emitted to the sky on a plane to the total blessing flux [17]. The estimation of sky visibility factors mainly includes geometric mathematical analysis, fisheye lens photography, and total blessing ball positioning system method and software calculation method [18].

(3) Leaf area index (LAI)

Leaf area index refers to the multiple of the total area of plant leaves in the land per unit land area, which directly determines the difference of plant on the solar penetration rate [19], water transpiration capacity and other aspects, and then the impact on the thermal environment. Leaf area index refers to the total plant leaf area (m^2) per unit community volume (m^3). The relationship between leaf area density and leaf area index is $LAI = \int_0^h LAD.\Delta z$ (where h is the height of the tree (m) and ΔZ is the vertical grid size) [20].

(4) Mean radiant temperature (MRT)

The mean radiant temperature is defined as the surface temperature of an imaginary isothermal enclosure surface. The radiant heat exchange between the surface and the human body is equal to the actual radiant heat exchange between the non-isothermal enclosure surface around the human body and the human body, reflecting the radiant heat exchange between the human body and the surrounding environment. The calculation formula is as follows [21]:

$$T_{\mathrm{mrt}} = [(T_g + 273.15)^4 + \frac{1.1 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} \times (T_g - T_a)]^{1/4} - 273.15$$

where Tg is the globe temperature, v is wind velocity (m. s^{-1}), D is the globe diameter (m), ε is the globe emissivity (0.95), and Ta is air temperature.

(5) Physiological equivalent temperature (PET)

Table 4. Outdoor thermal comfort classification table (Table source: [22]).

PET (°C)	Thermal comfort	Physiological stress
<4	Very cold	Extreme cold stress
4–8	Cold	Severe cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Mild cold stress
18–23	Comfort	No thermal stress
23–29	Slightly warmer	Mild heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

In this paper, the physiological equivalent temperature pet is calculated by using the software Rayman. The PET of the measuring point can be obtained by inputting the measured temperature, humidity, wind speed, radiation temperature and other parameters into Rayman. The classification range of physiological equivalent temperature PET is as follows (Table 4) [22], PET can directly reflect the human thermal feeling in a certain environment. Human body is comfortable at 18–23 °C.

3. Analysis

In order to ensure the accuracy of the data, the datas from 10:00 to 19:00 were selected as the effective datas of the actual measurement and analysis. The meteorological parameters analyzed in this experiment mainly including air temperature, relative humidity, wind speed, black sphere temperature, solar radiation and average radiation temperature. In addition, the physiological equivalent temperature (PET), an outdoor thermal comfort evaluation index, was introduced to analyze the microclimate impact of greening and water area on the local space of the street from four aspects: the same side of the same street, the different sides of the same street, the streets with different directions, and the water area. The specific results are as follows.

3.1. The analysis of actual measurement results of the impact of greening on thermal environment of street

3.1.1. The impact of greening on street thermal environment on the same side of the same street

The impacts of greening on the street thermal environment of the same side of the same street were compared. The measuring point 2 (under the tree shade) and the measuring point 3 (without shade) on the north side of the east-west Yutuo Road, the measuring point 4 (under the tree shade) and the measuring point 5 (without shade) on the south side of the road, the measuring point 6 (without shade) and measuring point 7 (under the shade) on the west side of the south-north Duosen Road, measuring point 8 (under the shade) and measuring point 9 (no shade) on the east side of the road were selected. The measuring points under the shade and outside the shade on the same side of the same street were compared pairwise, as shown in Figure 6a, b below. The analysis can be obtained.

In summer, the measuring points 3, 5, 6, and 9 without tree shade are under direct solar radiation, and their air temperature, solar radiation value, black sphere temperature value, and average radiation temperature are higher than those measured under the shade of trees. The time of PET value in the “comfortable” thermal sensation is also significantly shorter. The relative humidity of each measuring point corresponds to the temperature. The higher the temperature, the lower the humidity. The average humidity of the four measuring points under the shade is greater than that of the measuring points without shade, suggesting the obvious effect of trees on cooling and humidifying the street thermal environment. Similarly, by comparing the average wind speed of the four pairs of measuring points, it can be found that the average wind speed of the measuring points under the shade can be slightly smaller, and the shielding of the trees has a certain effect on the wind speed, but the influence is relatively small.

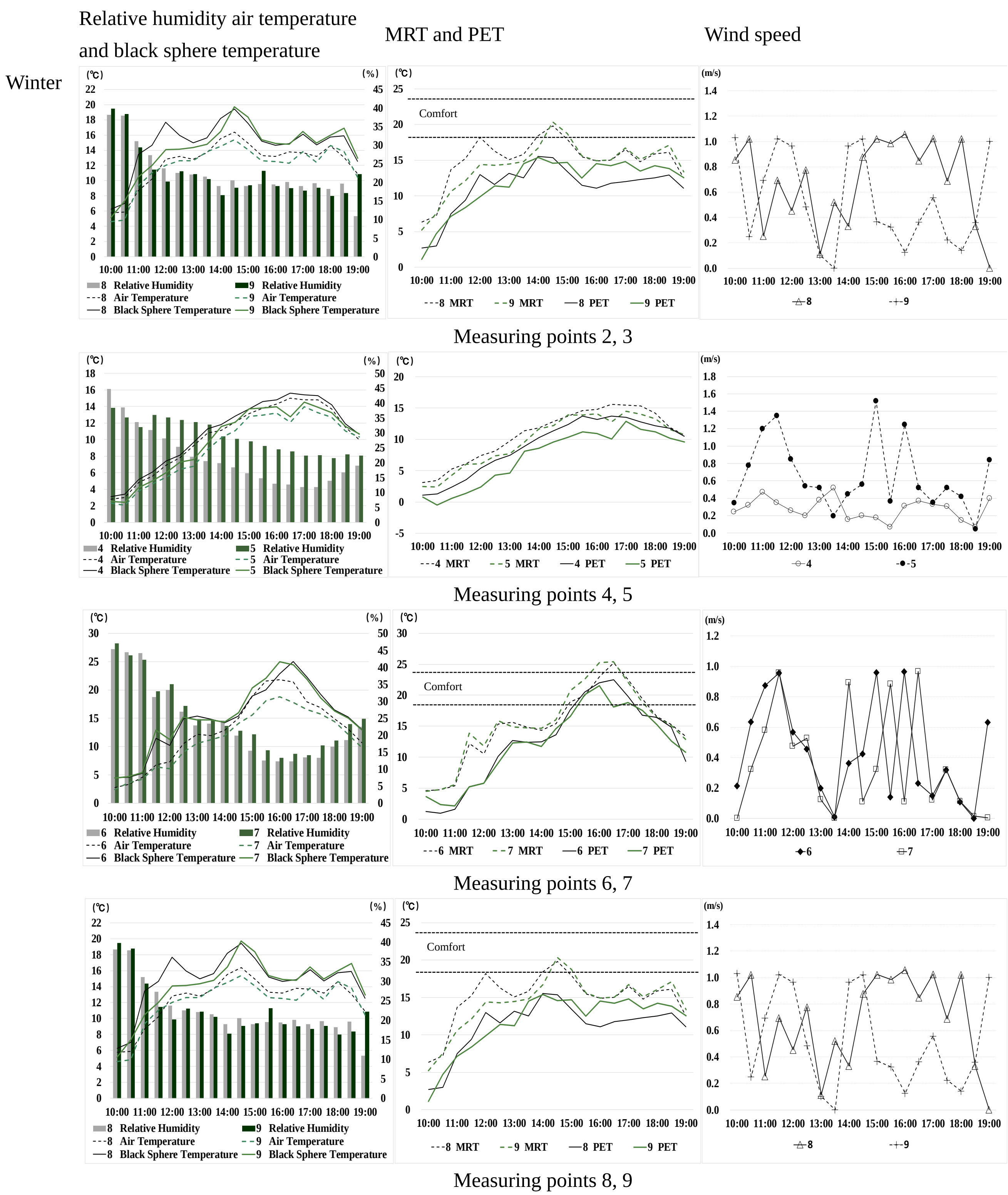

Figure 6a. Measured drawing of measuring points on the same side of the same street.

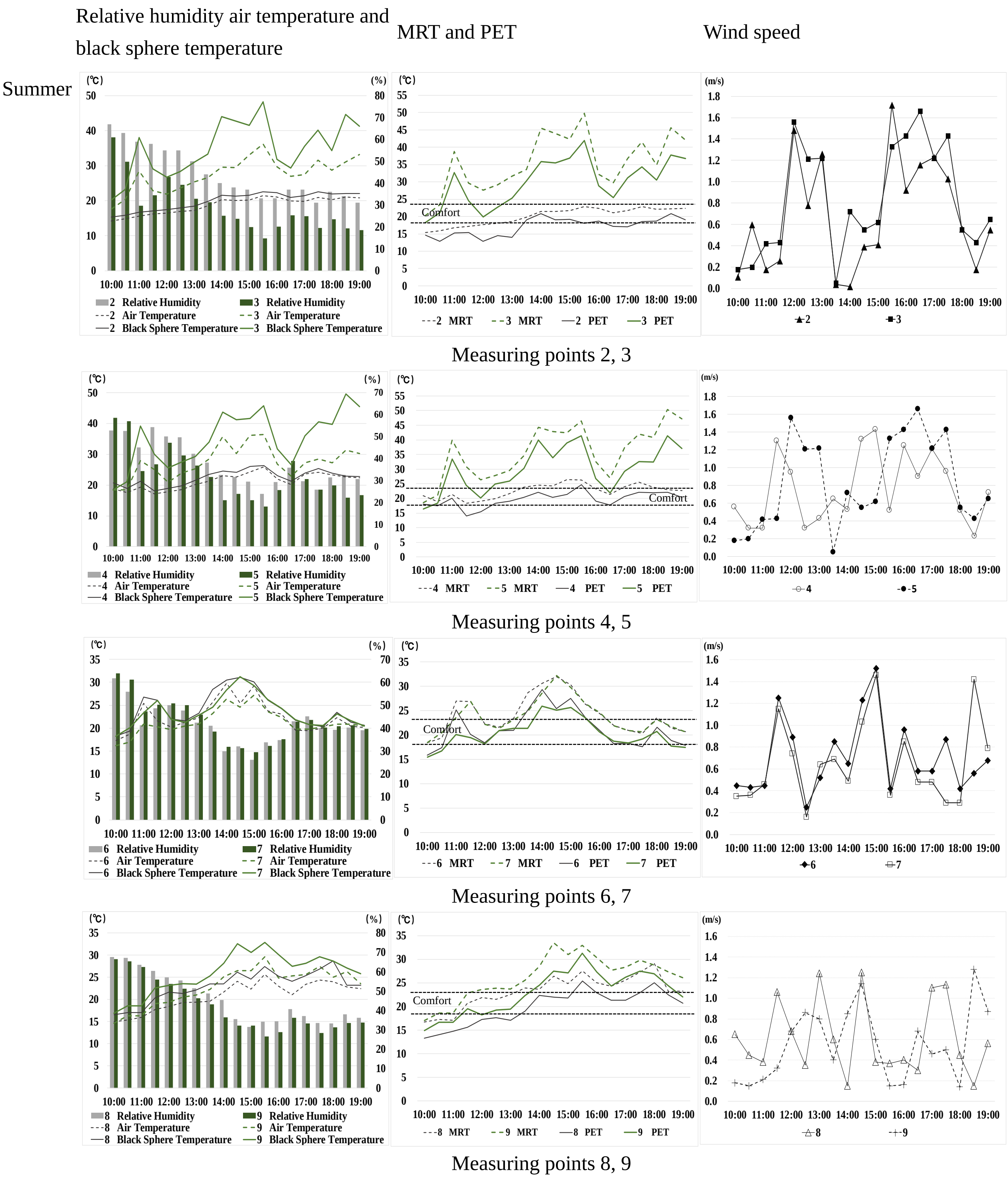

Figure 6b. Measured drawing of measuring points on the same side of the same street.

In winter, due to the shielding of buildings, the measuring points on the south and north side of Yutuo Road received uneven solar radiation and the temperature difference is significant. The air temperature, black sphere temperature and average radiation temperature of the measuring point 2 (under the shade) on the north side of the road are lower than those of measuring point 3 outside the shade, and the time of PET value in the “comfortable” thermal sensation is longer. All of those indicating that although the leaf fall in the winter causes the decreased leaf area index (LAI), the shading effect of the trees is still necessary in the east-west street of Lhasa. The average temperature of the measuring point 4 (under the shade) on the south side of the road is slightly higher than that of the measuring point 5, suggesting that the trees are beneficial to improve the thermal environment of the Lhasa street in winter when the solar radiation is low. The relative humidity and average wind speed of the two measuring points 2 and 4 under the shade are lower than that of the measuring point 3 and 5, indicating that the greening reduces the relative humidity on both sides of the road and has a certain effect on weakening the wind speed. The solar radiation on the Duosen Road is more uniform. By comparing the other two pairs of measuring points, it can be seen that the temperature and relative humidity are not significantly different, but the wind speed fluctuates greatly, suggesting the effect of trees on the street thermal environment is not significant.

3.1.2. The impact of greening on street thermal environment on different sides of the same street

The impacts of greening on street thermal environment of different sides of the same street were compared. The measuring point 2 (under the shade) and 3 on the north side of the east-west Yutuo Road, the measuring point 4 (under the shade) and 5 on the south side of the road, the measuring point 6 and 7 (under the shade) on the west side of the south-north Duosen Road, the measuring point 8 (under the shade of the tree) and 9 on the east side of the road were compared pairwise to obtain the difference value between the two points (Figure 7a, b). The analysis can be obtained.

By comparing the air temperature, solar radiation value, black sphere temperature, average radiation temperature, relative humidity and average wind speed of two pairs of points on Yutuo Road. It can be found that in summer, the thermal environment of the north side is better than that of the south side, and the cooling effect of the trees increases the time in a comfortable state, and the influence of trees on the north side with a large amount of radiation and no shielding of buildings is greater. In winter, the air temperature, black sphere temperature, average radiation temperature, and solar radiation value on the north side of the road are much larger than that on the south side. The measuring point 3 can achieve a “hot” thermal sensation, while the time of “comfortable” thermal sensation of the point 2 under the shade is the longest. Due to the lack of solar radiation on the south side of the road, the thermal sensation at the measuring point 4, 5 is mainly cold, very cold, and the PET at the measuring point 4 under the shade is slightly higher than that at the measuring point 5. The trees also have a more significant impact on the north side of the road. By comparing the average wind speed on both sides, it can be known the average wind speed on the south side is larger than that on the north side, and the trees have a greater influence on the wind speed on the south side.

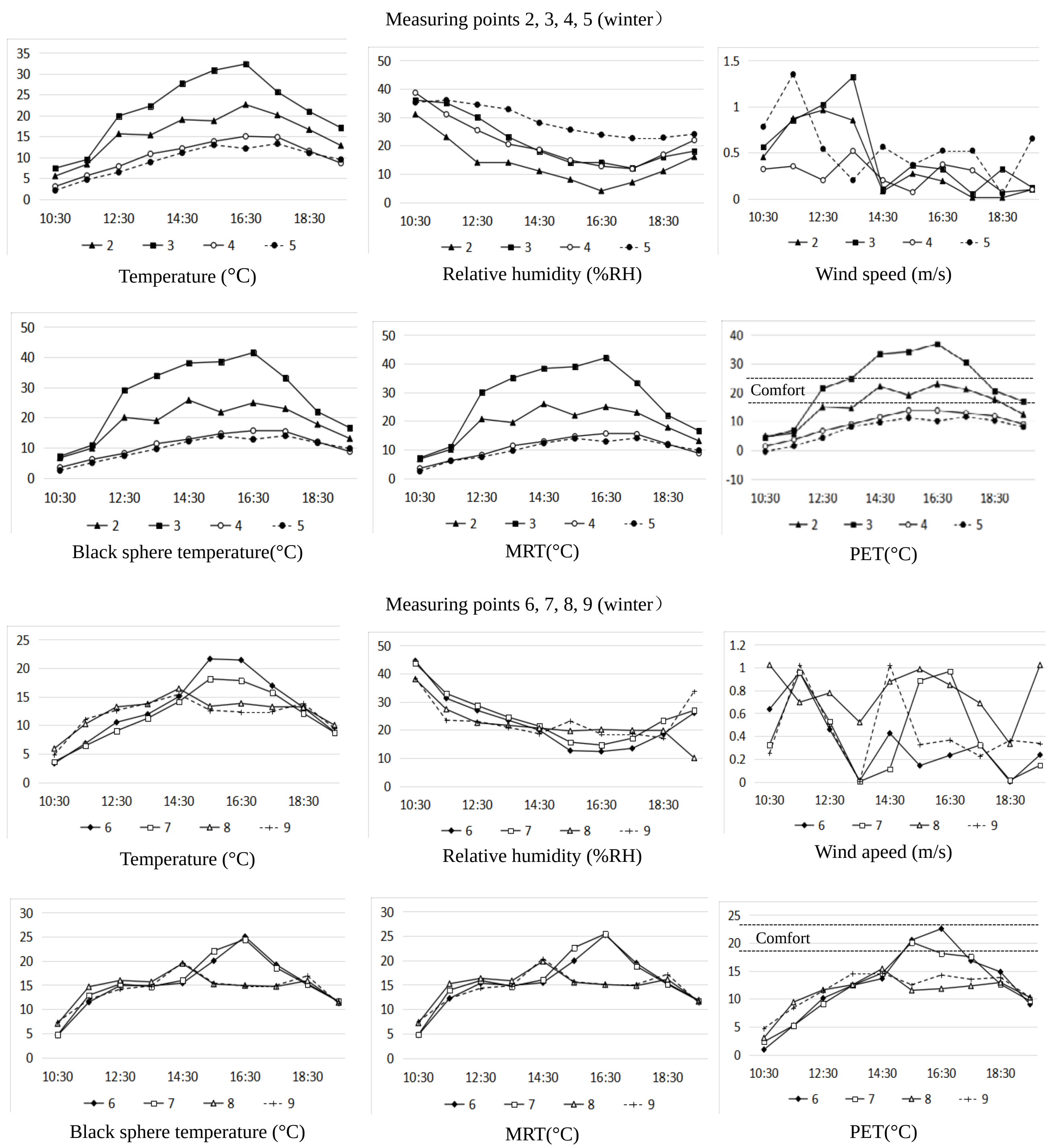

Figure 7a. Measured drawing of measuring points on the different sides of the same street.

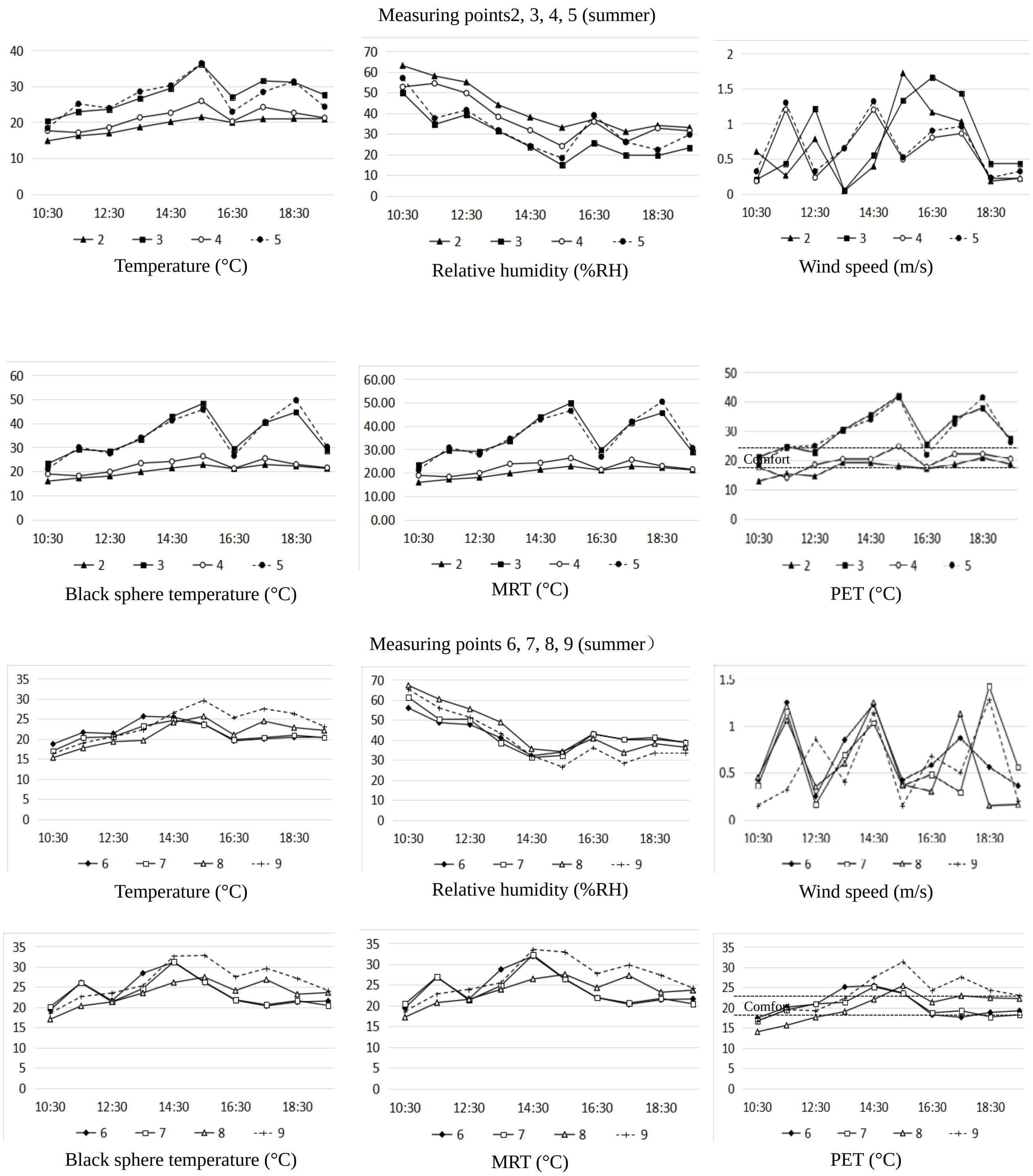

Figure 7b. Measured drawing of measuring points on the different sides of the same street.

By comparing the air temperature, solar radiation value, black sphere temperature, average radiation temperature and relative humidity of the two pairs of measuring points on the South Duosen Road. It can be found that the thermal environment on the east side is better than that on the west side in summer, and no significant difference can be found in the influence of trees on the thermal environment on both sides of the street. The wind speed variation of each measuring point fluctuates greatly without obvious law. Generally speaking, trees have a certain blocking effect on wind speed. In winter, the solar radiation value and relative humidity on the west side of the road are greater than that on the east side, and the time in the "comfortable state" is also longer, but no significant difference can be found in the influence of trees on the thermal environment on both sides of the street.

3.1.3. The impact of greening on thermal environment of streets with different directions

The impacts of greening on thermal environment of streets with different directions were compared, and each measuring point on the east-west Yutuo Road and the north-south Duosen Road were analyzed. By comparing the overall average temperature, solar radiation value, black sphere temperature value of the two streets in summer and winter, it can be obtained that the overall air temperature of Yutuo Road is higher than that of Duosen Road, and the time of PET in the "comfortable" thermal sensation is also longer, indicating that the thermal environment of east-west street is obviously not as good as that of the north-south street.The average radiation temperature of each measuring point was calculated by the formula. The average radiation temperature of the measuring points under the shade on Yutuo Road is significantly lower than that of the unshaded measuring points, while the tree shade has little impact on the changes of average radiation temperature on the Duosen Road, demonstrating the cooling effect of tree shade on the east-west street shade is greater than that on the north-south street. By comparing the average humidity of the two streets, it is concluded that the average humidity of Yutuo Road is lower than that of Duosen Road. In summer, the humidity under the shade is higher than that in area without shade, while in winter it shows opposite trend, and the impact of greening on Yutuo Road is greater than that on Duosen Road. There is no obvious law of wind speed at each measuring point, and the change is significant. Due to the shielding of trees, the wind speed is slightly reduced, but there is no obvious law of the influence on streets with different directions.

3.1.4. The impact of trees with different leaf area index on street thermal environment

The impacts of trees with different leaf area index (LAI) on street thermal environment were compared. The measuring point 4 (under the shade) and 5 on Yutuo Road, point 10 and 11 (under the shade) on the south side of the Hongqi Road were compared pairwise. The LAI of the tree at the measuring point 4 is larger, and the difference between the two pairs of measuring points is compared (Figure 8 below). The analysis can be obtained.

In summer, the air temperature, solar radiation value, black sphere temperature and average radiation temperature at the measuring point 4 and 11 under the trees are lower than that at the measuring point 5 and 10 outside the shade, and the measuring point 4 shows lower temperature, larger relative humidity, and longer PET value in a "comfortable" thermal sensation, it is suggested that the increase in LAI is beneficial to cool the street and increase humidity.

In winter, because the measuring point 4, 5, 10, and 11 are located on the south side of the east-west street, the amount of solar radiation is less throughout the day, so they are all in a state of "cold" and "coll". The temperature at point 4 with larger LAI under the tree is the highest in the whole day, and the measuring points under the tree with a small LAI has little effect on the thermal comfort. The humidity of Yutuo Road is less than that of Hongqi Road, and the trees play a humidifying role, while the influence of trees on Hongqi Road is not obvious. It can also be seen from the picture above that the LAI at measuring point 4 is larger than that at measuring point 11, and the blocking effect on the wind speed is also more obvious.

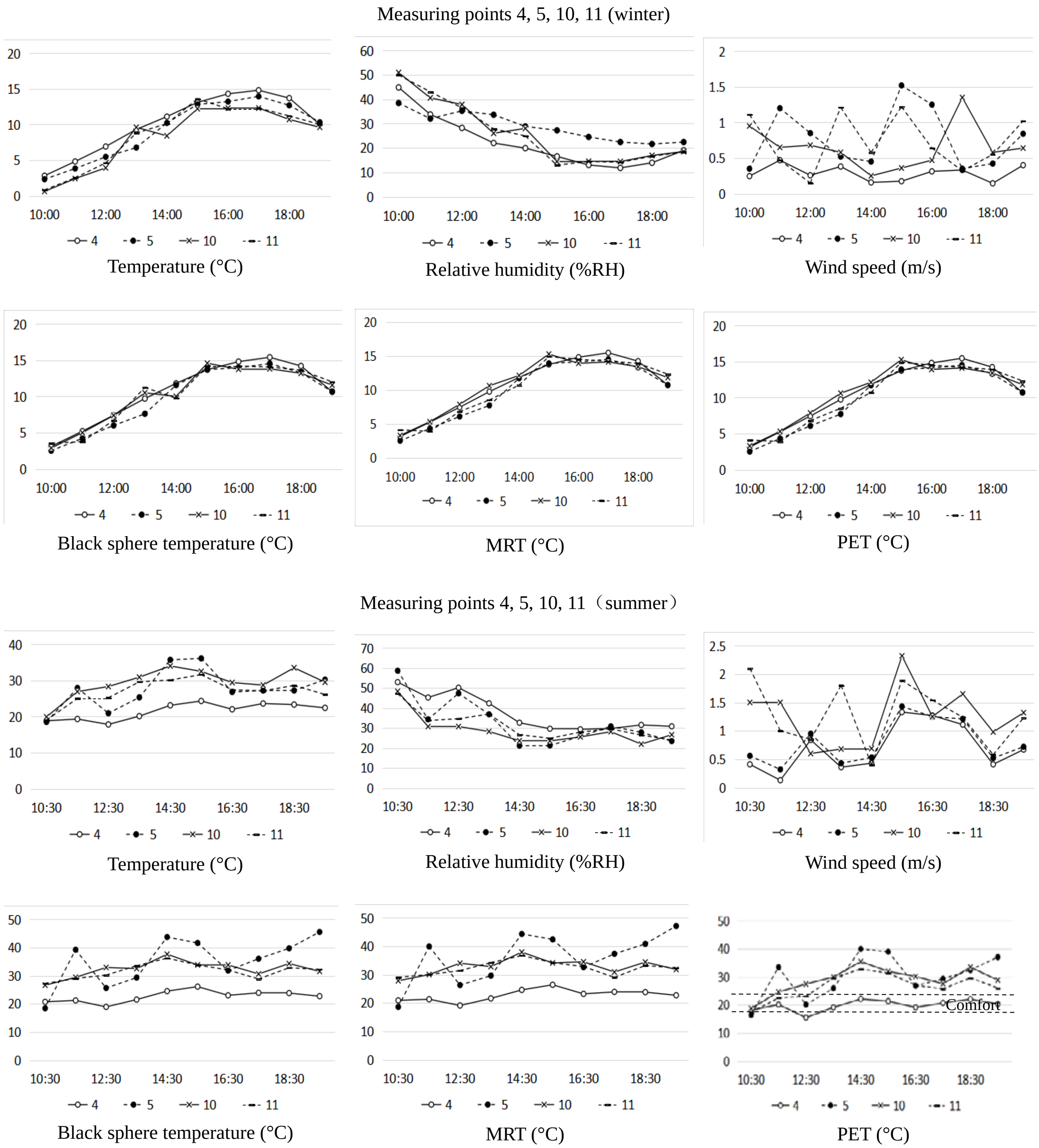

Figure 8. Measured drawing of measuring points under trees with different leaf area index.

3.2. Analysis of the measurement results of the effect of water area on street thermal environment in summer

The arrangement form of water area in the selected street is only fountain, which is only open in summer. Therefore, the measurement was conducted in summer only. The measuring point 1 near the fountain on the north side of the Yutuo Road and measuring point 3 without tree shade on the same side of the same street were selected for comparison, as shown in Figure 9 below. The analysis can be obtained: The two measuring points are both located on the north side of Yutuo Road, so the variation curve of wind speed at both points are consistent without significant difference, indicating that the water area has no evident impact on improving wind speed. Since there is no tree shading at both measuring points, the solar radiation value is large, the air temperature, black sphere temperature, and average radiation temperature are also high with consistent curves, but the temperature at the measuring point 1 is slightly lower than that at measuring point 3 and the time in a “comfortable” thermal sensation is longer. The flowing fountain at the measuring point 1 evaporates quickly and the relative humidity is greater than that at measuring point 3, demonstrating that the water area can exert a certain cooling and humidifying effect on the street thermal environment in summer.

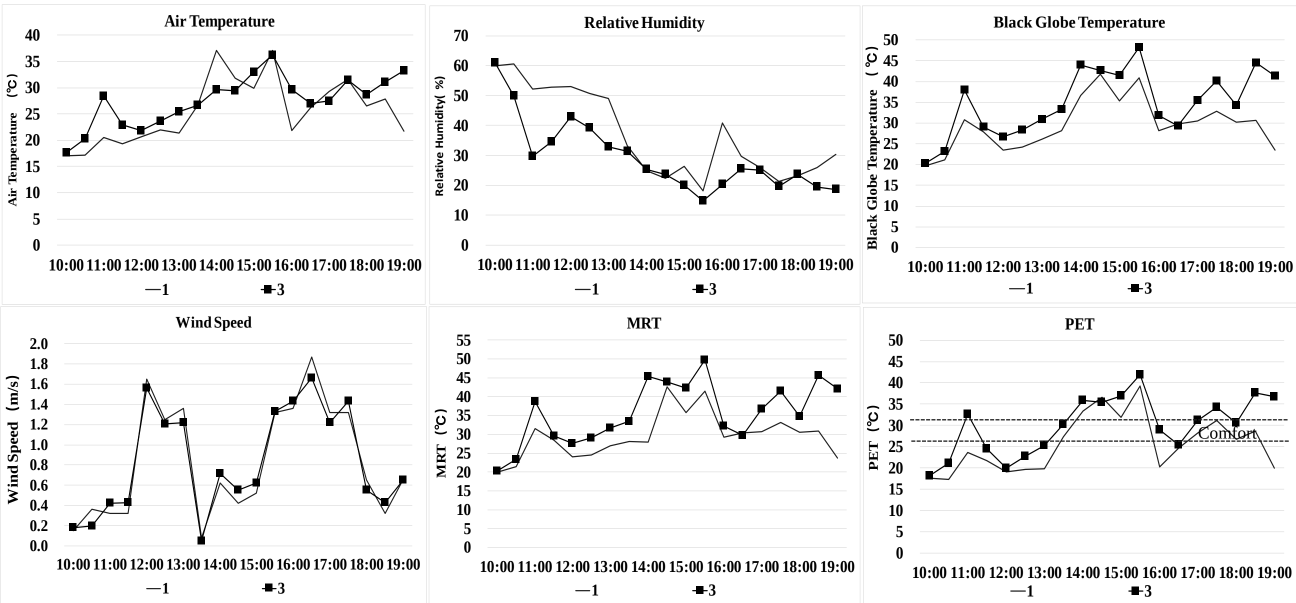

Figure 9. Analysis diagram of measured water points.

4. Discussion

In order to further study the effect of water and trees on the improvement of thermal environment in summer, in this paper, the variance analysis of SPSS software and Paired sample T-test were used to quantify the cooling effect of street trees and fountain. Through data analysis, it can be found that the cooling effect of fountains (C1, 3) is lower than that of trees (C2, 3) in the east-west street of Yutuo Road, while comparing the cooling effect of trees in the South (C5, 6) and North (C3, 4) of Yutuo Road, it is found that the cooling effect of trees in the south is not as obvious as that in the north. This is related to the SVF of the trees in the two measuring points. The SVF of the north measuring point is slightly larger than that of the south measuring point, resulting in the reduction of the solar radiation in the north side greater than that in the south measuring point. Moreover, the cooling effect of trees on the north-south direction of Duosen Road is obviously not as strong as that on the east-west direction of Yutuo Road, which also shows that the cooling effect of trees is more obvious in the case of worse thermal environment. In the Table 5, ΔTa, Δ Tmrt, ΔPET and ΔSR refer to the influence of greening and water area on air temperature, average radiation temperature, physiological equivalent temperature and solar radiation in different streets of Lhasa.

Table 5. Analysis of cooling effect of trees and water.

Comparative factors	ΔTa(°C)	ΔT_{mrt}(°C)	ΔPET(°C)	ΔSR (W.m^{-2})
	Mean ± S.E.Mean	Mean ±S.E.Mean	Mean ±S.E.Mean	Mean ± S.E.Mean
C1, 3	2.28 ± 0.95*	6.17 ± 1.18*	4.51 ± 0.91*	/
C2, 3	8.73 ± 0.64*	15.22 ± 1.45*	12.62 ± 1.10*	453.35 ± 87.7*
C4, 5	5.96 ± 0.78*	13.1 ± 1.66*	10.06 ± 1.25*	389.97 ± 76.50*
C6, 7	1.02 ± 0.29*	0.51 ± 0.27*	1.12 ± 0.30*	252.93 ± 65.74*
C8, 9	2.04 ± 0.30*	2.85 ± 0.45*	3.0 ± 0.36*	73.67 ± 73.55*

Note: *p is significant within 0.05.

The correlation coefficient R^2 = 0.824 ($P < 0.05$). It also shows the cooling effect of trees. Previous studies have highlighted the role of tree shadow on street microclimate, but also pointed out the limitations of its role.

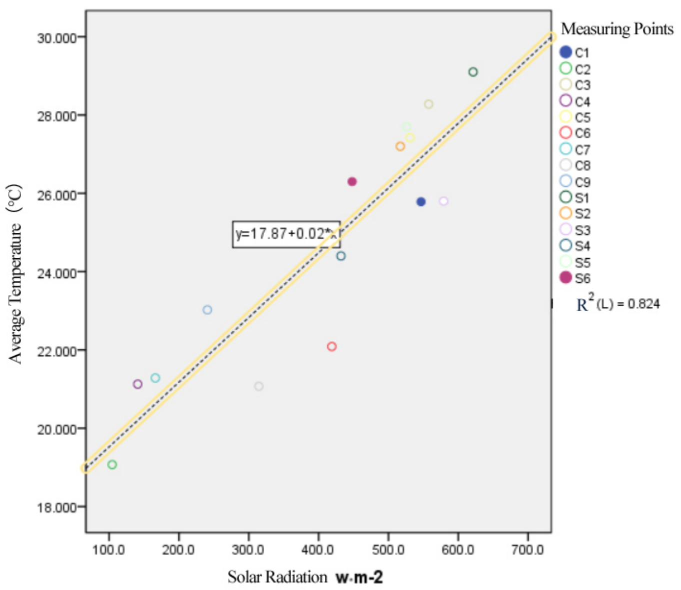

Figure 10. Correlation analysis of daytime average temperature and solar radiation of each measuring point in summer.

5. Conclusion

Through the field research on the streets of Lhasa and the actual measurement of the impact of the underlying surface design elements on the thermal environment of Lhasa Street, the main conclusions are as follows:

(1) In summer, the solar radiation intensity has a great influence on the street thermal environment. The surface temperature under the shade is much lower than the surface temperature without shade, and the temperature difference can reach 24 °C. In the winter, on the south side of the east-west street with poor thermal environment, the surface temperature under the shade is slightly higher than the surface temperature outside the shade. On the north-south street, the trend is opposite. It shows that trees can improve the thermal environment in winter.

In the winter, the measured results show that the north side of the east-west street can achieve a "hot" thermal sensation when there is no tree shade, and the time in a "comfortable" thermal sensation is less than 30 minutes. The time in "comfortable" thermal sensation under the shade is the longest, for four and a half hours, suggesting that the tree shade is necessary on the north side of the east-west streets in Lhasa. Due to the lack of solar radiation on the south side of east-west street, the buildings play a shielding role throughout the day. The main thermal sensations are "cool", "slightly cold" and "cold", and the tree has little effect on the improvement of the thermal environment. There is little difference in the thermal comfort on north-south street with shade or without shade.

(2) On the east-west street, the cooling effect of the trees on the south side is not as obvious as that on the north side. On the north-south street, there is no significant difference in the cooling effect of trees between both sides.

(3) The thermal environment of the east-west streets of Lhasa is inferior than that of the north-south streets in summer and winter. The cooling effect of trees on the north-south Duosen Road is obviously not strong as that of the east-west Yutuo Road, and the trees exert the most obvious cooling effect in summer on the east-west streets, which also shows that the cooling effect of the trees is more prominent in the poor thermal environment.

(4) The tree leaf area index (LAI) also has an effect on the improvement of the street thermal environment, and the increased leaf area index is more beneficial for improving the street microclimate.

(5) The water area can improve the thermal environment of the street in summer, but the cooling effect is inferior to that of trees.

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Conflict of interest

Finally, all authors declare that there is no conflict of interest in this article, submissions have not been published in other journals, and fully agree that the manuscript will be considered to be published in AIMS Press journal in Open Access Format.

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