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Horizontal Heat Flux between Urban Buildings and Soil and Its Influencing Factors

(Fluks Haba Mendatar antara Bangunan Bandar dan Tanah serta Faktor yang Mempengaruhinya)

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ABSTRACT

The soil temperature near four external walls with different orientations was investigated in spring and summer. In both seasons, the soil temperature was higher in the positions closest to the buildings, suggesting that the buildings were a heat source for the soil surrounding them. Therefore, it could be confirmed that there was lateral heat transfer between the soil and the buildings. Based on this, a soil heat flux plate was set between the soil and the buildings to investigate the horizontal heat flux. The data showed diurnal variations of the horizontal heat flux in both spring and summer. In order to determine the factors that influenced the horizontal heat flux and to provide a basis to understand its mechanism, the correlations between the data of several meteorological factors and the horizontal heat flux were analysed. The results showed that solar radiation was significantly correlated with the horizontal heat flux ($p<0.0001$*) in any single season and in the two seasons that were studied. Additionally, other meteorological factors (net radiation, air temperature, relative humidity and soil temperature and moisture) showed strong correlations with the horizontal heat flux on a diurnal scale only. On a seasonal time scale, the correlation might be significant (*$p<0.0001$*) as well, but the correlation coefficients decreased too significantly, such as those for soil temperature, air temperature and relative humidity. Alternatively, the correlation might not be significant (*$p>0.05$*), such as that for soil moisture. The stepwise regression results indicated that the relative importance of these meteorological factors was 48.63, 21.94, 14.44, 8.12 and 6.87% for solar radiation, soil temperature, air temperature, relative humidity and soil moisture, respectively, on a diurnal scale.*

Keywords: Building; construction; horizontal heat flux; soil temperature; urban area

ABSTRAK

Suhu tanah berhampiran empat dinding luar dengan orientasi yang berbeza telah dikaji pada musim bunga dan musim panas. Dalam kedua-dua musim, suhu tanah adalah lebih tinggi dalam kedudukan paling hampir dengan bangunan, menunjukkan bahawa bangunan adalah sumber haba untuk tanah di sekeliling mereka. Oleh itu, ia boleh mengesahkan terdapat pemindahan haba sisi antara tanah dan bangunan. Berdasarkan ini, plat fluks haba tanah telah ditubuhkan antara tanah dan bangunan untuk mengkaji fluks haba mendatar. Data menunjukkan variasi diurnal fluks haba mendatar dalam kedua-dua musim bunga dan musim panas. Untuk menentukan faktor yang mempengaruhi fluks haba mendatar dan untuk menyediakan asas untuk memahami mekanismenya, korelasi antara data daripada beberapa faktor meteorologi dan fluks haba mendatar telah dianalisis. Hasil kajian menunjukkan bahawa sinaran suria telah mempunyai hubungan yang signifikan dengan fluks haba mendatar ($p<0.0001$*) dalam mana-mana musim tunggal dan dalam dua musim yang dikaji. Selain itu, faktor meteorologi lain (sinaran bersih, suhu udara, kelembapan dan suhu tanah dan kelembapan) menunjukkan korelasi yang kuat dengan fluks haba mendatar pada skala yang diurnal sahaja. Pada skala masa bermusim, korelasi mungkin signifikan (*$p<0.0001$*) juga, tetapi pekali korelasi menurun terlalu ketara, seperti yang untuk suhu tanah, suhu udara dan kelembapan relatif. Sebagai alternatif, korelasi mungkin tidak signifikan (*$p>0.05$*), seperti untuk kelembapan tanah. Keputusan regresi ikut langkah menunjukkan bahawa kepentingan relatif faktor meteorologi adalah 48,63, 21,94, 14,44, 8.12 dan 6.87% masing-masing untuk radiasi solar, suhu tanah, suhu udara, kelembapan dan kelembapan tanah pada skala yang diurnal.*

Kata kunci: Fluks haba mendatar; kawasan bandar; pembinaan; suhu tanah

INTRODUCTION

In recent decades, rapid urbanization has taken place in China and the city is expanding unceasingly. The urban population accounted for 50% of the general population in China in 2011 and according to urban planning, it will reach 65% in the next two or three decades (Chen et al. 2015). Accelerated urbanization has caused deep impacts on urban climates (Pickett et al. 2008; Zhou et al. 2004), including the urban heat island effect (UHI). UHI occurs when the air temperature is higher in urban areas than in rural areas (Landsberg 1981; Oke 1982). The soil temperature is also higher in urban areas than rural areas (Shi et al. 2012; Tang et al. 2011; Turkoglu 2010). This phenomenon could be partly attributed to the heat impact caused by artificial facilities; soil that was close to artificial facilities, including buildings and roads, held a relatively higher temperature than the soil located at a distance from these facilities (Bogren & Gustavsson 1991; Delgado et al. 2007; Halverson & Heisler 1981; Yang 2006). Different soil and artificial facilities materials generated different thermal properties that resulted in different temperatures (Fan et al. 2008; Huang et al. 2003; Liu et al. 2011; Zhang et al. 2008). However, a higher soil temperature in urban area draws less attention than air temperature.

Previous research results implied that there was heat transfer between soil and artificial facilities, resulting in a higher soil temperature near the facilities. Some scholars reported that heat flow existed between soil and buildings when researching energy-saving construction and the indoor environment of buildings and some prediction models were generated (Dos Santos & Mendes 2006; Landman & Delsante 1987; Mihalakakou et al. 1995). Heat transfer from buildings to soil causes heat loss from the inside of buildings, meaning that the soil plays a role in cooling buildings and the soil temperature increases due to the heat flow from the buildings (Rees et al. 2000).

Many research results showed that the soil temperature was higher in cities and heat transfer existed between the soil and buildings, but few research results reported the changing pattern of horizontal heat flux at the surface soil layer between the buildings and soil and the factors influencing the horizontal heat flux. The purpose of this study was to fill this gap by focusing on the following: The comparison of the temperature of the surface soil layer (hereafter soil temperature) both near and far from buildings, including four different orientation-facing external walls; the changing process of horizontal heat flux between soil and buildings on a diurnal scale; and the meteorological factors that influenced the process. Only the combination of meteorological factors and thermal differences between the materials of the soil and buildings was considered in this research. The heat flow caused by anthropogenic heat was not considered, which has been a topic of previous studies.

There is a strong linear relationship between air temperature and land surface temperature, suggesting that land surface temperature is responsible for outdoor human thermal comfort. Therefore, only the temperature of the surface soil layer (0–2.5 cm) was considered in this study. Information about the changing process and pattern of horizontal heat flux between the soil and buildings at the surface soil layer, as well as its influencing factors, will help with understanding the formation of UHI and provide a basis for reducing UHI.

The General Situation of The Research Site

The research site is located between the 4th North Ring Road and 5th North Ring Road in the Haidian District in Beijing City, China, where the climate is hot and humid in summer and cold and dry in winter. The rainy season is usually between June and August. Spring is from March to May, summer is between June and August, autumn is between September and November and winter is between December and February.

The study area consisted of buildings, roads and green spaces (Figure 1(a)). The soil texture was loam, covered evenly by grass at the height of approximately 10 cm and compacted mildly due to regular mowing. The height of all the trees in the sample areas was less than 3 m and sunshine was not blocked by any trees, but it was blocked by buildings at different times for different direction-facing external walls.

Methods

Data Acquisition

Data of the soil temperature and moisture were acquired from a data logger with soil temperature sensors (with an accuracy of ± 0.2°C) and soil moisture sensors (with an accuracy of ± 3%). The sample interval was set to 30 s and the logging interval was set to 1 min. The arrangement of the soil temperature and moisture sensors was divided into two parts:

Part 1: All the soil temperature sensors were set at a depth of 0–2.5 cm (the length of sensor is 2.5 cm) and at 0 and 60 cm away from each building baseline of the different direction-facing external walls, as shown in Figure 1(b). The soil temperature around six buildings, 18 different orientation-facing external walls in total (there was a lack of green space at some external walls), was investigated for four days in the spring and summer. The temperature of the soil that was 0 cm from the building baseline represented the soil temperature that was close to the buildings, while the soil temperature that was 60 cm from the building baseline represented soil temperature that was far away from the buildings. The reason for this arrangement of soil temperature sensors is that the soil temperature changed significantly in the first 30 cm upon heating it for hours (Shao et al. 2006). Due to the limit of the number of sensors and data loggers, the soil temperature was investigated in different months, which included April and June for the south- and north-facing external walls, to represent spring and summer. The east– and west–facing external walls were investigated in March and July to represent spring and summer for these orientations.

Part 2: The soil temperature and moisture sensors were arranged at depths of 0–2.5 cm and 0–5 cm at the surface soil layer and 60 cm away from structures to avoid any influence from the buildings, for the same reason as that mentioned in Part 1. The soil temperature was investigated in March and July to represent spring and summer. The meteorological data were acquired from a portable weather station, which was set in the study area. The sensors of the weather station included solar radiation (with an accuracy of ± 3%), net radiation (with an accuracy of ± 5%), wind speed and direction (with an accuracy of ± 0.1 m/s and ±

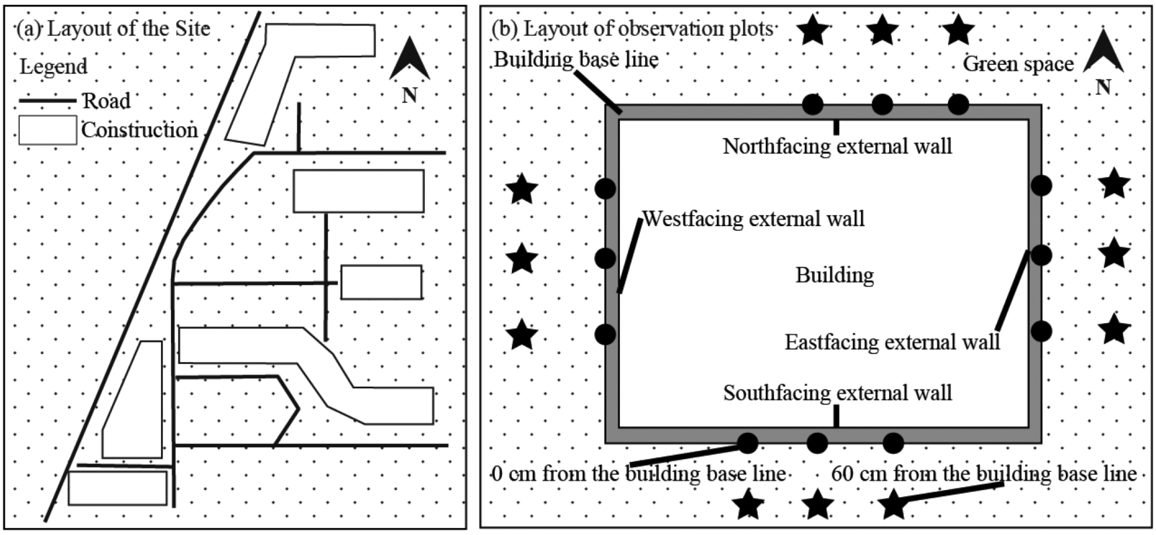

FIGURE 1. Arrangements of soil temperature and moisture sensors

5°), air temperature (with an accuracy of ± 0.5°C), and relative humidity (with an accuracy of ± 2%). All sensors were set at the height of 2 m above the ground surface, as shown in Figure 2. The sampling intervals were set to 1 min and the recording intervals were set to 10 min. The data in March represented the meteorological features in the spring, and the data in July represented the meteorological features in the summer.

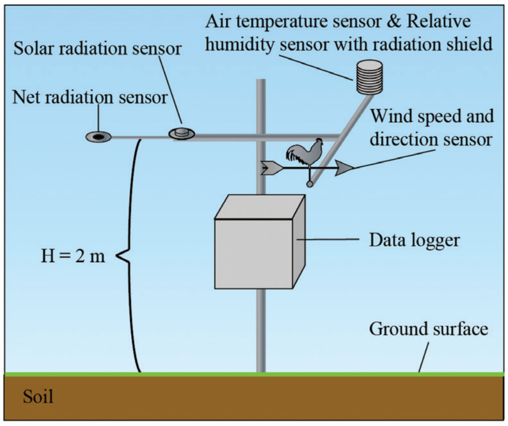

FIGURE 2. Weather station

The data of the construction-soil horizontal heat flux were acquired with a soil heat plate with a self-calibration function (with an accuracy of ± 5%), which was connected to the portable weather station. The soil heat flux plate was set between the construction and the soil and was placed 1 cm beneath the ground surface, with its up-side facing the building and its down-side facing the soil, as shown in Figure 3. The sampling interval was set to 1 min and the recording interval was set to 10 min. The data of the horizontal heat flux were collected in March and July to represent spring and summer.

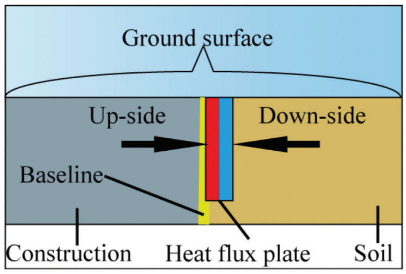

FIGURE 3. Soil heat flux plate setting

DATA PROCESSING

All the data were processed with the statistical software, SPSS (Version 17.0).

Spearman correlation analysis was used to analyse the correlation between the construction-soil horizontal heat flux (HHF) and meteorological factors, with a 95% confidence interval. Additionally, the correlation coefficients between the construction-soil horizontal heat flux and influencing factors were calculated.

Stepwise regression was adopted to determine the relative importance of the influencing factors and establish a regression equation of the construction-soil horizontal heat flux.

RESULTS AND DISCUSSION

COMPARISON OF SOIL TEMPERATURE CLOSE TO AND FAR AWAY FROM BUILDINGS

The soil temperatures of the same orientation-facing external walls (0 and 60 cm away from building baseline) were averaged and were recorded as T_C and T_F, respectively and their difference was recorded as ΔT. The results are shown in Table 1. For all four different direction-facing external walls, the soil temperature close to the buildings

TABLE 1. Comparison of soil temperature (T_C and T_F) in spring and summer

Orientation-facing	Spring			Summer		
	T_C (°C)	T_F (°C)	ΔT (°C)	T_C (°C)	T_F (°C)	ΔT (°C)
South	22.36	21.03	1.33	29.38	27.09	2.29
North	15.34	14.60	0.74	24.12	22.98	1.14
East	6.44	4.83	1.61	27.80	26.04	1.76
West	6.29	5.11	1.17	24.25	22.86	1.39

was higher than the soil temperature far away from the buildings in spring and summer.

The relatively higher soil temperature that was close to the buildings indicated that the buildings were a heat source for the adjacent soil and transferred thermal energy to the soil, increasing the soil temperature in both seasons. The direction of the horizontal heat flux is from the buildings to the soil.

DAILY CHANGE OF CONSTRUCTION-SOIL HORIZONTAL HEAT FLUX IN SPRING AND SUMMER

At the surface soil layer, the daily change of the construction-soil horizontal heat flux exhibited as wave curves in both the spring and summer, meaning the daily change patterns of the horizontal heat flux are similar in the two seasons. The construction-soil horizontal heat flux notably increased from morning to noon, whereas it decreased from noon to nightfall and decreased from nightfall to morning the next day, showing a gentle and steady trend.

As shown in Figure 4, the horizontal heat flux shares a similar variation on a diurnal scale. Nevertheless, the maximum and minimum values of the horizontal heat flux were different; the maximum and minimum were 92.12 and -12.72 W/m^2, respectively, in the spring and 106.92 and -26.82 W/m^2, respectively, in the summer. This indicated that a horizontal heat flux existed between the soil and the structure. For the soil, the structures played a role as a heat source the majority of the time and as a heat sink for a minority of the time. The change pattern of the horizontal heat flux is similar to the pattern of the vertical soil heat flux reported in previous research (Kustas & Daughtry 1990; Kustas et al. 2000).

THE RELATION BETWEEN CONSTRUCTION-SOIL HORIZONTAL HEAT FLUX AND METEOROLOGICAL FACTORS

The construction-soil horizontal heat flux and vertical soil heat flux share the same causation, which is a difference in soil temperature. The direction of the construction-soil horizontal heat flux flows from a position with a higher temperature to a position with lower temperature, in keeping with the second law of thermodynamics. The meteorological factors that influence the temperatures of the soil and the buildings could affect the temperature differences between them. Therefore, correlation analysis for the horizontal heat flux and meteorological factors was conducted and Spearman's correlation was applied.

SOLAR RADIATION AND NET RADIATION

The diurnal change of solar radiation is regular. If solar radiation is not blocked by clouds or other objects, it will

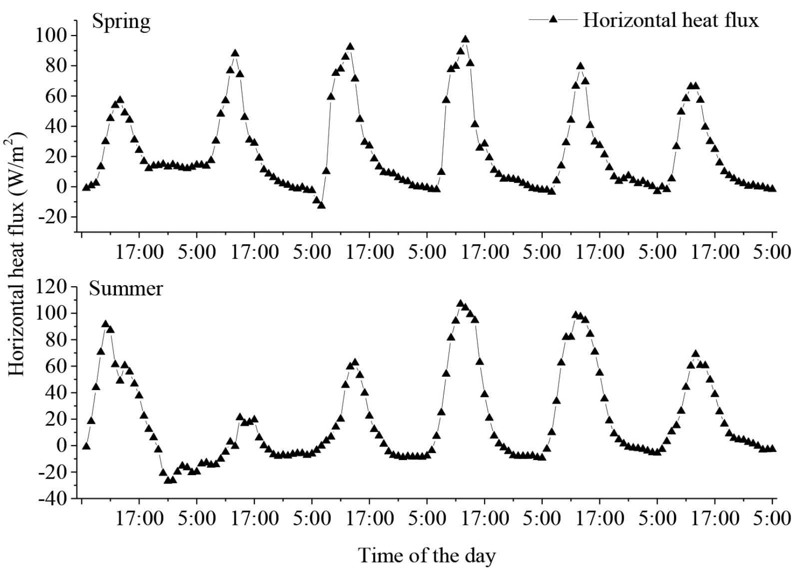

FIGURE 4. Diurnal change of horizontal heat flux

exhibit a wave variation that increases from sunrise to noon and decreases from noon to sunset in the day time, while maintaining a value of zero at night until sunrise.

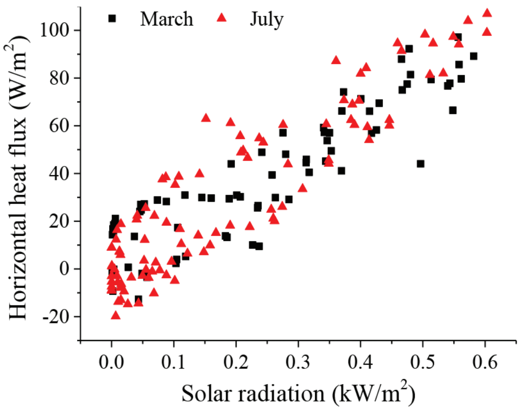

FIGURE 5. Scatter diagram of horizontal heat flux and solar radiation (spring and summer)

Based on the above description, a continuous data set of the horizontal heat flux and solar radiation was analysed with the Spearman correlation in spring and summer. In the spring, there was a significant correlation between the horizontal heat flux and solar radiation (p<0.0001) and the same situation was found in the summer (Figure 5). The correlation coefficients were 0.865 and 0.874 for the spring and summer, respectively.

Solar radiation is the most important energy source for the Earth, dominating the climate (Pang 1979). Hence, any factors that influence solar radiation in urban areas will change the micro-climate and micro-meteorology. They may also influence the temperature of the surface soil layer and surface structure and cause changes of the horizontal heat flux. Solar radiation plays a crucial role in the heat loss of buildings (Qu 2001). Most studies have focused on heat losses via external walls to the atmosphere or on the vertical soil heat flux. In contrast, few studies addressed the horizontal heat flux in which the soil was the subject of study. The vertical soil heat flux showed a very significant positive relationship with solar radiation (Idso et al. 1975). In this research, a similar trend and correlation were identified between the horizontal heat flux and solar radiation.

Solar radiation only exists in the daytime and decreases to 0 after sunset, whereas net radiation, which is defined as the solar radiation minus the long wave radiation, exists and can be detected all the time (Zhou et al. 1997). Due to malfunction of the net radiation sensor in a previous period, only the summer data were available for analysis.

On a diurnal scale, a significant positive relation between the horizontal heat flux and net radiation was found (p<0.0001, Figure 6); the correlation coefficient was 0.806.

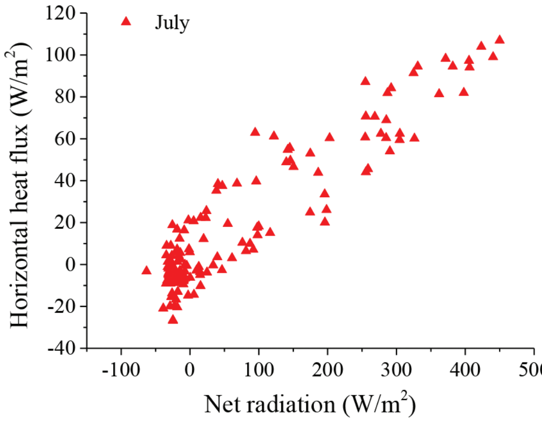

FIGURE 6. Scatter diagram of horizontal heat flux and net radiation (summer)

Similar to solar radiation, the vertical horizontal heat flux and net radiation shared a similar changing trend on a diurnal scale and there was a significant correlation between them (Idso et al. 1975; Santanello & Friedl 2003; Shi et al. 2012; Wei et al. 2014). Although this research studied the horizontal heat flux between soil and buildings rather than the vertical soil heat flux, a significant correlation between the horizontal heat flux and net radiation (p<0.0001) was found, which was similar to previous studies of vertical soil heat flux.

TEMPERATURE AND MOISTURE OF THE SURFACE SOIL LAYER

The temperature of the surface soil layer changes regularly; it increases rapidly after receiving solar radiation, reaches its maximum at noon, and then starts to decrease until sunrise the following day. Therefore, the horizontal heat flux was significantly correlated with the soil temperature (60 cm from building baseline) on a diurnal scale in both spring and summer (p<0.0001, Figure 7). The correlation coefficients were 0.702 for spring and 0.873 for summer.

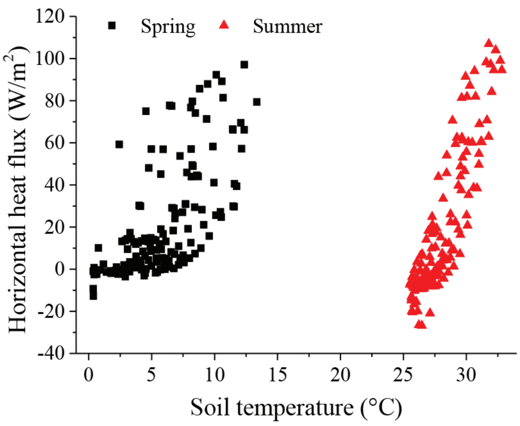

FIGURE 7. Scatter diagram of horizontal heat flux and soil temperature (spring and summer)

When analysing the data for spring and summer together, a significant correlation between the horizontal heat flux and the soil temperature ($p<0.0001$) was still found, but the correlation coefficient was only 0.298.

Vertical soil heat flux is considered as the main reason for changes of soil temperature, especially beneath the ground surface. This means that the change of soil temperature is dominated by vertical soil heat flux and there is a significant positive correlation between them (Sun et al. 2014). Moreover, the change of soil temperature can be used to estimate the vertical soil heat flux (Horton & Wierenga 1983). In this study, construction-soil horizontal heat flux was correlated with soil temperature on both a diurnal and seasonal scale. The difference between the two types of scale was observed in the correlation coefficients. The soil temperature was used to estimate the vertical soil heat flux (Norman et al. 1995), meaning soil temperature is a very important factor in determining the vertical soil heat flux. Our study also proved soil temperature is important to the horizontal heat flux; the soil temperature showed very good correlations to the horizontal heat flux on a diurnal scale, and the correlation between the soil temperature and horizontal heat flux was significant ($p<0.0001$).

On the pre-condition that the precipitation is zero, the diurnal moisture of the surface soil layer exhibits a fluctuating trend; it decreases in the daytime and rises at night. In spring, there was an extremely significant correlation between the construction-soil horizontal heat flux and the moisture of the surface soil layer ($p<0.0001$); the correlation coefficient was 0.602, as shown in Figure 8. However, a similar situation did not appear in summer. No significant correlation between the construction-soil horizontal heat flux and the moisture of surface soil layer was shown for the summer ($p>0.05$).

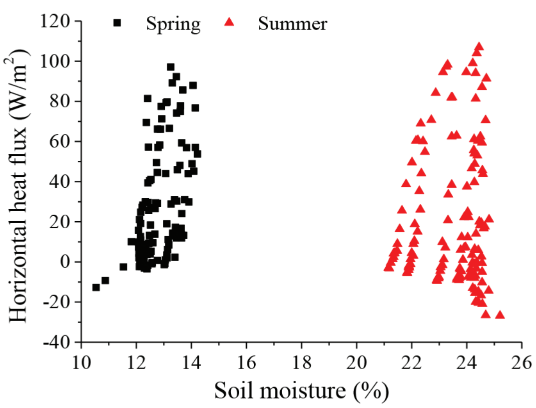

FIGURE 8. Scatter diagram of horizontal heat flux and soil moisture (spring and summer)

When analysing the data in spring and summer together, no significant correlation was found, based on the results ($p>0.05$).

Many studies have reported that the soil temperature and moisture could be used to estimate the vertical soil heat flux, meaning that the soil moisture influenced the vertical soil heat flux to some extent. The vertical soil heat flux was correlated with net radiation for every single month and the correlation coefficients differed from each other in every month and changed with the soil moisture. Both of these phenomena suggest that the soil moisture influenced the thermal properties of the soil and, thus, changed the correlation between the vertical soil heat flux and net radiation (Idso et al. 1975). In this study, the soil moisture was different in March and July. A significant correlation between horizontal heat flux and soil moisture was only found in March, which indicates that soil moisture is not the primary factor that influences the horizontal heat flux.

AIR TEMPERATURE AND RELATIVE HUMIDITY

The air temperature near the ground shares a similar changing pattern with the soil temperature; the air temperature rises rapidly after sunrise and achieves a maximum at noon and then falls until sunrise the next day. As shown in Figure 9, no matter whether in spring or summer, significant correlations between horizontal heat flux and air temperature were found ($p<0.0001$) and the correlation coefficients were 0.465 and 0.911 in spring and summer, respectively.

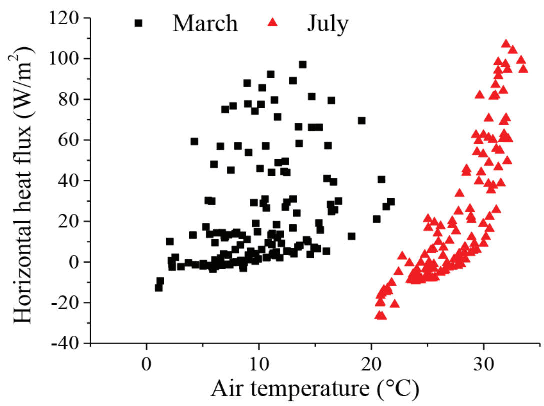

FIGURE 9. Scatter diagram of horizontal heat flux and air temperature (spring and summer)

Although the results in spring and summer showed that horizontal heat flux and air temperature were significantly correlated ($p<0.0001$) on a diurnal and seasonal scale, the correlation coefficient drops to 0.194, which represents 41.72% of its value in spring and 21.30% of its value in summer.

The relative humidity varied inversely with air temperature. It starts to decreases after sunrise, reaches a minimum at noon, and then begins to increase from noon to sunrise the next day. As shown in Figure 10, on a diurnal scale, the horizontal heat flux was significantly negatively correlated with the relative humidity in both spring and summer (p<0.0001). The correlation coefficients were -0.390 and -0.867 in spring and summer, respectively.

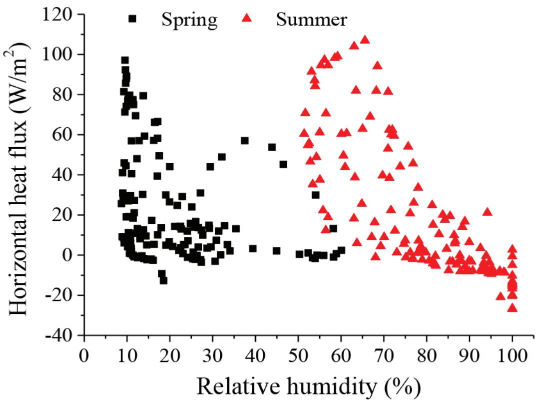

FIGURE 10. Scatter diagram of horizontal heat flux and relative humidity (spring and summer)

Similar to the air temperature, the relative humidity was significantly correlated with the horizontal heat flux on both the diurnal and seasonal scales. When analysing their correlation with the data in spring and summer taken together, a significant correlation was still found (p<0.0001) and the correlation coefficient was -0.487.

The air temperature and relative humidity exhibit a negative correlation on a diurnal scale and their variation trends are opposite (Zhou et al. 1997). Therefore, the results were very different. Regardless of the value of the air temperature or relative humidity, the correlation coefficient between the horizontal heat flux and each of these variables was lower on a seasonal scale than on a diurnal scale. These results showed that air temperature and relative humidity were non dominant factors for the horizontal heat flux between the constructions and soil (the correlation coefficient of air temperature was less than the correlation coefficient of solar radiation).

STEPWISE REGRESSION RESULTS

Because the data for the net radiation in spring was not available, only the data in summer were analysed with stepwise regression; the horizontal heat flux was considered as the dependent variable and other meteorological factors were considered as independent variables. F significance testing was set to 0.05 and 0.10, meaning that if the F significance of a factor was less than or equal to 0.05, it would be included in the regression equation; if the F significance of a factor was greater than 0.10, it would be excluded. After statistics testing, net radiation was excluded from the regression equation and other meteorological factors were included. The F-statistic was 895.802 and the significance level was 0.0000. Therefore, the correlation of the regression equation was extremely significant.

The stepwise regression results are shown in Table 2, where the unstandardized coefficient b is the multiplicative factor of each parameter in the regression model, whereas the standardized coefficient Beta is the indicator of the relative importance among the parameters (as the absolute value increases, the relative importance increases). The term Sig represents the statistical significance of the results.

Based on the result, the regression equation can be expressed as following equation:

$$HHF = 4.548 \times ST - 0.213 \times RH + 109.907 \times SR + 2.507 \times SM + 1.697 \times AT - 210.707. \tag{1}$$

Moreover, β can be used to represent the relative importance of the meteorological factors, as calculated in the following formula:

$$RI_i = \frac{|\beta_i|}{\sum_{i=1}^{n}|\beta_i|}, \tag{2}$$

where RI_i is the relative importance of the i-th meteorological factor.

The relative importance of all the investigated meteorological factors is shown in Figure 11.

TABLE 2. Stepwise regression results

	Unstandardized coefficients		Standardized coefficients	
	B	Std. Error	Beta (β)	Sig.
(Constant)	-210.707	33.695		0.000
ST	4.548	0.777	0.254	0.000
RH	-.213	0.103	-0.094	0.040
SR	109.907	4.990	0.563	0.000
SM	2.507	0.591	0.080	0.000
AT	1.697	0.626	0.167	0.008

HHF is the construction-soil horizontal heat flux (W/m^2), ST is soil temperature (°C), RH is relative humidity (%), SR is solar radiation (KW/m^2), SM is soil moisture (volumetric water content, %) and AT is air temperature (°C)

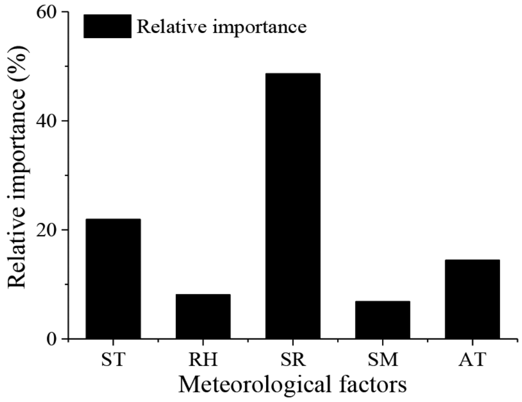

FIGURE 11. Relative importance of meteorological factors

The relative importance of the meteorological factors, in descending order, was solar radiation (48.63%), soil temperature (21.94%), air temperature (14.44%), relative humidity (8.12%) and soil moisture (6.87%).

CONCLUSION

In this research, the soil temperature near buildings and the horizontal heat flux between constructions and the soil were studied. In spring and summer, the temperature of the soil that was close to buildings was relatively higher than the temperature of soil that was far away. The diurnal periodicity of the horizontal heat flux between the constructions and the soil was showed, and its correlation with meteorological factors was studied and statistically analysed. The results showed that there are significant correlations between the horizontal heat flux between constructions and soil and most of the investigated meteorological factors ($p<0.0001$). Based on the statistical results, solar radiation was significantly correlated with the horizontal heat flux between constructions and the soil and the correlation coefficients were 0.893 in spring, 0.869 in summer and 0.874 for the two seasons. The relative importance of solar radiation was 48.63%, which ranked the highest among all the investigated meteorological factors, meaning solar radiation was the most important factor to influence the horizontal heat flux between constructions and soil. The relative importance of the soil temperature was 21.94% and ranked second among all the investigated meteorological factors. Other meteorological factors were covariant factors and influenced the horizontal heat flux between construction and soil indirectly.

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