Spatial variation of temperature of surface soil layer adjacent to constructions: A theoretical framework for atmosphere-building-soil energy flow systems

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Abstract

Lack of concern for spatial variation of urban soil temperature does not reflect the importance of soil temperature in ecosystem service. The method of construction-soil micro gradient transects (CSMGT) and in situ observations were applied in this study to understand the mechanism of higher soil temperatures in urban areas and the spatial variation of the temperature of surface soil layer adjacent to constructions. Based on experimental data, a new theoretical framework for atmosphere-building-soil energy flow systems was established to analyse the changing rate of the temperature of surface soil layer (RS) adjacent to constructions. The results of redundancy analysis and hierarchical partitioning showed horizontal heat flux between building and soil (HHF0) played a very important role in driving RS along the CSMGT at night, whereas joint effects of multiple energy factors drove it during daytime or on the scale of an entire day. Moreover, a formula was fitted to express the temperature of surface soil layer (TS) along the CSMGT. Each parameter (a, b and c) of the equation was significant relative to energy or meteorological factors (P < 0.01), and the distribution of the P value of parameter b matched the results of the redundancy analysis and hierarchical partitioning.

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1. Introduction

Urban soil is an important carrier of urban ecosystems and plays a crucial role in urban areas. Soil thermal environments relate to a citizen's daily life and many ecosystem processes [1,2]. In recent decades, accelerated global urbanization has changed surface properties significantly in urban areas, and a great quantity of buildings and roads made of concrete and asphalt have taken the place of original vegetation [3], forming unique micro-meteorological conditions. On the one hand, these structures provide human beings with places to conduct daily activities and convenient transportation options, making a highly effective urban system. On the other hand, a series of negative effects result from these structures, such as the urban heat island effect [4].

Due to being covered and sealed by impervious materials (asphalt, concrete and stone) [5], the physical, chemical and biological properties of soil are gradually changed by influences of structures and anthropogenic activities. Compacted and hardened soil is distributed widely in urban areas and most of the soil is isolated from the atmosphere, this type of soil limits gas effusion and rainfall infiltration, thus changing natural habitats. Moreover, energy transfer processes are changed by structures and anthropogenic activities [5]. Many scholars have reported an upward trend of soil temperature in urban areas [6–11] because of the synergistic action of multiple factors, such as energy flows within and between various spheres [5,12]. Soil temperature links many ecosystem processes and structures directly, such as food webs, soil heterotrophic respiration, microbial decomposition, nutrient
cycling, root respiration, and C and N mineralization [13–16]. Changes in soil thermal processes caused by structures and anthropogenic activities may lead to a degradation of soil ecological services. Thus, it is of great scientific significance to do researches on spatial variation of temperature of surface soil layer adjacent to constructions.

Gradient analysis is a traditional method used in ecological research. It has been applied in vegetation research [17] and in the analysis of urban landscape patterns [18]. In recent years, a wider scope regarding gradient analysis has been used, which has produced abundant results [19,20]. Therefore, gradient analysis can be appropriately applied to researches at an urban scale.

Numerous studies have focused on the relationship between air temperature and soil temperature [21,22], the process of how buildings lose heat to soil [13,23–25] and the response of the thermal performance of facades to external circumstances [26,27]. There have been few studies of the energy connections between the atmosphere, buildings and soil, and few studies that have considered exploring the spatial variation of soil temperature adjacent to buildings. Using gradient analysis, the aim of this research was to establish a preliminary theoretical framework for the atmosphere-building-soil energy flow system to study the horizontal spatial distribution of temperature of surface soil layer (T5) near to buildings facades in summer and to determine influencing factors. Additionally, an equation was fitted to express the relationship between the distance from a building and the T5 and influencing ecological and meteorological factors for the parameters of the equation were found out.

2. Method

2.1. Site condition

The research site is located in the Haidian District, Beijing City, China (40.008° N, 116.337° E). Summer is hot and humid in the region, with a sunshine duration of approximately 230 h per month. Several buildings, roads, and green spaces are distributed throughout the study area, which has loam soil (density of soil in study area is shown in Section S1 in the Supplemental Materials). The detailed situation for selected sample areas can be described as follows: most of the surface is evenly covered by grass (approximately 0.1 m in height), there are no large trees but some arbuscles were planted in the selected sample area, and sunshine is not blocked by any vegetation in this area.

2.2. Theoretical framework

This study focuses on the energy connections between the atmosphere, buildings and soil, referred to as the atmosphere-building-soil energy flow system. Fig. 1 shows energy flows in the atmosphere-building-soil system. In this research, not all energy flows were considered, only those marked as red arrows in Fig. 1, including solar radiation (SR), net radiation (NR), ground radiation (GR), atmospheric counter radiation (ACR), vertical soil heat flux (VHF), horizontal heat flux between building and soil (HHF0: 0 m from baseline) and horizontal heat flux in soil (HHF20: 0.2 m from baseline, HHF30: 0.3 m from baseline, and HHF60: 0.6 m from baseline).

Sensible heat flux (H) and latent heat flux (LE) are very important energetic factors that influence soil temperature very much, but they had to be ignored in this study, due to lack of relevant equipment to investigate them. The assessment of excluding sensible and latent heat flux from the theoretical framework was shown in the Section S2 in the Supplemental Materials. The result indicated that it did not influence the final conclusion without H and LE.

Fig. 1. Preliminary theoretical framework of atmosphere-building-soil energy flow systems.

2.3. Layout of the CSMGT

The scale of study changes with different research objects; hence, every study has to be conducted on an appropriate scale or it may lead to incorrect conclusions. Due to soil physical properties, soil temperature changes significantly at depths of 0.3–0.4 m on a diurnal scale [7,28]. Therefore, this research was conducted on a micro scale, with the gradient analysis scaled down the centimetre level. The construction-soil micro gradient transect (referred to as the CSMGT [29,30] henceforth) was considered appropriate for this research.

The green space next to one south facade was selected as the sample area for the experimental CSMGT. Observation points for soil temperature sensors were set as 0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.6, 0.9 and 1.5 m from the construction baseline respectively, where soil temperature were arranged (Fig. 2c). All observation points were in a straight line.

2.4. In situ observations

In situ observations are widely applied in ecological studies and often with reliable results [31–34]. We made in situ observations of T5 in this research. The entire observation period was divided into two phases. Phase I involved the analysis of changing rate of temperature of surface soil layer (TR) along the CSMGT and its influencing energy factors; a statistical approach was applied to explain the energy mechanisms of R5. Phase II involved fitting the data to an appropriate formula and determining which energy factors affect the parameters of the equation directly. The observation period and meteorological conditions are listed in Table 1.

Both phases included sunny days (with a total cloud cover less than 20%), partly sunny days (with a total cloud cover between 20% and 80%), cloudy days (with a total cloud cover greater than 80%) and rainy days.

T5 were observed with soil temperature sensors (unit: K, sensor accuracy: 0.2 K) and stored with data loggers. The arrangement of soil temperature sensor was shown in Section S3 in the Supplemental Materials. The sampling interval was 1 min, the logging interval was 10 min and data for each sensor were averaged for each hour (0-59th min). T5 at different observation points were recorded as T0, T5, T10, T15, T20, T30, T40, T50, T60 and T70. Soil temperature differences between two adjacent observation points (ΔT) were recorded as ΔT0, ΔT5, ΔT10, ΔT15, ΔT20, ΔT30, ΔT40, ΔT50 and ΔT60.

Most meteorological data were gathered and logged with a
A weather station that was placed by the authors, 5 m from the facade. Weather station sensors measured air temperature (unit: K, sensor accuracy: 0.25 K, 2 m above the ground surface), relative humidity (sensor accuracy: 2%, 2 m above the ground surface), SR (unit: W/m², sensor accuracy: 3%, 2 m above the ground surface), NR (unit: W/m², sensor sensitivity: 10 μV/W/m², 2 m above the ground surface), VHF (unit: W/m², sensor accuracy: 5%, 0.02 m beneath the ground surface, only during the Phase I), HHF₀ and HHF₂₀ (unit: W/m², sensor accuracy: 5%, 0.01 m beneath ground, 0 and 0.2 m from construction baseline respectively, upside faces to construction and downside faces to soil, only during Phase I, Fig. 2) and HHF₀, HHF₃₀ and HHF₆₀ (unit: W/m², sensor accuracy: 5%, 0.01 m beneath ground, 0, 0.3 and 0.6 m from construction baseline respectively, upside faces to construction and downside faces to soil, only during Phase II). The sampling interval was 1 min and the logging interval was 10 min.

Total cloud cover was obtained from the European Centre for Medium-Range Weather Forecasts, with an observation step of 6 h and logging timestamps of 2:00, 8:00, 14:00 and 20:00 Beijing time. The coordinates of the total cloud cover data were 40.000°N, 116.375°E, which was 3.39 km from the study site.

### 2.5. Calculation of ACR and GR

ACR was calculated by applying Weng’s method [35], shown as formula (1):

\[
ACR = \sigma T^4 \times \left[ 0.536 + 0.128 \ln(1 + E) \right] \left( 1 + 0.145n^2 \right) \tag{1}
\]

where \( \sigma \) is the Stefan-Boltzmann constant, \( T \) is air temperature (K), \( n \) is total cloud cover, and \( E \) is vapour pressure, calculated with formula (2):

\[
E = \frac{E_W}{\rho} \times RH \tag{2}
\]

where \( E_W \) is saturation vapour pressure and \( RH \) is relative humidity. \( E_W \) changes with air temperature and could have been calculated with formula (3) [36]:

\[
E_W = e \cdot \left( \frac{16.37379 - 1050.74}{T_a - 273.16} \right) \tag{3}
\]

where \( T_a \) is air temperature (°C).

However, due to a lack of continuous hourly observation data for...
total cloud cover, formula (1) was simplified as formula (4) [35]:

$$\text{ACR} = \sigma T^4 \times [0.536 + 0.128 \ln(1 + E)]$$

(4)

ACR was calculated based on formulas (2), (3) and (4).

GR was calculated as the SR minus the NR and then minus the ACR. NR was measured with a net radiometer. The output value of it is only the net radiation, not including the longwave or shortwave (downward and upward). While SR measured with a pyranometer, which investigated downward radiation only. Therefore, GR was calculated through “SR = NR – ACR”, meaning that only upward radiation was left and it included both the reflected solar radiation and thermal radiation from the ground.

2.6. Data processing

Curve fitting tools in Sigma Plot 10.0 were used to fit curves based on the available experimental data and to obtain the model parameters. The simulation results showed the P values for each parameter.

The non-parametric Spearman test in SPSS 17.0 was used to conduct correlation analysis between available $T_3$ data and meteorological factors data as well as between the parameters and the meteorological factors data.

Redundancy analysis aims to find one or a group of variables among many factors to explain significant environmental variation, meaning that the more one or a group of variables can explain the environmental variation, the higher the effect of contribution. In recent years, redundancy analysis was developed with the vegan package in R platform [37]. Many scholars have produced many important conclusions by using redundancy analysis in different fields [38–41].

The analytic hierarchy process is also a statistical analysis package (hier.part) that runs on the R platform. It has been applied successfully by many scholars in their research [42–44]. The analytic hierarchy process was used to analyse $R_S$ and energy factors in this research. By using this method, the contributions of different meteorological factors on $R_S$ were calculated.

The two-tailed T test in SPSS 17.0 was applied to verify that there were significant differences between the variable coefficients of $T_0$ and $T_{20}$ as well as between $T_0$, $T_{30}$ and $T_{60}$, with a confidence band of 95%.

3. Results

3.1. Spatial variance of $T_3$ along the CSMGT

By applying the mean $T_3$ in the observation period, the spatial distribution of $T_3$ is clearly observed; along the CSMGT, the slope of the curve is sharp at first and then turns flat (Fig. 3). Additionally, $\Delta T$ goes down with distance from the baseline (Fig. 3).

During the observation period, for the mean $T_3$, the highest value exhibited at the 0 m point (301.35 K) and the lowest value at the 1.5 m point (299.57 K); the gap between them was 1.77 K.

3.2. Correlation between $R_S$ and energy factors

In this study, $R_S$ is defined as a variable of spatial heterogeneity of $T_3$ along the CSMGT, indicating the spatial variation in $T_3$ with distance away from the baseline. $R_S$ is expressed as follows:

$$R_S = \Delta T_{0 - 20}/D$$

(5)

where $\Delta T_{0 - 20}$ is the difference between $T_0$ and $T_{20}$, and $D$ is the distance between $T_0$ and $T_{20}$; here $D$ is 0.2 m. Usually in this research, the value of $R_S$ (K/m) is expressed by an hour-scale calculation by formula (5).

Spearman correlation analysis was conducted between $R_S$ and various energy factors, including SR, NR, GR, ACR, HHF0, HHF20 and VHF in Phase I.

Table 2 shows the correlation coefficients between $R_S$ and the energy factors in Phase I; all factors chosen were extremely significantly correlated to $R_S$ ($P < 0.01$), positively for SR, NR, GR, ACR, HHF0 and VHF and negatively for HHF20.

3.3. Redundancy analysis

Based on different energy processes, energy factors were grouped into three categories: (1) Processes in the Atmosphere, including NR, GR and ACR; (2) Processes in Buildings, including HHF0 only; and (3) Processes in Soil, including VHF and HHF20 only in Phase I. SR data were used to differentiate daytime (SR > 0) with the night (SR = 0).

Phase I data were analysed by applying redundancy analysis; the result is exhibited in Fig. 4:

(1) For an entire day (Fig. 4a), the amount of variation captured by processes in the Atmosphere, Building and Soil was 80.56% for $R_S$, indicating that the theoretical framework for atmosphere-building-soil energy flow systems could explain 80.56% of the mechanism of $R_S$, the main reason for higher soil temperature next to facade was due to the theoretical framework. The undetermined variation could be attributed for factors not included in the theoretical framework. The decomposition of the variation showed that the largest fraction of the variability in $R_S$ was accounted for by the joint

### Table 2

| Energy factors | Correlation coefficient |
|----------------|-------------------------|
| SR             | 0.651**                 |
| NR             | 0.549**                 |
| ACR            | 0.196**                 |
| GR             | 0.725**                 |
| HHF0           | 0.869**                 |
| HHF20          | -0.388**                |
| VHF            | 0.711**                 |

Note: ** means correlation is significant at the 0.01 level.
effect of all three process groups (fraction g: 62.18%). The pure effect of each energy process was relatively low (fraction a, b and c: 2.71%, 1.88% and 9.28%, respectively), 13.86% in total. The joint effects of each pair of energy processes contributed 4.52% of RS in all (fraction d, e and f: 1.17%, 3.36% and 0.004%, respectively). These meant that all of energy processes did not act alone but in concert.

(2) For daytime (Fig. 4b), the amount of variation captured by processes in the Atmosphere, Building and Soil was 79.52% for RS, meaning that the 79.52% of variability could be explained with the theoretical framework and the rest 20.48% was not explained by the theoretical framework because of some energetic and environmental factors were not considered. The decomposition of the variation showed that the largest fraction of the variability in RS was accounted for by the joint effect of all the three process groups (fraction g: 54.60%). The pure effect of each energy process was relatively low (fraction a, b and c: 3.51%, 1.39% and 10.14%, respectively), 15.05% in total. The joint effects of each pair of energy processes contributed 9.87% of RS in all (fraction d, e and f: 1.76%, 8.12% and 0.004%, respectively). Similar with above consistent result, the three energetic processes work together.

(3) For night (Fig. 4c), the amount of variation captured by processes in the Atmosphere, Building and Soil was 82.80% for RS. It also suggested that the theoretical framework for atmosphere-building-soil energy flow systems accounted for 82.80% of the explanation. The decomposition of the variation showed that the largest fraction of the variability in RS was accounted for by the joint effect of all the three process groups (fraction g: 54.60%). The pure effect of each energy process was relatively low (fraction a and c: 7.42% and 2.68%, respectively), 10.10% in total. The joint effects of each of two energy processes contributed −3.12% of RS in all (fraction d, e and f: −4.56%, 1.47% and −0.001%, respectively). It indicated that soil process played a leading role on RS next to the south facade at night.

3.4. Hierarchical partitioning

By using the SR data, the observation was divided into daytime (SR > 0) and the night (SR = 0) to help our understanding of the roles the energy factors played at different times. The results of hierarchical partitioning were largely in accordance with those of redundancy analysis (Fig. 5).

(1) For an entire day (Fig. 5a and b), the independent explanatory power of each energy factor was 18.51%, 2.52%, 15.69%, 13.76%, 18.54% and 5.37% for NR, ACR, GR, HHF0, VHF and HHF20, respectively. Most of the explained variation was related to the joint effects of the variables (NR, GR, HHF0 and VHF; 43.90%, 39.60%, 36.44% and 44.58%, respectively), except for ACR and HHF20 (−0.50% and 0.47%). The decreasing order of the individual contributions of each energy factor was VHF (24.92%), NR (24.87%), GR (21.09%), HHF0 (18.50%), HHF20 (7.22%) and ACR (3.38%). The result meant these energy factors preferred working in concert, rather than taking effects alone. Therefore, no energy factors played a leading role in an entire day.

(2) For daytime (Fig. 5c and d), the independent explanatory power of each energy factor was 20.98%, 1.77%, 15.75%, 12.17%, 18.93% and 4.86% for NR, ACR, GR, HHF0, VHF and HHF20, respectively. Most of the explained variation was related to the joint effects of the variables (NR, GR, HHF0 and VHF; 42.77%, 37.55%, 31.29% and 43.36%, respectively), except for ACR and HHF20 (−0.50% and 0.47%). The decreasing order of the individual contributions of each energy factor was VHF (25.42%), NR (24.87%), GR (21.09%), HHF0 (18.50%), HHF20 (7.22%) and ACR (3.38%). The result meant these energy factors preferred working in concert, rather than taking effects alone. Therefore, no energy factors played a leading role in an entire day.

Fig. 4. Results of variation partitioning for RS. (Fraction a: pure effect of atmospheric process; fraction b: pure effect of building process; fraction c: pure effect of soil process; fraction d: joint effect of atmospheric process and building process; fraction e: joint effect of atmospheric process and soil process; fraction f: joint effect of building process and soil process; and fraction g: joint effect of the three processes.).

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For night (Fig. 5e and f), the independent explanatory powers of NR, ACR, GR, HHF0, VHF and HHF20 were 13.87%, 3.89%, 4.90%, 40.40%, 10.27% and 5.39%, respectively. Among all energy factors, HHF0 had the largest independent effect. Moreover, part of the explained variation was related to the joint effects of the variables (NR, GR, HHF0, VHF and HHF20; 14.02%, 3.53%, 18.78%, 12.25% and 6.99%, respectively), except for ACR (4.67%). The individual contribution of each energy factor was, in decreasing order, HHF0 (51.32%), NR (17.62%), HHF20 (13.04%), ACR (6.85%), GR (6.22%) and VHF (4.94%).

Different with above results, the situation changed at night; HHF0 played a dominant role on controlling the RS, due to its high independent and individual contribution.

Similar result was acquired next to a road in the study area (Section S4).

### 3.5. Curve fitting

Based on the spatial variation of TS next to the south facade, a formula for TS was generated as follows:

\[ TS = a \times \exp(-bx) + c \]  

(6)

where x is the distance from the construction baseline (m) and a, b and c are parameters of the equation. The formula represents the TS that is x metres from construction baseline. The formula was generated once for each hour of observation period in Phase II; 360 formulas were fitted using the experimental data in total.

R² for this fitting was distributed as shown in Table 3:

| R² | Frequency (%) |
|----|---------------|
| ≥0.95 | 44.17% |
| 0.90 ≤ R² < 0.95 | 18.61% |
| 0.80 ≤ R² < 0.90 | 14.44% |
| 0.70 ≤ R² < 0.80 | 5.83% |
| 0.50 ≤ R² < 0.70 | 3.89% |
| R² ≤ 0.50 | 13.06% |

In total, 77.22% of R² values were greater than 0.80 and usually appeared after nightfall and before midnight; whereas 13.06% of R² values were less than 0.50 and often appeared during dawn and before noon, or during or after rain.

The significance of each parameter (P value) was determined for three categories: (1) less than 0.01, (2) greater or equal to 0.01 and less than 0.05 and (3) greater or equal to 0.05. The frequency of the P value for each parameter is shown in Table 4.

Among the three parameters, parameter c shows the best fit, followed by a and b, respectively. P values for 95.84% of P_c were less than 0.05, and P values for 91.67% and 71.11% of P_a and P_b, respectively, were less than 0.05.

### 3.6. Relationship between three parameters and meteorological factors

Based on the R² value being lower during the rain or after the rain for a period of several hours, which was mentioned in section 3.5, all the data involved with rain were removed. Moreover, all data when the P value for parameter b was greater than 0.05 were also excluded. Thus, 221 groups of data remained for statistical analysis.

#### Table 4: Frequency of P value for the three parameters.

| P_a | P_b | P_c |
|-----|-----|-----|
| ≤0.01 | ≥0.01 and < 0.05 | ≥0.05 |
| 88.89% | 2.78% | 8.33% |
| 58.61% | 12.50% | 28.89% |
| 95.56% | 0.28% | 4.16% |
In applying the Spearman correlation analysis, the three parameters showed significant correlation \((P < 0.01)\) with the observed meteorological data (Table 5).

Linear regressions between the three parameters and observed meteorological data were conducted one by one. Parameter \(a\) and \(HHF_0\), parameter \(b\) and the square root of the absolute value of \(HHF_0\) and parameter \(c\) and air temperature had the best \(R^2\) values (Fig. 6). Additionally, the \(P\) value for each linear formula was less than 0.01.

As shown in Fig. 6, the three parameters were significantly relevant to meteorological factors \((P < 0.01)\) and were represented as follows:

\[
a = 0.056HHF_0 + 1.145
\]

\[
b = \begin{cases} 
0.82\sqrt{HHF_0} + 2.044 & (HHF_0 \geq 0) \\
-0.82\sqrt{HHF_0} + 2.044 & (HHF_0 < 0)
\end{cases}
\]

\[
c = 0.549T_a + 134.294
\]

4. Discussion

4.1. The source of horizontal heat flux

Usually, soil temperature is considered higher in urban areas because of anthropogenic heat. The seasonal or long-term high temperatures of urban infrastructure, such as sewage systems and heating pipes, leads to higher surrounding soil temperatures [45]. Moreover, subway tunnels increase surrounding soil temperatures by 5–10 K [46], and pipeline and cable tunnels make stable temperature fields in soil [47,48]. In addition, constructed objects such as buildings transfer heat from foundations [49,50]. Besides, anthropogenic heat could be the driving force that increases the temperature of shallow aquifers in urban areas [12,51].

The horizontal heat impacts studied in this research were not caused by anthropogenic heat. We attribute the main reasons for this as follows: there were different thermodynamic properties of building materials and soils, causing temperature differences between constructions and soil, which led to \(HHF_0\). A couple of scholars have performed research concerning the higher soil temperatures around structures [52–55]. Their research suggested that structures are heat sources for adjacent soil because of different thermal properties and the land cover between soil and structure materials. According to the China National Standard (GB50496-2009), the heat capacities of concrete is 920 J/(kg·K) and thermal conductivity of concrete is 1.74 W/(m·K). The heat capacity of soil changes with moisture (volumetric water content, VMC); the heat capacity of extremely dry soil is the same as concrete, whereas the heat capacity of soil at 50% of the VMC is 2093 J/(kg·K). Albedo, another physical property, is different for different materials, at 0.17 for soil and 0.37 for concrete [56]. Additionally, soil usually is covered by vegetation, while structures are not. The factors above dictate that the direction of \(HHF_0\) is transferred from a building to the surrounding soil.

4.2. The driver for spatial variation of \(T_s\) along the CSMGT

In this research, \(T_s\) was influenced by many energy factors, including NR, GR, AC, HHF0, HHF20 and HHF60. According to the results of redundancy analysis for the entire day, the joint effect of all three energy processes dominated \(R_e\). The pure effect of each energy process and the joint effect of each pair of energy processes were not greatly explanatory, especially the joint effect of processes in Building and Soil. For daytime, the result of the redundancy analysis is similar to the result of the redundancy analysis for the entire day. By contrast, the proportion of joint effects and pure effects changed at night. The energy processes in Building became the No. 1 dominant force driving \(R_e\), and the joint effect of the three energy processes ranked second; other joint effects and pure effects played relatively minor roles. The results of hierarchical partitioning were similar to the results of redundancy analysis; none of the chosen energy factors played a dominant role influencing \(R_e\) for the entire day and for daytime, while the situation became different for night. \(HHF_0\) played a dominant role, with its individual contribution exceeding that from all other energy factors. The results of both redundancy

Table 5
Correlation between the three parameters and meteorological data.

| Correlation Coefficient | SR | NR | GR | HHF0 | HHF30 | HHF60 | Ta |
|-------------------------|----|----|----|------|-------|-------|----|
| Parameter a             | 0.409**| 0.317**| 0.425**| 0.790**| 0.338**| 0.326**| 0.649**|
| Parameter b             | 0.555**| 0.496**| 0.457**| 0.897**| 0.561**| 0.509**| 0.780**|
| Parameter c             | 0.705**| 0.777**| 0.408**| 0.848**| 0.840**| 0.771**| 0.946**|

Note: ** means correlation is significant at the 0.01 level.
analyses and hierarchical partitioning show that Rs was affected synthetically by energy factors for the entire day and for daytime, but was mainly influenced by HHF0 at night.

Based on the evidence presented, horizontal heat flux is a key energy factor causing variation in Rs. However, HHF0 contributed more effects than HHF20. To further demonstrate this observation, the variable coefficients of T0 and T20 were sampled every 24 h in Phase I and analysed by T-test to isolate significant differences; the confidence band was 95%. The result of T-tests showed there were significant differences between the variable coefficients of T0 and T20 (P < 0.05). Moreover, the diurnal change of HHF0 and HHF20 exhibited the same evidence (Fig. 7a). The same method was applied in Phase II to examine the significant differences among the variable coefficients of T0, T30 and T60. The results of T-tests showed clearly that the variable coefficient of T0 was significantly different from variable coefficients of T30 and T60 (P < 0.05), whereas there was no significant difference between variable coefficients of T30 and T60 (P > 0.05). Additionally, the diurnal change of HHF0, HHF30 and HHF60 showed the same evidence (Fig. 7b). All of the evidence shows that HHF0 played a crucial role in driving Rs.

4.3. Meanings of parameters

Formula (6) can be used to express TS along the CSMGT, with parameters a, b and c representing different meanings, as follows:

(1) If x is a very large value, formula (6) is close to parameter c, which means that parameter c is considered to be the Ts that is not influenced by HHF0. Moreover, soil temperature shows a very good correlation with air temperature in past research [57]. In this study, a similar situation was found between parameter c and air temperature (Fig. 6c). Due to formula (6) being used to express Ts, it could be inferred that the parameter c is the Ts in urban area, which is beyond the range of influence caused by HHF0.

(2) If x is equal to zero, then formula (6) is equal to “a + c”. Parameter c is affirmed as the Ts in urban areas, which is beyond the range of influence caused by HHF0 in this study, and parameter a is considered to be the difference of Ts between the baseline and the area that is not influenced by HHF0 on a diurnal scale. The soil temperature difference is the reason for soil heat flux; the higher the soil temperature difference, the greater the soil heat flux, and vice versa. In this study, parameter a shows a positive and linear correlation with HHF0, demonstrating the above inference.

(3) Parameter b, is considered to be a coefficient which is related to the differences of Ts and the thermal conductivity of soil. Heat flux can be calculated by the following formula:

\[ q = -\frac{\lambda \, dt}{dx} \]  

(10)

where dt/dx is the change rate of soil temperature and \( \lambda \) is the thermal conductivity of soil. Parameter b shows a positive linear correlation with the square root of HHF0 (q in formula (10)). Therefore, parameter b is considered to be a variable that correlates to the change rate of soil temperature and thermal conductivity of soil.

4.4. P value of parameter b

According to section 3.5, parameters a and c showed very good statistical fits (95.84% of Pc and 91.67% of Pa are less than 0.05), whereas parameter b showed a relatively high sensitivity to the meteorological environment, especially to drastically changing energy flows, as follows:

(1) As shown in Fig. 8, when Pb was less than 0.01, high frequency was observed between 16:00 and 0:00 (from sunset to midnight), and low frequency was observed between 7:00 and 11:00 (from sunrise to noon).

(2) When Pb was greater than 0.05, the opposite situation occurred: high frequency was observed between 6:00 and 11:00 (from sunrise to noon), and low frequency was observed between 18:00 and 0:00 (from sunset to midnight) (Fig. 8).

(3) When Pb is between 0.01 and 0.05, the frequency distribution exhibited no regular pattern.

All the evidence showed that formula (6) resulted in a good fit after noon and before dawn. The distribution of frequency of Pb is largely in accordance with the former results of redundancy analysis and hierarchical partitioning; HHF0 played a dominant role at night rather than during the day.

5. Conclusion

By applying the method of CSMGT with in situ observations, a new theoretical framework of atmosphere-building-soil energy flow systems was established to observe and analyse spatial variations of Ts adjacent to constructions. Combining various statistical approaches, several conclusions were determined, and they support each other. Based on the established theoretical framework.

Fig. 7. Comparison between horizontal heat fluxes.

Fig. 8. Distribution of Pb on a diurnal scale.
and statistical results, this study concludes that:

(1) RS is relative to multiple meteorological factors. Energetic processes in the atmosphere, buildings and soil can explain over 80% of the RS along the CSMGT, no matter if over an entire day, in the daytime, or at night. The three energy processes play different roles in driving the RS along the CSMGT for different periods of time. For an entire day and during the daytime, the combination of the three energy processes dominates RS, explaining 61.64% and 54.24% of the variation over the entire day and during daytime, whereas the building processes drive RS at night, explaining 43.26% of the variation.

(2) The six energy factors play different roles in driving the RS through an entire day, in daytime, and at night. For the entire day, various energy factors drive the RS jointly (49.63%, 19.97%, 48.01%, 46.12% and 51.02% for NR, AC, GR, HHF0 and VHF, respectively), and no single factor plays a dominant role (20.29%, 18.32%, 14.31% and 19.12% for NR, GR, HHF0 and VHF, respectively). For daytime, the situation is similar; joint effects were 46.92%, 15.34%, 44.24%, 35.15% and 48.22% for NR, AC, GR, HHF0 and VHF, respectively. At night, the independent effect of HHF0 (44.69%) plays a key role in driving the RS, whereas other factors play subordinate roles (12.62%, 12.62%, 23.86%, 16.73% and 6.52% for NR, GR, VHF HHF0, and AC, respectively).

(3) Along the CSMGT next to the south facade, TS changes with the distance from the construction baseline and the relationship between them can be represented by $T_s = a \times \exp(-bx) + c$. This equation was used to express a kind of relation between TS and energetic factors and it was reliable next to the south facade in summer, if no precipitation happens. Parameters a, b and c were correlated with energy and meteorological factors significantly, positively and linearly ($P < 0.001$). For the surface soil layer next to the south facade, parameter a can be calculated by $a = 0.056H_{HF0} + 1.145$; parameter b can be calculated by $b = 0.82\sqrt{HHF0} + 2.044$ (HHF0 $\geq 0$) or $b = -0.82\sqrt{HHF0} - 2.044$ (HHF0 < 0); and parameter c can be calculated by $c = 0.549T_s + 134.294$. Parameter a is considered to be the differences of TS between the construction baseline and areas that are not influenced by HHF0; parameter b is considered to be a coefficient related to the difference of TS and the thermal conductivity of soil; and parameter c is identified as the TS that is not influenced by HHF0. All these equations suggested the relation between the parameters and energetic factors.

In this paper, research was reported on the specific mechanisms for spatial variation of the temperature of surface soil layer adjacent to buildings, but further quantitative analyses are needed to for deep soil layers. Additionally, more energy flows need to be considered to improve the theoretical framework of atmosphere-building-soil energy flow systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2017.08.002.

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