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 (R_s) adjacent to constructions. The results of redundancy analysis and hierarchical partitioning showed horizontal heat flux between building and soil (HHF_0) played a very important role in driving R_s 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 (T_s) 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

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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 the temperature of surface soil layer (T_s) next to building 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 T_s 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 was 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 T_s 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 (R_s) along the CSMGT and its influencing energy factors; a statistical approach was applied to explain the energy mechanisms of R_s . 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.

T_s 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). T_s at different observation points were recorded as T_0 , T_5 , T_{10} , T_{15} , T_{20} , T_{30} , T_{40} , T_{60} , T_{90} and T_{150} . Soil temperature differences between two adjacent observation points (ΔT) were recorded as ΔT_0 , ΔT_5 , ΔT_{10} , ΔT_{15} , ΔT_{20} , ΔT_{30} , ΔT_{40} , ΔT_{60} and ΔT_{90} .

Most meteorological data were gathered and logged with a

Fig. 2. Layout of the CSMGT and weather station arrangement. (a) location of CSMGT and weather station; b. South facade of selected building; c. Layout of the CSMGT; d. Arrangement of soil heat flux plate during the Phase I; e. Arrangement of soil heat flux plate during the Phase II; f. Weather station and its sensors.)

Table 1

Weather condition during the two observations.

Phase I	June					July									
Date	27	28	29	30	1	2	3	4	5	6					
TCC (%)	11	33	99	43	61	80	73	69	48	58					
SR _m (W/m ²)	475	461	333	321	186	75.7	123	270	272	161					
Ta-max (K)	307	309	308	308	304	299	303	306	305	305					
Ta-min (K)	294	297	298	298	294	294	297	297	298	298					
P (mm)	0	0	0	0	0	48.1	0	0	0	0					
Phase II August															
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TCC (%)	25	21	50	81	99	44	28	16	20	8	54	76	48	3	7
SR _m (W/m ²)	184	234	178	45	300	424	406	315	311	455	426	342	72	440	414
Ta-max (K)	307	309	309	301	307	309	307	306	306	308	308	307	298	305	307
Ta-min (K)	299	300	299	293	294	295	296	296	292	294	295	294	291	292	294
P (mm)	0	0	0.5	16.2	0	0	0	0	0	8	0	0	20	0	0

Note: TCC is total cloud cover, SR_m is mean solar radiation, Ta-max is the maximum air temperature, Ta-min is the minimum air temperature and P is precipitation.

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):

$$ACR = \sigma T^4 \times [0.536 + 0.128 \ln(1 + E)] (1 + 0.145n^2) \quad (1)$$

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

$$E = E_w \times RH \quad (2)$$

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]:

$$E_w = e^{\left[\frac{16.37379 - \frac{38763.659}{T_a + 229.73}}{T_a} \right]} \quad (3)$$

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]:

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

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_s 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_s along the CSMGT

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

During the observation period, for the mean T_s , 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_s along the CSMGT, indicating the spatial variation in T_s with distance away from the baseline. R_s is expressed as follows:

$$R_s = \Delta T_{0-20}/D \quad (5)$$

where ΔT_{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

Fig. 3. Spatial variance of T_s and ΔT .

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% 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

Correlation coefficient between R_s and energetic factors.

Energy factors	Correlation coefficient
SR	0.651**
NR	0.549**
ACR	0.196**
GR	0.725**
HHF ₀	0.869**
HHF ₂₀	−0.388**
VHF	0.711**

Note: ** means correlation is significant at the 0.01 level.

Fig. 4. Results of variation partitioning for R_s . (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.).

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 R_s 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 R_s , 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 R_s 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 R_s 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 R_s . 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 R_s was accounted by the Building process (fraction b; 43.72%), then by the joint effect of all the three process groups (fraction g; 32.10%). The pure effect of the other two energy processes 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 R_s 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 R_s 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 (-1.68% and -2.08%). The individual contributions of each energy factor were, in decreasing order, NR (28.18%), VHF (25.42%), GR (21.15%), HHF₀ (16.35%), HHF₂₀ (6.53%) and ACR (2.37%). Similar with above, at daytime no energy factors dominated the R_s and it was an effect of multiple-factor.

Fig. 5. Independent, joint and individual contributions of each energy factors. (* means significance at the 0.05 level.). (a) and (b) denote the result for an entire day, (c) and (d) denote the result for day time, and (e) and (f) represent the situation of night. Note: **Independent contribution** is the part that a single factor takes effect solely. Usually, the sum of independent contribution is less than or equal to 1. **Joint contribution** is the part a single factor takes effect with other factors. **Individual contribution** of one single factor is made up of 2 parts. One is independent contribution of one single factor and the other is the part of joint contribution that the single factor makes.

(3) 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 (−3.67%). 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 R_s, 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 T_s next to the south facade, a formula for T_s was generated as follows:

$$T_s = a \times \exp(-bx) + c \quad (6)$$

where x is the distance from the construction baseline (m) and a, b and c are parameters of the equation. The formula represents the T_s 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:

Table 3
Frequency of R² for the fitting formula.

R ² ≥ 0.95	0.90 ≤ R ² < 0.95	0.80 ≤ R ² < 0.90	0.70 ≤ R ² < 0.80	0.50 ≤ R ² < 0.70	R ² < 0.50
44.17%	18.61%	14.44%	5.83%	3.89%	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.

	<0.01	≥0.01 and < 0.05	≥0.05
P _a	88.89%	2.78%	8.33%
P _b	58.61%	12.50%	28.89%
P _c	95.56%	0.28%	4.16%

Table 5

Correlation between the three parameters and meteorological data.

Correlation Coefficient	SR	NR	GR	HHF ₀	HHF ₃₀	HHF ₆₀	T _a
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.

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 HHF₀, parameter b and the square root of the absolute value of HHF₀ 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:

$$a = 0.056\text{HHF}_0 + 1.145 \quad (7)$$

$$b = \begin{cases} 0.82\sqrt{|\text{HHF}_0|} + 2.044 & (\text{HHF}_0 \geq 0) \\ -0.82\sqrt{|\text{HHF}_0|} + 2.044 & (\text{HHF}_0 < 0) \end{cases} \quad (8)$$

$$c = 0.549T_a + 134.294 \quad (9)$$

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 HHF₀. 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 $920 \text{ J} \cdot (\text{kg} \cdot \text{K})^{-1}$ and thermal conductivity of concrete is $1.74 \text{ W}/(\text{m} \cdot \text{K})$. 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 $2093 \text{ J} \cdot (\text{kg} \cdot \text{K})^{-1}$. 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 HHF₀ 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, ACR, HHF₀, VHF and horizontal heat flux in soil (HHF₂₀, HHF₃₀ and HHF₆₀). According to the results of redundancy analysis for the entire day, the joint effect of all three energy processes dominated R_s . 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_s , 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_s for the entire day and for daytime, while the situation became different for night. HHF₀ played a dominant role, with its individual contribution exceeding that from all other energy factors. The results of both redundancy

Fig. 6. Linear relation between parameters and meteorological factors.

analysis and hierarchical partitioning show that R_5 was affected synthetically by energy factors for the entire day and for daytime, but was mainly influenced by HHF_0 at night.

Based on the evidence presented, horizontal heat flux is a key energy factor causing variation in R_5 . However, HHF_0 contributed more effects than HHF_{20} . To further demonstrate this observation, the variable coefficients of T_0 and T_{20} 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 T_0 and T_{20} ($P < 0.05$). Moreover, the diurnal change of HHF_0 and HHF_{20} exhibited the same evidence (Fig. 7a).

The same method was applied in Phase II to examine the significant differences among the variable coefficients of T_0 , T_{30} and T_{60} . The results of T-tests showed clearly that the variable coefficient of T_0 was significantly different from variable coefficients of T_{30} and T_{60} ($P < 0.05$), whereas there was no significant difference between variable coefficients of T_{30} and T_{60} ($P > 0.05$). Additionally, the diurnal change of HHF_0 , HHF_{30} and HHF_{60} showed the same evidence (Fig. 7b). All of the evidence shows that HHF_0 played a crucial role in driving R_5 .

4.3. Meanings of parameters

Formula (6) can be used to express T_5 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 T_5 that is not influenced by HHF_0 . 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 T_5 , it could be inferred that the parameter c is the T_5 in urban area, which is beyond the range of influence caused by HHF_0 .
- (2) If x is equal to zero, then formula (6) is equal to “a + c”. Parameter c is affirmed as the T_5 in urban areas, which is beyond the range of influence caused by HHF_0 in this study, and parameter a is considered to be the difference of T_5 between the baseline and the area that is not influenced by HHF_0 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 HHF_0 , demonstrating the above inference.

- (3) Parameter b, is considered to be a coefficient which is related to the differences of T_5 and the thermal conductivity of soil. Heat flux can be calculated by the following formula:

$$q = -\lambda \frac{dt}{dx} \quad (10)$$

where dt/dx is the change rate of soil temperature and λ is the thermal conductivity of soil. Parameter b shows a positive linear correlation with the square root of HHF_0 (q in formula (10)). Therefore, parameter b is considered to be a variable that correlates to the change rate of soil temperature and the 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 P_c and 91.67% of P_a 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 P_b 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 P_b 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 P_b 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 P_b is largely in accordance with the former results of redundancy analysis and hierarchical partitioning; HHF_0 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 T_5 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 P_b on a diurnal scale.

and statistical results, this study concludes that:

- (1) R_s is relative to multiple meteorological factors. Energetic processes in the atmosphere, buildings and soil can explain over 80% of the R_s 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 R_s along the CSMGT for different periods of time. For an entire day and during the daytime, the combination of the three energy processes dominates R_s , explaining 61.64% and 54.24% of the variation over the entire day and during daytime, whereas the building processes drive R_s at night, explaining 43.26% of the variation.
- (2) The six energy factors play different roles in driving the R_s through an entire day, in daytime, and at night. For the entire day, various energy factors drive the R_s jointly (49.63%, 18.97%, 48.01%, 41.62% and 51.02% for NR, ACR, 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, ACR, GR, HHF₀ and VHF, and independent effects were 20.29%, 18.03%, 12.46% and 19.29% for NR, GR, HHF₀ and VHF, respectively. At night, the independent effect of HHF₀ (44.69%) plays a key role in driving the R_s , while other factors play subordinate roles (12.62%, 12.62%, 23.86%, 16.73% and 6.52% for NR, GR, VHF, HHF₂₀, and ACR, respectively).
- (3) Along the CSMGT next to the south facade, T_s 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 T_s 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 $a = 0.056\text{HHF}_0 + 1.145$; parameter b can be calculated by $b = 0.82\sqrt{|\text{HHF}_0|} + 2.044$ ($\text{HHF}_0 \geq 0$) or $b = -0.82\sqrt{|\text{HHF}_0|} + 2.044$ ($\text{HHF}_0 < 0$); and parameter c can be calculated by $c = 0.549T_a + 134.294$. Parameter a is considered to be the differences of T_s 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 T_s and the thermal conductivity of soil; and parameter c is identified as the T_s 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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