Abstract: There is a lot of research on the urban thermal environment, mainly on air temperature. However, fewer studies focus on soil temperature that is influenced by built environment, especially on the horizontal heat impacts from buildings. In this research, soil temperature was investigated at different depths in Beijing, China, to compare the differences between two locations. One was next to the building and the other was far away from the building (10 m). The locations are referred to as site A and site B, respectively. These two sites were chosen to compare the differences in soil temperatures between them to present the horizontal heat impact from facade. The results show that facades caused horizontal heat impacts on the soil at different depths in the winter, spring, and summer. Basically, facades functioned as heat sources to the soil surrounding them. The mean temperature differences between the two sites were 3.282, 4.698 and 0.316 K in the winter, spring and summer, respectively. Additionally, the thermal effects of the buildings were not only exhibited as higher soil temperatures but the temporal appearance of the maximum and minimum temperature was also influenced. Buildings functioned as heat sources to heat soil in the winter and spring and stabilized soil temperature so that it would not fluctuate too much in the summer. Additionally, the coefficient of variation indicates that buildings primarily increased the soil temperature in the winter and spring and stabilized the soil temperature in the summer.

Keywords: underground urban heat island; soil temperature; construction; facade; thermal process; thermal pollution

1. Introduction

Global warming seems to be an unreturnable trend, it is said that the average air temperature is going to increase by 2–4.9 °C by the end of the 21st century [1]. Also, heat waves happened more and more frequently in recent years [2] and, as a result, a lot of people were killed. Furthermore, the situation is worse in urban areas. Due to rapid urbanization in China, more and more buildings are constructed in cities, causing a densely built-up environment in urban areas. Consequently, solar radiation capture is increased and natural ventilation is decreased by these dense buildings [3,4]. Then a series of urban issues have emerged, such as urban heat island effects, air pollution, and increased energy consumption [4,5], all of these issues are to be solved. Urban heat island effects have been a research hotspot for decades [6] and have been determined by scholars to be the results of artificial
surfaces and anthropogenic heat due to urbanization. Some of the factors mentioned above lead to changes in radiation and energy budget and then higher air temperature in urban areas. In recent years, scholars started to notice that in urban areas temperature did not only rise in the atmosphere but also in soil and groundwater. Since then, underground urban heat islands have drawn more attention in academia. Underground urban heat islands demonstrate that soil temperature is higher in urban areas than in rural areas and the temperature of underground aquifers has increased abnormally in Asia, North America and Europe [7–13].

There is plentiful research on the urban heat island effect, and underground urban heat island effect is receiving more attention. Compared with atmospheric and underground studies, research on surface soil layer is still lacking, but it happens to be the most active area where energy exchanges and relates to the eco-environment and the lives of residents. Current research indicates that urbanization causes higher soil temperature in cities, but few studies concern heat impact from buildings and other infrastructure. Nevertheless, heat impacts caused by the infrastructure are not negligible [14,15]. For example, groundwater temperature has risen in Cologne (Germany), due to increased downward heat flux in urban areas. However, the horizontal heat flux has not been considered [16], while there is some evidence that it could be attributed to horizontal heat flux from surrounding buildings [17].

There was, in fact, horizontal heat flux between buildings and soil, causing a gradient distribution of soil temperature next to buildings [18–20]. Distribution of soil temperature was simulated, and the most optimal thermal barrier arrangement was figured out via interzone temperature profile estimation (ITPE) technique, indicating buildings were a heat source for the soil [21]. Stable temperature field was simulated around buildings by using computer simulation, also indicating the same process mentioned above [22]. Echoing previous studies, buildings lose heat via the soil, suggesting that the soil is a heat sink for construction [23].

Constructions are important factors that contribute thermal energy to the atmosphere, helping with the formation of urban heat island effects. Meanwhile, all the above research demonstrates that buildings are considered a heat source for the ground, providing soil with thermal energy. Thus, the atmospheric and underground spaces were studied adequately. However, there is a gap, the surface soil layer, between the atmosphere and underground, needs to be studied to fill. Although some research referred to the thermal influence of buildings on the surface soil layer, there is still a lack of research studying the process for different seasons. While Zhou’s study was conducted over the course of changing seasonality and also discovered diurnal patterns of horizontal heat impact [18], it focused primarily on the very surface soil layer (0–0.025 m) and lacked research on deeper soil layer (beneath 0.025 m). The present study expands the scope of research and fills up the gap to some extent. It focuses on the soil temperature difference between sites that are next to a building and also far away from the construction, in order to acquire the degree and pattern of heat impacts caused by buildings at various depths of soil layer in different seasons.

2. Materials and Methods

2.1. Study Area

The study area was located in the Haidian District in Beijing City, China (Figure 1). Beijing belongs to a monsoon-influenced humid continental climate. Winter lasts from December to February, spring lasts from March to May and summer is between June and August.

In the study area, urban buildings and paths were scattered, while the loam texture soil was evenly covered with 10-cm grass, no large trees were planted, and only a few small trees had grown to a height of less than three meters. Sunshine was not significantly blocked by any of the trees in the sample area. The soil conductivity was between 0.96 and 1.36 W s⁻¹·m⁻¹, which was determined with a thermal property analyzer. Therefore, the influence of land cover and soil composition was too limited to affect the results of observation.
The selected building in this study had seven floors, was 34 m in height, and was used as a chemical laboratory. No external air conditioning units were located on the facade, where sensors were arranged. Several windows were distributed as a vertical straight line.

2.2. Data

This study was conducted in three seasons; 23 January–13 February 2014 for winter, 18 March–4 April 2014 for spring, and 17–27 July 2014 for summer. The top surface layer of soil (0–0.30 m) was investigated in this study, where the energy exchange was very active. The scope of heat impact was limited to the first 0.30 m of soil at the diurnal scale [24], meaning that the heat from the sun and other sources relevant to the sun penetrated the soil at a level of 0.30 m at the depth only from the surface on a diurnal scale. Therefore, the surface soil layer (0–0.30 m) was chosen as the object of the study.

Soil data were collected with soil temperature sensors (with an accuracy of ± 0.2 K) and stored with data loggers. The sampling interval was set to 30 secs, and the logging interval was set to one minute. The observed data were averaged every ten minutes for each sensor (0th–9th, 10th–19th, 20th–29th, 30th–39th, 40th–49th, 50th–59th). Thus, six numerical values were obtained for each sensor every hour, which represented one sample, and processed as an observation group every hour (0–59th minute). The number of samples for each sensor was 3024 in the winter, 2448 in the spring, and 1440 in the summer.

The soil temperature sensors were set as shown in Figure 2. According to Zhou’s results, a single facade causes a corresponding heat impact on the surrounding surface soil layer [19,24]. It is deduced that facades with the same orientation create similar thermal impacts on deeper soil layers under the condition of homogeneous soils. Therefore, only two sample sites (site A, next to the facade and site B, 10 meters away from the facade) were selected to be investigated to represent the differences between soils adjacent to and far away from buildings at depths of 0, 0.05, 0.10, 0.20 and 0.30 m, as shown in Figure 2a. Data were recorded as TA0, TA5, TA10, TA20, and TA30 for site A and as TB0, TB5, TB10, TB20, and TB30 for site B. In a manner similar to the setting of soil temperature sensors, soil moisture sensors
were located at various depths in the soil, and data were recorded as $W_{A0}$, $W_{A5}$, $W_{A10}$, $W_{A20}$, and $W_{A30}$ for site A and as $W_{B0}$, $W_{B5}$, $W_{B10}$, $W_{B20}$, and $W_{B30}$ for site B. The horizontal heat flux was monitored with two heat flux plates at different depths (0–0.10 m and 0.10–0.20 m) in summer, in order to analyze the differences in horizontal heat flux from the building at different depth, shown in Figure 2b.

![Figure 2. Arrangement of soil temperature sensors (a) and heat flux plate (b).](image)

The mean soil moisture content at sites A and B during the three observation periods is shown in Table 1. Under most conditions, the soil moisture contents were similar in numeric value at the same depth between the two sites during the three seasons. Additionally, there were certain larger differences, such as at the 0.30 m depth in the winter and at depths of 0.05, 0.20 and 0.30 in the summer.

| Season   | $W_{A0}$ | $W_{B0}$ | $W_{A5}$ | $W_{B5}$ | $W_{A10}$ | $W_{B10}$ | $W_{A20}$ | $W_{B20}$ | $W_{A30}$ | $W_{B30}$ |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Winter   | 3.5      | 2.8      | 4.22     | 9.23     | 7.24     | 11.78    | 13.44    | 13.88    | 4.42     | 16.16    |
| Spring   | 0.88     | 2.31     | 12.52    | 11.9     | 12.26    | 15.17    | 9.53     | 13.28    | 10.89    | 6.56     |
| Summer   | 15.44    | 15.39    | 10.65    | 26.12    | 18.06    | 20.73    | 19.69    | 28.9     | 17.38    | 27.19    |

Due to the similar location, weather, cover type, and texture, the influence factor was the distance to the building at both sites.

Meteorological data were obtained from a weather station that was located in the study area and was 47 m from the façade, as shown in Figure 1. The meteorological sampling interval was synchronous with that of the soil sensors mentioned above. Experiments were conducted in three different seasons including the winter, spring, and summer. The weather conditions during the experiments are shown in Table 2.

| Season | Winter | Spring | Summer |
|--------|--------|--------|--------|
| Value  | Min    | Max    | Mean   | Min    | Max    | Mean   | Min    | Max    | Mean   |
| TA (K) | 262.65 | 284.65 | 272.13 | 277.45 | 303.25 | 288.55 | 294.65 | 308.25 | 301.77 |
| RH (%) | 7.00   | 91.00  | 46.53  | 4.00   | 93.00  | 39.05  | 28.00  | 100.00 | 60.68  |
| Date   | 23 January–13 February 2014 | 18 March–4 April 2014 | 17–27 July 2014 |

Note: $T_A$ denotes air temperature and RH denotes relative humidity.

In addition, the air temperature near the ground ($T_{AN}$) was monitored with air temperature sensors (with an accuracy of ±0.2 K) and logged with a data logger. The air temperature sensors were located near the soil surface, namely 0.02 m above the ground.
2.3. Model Simulation

Microclimate software, known as ENVI-met (version 4.0), was employed in this study to simulate
the relative energy factors at the surface of the ground in the study area, including the sensible heat
flux (H), latent heat flux (LE), vertical soil heat flux (G), and reflected received horizontal short-wave
radiation (RR).

2.4. Statistical Approaches

In this study, several statistical approaches were used, including the mean value, independent-samples $t$-test, and coefficient of variation.

(1) Mean value: in each investigated season, the soil temperature at each depth was averaged
during the season, as shown in Formula (1).

$$T = \frac{\sum_{i=1}^{n} T_i}{n}$$

where $T$ is the mean soil temperature, $T_i$ is the soil temperature at each depth at each site, and $n$ is the
total number of samples at each depth at each site during an independent period of observation.

(2) Independent-samples $t$-test:
The soil temperature of each sensor was averaged every ten minutes during each investigated
season. Thus, six numerical values were obtained for each sensor every hour. All of the data from
both sites A and B at the same depth were compared hourly using an independent-samples $t$-test
(SPSS software, version 17.0) to determine whether there were significant differences between site A
and site B at the same depth at a significance level of 0.05.

(3) Coefficient of variation: the coefficient of variation is a common approach to estimate the
degree of variation at each sample site. The coefficient of variation can be calculated as follows:

$$CV = \frac{SD}{MN} \times 100\%$$

where CV is the coefficient of variation, SD is the standard deviation, and MN is the mean
soil temperature.

(4) Average timestamp of the maximum and minimum soil temperature: due to time being
cyclical, time cannot be simply calculated as an average value. Therefore, the following algorithm [25]
was introduced to calculate the time frequency of the maximal and minimal soil temperature.

Timestamps were transformed into angles, meaning that one hour corresponded to 15°, 0:00 was
defined as 0°, 6:00 was defined as 90°, etc. Then, every timestamp was converted to a corresponding
angle. Hence, its sine value and cosine value could be obtained. The average sine value and cosine
value were calculated using the following formulas and Figure 3:

$$Y = \frac{\sum \sin \theta}{n}$$

$$X = \frac{\sum \cos \theta}{n}$$

$$r = \sqrt{X^2 + Y^2}$$

$$\sin \bar{\theta} = \frac{Y}{r}$$

$$\cos \bar{\theta} = \frac{X}{r}$$

Based on the sine value and cosine value of the angle, obtained with Formulas (6) and (7),
we calculated the angle and corresponding timestamp.
(5) Analytic hierarchy process: The analytic hierarchy process was conducted with a statistical analysis package (hier.part) running on the R platform. This method was successfully employed in previous studies [20,26]. The analytic hierarchy process was used to analyze the leading influence factor for the temperature differences of the various surface soil layers between site A and site B and the relative energy factors in the summer in this study.

3. Results

3.1. Mean Soil Temperature

The diurnal pattern of the mean soil temperature variation is depicted in Figure 4. The soil temperature always exhibited a wavy curve, regardless of the depth or the site. In the winter, when comparing the soil temperature of the two sites, the results show that at the same time and at the same depth, the soil temperature was always higher at site A than that at site B. Nevertheless, there were certain timestamps when the soil temperature was lower at site A than at site B because the surface was partially shaded by grass at the very bottom of the façade. As a result, the soil temporarily absorbed more heat at site A than at site B.

**Figure 3.** Variable of relations 3–7.

**Figure 4.** Mean soil temperature and differences in soil temperature of various depths at different sites: (a) soil temperature at Site A in the winter, (b) soil temperature at Site B in the winter, (c) soil temperature difference between the two Sites in the winter, (d) soil temperature at Site A in the spring, (e) soil temperature at Site B in the spring, (f) soil temperature difference between the two Sites in the spring, (g) soil temperature at Site A in the summer, (h) soil temperature at Site B in the summer, (i) soil temperature difference between the two Sites in the summer.
In the spring, the pattern of the mean soil temperature variation was similar to that in the winter. As shown in Figure 4d,e, the soil temperature still presented as a wavy curve. The pattern did not change with the depth. After comparing soil temperatures between the two sites, the observation results demonstrated that the soil temperature was always higher at site A than at site B at the same timestamp and at same depth, except at 10:00 and 11:00 in the surface soil layer.

In the summer, the pattern of the mean soil temperature variation was also similar to that in the winter and spring. However, it was more complicated to compare the two sites. For each soil layer depth, \( T_{A0} \) was lower than \( T_{B0} \) from 13:00 to 16:00, \( T_{A5} \) was lower than \( T_{B5} \) from 9:00 to 15:00, \( T_{A10} \) was lower than \( T_{B10} \) from 12:00 to 18:00, \( T_{A20} \) was lower than \( T_{B20} \) from 13:00 to 17:00, and \( T_{A30} \) was lower than \( T_{B30} \) from 13:00 to 15:00. The opposite was the case for other times at each depth.

As shown in Figure 4c,f,i, the mean soil temperature difference between the two sites exhibited wavy curves in all three seasons. Table 3 shows the maximum, minimum and mean difference of the soil temperature at the different observation sites in different seasons, in which the mean difference of the soil temperature could be regarded as the intensity of the horizontal heat impact from the building. In the winter, the maximum soil temperature difference occurred at 14:00 at a depth of 0.05 m, and the value was 6.62 K, while the minimum soil temperature difference occurred at 9:00 in the surface soil layer, the value was 0.91 K. In the spring, the mean soil temperature difference between the two sites was the greatest at 15:00 at a depth of 0.05 m, with a value of 9.79 K, the difference was at its minimum at 11:00 in the surface soil layer, and the value was \(-0.41\) K. In the summer, the mean soil temperature difference between the two sites had its maximum value (0.81 K) at 7:00 at a depth of 0.10 m, but reached its minimum value (\(-0.69\) K) at 14:00 at a depth of 0.10 m.

### Table 3. Maximal, minimal and average difference of soil temperature at different sites in different seasons.

| Season | Depth (m) | SL  | 0.05 | 0.1  | 0.2  | 0.3  |
|--------|-----------|-----|------|------|------|------|
| Winter | \( \Delta T\text{-max} \) (K) | 5.54 | 6.62 | 4.99 | 4.29 | 3.93 |
|        | \( \Delta T\text{-min} \) (K) | 0.91 | 0.93 | 2.08 | 3.09 | 3.52 |
|        | \( \Delta T\text{-mean} \) (K) | 2.68 | 2.97 | 3.33 | 3.69 | 3.74 |
|        | \( \Delta T\text{-max} \) (K) | 5.15 | 9.79 | 6.06 | 6.64 | 5.02 |
| Spring | \( \Delta T\text{-max} \) (K) | 3.33 | 5.52 | 4.97 | 4.94 | 4.73 |
|        | \( \Delta T\text{-max} \) (K) | 0.74 | 0.68 | 0.81 | 0.78 | 0.41 |
|        | \( \Delta T\text{-min} \) (K) | \(-0.11\) | \(-0.64\) | \(-0.69\) | \(-0.14\) | \(-0.04\) |
| Summer | \( \Delta T\text{-max} \) (K) | 0.44 | 0.29 | 0.28 | 0.35 | 0.22 |

Note: SL denotes the surface soil layer, \( \Delta T\text{-max} \) denotes the maximum soil temperature difference, \( \Delta T\text{-min} \) denotes the minimum soil temperature difference, and \( \Delta T\text{-mean} \) the mean soil temperature difference.

In the winter, the mean soil temperature difference was 2.68, 2.97, 3.33, 3.69 and 3.74 K at various depths, indicating that the mean soil temperature increased with increasing depth. In the spring, the mean soil temperature difference was 3.33, 5.52, 4.97, 4.73 and 4.94 K in the surface soil layer and at depths of 0.05, 0.10, 0.20 and 0.30 m, respectively, exhibiting no regular trends. In the summer, based on the order listed above, the mean soil temperature difference was 0.44, 0.29, 0.28, 0.35 and 0.22 K, respectively, exhibiting a trend that was the opposite to that in the winter. The average value of the soil temperature difference at all depths was considered the average intensity in a season and was 3.282, 4.698 and 0.316 K in the winter, spring and summer, respectively.

### 3.2. Soil Moisture

As an important factor that affects specific heat of soil, soil moisture determines its temperature to some extent. As shown in Table 1, soil moisture was very close between site A and site B at same depths, except for that at the depth of 0.3 m in winter and 0.05 m, 0.2 m and 0.3 m in summer. This indicates that soil moisture affected its temperature at a very limited level.
Daily change of soil moisture is shown in Table 4. It fluctuated at a very low level (less than 0.01%). This phenomenon indicates the balance of water budget in the soil, the evaporation was at a low level, especially at the top surface soil.

Table 4. Change of diurnal soil moisture (%).

|          | W_{A0} | W_{B0} | W_{A5} | W_{B5} | W_{A10} | W_{B10} | W_{A20} | W_{B20} | W_{A30} | W_{B30} |
|----------|-------:|-------:|------:|-------:|------:|-------:|-------:|-------:|------:|-------:|
| Winter   |  -0.005 |  -0.004 |  -0.005 |  0.000 |  -0.001 |  0.003 |  0.001 |  0.000 |  0.000 |  0.000 |
| Spring   |   0.002 |   0.002 |   0.002 |  0.017 |   0.004 |  0.004 |  0.001 |  0.005 |  -0.001 |   0.001 |
| Summer   |  -0.022 |  -0.044 |  -0.012 |  0.006 |  -0.005 |  0.002 |  0.012 |  0.016 |   0.020 |   0.018 |

3.3. Non-Significant Soil Temperature Difference (at the 0.05 Significance Level)

Data from the two sites at the same depth were compared on an hourly basis with the independent-samples t-test during the investigation. The results show that there were both significant differences (P < 0.05) at most of the timestamps and non-significant differences (P > 0.05) at only a few of the timestamps at the same depths between the two sites. Table 5 shows the probability of non-significant soil temperature differences between the two sites during the experiment at various depths.

Table 5. Probability of non-significant soil temperature difference between the two sites.

| Depth (m) | SL  | 0.05 | 0.10 | 0.20 | 0.30 |
|-----------|-----|------|------|------|------|
| Winter    | 2.78% | 1.19% | 0.00% | 0.00% | 0.00% |
| Spring    | 11.76% | 0.00% | 0.00% | 0.00% | 0.00% |
| Summer    | 18.33% | 9.58% | 8.75% | 5.42% | 5.00% |

Note: SL denotes surface soil layer.

In the winter, the non-significance only contributed probabilities of 2.78 and 1.19% to the investigation of the surface soil layer and depth of 0.05 m, respectively, while the soil temperature showed no non-significance at the other depths between the two sites. In the spring, non-significance was obtained in the surface soil layer only, contributing a probability of 11.76%. In contrast to the winter and spring, non-significance was observed at every single soil depth in this experiment, contributing probabilities of 18.33, 9.58, 8.75, 5.42, and 5.00% to the investigation of the surface soil layer and depths of 0.05, 0.10, 0.20, and 0.30 m, respectively. These results indicate that the probability of a non-significant soil temperature difference between the two sites decreased with increasing soil depth. Moreover, there was a greater probability of non-significance in the surface soil layer than in deeper soil layers.

Non-significance occurred somewhat regularly. In the winter, non-significant situation occurred between 9:00 and 13:00 in the surface soil layer, during which the period between 9:00 and 10:00 contributed a probability of 78.57%. Non-significance was concentrated between 5:00 and 8:00, and accounted for 66.67% of the non-significant probability at a depth of 0.05 m. In the spring, a non-significant situation occurred only in the surface soil layer, which was concentrated between 9:00 and 15:00; the time span between 9:00 and 12:00 contributed 77.08% of this non-significant situation. It was a more complicated situation in the summer compared to the other two seasons: in the surface soil layer, a non-significant situation was present for 19 hours of the day and was concentrated between 7:00 and 12:00, accounting for 59.09% of the probability. In general, at a depth of 0.05 m, the non-significance was distributed across 15 hours of the day, during which the 10:00 timestamp contributed the highest probability, accounting for 13.04%. Non-significance also occurred at 15 different hours of one day at a depth of 0.10 m but was concentrated between 9:00 and 11:00 and accounted for 38.10%. At a depth of 0.20 m, non-significance usually occurred between midnight and dawn and around noon, among which 12:00 and 13:00 contributed the highest probability, accounting
for 30.77% of the probability. At a depth of 0.30 m, non-significance was present during the daytime, contributing the highest probability (33.33%) between 7:00 and 8:00.

3.4. Frequency of the Maximum and Minimum Soil Temperature

According to the statistical results of the soil temperature during the investigation, the time frequency of the daily maximum and minimum temperature for the two different sites is shown in Figures 5 and 6.

Figure 5. Distribution of the maximum of soil temperature at the two sites (a, b, c, d, and e denote winter; f, g, h, i and j denote spring; k, l, m, n, and o denote summer).

Figure 6. Distribution of the minimum of soil temperature at the two sites (a, b, c, d, and e denote winter; f, g, h, i and j denote spring; k, l, m, n, and o denote summer).
To a certain extent, the time frequency of the maximum temperature exhibited a phase-divergence between the two sites at the same depths for the three different seasons. Periods of the maximum temperature were more concentrated at site A than at site B at various depths in the winter, while the maximum temperatures showed no regular pattern in the spring and summer (Figure 4).

Figure 6 shows the time frequency of the minimal soil temperature at various depths at the two sites in different seasons.

The results show that the time frequencies of minimal soil temperatures were more concentrated than those of the maximum temperatures. Comparing the data from the two sites at the same depths in the three seasons, the results indicate that site A exhibited a more concentrated trend compared to site B for most of the time, except for the surface soil layer in the spring and at depths of 0.05 and 0.10 m in the summer.

3.5. Time of the Maximal and Minimal Soil Temperature between the Two Sites

As mentioned above, the temporal phase of the soil temperature shifted between the two sites in the three seasons. Based on the calculations, the average time at each depth at both sites is shown in Table 6 to compare the difference between sites A and B.

Table 6. Average timestamp of maximal and minimal soil temperature.

| Depth (m) | Winter | Spring | Summer |
|-----------|--------|--------|--------|
|           | Site A | Site B | Site A | Site B | Site A | Site B |
| Max       |        |        |        |        |        |        |
| SL        | 14:11  | 13:29  | 14:00  | 12:58  | 14:04  | 14:30  |
| 0.05      | 14:39  | 17:36  | 14:36  | 17:24  | 15:51  | 14:30  |
| 0.10      | 16:28  | 18:22  | 17:48  | 18:40  | 17:30  | 19:45  |
| 0.20      | 19:58  | 3:40   | 18:04  | 20:16  | 22:28  | 19:39  |
| 0.30      | 3:08   | 5:13   | 20:51  | 0:38   | 2:31   | 0:20   |
| Min       |        |        |        |        |        |        |
| SL        | 6:11   | 6:06   | 6:00   | 6:06   | 6:11   | 5:54   |
| 0.05      | 6:52   | 8:14   | 6:52   | 8:14   | 6:52   | 5:48   |
| 0.10      | 8:40   | 9:53   | 8:40   | 9:53   | 8:40   | 6:30   |
| 0.20      | 11:07  | 10:42  | 11:07  | 10:10  | 11:07  | 8:04   |
| 0.30      | 13:52  | 12:05  | 15:24  | 12:08  | 13:41  | 9:27   |

Note: SL denotes the surface soil layer.

With regard to occurrences of the maximum temperature, they occurred later at site A than at site B in the surface soil layer and a depth of 0.05 m, and occurred earlier at site A than at site B at depths of 0.10, 0.20 and 0.30 m in the winter. However, the maximum temperature occurred later at site A than at site B in the surface soil layer and earlier at site A than at site B at depths of 0.05, 0.10, 0.20 and 0.30 m in the spring. The situation was very different in the summer. The maximum temperature occurred earlier at site A in the surface soil layer and at a depth of 0.10 m and occurred later at site A at depths of 0.05, 0.20 and 0.30 m, exhibiting no significant regularity.

As for occurrences of the minimum temperature, the minimum temperature occurred earlier at site A at depths of 0.05 and 0.10 m and earlier at site B at other depths in the winter. In the spring, the minimum temperature occurred earlier at site A in the surface soil layer and at depths of 0.05 and 0.10 m and earlier at site B at other depths. In the summer, the minimum temperature occurred earlier at site B at all depths.

3.6. Changes in the Soil Temperature at Various Depths at the Two Sites

Table 7 shows the maximum/minimum, differences between the maximum and minimum, and the mean value of the soil temperature at various depths at the two different sites. In general, from the surface soil layer to a depth of 0.30 m, the maximal soil temperature decreased with depth, while the minimum increased with depth.
Table 7. Maximum, minimum, difference between maximum and minimum and average soil temperature at the two sites.

| Season | Location | Depth (m) | 0.00 | 0.05 | 0.10 | 0.20 | 0.30 |
|--------|----------|-----------|------|------|------|------|------|
| Winter | Site A   | Maximum (K) | 281.90 | 280.89 | 279.13 | 278.69 | 278.79 |
|        |         | Minimum (K) | 273.03 | 274.03 | 275.78 | 277.30 | 278.28 |
|        |         | Difference (K) | 8.86 | 6.86 | 3.35 | 1.38 | 0.52 |
|        | Site B   | Maximum (K) | 276.17 | 276.57 | 277.23 | 278.01 | 278.57 |
|        |         | Minimum (K) | 274.88 | 274.26 | 274.15 | 274.40 | 274.86 |
|        |         | Difference (K) | 1.29 | 0.31 | 0.08 | 0.17 | 0.40 |
|        |          | Mean (K) | 276.17 | 276.57 | 277.23 | 278.01 | 278.57 |
| Spring | Site A   | Maximum (K) | 285.99 | 286.94 | 288.00 | 288.38 | 287.52 |
|        |         | Minimum (K) | 276.88 | 274.26 | 274.15 | 274.40 | 274.86 |
|        |         | Difference (K) | 11.11 | 2.68 | 3.85 | 4.00 | 4.66 |
|        | Site B   | Maximum (K) | 297.16 | 295.45 | 292.30 | 290.55 | 291.03 |
|        |         | Minimum (K) | 285.99 | 286.94 | 288.00 | 288.38 | 287.52 |
|        |         | Difference (K) | 11.17 | 8.51 | 4.30 | 2.16 | 3.51 |
|        |          | Mean (K) | 290.84 | 290.61 | 290.11 | 289.56 | 289.29 |
| Summer | Site A   | Maximum (K) | 303.53 | 302.12 | 301.56 | 300.95 | 300.47 |
|        |         | Minimum (K) | 299.29 | 299.46 | 299.90 | 299.90 | 299.74 |
|        |         | Difference (K) | 4.24 | 2.66 | 1.65 | 1.05 | 0.73 |
|        | Site B   | Maximum (K) | 307.64 | 305.27 | 304.85 | 304.77 | 304.21 |
|        |         | Minimum (K) | 298.71 | 299.07 | 299.18 | 299.51 | 299.72 |
|        |         | Difference (K) | 8.93 | 3.19 | 2.67 | 1.26 | 0.49 |
|        |          | Mean (K) | 300.66 | 300.41 | 300.42 | 300.16 | 299.98 |

According to Table 6, in the winter, the difference between the maximum and minimum soil temperature was higher at site A than at site B at various depths. In the spring the situation was similar to that in the winter, except for the surface soil layer. When it was summer, the situation changed substantially. The difference between the maximum and minimum soil temperature was lower at site A than at site B at various depths, except at a depth of 0.30 m.

The coefficient of variation (CV) exhibited similar behavior to that of the difference between the maximum and minimum soil temperature, as shown in Figure 7.

![Figure 7](image-url)

**Figure 7.** Coefficient of variation of soil temperature at various depths at different sites ((a) winter; (b) spring; (c) summer).

In the winter, the CV was higher at site A than at site B at the same depths. In the spring, the CV was also higher at site A than at site B at the same depths, except for the surface soil layer. In the summer, the situation was very different. The CV was lower at site A than that at site B at the same depths, not including the depth of 0.30 m.
3.7. Comparison between the Soil and Air Temperature near the Surface

Due to the high degree of correlation and interaction between the soil temperature and air temperature, the air temperature was used to reflect and calculate the soil temperature. In this study, the average $T_{aN}$ was higher at site A than at site B during the three observation periods, as shown in Table 8.

| Location | Winter | Spring | Summer |
|----------|--------|--------|--------|
| Site A   | 274.06 | 289.00 | 302.66 |
| Site B   | 273.01 | 288.09 | 300.92 |

The difference in $T_{aN}$ between sites A and B was 1.05 K in the winter, and was 0.91 K and 1.74 K in the spring and summer, suggesting that the air temperature at site A was thermally affected by certain factors in such a way that the mean $T_{aN}$ value was greater at site A than that at site B.

Correlation analysis was carried out between the temperature of the surface soil layer and near-surface air temperature at site A and site B for each of the three seasons. Scatter was observed between the temperature of the surface soil layer and near-surface air temperature at both sites (Figure 8). The results indicate that regardless of the site or season, the soil temperature and air temperature were correlated ($P < 0.05$).

![Figure 8. Scatter plot of $T_S$ and $T_{aN}$ (CC indicates the correlation coefficient).](image-url)

The only values that changed were the correlation coefficients. In the winter and spring, the correlation coefficient was approximately 0.9, with relatively high values at both site A and site B, but the correlation coefficient reached very low values in the summer at both sites with values of less than 0.2. The decrease of correlation coefficient could be attributed to the regular irrigation in the study area in summer.
3.8. Analysis of the Energy Flows between the Two Sites

Energy factors, including both the simulated and observed factors, were analyzed with hierarchical partitioning to verify the dominant factors influencing the temperature difference between site A and site B in the very first surface soil layer (the soil temperature at a depth of 0–0.025 m). The differences of H, LE, G, RR, and HHF0 between site A and site B were defined as X, and the temperature difference between the two sites was defined as Y. The differences in H, LE, G, and RR were calculated with exported data resulting from the ENVI-met simulation. However, the HHF0 difference was considered to be the value of HHF0 itself, due to the horizontal heat flux very rapidly becoming attenuated with distance from the building [20]. As such, HHF0 could be ignored at site B. The results are shown in Figure 9. Only the significances of LE and HHF0 were less than 0.05. In contrast, H, G, and RR exhibited no significance in relation to the temperature difference between site A and site B at the 0.05 significance level.

![Figure 9](image.png)

**Figure 9.** Independent, joint and individual contributions of each energy factor (* indicates significance at the 0.05 significance level).

The independent explanatory power of each energy factor was 2.14, 6.79, 1.59, 3.07, and 19.50% for H, LE, G, RR, and HHF0, respectively. However, the joint explanatory power was negative for all of the energy factors, with values of −0.34, −4.82, −0.40, −0.81, and −0.39% for H, LE, G, RR, and HHF0, respectively. The decreasing order of the individual contributions of each energy factor was HHF0 (58.94%), LE (20.52%), RR (9.27%), H (6.46%), and G (4.81%). The results indicate that HHF0 plays a leading role in affecting the temperature difference in the surface soil layer between the two sites.

4. Discussion

4.1. Reason for Higher Soil Temperature next to the Building

For most of the time, the soil temperature was higher next to the building compared to that far from the building, indicating that the building was a heat source that caused higher soil temperatures around it. This result was consistent with Zhou’s results. There was a horizontal heat flux between the building and soil in the surface soil layer, which was transferred from the building to the soil at most times [24]. This study indicates that soil temperature differences appeared not only in the very top surface soil layer but also in the deeper soil layers (0.05–0.30 m), exhibiting different patterns in different seasons. The soil temperature difference increased with increasing depth in the winter, while the difference decreased with increasing soil depth in the summer. The soil temperature differences between the two sites were different in different soil layers, indicating that the intensity of the heat impact from the building on the soil changed with depth. It is deduced that the horizontal heat flux between the building and soil was different in different soil layers. Figure 10 shows the comparison of two different soil layers at the very end of the summer, including the first layer (0–0.10 m) and the second layer (0.10–0.20 m), which were respectively recorded as HHF0 and HHF10-20. The mean horizontal heat fluxes were 3.89 and 0.13 W/m² for the first soil layer and the second layer, respectively. The difference between the horizontal heat fluxes was reflected not only in the numerical value but also in the daily variation, explaining the soil temperature difference at various depths between the two sites.
In addition, soil moisture, vertical soil heat flux, and anthropogenic heat could result in this phenomenon as well. In this study, the difference in soil moisture was a small value between site A and B at the very surface soil layer in winter, contributing mean values of 3.5% and 2.8%, respectively. A similar situation happened in the other two seasons. The soil moisture was 0.88% and 2.31% at the surface soil layer at site A and B in spring and it was 15.44% and 15.39% in summer. Soil moisture at the surface soil layer suggests that the very little difference of soil moisture at the very surface soil layer was not an important factor to affect soil temperature. The mean soil moisture was very similar at the same soil layers in most conditions. Several significant differences in soil moisture were found at the depth of 0.3 m in winter and 0.05 m, 0.2 m, and 0.3 m in summer (Table 1). Correlation analysis was carried out by day and season to verify the soil moisture’s role in soil temperature. The results show that the differences in soil temperature and moisture between site A and B were correlative on a diurnal scale but not on a seasonal scale. Some correlation coefficients were positive and others were negative. However, the mean soil temperature was always higher at site A than B. This suggests that soil moisture was not the most important factor.

Though higher soil moisture results in higher specific heat, the soil temperature depends on the energy budget primarily. For example, the mean soil temperature was higher at the depth of 0.3 m at site A than B in spring, while the mean soil moisture was higher at site A (10.89%) than site B (6.56%), suggesting more heat was absorbed at the depth of 0.3 m at site A. Thus, it is very important where the heat source came from. As studies conducted before, buildings were seen as heat source for the very surface soil layer (0.00–0.025 m) and part of heat was from façades to the surface soil layer, due to higher temperature near the façade and lower temperature far away from the building [20,24]. In general, soil temperature went down with distance from buildings (Figure 11). But the soil moisture shows no obvious trend between different seasons, indicating that soil moisture was not the main factor that influenced the temperature of surface soil layer.
The soil moisture was stable at site A and B in winter and spring and the differences between them were stable at the same depth as well (Figure 12). But there were several sharp decreases between the two sites, due to irrigations. In summer, the differences between the two sites were larger than in winter and spring. No matter what soil moisture between the two sites was, mean soil temperature was higher at site A than site B in this study, suggesting that soil moisture did not play a key role.

As the daily change of soil moisture was not very high in winter, spring, or summer (Table 4), evaporation was too limited to influence soil temperature. Therefore, soil moisture was not seen as the most important factor that influenced soil temperature in this study.

A simulation (ENVI-met software) was employed to simulate the vertical heat flux at the surface in spring and summer. According to the results, the vertical heat flux was 6.49 W/m² and 7.49 W/m² at site A and B in summer, and it was 3.02 W/m² and 2.42 W/m² at site A and B in spring. However, in both of the seasons, mean soil temperature was higher at site A than B at the surface soil layer. It indicates that soil temperature at site A and B was not mainly affected by vertical heat flux.

Anthropogenic heat is an important part of the horizontal heat flux between buildings and soil, and it transfers from the facade of buildings to the soil [27,28]. According to the analysis of the correlation between the horizontal heat flux between the building and soil, including the first and second soil layer, and solar radiation, a positive correlation was found between HHF₀ and solar radiation (P < 0.01). However, a negative correlation was observed between HHF₁₀⁻₂₀ and solar radiation (P < 0.01), which verified that HHF₀ and HHF₁₀⁻₂₀ came from different sources. This result correlates well with a study in Tokyo which reported that anthropogenic heat increased the soil temperature. The temperature increased between 6:00 and 8:00, remained at a high level from 8:00 to 17:00 with little fluctuation, and then decreased from 17:00 to 5:00 of the next day [29]. The changing pattern was different from those of HHF₀ and HHF₁₀⁻₂₀ in this study, but still a little similar. Because the emission pattern of anthropogenic heat in Beijing was similar to that in Tokyo [30], it was inferred that the horizontal heat flux between the building and soil could be considered a part of anthropogenic heat in a way. Based on Zhou’s research [31], solar radiation determined the horizontal heat flux between the building and soil in the very top surface soil layer, which meant that solar radiation led to higher temperatures of the facade compared to that of the soil. Therefore, it is concluded that the horizontal heat flux between buildings and soil was the result of the higher temperatures of facades, which were caused by the sun and waste heat emission via walls by human beings.

4.2. Less Non-Significant Soil Temperature Differences in Deeper Soil Layer (at a 0.05 Significance Level)

During the three-season investigation, the non-significant soil temperature difference (calculated with the independent-samples t-test) between the two sites decreased with the soil depth, indicating that the building affected the soil temperature more notably in deeper soil layers. This phenomenon could be attributed to different energy budget processes occurring between the top surface soil layer and deeper soil layers. For the top surface soil layer, the energy source was the absorption of solar radiation, referred to as net radiation. The absorbed solar radiation was transformed into a vertical
soil heat flux from the top surface soil layer to the deep soil layers. The vertical heat flux passed through the surface soil layer with a high degree of attenuation. The deeper the soil, the smaller the vertical heat flux, and the lower its thermal impacts. Vertically, the soil temperature difference between soil layers showed a downward trend with the soil depth, and it was inferred that there was a lower vertical heat flux in the deeper soil layers regardless of geothermal energy. In addition, the vertical soil heat flux (at a depth of 0.02 m) was lower than the net radiation in the summer based on meteorological data from the weather station: the mean vertical heat flux was 1.75 W/m², the mean net radiation was 111.44 W/m², the minimal vertical heat flux was −39.29 W/m², the minimal net radiation was −111.30 W/m², and the maximal vertical heat flux and maximal net radiation were 28.31 and 700.00 W/m², respectively. These results indicate that net radiation had a larger heat impact on the soil temperature than that caused by the vertical heat flux in the surface soil layer and shallower soil layers. Therefore, the surface soil layer was easily affected by net radiation, while the deeper soil layers tended to be affected by the vertical soil heat flux and horizontal heat flux between the building and soil. Therefore, the non-significant soil temperature difference (calculated by the independent-samples t-test) between the two sites decreased with the soil depth in the three different seasons.

4.3. Timestamps of the Maximal and Minimal Soil Temperature

The timestamps of the maximal and minimal soil temperature were different in the winter, spring and summer, and the following could be concluded:

(1) Thermal conductivity: Due to the impact of different concrete materials, the integrated thermal conductivity of the two kinds of substances in the ecotone between the soil and building ($\lambda_m$) was different from that of soil or concrete. Based on the measurements, the thermal conductivity of soil and concrete was 1.12 and 1.74 W·m⁻¹·K⁻¹, respectively. According to Sun’s method [32], the thermal conductivity of the ecotone can be calculated using the following formula:

$$\lambda_m = \frac{2\lambda_1\lambda_2}{\lambda_1 + \lambda_2}$$

where $\lambda_m$ is the integrated thermal conductivity of the soil and building, $\lambda_1$ is the thermal conductivity of the soil, and $\lambda_2$ is the thermal conductivity of concrete. Thus, $\lambda_m$ is calculated as 1.36 W·m⁻¹·K⁻¹ based on the thermal conductivity of soil and concrete.

(2) Temperature difference: Due to the different thermodynamic properties of the soil and concrete and 3D structures of buildings, the surface temperature of facades is higher than that of soil due to solar radiation. In the winter, the surface temperature of the facade, slab, and soil was 288.02, 285.72 and 284.92 K, respectively, indicating that the building functioned as a heat source to the soil. In essence, the building stored heat within itself, released it to the soil, and raised the soil temperature.

The two reasons mentioned above led to different timestamps of the maximal and minimal soil temperatures between the two sites.

4.4. Soil Temperature Fluctuation

The soil temperature fluctuation decreased with the soil depth. Solar radiation was the most important energy source for the soil. When solar radiation reached the surface of the soil, a portion of it was absorbed by the soil, which is referred to as net radiation, and the rest of it was reflected to the atmosphere. A portion of the net radiation increased the soil temperature, and another portion was transformed into vertical heat flux, which was attenuated with the soil depth and fluctuated little along the path of heat propagation [33,34]. Therefore, the soil temperature fluctuated slightly with the soil depth.

For soil in natural environments, the vertical energy flux is the main heat source, while thermal energy from buildings is the heat source for soil adjacent to buildings [20,31]. Based on the soil temperature fluctuations and values of the CV in the three seasons, it was generally concluded in this study that the building could be considered as the heat source in the winter and spring, and increased
the soil temperature. Even though the building was still considered as a heat source for the soil in
the summer, the building stabilized the soil temperature and lowered the soil temperature fluctuation.

4.5. Heat Source for Deep Soil

Net radiation dominates the energy budget of very surface soil layer and it was equal to the sum
of sensible heat flux (H), latent heat flux (LE) and vertical soil heat flux (G). However, in the deep soil
layer, direct radiation is blocked by the surface soil layer, hence the important heat source is heat flux,
in most cases the vertical one, in the natural conditions. For site B, soil temperature beneath the surface
changed with vertical heat flux due to the lack of other heat source, while for site A, it changed with
both vertical and horizontal heat flux.

As mean horizontal heat flux was greater than 0, it was inferred that building was a heat source
for soil at the depth between 0–0.20 m. Besides, mean temperature was greater at site A than site B at
various depths, proving soil absorbed more heat at site A than site B. Via the very limited numeric
value of vertical heat flux at the ground surface that simulated with ENVI-met, the vertical heat flux
could not be seen as dominant role of affecting soil temperature at the depth of 0.30 m, due to vertical
heat flux attenuated with depth.

According to the data of horizontal heat flux and comparison of soil temperature between site A
and B at the depth between 0–0.20 m, it was concluded that the building was one but not the only one
heat source for surface soil layer in this study. In addition, soil moisture and vertical heat flux was not
the dominant factor in the temperature difference between the two sites at the depth 0.30 m. Therefore,
it is inferred that building was a heat source for the soil at the depth 0.30 m at site A.

4.6. Determination of the Leading Factors

The mean values of \( T_{A0} \) and \( T_{B0} \) proved that the soil was heated more notably at site A than
at site B. The difference in air temperature near the surface also demonstrates the same. However,
why was this phenomenon happening and what was the heat source? According to the setting in
this study, the distance from the facade distinguished site A from site B. Therefore, it was inferred
that the building heating the adjacent soil could somehow be attributed to reflected radiation and
heat transfer from the building. Energy factor analysis demonstrates that the difference in reflected
radiation between site A and site B was not the main reason for the higher temperature of the surface
soil layer at site A, which scored only 9.27% in the individual effect analysis. In contrast, the horizontal
heat flux between the building and soil accounted for 58.94% of the individual effects, making it the
dominant factor. This result was similar to those of previous studies [20,24]. In addition, the horizontal
heat flux between the building and soil was one of two correlated energy factors (at a 0.05 significance
level), while the other was the latent heat flux. The latter contributed 20.52% of the individual effects,
which was much less than that of the horizontal heat flux, suggesting that the latent heat flux was not
the leading factor determining the temperature difference between site A and site B. However, all the
energy fluxes restricted each other because the joint effects were all negative values. This phenomenon
could be attributed to the different directions of the various energy flows.

5. Conclusions

After the soil temperature investigation at the two different sites in the three seasons, this study
could be concluded as follows:

(1) In general, for soil at depths of 0, 0.05, 0.10, 0.20 and 0.30 m, the building was a heat source.
The average intensity of the heat impact from the building to the soil changed with the season.
The average intensity of the heat impact was 3.282, 4.698 and 0.316 K in the winter, spring and summer,
respectively. The order based on the average intensity of the heat impact was the spring, winter
and summer.

(2) At depths from 0 to 0.30 m, the heat impact of the building increased with increasing soil
depth because the solar radiation and vertical soil heat flux decayed along the path of heat propagation
in the soil. Therefore, the contribution of the horizontal heat flux between the building and soil in affecting the soil temperature was increased.

(3) With the influence of the building, the timestamp of the maximal soil temperature was different at various soil depths between the two sites. The same was true for the minimum temperature. It can thus be concluded that the ecotone between the building and soil had a higher thermal conductivity than that of the soil and heat was stored in the building.

(4) The soil temperature fluctuations and CV values in different soil layers indicate that the vertical energy flux decayed with the soil depth. The comparison of the soil temperature fluctuations and CV values between the two sites suggested that the building played different roles in different seasons. In the winter and spring, the building heated the soil and increased the soil temperature, which resulted in a significant soil temperature difference, while in the summer, the building maintained the soil temperature at a stable level.

(5) The horizontal heat flux between the building and soil played a leading role in dominating the temperature difference between the site that was near the building and the site that was far away from the building in the surface soil layer in the summer.

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