Variation characteristics of soil temperature, moisture, and heat flux in the understory of evergreen broadleaf forest in South China

Shuting Wu · Zhigang Wei · Xianru Li · Huan Wang · Shitong Guo

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Abstract
Based on observation data from the observation tower station in Zhuhai in South China from October 2015 to May 2018, the variations in soil temperature, moisture, and heat flux in the understory of evergreen broadleaf forest are analyzed. The ground surface temperature is slightly greater than the canopy surface temperature; the soil temperature is the smallest. The seasonal variation in the soil moisture fluctuates around a relative equilibrium as the rain increases or decreases. Both ground and canopy surface temperatures have valley values before sunrise and peak values in the afternoon. The diurnal variations in soil temperature are characterized by a cosine function. With the deepening of the soil layer, the time of valley and peak lag and the amplitude of the variation in the soil temperature decrease. There is almost no diurnal variation in soil temperature at 40 cm depth or the soil heat flux at 30 cm depth. The heat fluxes at depths of 7.5 cm and 15 cm show an “S” pattern variation, with a peak at 17:30. The net radiation of the canopy surface shows a bell-shaped variation, with a peak at 12:30. The averaged soil thermal conductivities are 2.18 W·m\(^{-1}\)·K\(^{-1}\), 1.22 W·m\(^{-1}\)·K\(^{-1}\), and 1.26 W·m\(^{-1}\)·K\(^{-1}\) for 5–10 cm, 10–20 cm, and 20–40 cm depths, respectively.

1 Introduction

In recent years, extreme events have occurred frequently and have increased climate variability. It is more difficult for societies to adapt to extreme changes. As human society develops and human activities lead to changes in the condition of the Earth’s land surface, the physical, chemical, and biological processes on the land surface profoundly affect the exchange of energy and materials between land and atmosphere and land and ocean. An accurate description of land surface processes is of great scientific and social importance for disaster prevention and mitigation and for sustainable economic development (Sonia et al. 2006; Zhang and Wu 2011; Li et al. 2013; Alexis et al. 2016; Miralles et al. 2018). Since the 1980s, driven by international programs such as IGBP, GEWEX, and BAHC, many field observation experiments have been completed globally on different underlying surfaces. Research on the mechanisms of physical processes and model development on the land surface has continued to integrate the fields of physics, physiology, ecology, geography, mathematics, and high-performance computing into a unique and powerful crossover that has made remarkable progress. The China Terrestrial Ecosystem Flux Observation and Research Network has conducted large-scale field observation experiments and developed land surface process models such as AVIM, IAP-LSM-94, and CoLM. These models have been adopted for different weather, climate, and Earth system models (Sun 2002; Dai 2020; Fisher and Koven 2020).

Surface hydrothermal dynamics are an important part of land surface processes, and both soil temperature and moisture are important factors influencing soil respiration, which is now a central issue in studies such as the global carbon cycle (Zhang et al. 2015; Wang et al. 2019). Both the absorption and loss of heat from the soil surface are relevant to climate change, and soil heat fluxes are an important component of the surface energy balance (Ogée et al. 2001; Zhang et al. 2012). The estimation of soil heat fluxes involves almost all analytical experiments of the atmospheric boundary layer and the analysis of land surface-atmosphere interactions (Yang and Wang 2008). The radiant energy entering the ground alters the transfer of soil temperature...
and soil moisture as well as the transport of turbulence at the soil surface, and a reliable estimate of the energy budget requires an accurate estimate of the soil heat flux (Steven et al. 2012; Huang et al. 2016).

At present, scholars have examined the characteristics of soil temperature and moisture as well as heat fluxes in arctic alpine environments (Aalto et al. 2013), in northeastern Japan (Brandt et al. 2020), in eastern Brazil, and in tropical rainforests and savannas (Grimm et al. 2007; Rocha et al. 2009) and temperate grasslands (Carlyle et al. 2011). Soil temperature and moisture patterns are also often analyzed in conjunction with corresponding models to reduce uncertainty in regional predictions (Bhattacharya et al. 2014; Müller et al. 2016; Purdy et al. 2016; Cheruy et al. 2017; Vogel et al. 2017).

Miralles et al. (2012) found that soil temperature and moisture were more strongly coupled in the transition zone between dry and wet climates. Lakshmi et al. (2003) conducted field experiments to fit the relationship between soil temperature and moisture variability. Hsieh et al. (2009) inverted soil heat fluxes through single-layer soil temperature changes. Demetrescu et al. (2007), Tarnawski et al. (2014), and Wilhelm and Bockheim (2016) analyzed the characteristics of the main influencing factors and variation patterns of soil heat transfer coefficients by using multiple soil samples, field measurements, or simulation experimental data. Alvalá et al. (2002) and Li et al. (2016) selected two places with different dry and wet conditions for comparison and found that the soil heat flux would be larger in humid areas.

In general, there are few studies on the variation in soil temperature and moisture in the understorey surface. To study the characteristics of land–atmosphere interactions on the forest canopy surface, we established an observation tower station on the Phoenix Mountain of Zhuhai, Guangdong Province, South China (Wei et al. 2016). Based on the meteorological and radiation data measured at this station, the variation characteristics of the soil temperature and moisture and heat flux in the understorey of evergreen broadleaf forest are studied and analyzed in this paper, which provides more reference and help for the follow-up related research of this substrate with special land–atmosphere interaction.

2 Data and methods

2.1 Study area and data sources

Zhuhai is located on the west coast of the Pearl River Estuary, a low hilly coastal area bordering the South China Sea, with a subtropical maritime climate. The year-round temperature is high, with an annual average temperature of 22.4 °C; the climate is humid, with an annual average relative humidity of 80%; and the rainfall is abundant, with an annual average rainfall of 1770–2300 mm (Tang et al. 2021).

The tower is located at the northern foot of Phoenix Mountain, Zhuhai, in the western forest area of the campus of Beijing Normal University. Zhuhai (22°21′15.5″N, 113°31′34.2″E), at an altitude of 38.5 m. The underlying surface of the tower station is a typical subtropical forest that is dominated by forests of Acacia and Eucalyptus and various scrub and grass slopes, with an average forest canopy height of 18 m. The meteorological observation system, flux observation system, and radiation observation system were set up here to conduct long-term observations of land-air interactions and CO2 fluxes (Wei et al. 2016; Wang et al. 2021).

The variables used in this study included soil temperature and moisture at 5 cm, 10 cm, 20 cm, and 40 cm depths; soil heat flux at 7.5 cm, 15 cm, and 30 cm depths; canopy surface temperature, ground surface temperature, and rainfall at 25 m and 1.5 m heights; and total solar radiation and its reflected radiation and upwards and downwards longwave radiation. Table 1 shows the instruments and their models, manufacturers, and observation accuracy. The time span is from 14 October 2015 to 4 May 2018 with data recorded every 30 min.

2.2 Data quality control

The observation tower station was built in November 2014 and was commissioned after a 2-month trial run before formal observations began. However, due to the sensitivity of the sensors and the stability of the instrument’s power supply and other external factors, errors or outliers are still inevitable, so quality control of the data is required at first.

Quality control methods include range checks, extreme value checks, stiffness checks, internal consistency checks, temporal consistency checks, spatial consistency checks, and integrated analyses. For the spatial consistency check, data from the same time between soil layers are used for the intercomparison analysis.

The range check uses climatological limit values to screen the observations to ensure that the data used are within the climatology. The extreme value check uses the mean value M and standard deviation σ of the single-month observations to determine the threshold, and data within $M \pm 3\sigma$ are considered valid. The internal consistency check compares the frequency by comparing the standard deviation of the single months. The temporal consistency check and spatial consistency check calculate the mean value $M_t$ and standard deviation $\sigma_t$ for each day’s data. If every half-hour observation $x_i$ satisfies $|M_t-x_i| > 3\sigma_t$, then the data $x_i$ is recorded as suspicious (Wang et al. 2006; Huang et al. 2010).
Figure 1 shows the variation in the soil temperature from 12:00 on 20 February 2016 to 12:00 on 21 February 2016. This is an example of not passing quality control. A low value suddenly appeared at 00:00 in the 40-cm-deep soil layer, but the rest of the soil layer did not show this variation, which also did not appear with soil moisture and other variables at the same time, so it was removed and interpolated by averaging the preceding and following values.

Quality control for the radiation data is as follows: there is no solar radiation at night. The nighttime radiation data are corrected and removed. The data that did not pass the logical polarity check and the stiffness check were removed; the data that did not conform to the spatial and temporal continuity and variability were removed; and the data from rainy days were removed because water on the instrument probe had a significant effect on albedo (Wang et al. 2021).

Figure 2 shows the variations in canopy and ground surface temperature, soil temperature, soil moisture, and soil heat flux with a half-hour step after quality control. The breaks in the middle of the graph are brief data losses due to instrument damage caused by summer thunderstorms and other reasons. The soil temperature probe was damaged after 4 September 2017 at 40 cm depth and damaged after 9 November 2017 at 20 cm depth. The overall quality of the observation data used in this paper is good, and the amount of anomalous data is less than 1‰ of the total data.

### 2.3 Research methods

The period from the beginning of the pre-flood period to the end of the summer monsoon in South China is regarded as the wet season with the rest of the year regarded as the dry season. Referring to the annual reports on the climatic characteristics and major meteorological events over China from 2015 to 2018 (Liao et al. 2016; Mei et al. 2017; Feng et al. 2018; Zhou et al. 2019), the specific periods of dry and wet seasons for each year were divided as shown in Table 2.

The weather conditions are defined as follows. If the rainfall is 0 mm and the sunshine time is greater than 25 min per half hour from sunrise to sunset, the day is treated as a typical sunny day. If the rainfall is 0 mm and the sunshine time is less than 25 min per half hour from sunrise to sunset, the day is treated as a cloudy day. If the rainfall is more than 0 mm, the day is treated as a rainy day. However, only the days with more than 50 mm of rain are selected to represent the heavy rainy days for analysis since most rainy days have less rainfall. The diurnal variations in temperature, moisture, and heat flux under different weather conditions are investigated.

### 3 Results

#### 3.1 Ground and canopy surface temperature

The forest canopy receives direct solar radiation, and the canopy surface temperature varies with the intensity of solar
In the analysis period, the variation in the ground and canopy surface temperatures (Fig. 2a) fluctuated with the seasons, but the ground surface temperature was slightly greater than the canopy surface temperature. Fitting between the ground and canopy surface temperature (Fig. 3) shows a good positive correlation, while the expression in the figure indicates that the data of $T_{\text{soil, 20}}$ and $T_{\text{soil, 40}}$ are missing after 4 September 2017, and the following study did not use subsequent relevant impaired data.

**Table 2** Specific periods for dry and wet seasons

| Dry season   | Wet season   |
|--------------|--------------|
| 2015.10.15–2016.03.20 | 2016.03.21–2016.07.13 |
| 2016.11.05–2016.12.06 | 2017.04.25–2017.06.29 |
| 2016.12.23–2017.03.19 | 2017.08.25–2017.09.03 |

Radiation. In the analysis period, the variation in the ground and canopy surface temperatures (Fig. 2a) fluctuated with the seasons, but the ground surface temperature was slightly greater than the canopy surface temperature. Fitting between the ground and canopy surface temperature (Fig. 3) shows a good positive correlation, while the expression in the figure...
shows that the ground surface temperature varies lag slightly compared to the canopy temperature, which is caused by the blockage of solar radiation by the canopy of tall local trees.

Figure 4 shows the diurnal variation in the averaged ground surface and canopy surface temperatures under different types of weather conditions. Overall, both ground and canopy surface temperatures have valley values before sunrise and then rise gradually with the rise of the sun, reach a peak in the late afternoon, and decline after sunset. Ground surface temperatures are slightly higher throughout the day than the canopy surface temperatures. The ground surface temperature cooled slightly faster than the canopy surface temperature at night. The rate of cooling varies with weather conditions and is higher in the dry season than in the wet season and faster on typical sunny days than on cloudy days. The diurnal variation is steeper and less smooth on heavy rainy days.

The averaged ground surface temperatures are higher for the period from 9:30 to 20:00 and slightly lower for the rest of the time than the averaged canopy surface temperatures on all days (Fig. 4a) and cloudy days (Fig. 4e). This time span lengthens to 9:30 to 20:30 in the dry season (Fig. 4b), shortens to 10:30 to 19:30 in the wet season (Fig. 4b), shortens to 10:00 to 20:00 on typical sunny days (Fig. 4d), and shortens to 9:30 to 19:00 on heavy rainy days (Fig. 4a).

After overnight cooling, the minimum values of the averaged ground and canopy surface temperature both occur at 6:30 am on all days and on cloudy days, earlier at 6:00 am in the wet season, later at 7:00 am in the dry season, and delayed at 7:30 am on typical sunny days. However, the minimum values of the averaged ground and canopy surface temperatures occur at 23:00 on heavy rainy days. This is because most heavy rains occur from evening to midnight.
Except for typical sunny days, the canopy surface temperatures reach a peak at 14:00, while the ground surface temperatures reach a peak at 14:30, with a half-hour delay. On typical sunny days, the ground surface temperatures reach a peak at 15:30, and the delay grows to 1.5 h. This shows that the forest receives more solar energy and has a stronger ability to heat the ground surface on typical sunny days.

### 3.2 Soil temperature, moisture, and heat flux

#### 3.2.1 Soil temperature

The seasonal variations in the soil temperatures at all layers were similar to those of the soil surface and canopy surface temperatures, but the soil temperatures were smaller (Fig. 2b). The diurnal variations in soil temperature (Fig. 5) are characterized by a cosine function. After sunrise and sunset, the inflection points of temperature are delayed, and the lag time increases as the soil layer deepens. The amplitude of the variation in soil temperature decreases with the depth of the soil layer, and there is almost no diurnal variation at 40 cm depth.

On the overall average for all days (Fig. 5a) and cloudy days (Fig. 5e), the soil temperature exhibits a valley at 9:30, 10:00, and 11:30 at 5 cm, 10 cm, and 20 cm, respectively, and reaches a peak at 18:00, 19:30, and 23:00, at depths of 5 cm, 10 cm, and 20 cm, respectively. With the deepening of the soil layer, the times of the valleys and peaks lag behind. There is no diurnal variation in soil temperature at 40 cm depth. The time of the valley (peak) at 5 cm depth delay is 0.5 (1.5) h later than that at a 10 cm depth. There is a delay of 3.5 h for the peak time in the 5 cm soil temperature compared to the ground surface temperature. Under other weather conditions, the main characteristics of the diurnal variation in the averaged soil temperature in each layer are similar to those of all days.

During the wet season (Fig. 5c) and on heavy rainy days (Fig. 5f), the soil temperature gradually decreases with depth. On average, in the dry season (Fig. 5b) and on typical sunny days (Fig. 5d), the soil temperature at a depth of 40 cm is higher than that in shallow layers. In the dry season, the soil temperature at 20 cm depth is also relatively high and lower than the soil temperature at 5 cm depth only from 16:00 to 19:00.

On heavy rainy days, the soil temperatures in shallow layers show a decreasing trend, and the closer to the surface layer, the greater the soil temperature decreases. However, at the 40 cm depth, the soil temperature increases at 00:00~9:00 and remains stable thereafter, which indicates that the deep soil first absorbs heat from the water layer; subsequently, the water content increases, and the accumulation and consumption of heat remain relatively stable.

**Fig. 5** Same as Fig. 4 but for soil temperature. $T_{soil, 5 cm}$ represents the temperature at 5 cm depth in the soil, and the rest may be deduced by analogy.
3.2.2 Soil moisture

The average height of the forest canopy at the observation site is 18 m. During non-rainy days, the soil moisture fluctuates very little. The forest canopy resembles a mulch on the soil surface and becomes a barrier between the soil and the outside world, reducing the heat flow between them and inhibiting the evaporation of water to the atmosphere and reducing the influence of the outside environment. In general, the seasonal variations in the soil moisture (Fig. 2c) are not as seasonal as the variation in temperature. The soil moisture fluctuates around a relative equilibrium as the rain increases or decreases. Due to the hot and rainy climate at the site, evaporation increases as the temperature rises, causing the moisture to rise as well, rather than simply falling as the temperature rises.

Figure 6 shows the diurnal variation in the averaged soil moisture in all layers. Only during heavy rainy days did the soil moisture increase with time due to infiltration. The diurnal variations in the averaged soil moisture under other conditions are stable around the values shown in Table 3. The values of soil moisture at 5 cm depth and 10 cm depth are close, with a slight diurnal variation. The soil moisture at depths of 20 cm and 40 cm is less disturbed and almost constant.

The average soil moisture was in the order of $V_{40cm} > V_{20cm} > V_{5cm} > V_{10cm}$ under all conditions (Table 3). $V_{5cm}$, $V_{10cm}$, $V_{20cm}$, and $V_{40cm}$ are the soil moisture at depths of 5 cm, 10 cm, 20 cm, and 40 cm, respectively. The differences between $V_{5cm}$ and $V_{10cm}$ are smaller in the dry season than in the wet season. The differences between $V_{20cm}$ and $V_{40cm}$ are also smaller in the dry season than in the wet season. The differences are mainly caused by precipitation. As shown in Fig. 6f, the deep soil moisture continues to increase after 12:00, but the shallow soil moisture starts to fall slowly.

*Table 3* Average soil moisture (volumetric water content) in various layers under different conditions (m$^3$·m$^{-3}$)

|        | All    | Dry season | Wet season | Typical sunny | Cloudy | Heavy rain |
|--------|--------|------------|------------|---------------|--------|------------|
| 5 cm   | 0.1850 | 0.1724     | 0.2033     | 0.1695        | 0.1729 | 0.2320     |
| 10 cm  | 0.1836 | 0.1711     | 0.2018     | 0.1691        | 0.1722 | 0.2294     |
| 20 cm  | 0.2404 | 0.2250     | 0.2628     | 0.2229        | 0.2314 | 0.2748     |
| 40 cm  | 0.2535 | 0.2392     | 0.2741     | 0.2384        | 0.2460 | 0.2841     |
3.2.3 Soil heat flux

The soil heat flux is a physical quantity used to describe the amount of heat exchange in the soil, and it follows a similar seasonal variation to the soil temperature (Fig. 2d). Figure 7 shows the diurnal variation in the average soil heat flux in all layers. The heat flux at 7.5 cm depth exhibits a low value at 09:00 and a peak at approximately 17:30. The soil heat flux at 15 cm depth shows the same characteristics. The diurnal variation in the soil heat flux at 30 cm depth is gentle, and there is no obvious peak and valley value.

On all days (Fig. 7a) and cloudy days (Fig. 7e), the averaged soil heat flux is consistently positive from approximately 15:00 to 22:00 at 7.5 cm depth and consistently positive from approximately 14:30 to 21:30 at 15 cm depth, indicating that heat is transferred from the upper layer to the deep layer. The averaged soil heat fluxes are negative in the rest time, meaning that the soil releases heat to the outside. The averaged heat fluxes are negative in all layers in the dry season (Fig. 7b) but positive in all layers in the wet season (Fig. 7c). In other words, on average, the deep soil absorbs energy from the surface layer in the dry season, while it releases energy from the deep layer to the surface layer in the wet season. The diurnal variation in the soil heat flux on typical sunny days (Fig. 7d) is consistent with that in the dry season.

The diurnal variation in the soil heat flux on heavy rainy days (Fig. 7f) is similar to that in the wet season but not smooth and serrated.

3.2.4 The response of soil to rain (Fig. 8)

The average annual precipitation exceeds 2000 mm in Zhusai. Here, we select the severe rainstorm weather events with daily rainfall greater than 100 mm and analyze the variations in the averaged soil temperature, moisture, and heat flux on that day and the next 3 days.

When rainstorms occur, the soil temperature and the soil heat flux show an overall decrease; the closer to the soil surface, the greater the variation. The soil temperature at 40 cm depth is higher than those at the layers above it. The soil heat flux at 40 cm depth is greater than those at the relatively shallower layers. The heat flux in the shallow layers remains negative. The soil moisture varies in waves with rainfall, and the amplitude of variation in the shallow layer is larger than that in the deep layer.

At the end of the day of the storm, approximately 11 h later, the soil temperature and heat flux returned to normal variability, while the soil moisture continued to decline slowly over the next few days, returning to normal after approximately 3 days.

Fig. 7 Same as Fig. 4 but for soil heat fluxes. shf_7.5 cm represents the soil heat flux at a depth of 7.5 cm, and the rest may be deduced by analogy. The positive values of soil heat fluxes indicate that the transport direction is downwards.
3.3 Soil heat fluxes and canopy surface net radiation

Here, we only analyze the relationship between the soil heat flux at a depth of 7.5 cm in the uppermost soil layer and the net radiation on the canopy surface. On all days (Fig. 9a) and cloudy days (Fig. 9e), the net radiation of the canopy surface gradually increases with sunrise, reaches a maximum at 12:30, and then gradually decreases, with a bell-shaped variation. The averaged soil heat flux shows an “S” pattern variation, with a maximum at 17:30.

In the dry season (Fig. 9b), the peak time of the net radiation remains the same as that on all days, but the peak time of the soil heat flux lags half an hour. In the wet season (Fig. 9c), the peak of the net radiation occurs half an hour earlier (at 12:00), but the peak time of the soil heat flux is not advanced. The delay effect is 5.5 h in the two cases. The peak of the canopy net radiation lags half an hour, with the delay effect shorter than 4.5 h on typical sunny days (Fig. 9d) and heavy rain days. On average, the peak of the soil heat flux lags behind the peak of the canopy net radiation by approximately 5 h.

3.4 Soil thermal conductivity

The soil thermal conductivity at depths of 7.5 cm, 15 cm, and 30 cm are calculated for the soil temperatures from 5 to 10 cm, 10 to 20 cm, and 20 to 40 cm, respectively. The equation to define the soil thermal conductivity is as follows:

\[ \lambda = -\frac{G}{\partial T/\partial z} \]  

(1)

In the equation, \( G \) is the soil heat flux in the vertical direction measured by the soil heat flux plate in W·m\(^{-2}\). \( \partial T/\partial z \) is the soil temperature gradient in the vertical direction in K·m\(^{-1}\). \( \lambda \) is the soil thermal conductivity in W·m\(^{-1}\)·K\(^{-1}\).

Due to the measurement accuracy and other reasons, when the difference in the soil temperature between two adjacent layers is too small, it will lead to the appearance of unnaturally large values, so the soil thermal conductivity is set to a certain threshold range in the calculation. The heat fluxes during positive and negative transitions may produce unnaturally small values, so the data for 2 h before and after the sign transition of the heat flux direction are excluded (Li et al. 2012).
The soil thermal conductivity is mainly influenced by the moisture, dry density, and mineral composition of the soil. The thermal conductivity in dry sand is 0.026 W·m⁻¹·K⁻¹, while quartz, as the largest mineral with a significantly higher thermal conductivity than other minerals, has an average thermal conductivity of 5.0 W·m⁻¹·K⁻¹ (Côté and Konrad, 2005); thus, the range of the soil thermal conductivity is set from 0.026 to 5.0 W·m⁻¹·K⁻¹.

The calculated soil thermal conductivity for all three layers of soil is relatively smooth with a gentle trend (figure omitted). The averaged soil thermal conductivities on all days are 2.18 W·m⁻¹·K⁻¹, 1.22 W·m⁻¹·K⁻¹, and 1.26 W·m⁻¹·K⁻¹ for depths of 5–10 cm, 10–20 cm, and 20–40 cm, respectively. The upper layer is the highest, followed by the deep layer, and the middle layer is the lowest. The main causes may be the difference in soil composition and water content in each layer.

4 Conclusion

In this study, by using observation data from the Phoenix Mountain observation tower in Zhuhai in South China from October 2015 to May 2018, the variations in the soil temperature, moisture, and heat flux in the understorey of evergreen broadleaf forest were analyzed. The main conclusions can be summarized as follows.

(1) In the analysis period, the variations in the ground and canopy surface temperature, soil temperature, and soil heat flux at all layers were similar, and they fluctuated with the seasons. During non-rainy days, the soil moisture fluctuates very little. In general, the variation in the soil moisture is not as seasonal as that of the soil temperature. The soil moisture fluctuates around a relative equilibrium as the rain increases or decreases.

(2) The ground and canopy surface temperatures show a good positive correlation. However, the ground surface temperature varies lag slightly compared to the canopy temperature. Both ground and canopy surface temperatures have valley values before sunrise and peak values in the late afternoon. The ground surface temperature cooled slightly faster than the canopy surface temperature at night, and the rate of cooling varied with weather conditions, which was higher in the dry season and faster on typical sunny days. The diurnal variation is steeper and less smooth on heavy rainy days.

(3) The diurnal variations in soil temperature are characterized by a cosine function. With the deepening of the soil layer, the times of the valleys and peaks lag behind, and the amplitude of the variation in soil temperature decreases. There is almost no diurnal variation in soil...
temperature at 40 cm depth. Only during heavy rainy days did the soil moisture increase with time due to infiltration.

(4) The heat flux at 7.5 cm depth shows an “S” pattern variation, which occurs at a low value at 09:00 and a peak at approximately 17:30. The soil heat flux at 15 cm depth shows the similar characteristics. There are no obvious peak and valley values in the soil heat flux at 30 cm depth. The net radiation of the canopy surface shows a bell-shaped variation, which gradually increases with sunrise, reaches a maximum at 12:30, and then gradually decreases. On average, the peak of the soil heat flux lags behind the peak of the canopy net radiation by approximately 5 h.

(5) The calculated soil thermal conductivity for all three layers of soil is relatively smooth with a gentle trend. The averaged soil thermal conductivities are 2.18 W·m⁻¹·K⁻¹, 1.22 W·m⁻¹·K⁻¹, and 1.26 W·m⁻¹·K⁻¹ for 5–10 cm, 10–20 cm, and 20–40 cm depths, respectively. The upper layer is the highest, and the middle layer is the lowest. The main causes may be the difference in soil composition and water content in each layer.

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Author contribution Conceptualization: Shuting Wu, Zhigang Wei. Methodology: Shuting Wu, Zhigang Wei. Formal analysis and investigation: Shuting Wu, Xianru Li, Huan Wang, and Shiting Guo. Writing—original draft preparation: Shuting Wu, Xianru Li, Huan Wang, and Shiting Guo. Funding acquisition: Zhigang Wei.

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Data availability The observation data used in this study have not been released and will be uploaded to this website in the future: http://feri.bnuz.edu.cn/zygx.htm. The data can also be obtained by contacting the corresponding author.

Code availability Python and origin pro were used to process the data and plot the figures.

Declarations

Ethics approval We think ethics approval is not applicable for this study.

Consent to participate We think consent to participate is not applicable for this study.

Consent for publication The work described has not been published before and is not under consideration for publication elsewhere.

Conflict of interest The authors declare no competing interests.

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