Temporal and Spatial Thermal Radiation Distribution Analysis within and above Crop Canopies by 3D Simulation

Huaguo Huang 1, 2, Lei Wang 1, Yang Zhang 2 and Qinhuo Liu 2

1 Key Laboratory for Silviculture and Conservation, Ministry of Education; College of Forestry, Beijing Forestry University, 100083, Beijing, P.R. China
2 State Key Laboratory of Remote Sensing Science, Jointly Sponsored by the Institute of Remote Sensing Applications of Chinese Academy of Sciences and Beijing Normal University, 100101, Beijing, P.R. China

Abstract. The thermal radiation distribution within and above the canopy is explored. CUPID model is chosen to simulate the canopy component temperatures. TRGM model, based on 3D realistic structure and radiosity solution, is used to simulate the component brightness temperature distribution within canopy and thermal radiation emission directionality distribution $T_B(\theta)$ above canopy. It is noted that the shape of vegetation component temperature profile mostly like an inverse “S” curve. Component temperature histogram is very good indicator to show daily variation. The difference between component brightness temperature and thermodynamic temperature mainly varies with LAI, relative height and leaf angle distribution. Through establishing relationship between $T_B(\theta)$ variation, LAI and environmental parameters on crop canopies, the temporal effects or angular effects of the thermal radiation distribution is discussed.

Keywords: 3D simulation, thermal radiation distribution, TRGM, CUPID model

1. Introduction

Land surface temperature (LST) is of great interest in many research areas such as assessing water and energy budgets at the biosphere-atmosphere interface. LST measured by remote sensors varies with sensor view angle (up to 13K), canopy structure and time. That high variation makes it difficult to retrieve accurate flux (Norman et al., 2000) or component temperature by directly using single surface radiative temperature measured by remote sensors (Kimes, 1983). This issue becomes more important for satellite sensors with a large swath angle, like MODIS, NOAA, ATSR and AATSR.

Therefore, it is necessary to know the temporal and spatial distribution of canopy thermal radiation distribution within and above canopy because this information can help to normalize directional effects of remotely sensed TIR data, provide a prior knowledge to the surface flux inversion from multiple view angle temperatures $T_B(\theta)$ and explore the potential to extract canopy structural parameters or soil water content from temporal variation of $T_B(\theta)$.

However, carried out in a limited space of time, continual experimental measurement of component temperature and $T_B(\theta)$ during a relative long time is lacking. Therefore, we use a simulation analysis method by coupling energy balance model and $T_B(\theta)$ model to overcome the above difficulties. In this study, the CUPID model, which was further developed by Huang et al. (2006) and the TRGM model (Liu et al., 2007) are linked to analyze the temporal and spatial variations of thermal emission within and above wheat canopy.

2. Methodology

2.1. Model Coupling

The CUPID model (http://www.soils.wisc.edu/~norman/cupid/) is chosen to simulate the canopy component temperatures. The canopy component $T_B(\theta)$ is simulated by CUPID model and the components brightness temperature distribution within canopy is simulated by TRGM model. The component brightness temperature histogram is very good indicator to show daily variation. The difference between component brightness temperature and thermodynamic temperature mainly varies with LAI, relative height and leaf angle distribution.

Therefore, it is necessary to know the temporal and spatial distribution of canopy thermal radiation distribution within and above canopy because this information can help to normalize directional effects of remotely sensed TIR data, provide a prior knowledge to the surface flux inversion from multiple view angle temperatures $T_B(\theta)$ and explore the potential to extract canopy structural parameters or soil water content from temporal variation of $T_B(\theta)$.

However, carried out in a limited space of time, continual experimental measurement of component temperature and $T_B(\theta)$ during a relative long time is lacking. Therefore, we use a simulation analysis method by coupling energy balance model and $T_B(\theta)$ model to overcome the above difficulties. In this study, the CUPID model, which was further developed by Huang et al. (2006) and the TRGM model (Liu et al., 2007) are linked to analyze the temporal and spatial variations of thermal emission within and above wheat canopy.

2. Methodology

2.1. Model Coupling

The CUPID model (http://www.soils.wisc.edu/~norman/cupid/) is chosen to simulate the canopy component temperatures. The canopy component $T_B(\theta)$ is simulated by CUPID model and the components brightness temperature distribution within canopy is simulated by TRGM model. The component brightness temperature histogram is very good indicator to show daily variation. The difference between component brightness temperature and thermodynamic temperature mainly varies with LAI, relative height and leaf angle distribution.

However, carried out in a limited space of time, continual experimental measurement of component temperature and $T_B(\theta)$ during a relative long time is lacking. Therefore, we use a simulation analysis method by coupling energy balance model and $T_B(\theta)$ model to overcome the above difficulties. In this study, the CUPID model, which was further developed by Huang et al. (2006) and the TRGM model (Liu et al., 2007) are linked to analyze the temporal and spatial variations of thermal emission within and above wheat canopy.

2. Methodology

2.1. Model Coupling

The CUPID model (http://www.soils.wisc.edu/~norman/cupid/) is chosen to simulate the canopy component temperatures. The canopy component $T_B(\theta)$ is simulated by CUPID model and the components brightness temperature distribution within canopy is simulated by TRGM model. The component brightness temperature histogram is very good indicator to show daily variation. The difference between component brightness temperature and thermodynamic temperature mainly varies with LAI, relative height and leaf angle distribution.

However, carried out in a limited space of time, continual experimental measurement of component temperature and $T_B(\theta)$ during a relative long time is lacking. Therefore, we use a simulation analysis method by coupling energy balance model and $T_B(\theta)$ model to overcome the above difficulties. In this study, the CUPID model, which was further developed by Huang et al. (2006) and the TRGM model (Liu et al., 2007) are linked to analyze the temporal and spatial variations of thermal emission within and above wheat canopy.
temperature distribution because it accounts for leaf inclined angle effect on leaf temperature distribution. The extended CUPID version (Huang et al. 2006) can output both sunlit and shaded soil temperatures, which meet the basic needs of TRGM model for component temperature distribution input. 3D Thermal Radiosity-Graphics Model TRGM (Liu et al., 2007) is employed to simulate the brightness component temperature within canopy and $T_B(\theta)$ distribution because of its high accuracy for realistic canopies. These two models are both originally developed for crop canopies so it is feasible to couple them together.

Fig. 1 shows the coupling strategy of the above two models. There are three main steps to couple CUPID and TRGM. At first, CUPID predicts THERMAL.IN, which describes hourly leaf temperature profiles, sunlit and shaded soil temperatures. Then, according to the measured canopy structures, the virtual canopy scenes of wheat (POLY.IN) are generated by MELS (Qin and Gerstl, 2000). Finally, TRGM simulates the component brightness temperature and $T_B(\theta)$ according to the corresponding POLY.IN and THERMAL.IN. Since POLY.IN stores the 3D coordinates and THERMAL.IN saves the quasi-2D temperature profiles organized by thin layers with equivalent leaf area volume density and ten leaf angles, each polygon in POLY.IN is classified into the corresponding layer and leaf angles to match THERMAL.IN. When a polygon is partly shaded, its temperature is estimated as the weighted average of matched temperature and shaded temperature by sunlit fraction.

2.2. Why Coupling?
In fact, CUPID can simulate $T_B(\theta)$. Why TRGM is need? Why is the soil temperature extension needed for original CUPID? The primary reason is that CUPID model has it’s the limitation on simulating $T_B(\theta)$ variation for crop canopies with significant row structure, which can be overcome by TRGM. Fig. 2 shows that CUPID model underestimates the hot spot effect in both solar principle plane and its cross plane, while overestimates the $T_B(\theta)$ at the off-nadir view. Except the absolute value difference, the trend is similar between results from TRGM using homogeneous canopy and CUPID using clumping index. While, only the coupled model presents a perfect hot spot at the solar position $(39^\circ, 149^\circ)$. In addition, CUPID mode can’t simulate the row stripe effect for the row crop, where the variation of $T_B(\theta)$ along the crop row direction is small (Kimes etc, 1980; Yu etc, 2004). Therefore, the advantage of TRGM is obvious and indubitable for row structure canopies. If the mean soil temperature is used as input for TRGM, the simulated $T_B(\theta)$ will also lose the hot spot character, which can explain the essentiality of model extension to separate sunlit and shaded soil temperatures.
2.3. Input Parameters
The required driving data for the coupled model comes from field measurement over winter wheat canopies, which was obtained from April 1 to April 21 in 2001, in Beijing (116°34′33″, 40°11′40″), China (Liu et al., 2002). The winter wheat was planted in the last fall. The row orientation was North-South (row spacing =0.14m, average canopy height =0.10~0.32m, LAI=0.5~2.3, clumping index=0.3~0.7). The mean leaf angle is about 60°. The micrometeorology data at 2m height from ground and soil water content were measured in situ. The soil type is Aquic Brown Soil (a kind of silty loam in China) with a bulk density of 1.3g/cm³ at the soil surface. Field moisture capacity and wilting coefficient are 22% and 10% respectively. There was a rainfall (about 2-3cm) at night of April 5 and the field was irrigated (about 0.6cm) in April 14.

2.4. Indicators Selection
Component temperature and \( T_B(\theta) \) are the two main output of the coupled model. Accurate measured component thermodynamic temperatures are needed to validate remote sensing inversion data or provide input parameters for thermal emission directionality models. However, thermal camera can only capture component brightness temperature distribution at the same time. Atmosphere downward radiation and emissivity effect have to be removed to obtain the thermodynamic temperature. Therefore, it is necessary to estimate how large the differences are between the two types of component temperatures. Then, four aspects of analysis are chosen to present the thermal emission within and above wheat canopy:

- Canopy component temperature distribution features presented by profile shape and component histogram: in the histogram, each peak can present one component;
- The relationship between component brightness temperature (CBT) and thermodynamic temperature (CT);
- The relationship between view angle effect \( \Delta T_B (=T_B(0)- T_{B,mean}(55)) \) and weather parameters and soil water content, where \( T_{B,mean}(55) \) is a mean value of \( T_B(55) \) for all azimuth angles;
- The azimuth variation of \( \Delta T_B \);
- The temporal variation of \( \Delta T_{B,c} \).

3. Results and Discussions

Inverse “S” leaf temperature profile

Fig. 3 demonstrates significant spatial and temporal variations of leaf temperature distribution. Spatial variation means leaf temperature varies with leaf inclination angle and relative height. Temporal variation can be divided into three stages. First, in the early morning from 00:00pm to 6:00am, all leaves almost have the same temperature. Second, from 8:00am to 16:00pm, leaf temperature profile looks like inverse an “S” shape, with the highest temperature in the bottom of canopy. At this stage, the leaf temperature variation comes both from leaf inclination angle difference (up to 4 degree at 14:00pm) and vertical difference (up to 3 degree at 14:00pm). Third, in the night from 18:00pm to 22:00pm, leaf temperature has only small vertical...
variation of about 0.5°C.

Fig. 3: Winter wheat leaf temperature profile in April 2, 2001 (LAI = 0.5; Canopy Height = 0.10m); layer 19 refers to the top of the canopy; layer 0 is the soil surface; ten curves in each sub figure refer to ten classes of leaf inclination angles from being fully sunlit to being completely shaded.

In other days, results are similar. However, due to the limited measurement data, only one group of measurement in May 9, 2001 may be used as a reference (Fig. 4). Leaf temperatures were measured at three heights by a thermocouple thermometer (JM424 digital thermometer). From the measurement data, it is obvious that the shaded leaf has an inverse “S” shape (“DM”), while the sunlit leaf (“SM”) has an unexpected low temperature at the lowest position. That may come from the measurement error. Anyway, the simulation curves (“DS” and “SS) have good inverse “S” shapes.

![Fig. 4 measured canopy temperature profile, including 3 leaf layers and 1 soil layer at 10:30am in May 9, 2001; SM: measured sunlit profile; SS: simulated sunlit profile; DM: measured shaded profile; DS: simulated shaded profile.](image)

**Component temperature histogram variation**

Component temperature histogram is another demonstration of the daily variation (Fig. 5). Generally, there are only two components (soil and leaf) during night. From 8:00am to 16:00pm in clear days, three or four components (sunlit soil components, shaded soil components, sunlit leaf components, and shaded leaf components) appear. In the early morning or late afternoon, it is difficult to distinguish between the sunlit
leaf temperature and shaded soil temperature. For heavy cloudy days, there are only two components even in the daylight. For a canopy nearly full cover, the leaf (either sunlit or not) has the same temperature range with that of the shaded soil.

![Component temperature histogram variation in April 2, 2001 (LAI = 0.5; Canopy Height = 0.10m)](image)

**Component brightness temperature (CBT) vs. thermodynamic temperature (CT)**

A special condition is constructed to test the difference between CBT and CT. Two homogeneous canopies are generated with LAI of 1.2 and 3.0 and height of 1m. The canopies are divided into 19 layers of leaf. The leaf angle is randomly distributed with mean leaf inclined angle of 50 degree. The emissivity of leaf varies from 0.90 to 0.99. Soil emissivity is 0.95. Simulation takes 9μm spectral region as an example. The leaf temperature is 31°C. Sunlit and shaded soil temperatures are 46°C and 36°C.

Fig. 6 shows that the leaf CBT increases from the top to bottom of the canopy though the CT is the same. The CBT of the bottom leaf increases when LAI increases, which is explained by the “cavity effect” (Sutherland and Bartholic, 1977; François et al., 1997). Based on the single scattering radiation, the averaged soil CBT are 39.1°C and 35.4°C. After multiple scattering calculations, the soil CBT become to be 40.4°C and 36.7°C, which means an error of 1.3°C for CBT estimation if omitting multiple scattering.

![Leaf brightness temperature profile for LAI of 1.2 (a) and 3.0 (b); the eleven curves from left to right in each sub figure refer to leaf emissivity from 0.90 to 1.0.](image)
The capability of our coupled model to simulate CBT can be used to validate a component temperature inversion method based on “canopy openness” (Huang et al. 2007). Fig. 7 shows that the corrected leaf CTs are around the real value (31°C). Without correction, the differences between soil CBT (40.4°C/36.7°C) and CT (44.2°C/40.4°C) are about 3.8°C. If simply using Planck function to remove emissivity effects, the error of the corrected CT (47.0°C/43.2°C) decreases to be about 2.8°C. If using the “canopy openness” to correct soil CBT, the error of the final corrected soil CT (42.8°C/38.9°C) are only about 1.3°C.

Fig. 7 Leaf Brightness Temperature (CBT) and Corrected Temperature (CT) profiles based on “canopy openness”; LAI=1.2; soil emissivity = 0.92; leaf emissivity = 0.90; 8-14μm spectral region; Leaf CT=31°C; Sunlit and shaded soil CBT are 40.4°C and 36.7°C.

**Thermal radiation distribution above canopy**

Thermal radiation distribution above canopy varies with view angle and time significantly. In most days from April 1 to 21, the daily $\Delta T_B$ behaves a “W” shape (Fig. 8). The middle peak is at noon. The two valleys are in the early morning and in the late afternoon. The strongest temperature contrast between the soil and leaf plays the major role on the maximum $\Delta T_B$ which can be up to 2.8°C. At late afternoon, most of the soil is shadowed, and $T_B(\theta)$ is mainly related to the leaf temperature differences and $\Delta T_B$ is low.

![Fig. 8 Simulated daily $\Delta T_B$ in 20 days (a) and measured daily $\Delta T_B$ in April 21, 2001 (b).](image)

In the whole growth stages, $\Delta T_B$ has a maximum value (about 4.0°C) when LAI is about 0.8. The azimuthally variation is relatively small (up to 0.5°C).

A statistical equation is provided to predict the $\Delta T_B$ variation with environmental parameters including soil water content ($W_{soil}$, %), air temperature ($T_a$, K), wind speed ($u$: m/s), LAI and solar total radiation ($R_{sun}$, W/m²).
$Wm^{-2}$). $\Delta T_B$ is not sensitive to air humidity. The equation is a first estimation of the angular effect, which can be used as an indicator whether it is necessary to consider the spatial and temporal effect from remote sensing sensors.

$$\Delta T_B = \frac{278 - T_a}{35} + 0.44 \ln \left( \frac{W_{\text{soil}}}{W_{\text{sat}}} \right) + 0.35 \frac{R_{\text{sun}}}{600} - \frac{|\mu - 2|}{20} - \frac{|LAI - 0.8|}{26.5} + 0.05$$

Where, $W_{\text{sat}}$ is the saturated soil water content (%). The 90% of the fitness error is between -0.5°C and 0.5°C, and the maximum error is about 0.8°C. This formulation statistically shows the contribution of the five parameters on DBTE and will be helpful on understanding the mechanism of TIR emission directionality.

4. Conclusions and significance on remote sensing application

The two-model combination approach shows us some simulation results to reveal the changing rules on thermal radiation within and above vegetation canopy. It is noted that the shape of vegetation component temperature profile mostly looks like an inverse “S” shape. Component temperature histogram is a very good indicator to show daily variation. The difference between component brightness temperature and thermodynamic temperature mainly varies with LAI, relative height and leaf angle distribution.

We also see that the $T_B(\theta)$ distributions have significant temporal variation related to the different land surface parameters. The daily $\Delta T_B$ have a peak value at noon (12:00am). $\Delta T_B$ is mainly controlled by the soil moisture, air temperature, LAI, wind speed and solar radiation. The maximum $\Delta T_B$ reached 4.0°C when the LAI of the row structured canopy is about 0.8.

The first potential application is to provide prior knowledge to improve component temperature inversion. Another application is to normalize the brightness temperature to a single view angle for mapping comparable and accurate surface temperature distribution in a whole image covering large areas. For example, in MODIS images, the view angle varies from 0 to 55 degree from the centre to the edge. In order to improve the accuracy to inverse latent flux, the directional effect of brightness temperature can be normalized to one angle (e.g. nadir view brightness temperature). Our simulation results can tell how and when to correct the directional effect simply based on LAI and weather conditions.

5. Acknowledgements

This work is supported by Chinese Natural Science Foundation Project (40730525) and China’s Special Funds for Major State Basic Research Project (2007CB714402).

6. References


