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Thermal Vegetation Canopy Model Studies

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An iterative-type thermal model applicable to forest canopies was tested with data from two diverse forest types. The model framework consists of a system of steady-state energy budget equations describing the interactions of short- and long-wave radiation within three horizontally infinite canopy layers. A state-space formulation of the energy dynamics within the canopy is used which permits a factorization of canopy geometrical parameters from canopy optical and thermal coefficients as well as environmental driving variables. Two sets of data characterizing a coniferous (Douglas-fir) and deciduous (oak–hickory) canopy were collected to evaluate the thermal model. The results show that the model approximates measured mean canopy temperatures to within 2°C for relatively clear weather conditions and deviates by a maximum of 3°C for very hazy or foggy conditions.

Introduction

Rapid and accurate assessment of renewable resources is an increasingly important task facing remote sensing specialists. Mathematical abstraction of energy processes of vegetation canopies is a useful technique for relating sensor response to environment–canopy interactions. Such an understanding is required in order to make timely inferences about the condition of forestry and agricultural resources from remote sensors. In the thermal regime, several authors have reported success in estimating evapotranspiration of crops from thermal sensor data (Heilman et al., 1976; Reginato et al., 1976; and Soer, 1980). Several models have been reported that describe the energy balance of vegetation either in terms of a single leaf (Gates, 1968; Wiebelt and Henderson, 1977; and Kimes et al., 1978), or an abstract layered canopy (Alderfer and Gates, 1971; and Deardorff, 1978). Few models have been described that characterize the energy flows within vegetation canopies as a function of the canopy geometry (Goudriaan, 1977; Norman, 1979; and Kimes et al., 1981).

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In this study, a modification of the thermal canopy model reported by Kimes et al. (1981) that is applicable to forest canopies is described and evaluated. The model is an iterative type formulation of a system of steady-state energy budget equations describing a canopy as three horizontal layers. Each layer is described in terms of reflective and thermal radiation coefficients and leaf inclination angle distributions.

The model emphasizes the radiative energy processes occurring both within and above the vegetation canopy layers and relates these flux transfers to detailed consideration of the canopy geometry. Other energy transfer processes such as sensible heat and evapotranspiration are included but in a fairly simplistic manner. Standard expressions from the literature are utilized. The modular form of the model makes it fairly easy to replace the existing expressions as warranted. Thus, the model is capable of evaluating particularly the radiative energy processes from widely diverse canopies.

There were two broad objectives of the work reported here. First was to determine if we could re-express a previously developed thermal exitance model (Kimes et al., 1981) in a more usable form which would permit a wide variety of engineering-type target/background studies to be performed in a more practical computational fashion. The second objective was to evaluate the model with validation data collected from two different forest types; a Douglas fir (*Pseudotsuga menziesii*) canopy and a mixed deciduous canopy.

Here, we first describe the updated model structure and solution approach. This is followed by a description of the experimental sites and methods for obtaining the required model input data. Finally, the results and summary are given.

Model Structure

The updated model formulation given below differs in three major aspects from the original model developed by Kimes et al. (1981). First, the model has been rewritten in a vector–matrix form with a state-space characterization. That is, there is a specific identification of a state vector **X**, the canopy layer temperatures, a control vector **U**, the meteorological driving variables, and a parameter vector **P**. In this formulation, the long-wave energy budget terms have been factored into a geometric-dependent term, the **S** matrix, and the long-wave thermal source terms. This factorization permits the precalculation of the **S** matrix for a wide variety of canopy situations and then the subsequent convolving of these matrices with the **U** and **P** vectors to evaluate canopy thermal variations. A second potential advantage of this factorization is that it results in a linear system of equations with respect to **S** suggesting the use of linear filtering theory to estimate S from **X** (Sorenson, 1966).

The second modification is the use of more simplifying assumptions in the model, particularly with regard to the short-wave absorption calculation as discussed later. Finally, in solving the nonlinear energy budget equations, explicit use was made of the closed form expressions for the Jacobian of the system in a Newton–Raphson technique.

In the material that follows, individual expressions for the component energy budget processes are summarized and an explicit expression for the elements of the

Jacobian matrix are given. The geometrical factorization of the energy budget equation for the long-wave flux transfers is derived.

Energy balance framework

The model is a plane-parallel abstraction of a vegetation canopy divided into three horizontal layers. Two additional source layers are given by the atmosphere above the canopy and by the underlying ground. An energy balance framework, assuming steady-state conditions, is formulated for each of the three vegetation layers (sinks) as a function of the five source layers. In the expressions that follow, $i=1,2,3$ represents the sink or vegetation layers and $j=1,2,3,4,5$ represents respectively the atmosphere, the three vegetation layers, and the ground source layers of energy flux. The combination of the i,j indices thus represents flux from source layer j to sink layer i.

The vector expression for the energy balance equations for layers 1, 2, 3 considering long-wave transfers, short-wave transfers, sensible heat, and evapotranspiration can be written as

$$\mathbf{F}(\mathbf{X},\mathbf{P},\mathbf{U})=\mathbf{0}, \qquad (1)$$

where

$\mathbf{X}\overset{\Delta}{=}(X_1X_2X_3)^T$ = the average layer temperature vector for layers 1, 2, 3;

$\mathbf{P}\overset{\Delta}{=}(\varepsilon_i,\ i=1,2,3;\ \alpha_i,\ i=1,2,3;\ \varepsilon_g;\ R_l;\ \mathbf{S};\ \mathbf{A})$ = the parameter vector characterizing the canopy layers;

ε_i, α_i = emissivity and absorptivity of the vegetation layers;

ε_g, α_g = emissivity and absorptivity of the ground layer;

R_l = leaf stomatal resistance to water vapor diffusion (Note that the resistance of the boundary layer to diffusion is estimated from other measured parameters);

$\mathbf{S}$ = long-wave flux transfer matrix calculated from geometrical properties of the canopy;

$\mathbf{A}$ = short-wave flux absorption coefficient vector;

$\mathbf{U}\overset{\Delta}{=}(T_aT_gWS\ RH\ SW)^T$ is the control or input vector;

T_a = air temperature (°C);

T_g = ground temperature (°C);

WS = wind speed (m/sec);

RH = relative humidity;

SW = short-wave flux (w/m^2).

$\mathbf{F}$ may be rewritten in the following matrix form which explicitly separates the geometrical properties of the canopy $\mathbf{S}$ from the remaining energy terms (Smith et al., 1981).

$$\mathbf{F}\overset{\Delta}{=}\tfrac{1}{2}\alpha\sigma\mathbf{B}(\mathbf{X})^T\mathbf{S}-\sigma\mathbf{B}(\mathbf{X})+\mathbf{A}+\mathbf{H}(\mathbf{X})+\mathbf{LE}(\mathbf{X})=0, \qquad (2)$$

where

$\mathbf{B}$ = vector of long-wave emission terms,

$\mathbf{H}$ = vector of sensible heat,

$\mathbf{LE}$ = vector of evapotranspiration terms,

σ = Stefan–Boltzmann constant.

The significance of this factorization is that a wide variety of abstract or cannonical canopies may be characterized by precalculation of the S matrix. This matrix table may then be convolved with the appropriate meteorological driving variables to simulate diurnal behavior for a wide spectrum of scenarios.

The vector equation (2) may be expanded for each layer and the explicit dependence on parameters or input variables may be indicated by

$$\tfrac{1}{2}\alpha_1\sigma\{B(T_a)S_{11}+B(X_1)S_{12}+B(X_2)S_{13}+B(X_3)S_{14}+B(T_g)S_{15}\}+A_1-\sigma B(X_1)+H(X_1;WS,T_a)+LE(X_1;WS,T_a,R_l,RH)=0, \tag{3a}$$

$$\tfrac{1}{2}\alpha_2\sigma\{B(T_a)S_{21}+B(X_1)S_{22}+B(X_2)S_{23}+B(X_3)S_{24}+B(T_g)S_{25}\}+A_2-\sigma B(X_2)+H(X_2;WS,T_a)+LE(X_2;WS,T_a,R_l,RH)=0, \tag{3b}$$

$$\tfrac{1}{2}\alpha_3\sigma\{B(T_a)S_{31}+B(X_1)S_{32}+B(X_2)S_{33}+B(X_3)S_{34}+B(T_g)S_{35}\}+A_3-\sigma B(X_3)+H(X_3;WS,T_a)+LE(X_3;WS,T_a,R_l,RH)=0. \tag{3c}$$

The formulation for each energy budget component used in the model is given by

Long-wave: $B(X_i)=\varepsilon_i(X_i+273)^4$, (4)

Short-wave absorption: $A_i=\mathrm{ABS}(i)\cdot SW$, (5)

where

ABS(i) = short-wave absorption coefficient calculated by an optical absorption model which uses a Monte Carlo technique to include multiple scattering effects (Kimes and Smith, 1980; Kimes et al., 1980).

Sensible heat:

$$H(X_i;WS,T_a)=h_c(WS)(X_i-T_a) \tag{6}$$

where h_c, the convection coefficient, is taken from Tibbals et al. (1964)

Evapotranspiration:

$$LE(X_i;WS,T_a,R,RH)=\frac{1}{R+R_a}[s(X_i)-RHs(T_a)]h(X_i), \tag{7}$$

where

$h(X_i)$ = latent heat of vaporization of water at temperature X_i;

$s(X_i)$ = water vapor density inside the leaf at saturation at the leaf temperature X_i (g cm^{-3});

$s(T_a)$ = water vapor density at saturation of the free air beyond the boundary layer of the leaf at the air temperature T_a (g cm^{-3});

R_a = resistance of the boundary layer to water vapor diffusion;

The terms $s(X_i)$, $s(T_a)$, and R_a are calculated from measured driving variables, U (Kimes et al., 1981).

The discussion of the S matrix, which controls the interception of long-wave flux within the canopy layers, is given later.

Explicit evaluation of the Jacobian

An iterative Newton–Raphson Technique (Burden et al., 1978) was used to solve the system of nonlinear thermal equations (2) since the Jacobian of the system may be analytically derived in closed form. This method involves iterative evaluation of the following expression about an initial guess $\mathbf{X}_0$ until $\delta\mathbf{X}$ converges;

$$\delta\mathbf{X}\overset{\Delta}{=}(\mathbf{X}-\mathbf{X}_0)=(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{J}^T[-\mathbf{F}(\mathbf{X}_0)], \tag{8}$$

where

$$\mathbf{J} = \text{system Jacobian} = [\partial \mathbf{F}/\partial \mathbf{X}]_{\mathbf{X}=\mathbf{X}_0}.$$

The Jacobian of the system is given by:

$$\begin{aligned} J_{nm} &= \frac{\partial F_m}{\partial X_n}, \\ &= 2\alpha_n \varepsilon_m S_{nm} J(X_m+273)^3 + \delta_{nm} \\ &\times \Bigg\{ 4\varepsilon_m J(X_m = 273)^3 + h_c T_a \\ &+ \frac{1}{R_l + R_a}\left[s(X_n) - RHs(T_a)\right]\frac{\partial h(X_n)}{\partial X_m} \\ &+ \frac{h(X_n)}{R_l+R_a}\frac{\partial s(X_n)}{\partial X_m}\Bigg\}; \qquad n,m = 1,2,3. \end{aligned} \tag{9}$$

δ_{nm} is the Dirac delta function. Given specific algebraic expressions for $s(X_n)$ and $h(X_n)$ the partial derivatives are easily evaluated.

Geometrical factorization—S matrix

A significant simplification of the thermal model from the development reported earlier (Kimes et al., 1981) is the factorization of the geometric-dependent terms from the energy related source terms for the long-wave flux transfer processes. This factorization is made possible essentially because of the lack of multiple scattering in the thermal regime between canopy components whose emissivities (absorptivities) are assumed nearly unity and by the fact that the thermal properties on both sides of a canopy component are assumed equal. The multiplicative separation of the geometry dependent terms from the energy terms permits the possibility of precalculating the geometric matrix $\mathbf{S}$ for a wide variety of plant canopies as a means of characterizing their long-wave thermal behavior. These precalculated matrices may then be convolved with the appropriate meteorological driving variables as required in order to simulate a multitude of target/background scenarios. In addition, the linear form of Eq. (2) with respect to $\mathbf{S}$ suggests the possibility of applying linear filtering theory to estimate $\mathbf{S}$ from measurements of canopy temperature, $\mathbf{X}$.

The elements of the S_{ij} matrix describe the fraction of long-wave emitted flux from a source layer, j (which includes the air above the canopy and ground layers as well as the three vegetation layers), that is intercepted by a sink layer i. This flux must escape the specific source layer j and then pass unimpeded through all intermediate layers between the source layer j and the sink layer i before being intercepted by the canopy elements in layer i.

To calculate S_{ij}, we integrate over all emitting directions θ_r, ϕ_r the total flux that escapes a source layer j and is intercepted by a foliage element in layer i that has an orientation direction described by foliage inclination angle θ_k. To calculate the total flux intercepted in layer i from a source layer j, we then sum the energy intercepted by each foliage inclination class over the foliage inclination angle distribution occurring in layer i. Specifically,

$$S_{ij} = \sum_{k=1}^{9} f_{ik} C_{ijk}, \tag{10}$$

where

f_{ik} = the leaf slope distribution for layer $i = 1,2,3$ and foliage inclination angle $\theta_k = 5°, 15°, \ldots, 85°$.

C_{ijk} = fraction of emitted flux from a source layer j that is intercepted by a foliage element inclined at angle θ_k within layer i.

If $\hat{r}$ represents a unit vector in the direction of an emitting source element, described by θ_r, ϕ_r, and $\hat{a}$, a unit vector describing the orientation of an absorbing sink foliage element, then the amount of flux intercepted by this foliage element from direction $\hat{r}$ is proportional to $|\hat{a} \cdot \hat{r}|$. If we let CONT_{ijr} represent the fraction of long-wave flux that is emitted from layer j along direction $\hat{r}$ and is finally intercepted in layer i, then, C_{ijk}, the total flux intercepted by the foliage element emitted over all directions $\hat{r}$ in layer j is given by

$$C_{ijk} = \int_0^{\pi/2} \int_0^{2\pi} |\hat{a} \cdot \hat{r}| \mathrm{CONT}_{ijr} \, d\phi_r \, d\theta_r. \tag{11}$$

Several investigators have described the calculation procedure for estimating CONT_{ijr} for various theoretical canopies, e.g., deWit (1965) and Verhoef and Bunnik (1975). Basically the calculations require the determination of the probability of encountering a gap (or hit) in traversing a vegetation layer which is populated by foliage elements possessing a leaf slope distribution f_{ik} and a leaf or foliage area index. We have generalized these ideas to multiple layers (Oliver and Smith, 1974). The specific expressions for these weighting coefficients for an arbitrary source direction $\hat{r}$ are summarized in Table 1. In this table, $P_0(i, r)$ represents the probability of encountering a gap along direction $\hat{r}$ in traversing layer i. Note that the probability of traversing half a layer is given by $P_0^{1/2}(i, r)$ and that the probability of encountering emitting foliage elements in a layer along a direction $\hat{r}$ is given by $1 - P_0(i, r)$. For example, CONT_{13r} represents the flux that is emitted along direction $\hat{r}$ from source layer 3 (which is vegetation canopy layer 2) and is intercepted by sink layer 1 (which is vegetation canopy layer 1). This is equal to the probability of having emitting elements in canopy layer 2: i.e., the probability of a hit in layer 2, $[1 - P_0(2, r)]$, times the probability that this flux encounters a gap in traversing to the mid-elements of absorbing foliage in layer 1, $P_0^{1/2}(1, r)$. It is thus given by

$$\begin{aligned} \mathrm{CONT}_{13r} &= P_0^{1/2}(1, r)[1 - P_0(2, r)] \\ &= P_0^{1/2}(1, r) - P_0^{1/2}(1, r) P_0(2, r) \end{aligned} \tag{12}$$

TABLE 1 Expressions for contribution coefficients CONT_{ijr} for sink layer i, source component j, and arbitrary direction θ_r. $P_0(i, r)$ = probability of gap in layer i in direction θ_r.

Source Layer	Sink Layer 1	Sink Layer 2	Sink Layer 3
1	$P_0^{1/2}(1, r)$	$P_0(1, r) P_0^{1/2}(2, r)$	$P_0(1, r) P_0(2, r) P_0^{1/2}(3, r)$
2	$2[1 - P_0^{1/2}(1, r)]$	$P_0^{1/2}(2, r) - P_0^{1/2}(2, r) P_0(1, r)$	$P_0^{1/2}(3, r) P_0(2, r) - P_0^{1/2}(3, r) P_0(2, r) P_0(1, r)$
3	$P_0^{1/2}(1, r) - P_0^{1/2}(1, r) P_0(2, r)$	$2[1 - P_0^{1/2}(2, r)]$	$P_0^{1/2}(3, r) - P_0^{1/2}(3, r) P_0(2, r)$
4	$P_0^{1/2}(1, r) P_0(2, r) - P_0^{1/2}(1, r) P_0(2, r) P_0(3, r)$	$P_0^{1/2}(2, r) - P_0^{1/2}(2, r) P_0(3, r)$	$2[1 - P_0^{1/2}(3, r)]$
5	$P_0^{1/2}(1, r) P_0(2, r) P_0(3, r)$	$P_0^{1/2}(2, r) P_0(3, r)$	$P_0^{1/2}(3, r)$

Model Validation Experiments

Data obtained at two existing research sites were utilized to evaluate the validity of the model. One site is located in a Douglas fir canopy in the Cedar River watershed near Seattle, Washington. The second site, at the Walker Branch Watershed near Oak Ridge, Tennessee, is typical of an Appalachian mixed-deciduous forest. Both research sites were being used for ongoing research in forest meteorology and had extensive instrumentation and computerized data acquisition support.

Cedar River, Washington site

The Cedar River, Washington study site is located on the A. E. Thompson Research Center at a micrometeorological observatory maintained and operated by the University of Washington 55 km southeast of Seattle, Washington. The average elevation is approximately 215 m above sea level.

The dominant, naturally regenerated stand of Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] was approximately 41 years old with an average tree spacing of 5.8 m. Average height of the Douglas fir stand was about 28 m with an average leaf-area index (LAI) of approximately 7.8. Ground cover consisted of fern, salal, huckleberry, mosses, and litter. Soil at the site consisted of Barneston gravelly loamy sand originating from glacial outwash (Jensen, 1976).

Located at this site was a 28-m tall Douglas fir tree contained in a lysimeter (Fritschen et al., 1973). The site adjacent to this tree was instrumented to provide data for evapotranspiration studies. These data included wet and dry bulb temperature profiles, soil temperatures, global short-wave radiation, precipitation, and wind speed and direction. In addition, needle surface temperatures were monitored at several points around the lysimeter tree near the top and center of the canopy.

Walker Branch, Tennessee site

The Walker Branch study site is located near the Walker Branch Watershed research facility on the U.S. Department of Energy Reservation near Oak Ridge, Tennessee. This research area is situated on a ridge top about 70 m above the valley floor at an elevation of 335 m above mean sea level.

The area is representative of an Appalachian deciduous forest (Hutchison, 1977). The species composition of the stand is dominated by various species of oak and hickory. The average height of the codominant trees is about 21.5 m with lower limit of the live crown being 15 m above the ground. Basal area was approximately 26 m^2 ha^{-1}. Understory growth is abundant and the ground is covered by a shallow accumulation of litter. Hutchison (1977) gives a detailed description of the site and data available at the research facility.

Modeling Input Data

The data collected at the two sites include foliage and background optical parameters, geometry characterization measurements, and environmental measurements. This section describes the data required for our models and the techniques or sources used to acquire it.

Foliage geometry

The procedure for determining foliage inclination angles for the Douglas fir canopy included acquiring high contrast black and white slide photography of canopy silhouettes. For the purposes of our modeling, the canopies were partitioned into three layers of equal height. High contrast slides were used as input to a laser diffractometer and the diffraction patterns then optically sampled (Kimes et al., 1979). Separate branch and foliage measurements were combined to provide the inclination angle distributions for each layer.

Leaf inclination distributions for the oak-hickory canopy were sampled in situ for several leaves at 1-m intervals throughout the stand. The recorded distributions were summed and averaged over the appropriate layer-height intervals to provide the three-layer leaf-inclination angle distributions. The leaf-angle distributions for the two canopies are compared on a layer by layer basis in Fig. 1.

Leaf-area index (LAI) is defined as the total one-sided leaf area occupying the horizontally projected area of the canopy. LAIs for the Douglas fir canopy were derived from measurements reported by Kinerson and Fritschen (1971). In this paper, graphs of canopy height $z(m)$ versus surface area density $F(z)$, (m^2m^{-3}) for nine sample plots are given. Integrating $F(z)$ over height gives the needle-surface area index (NSAI) for a particular height increment (dz). For our modeling purposes, LAI values were determined by dividing NSAI for each layer by two. Data collected at the site since these measurements were made indicate no substantial change of LAI since 1971. Values of LAI for the oak–hickory canopy layers

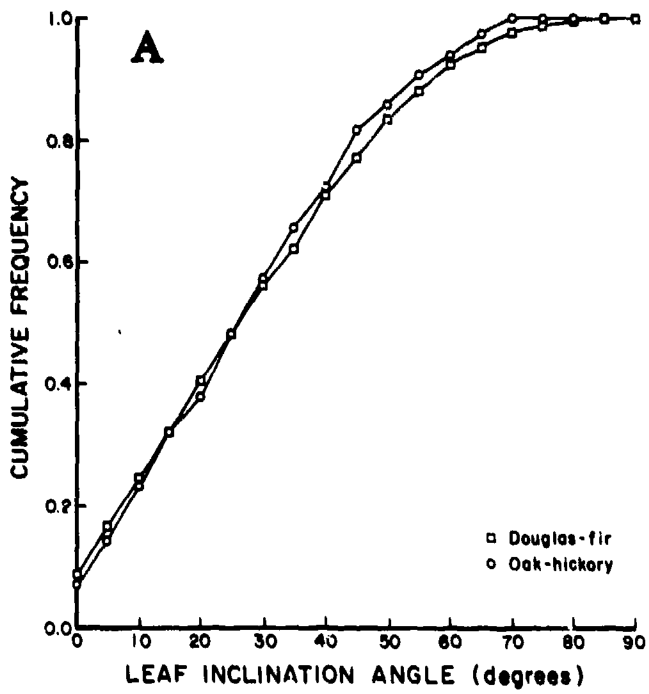
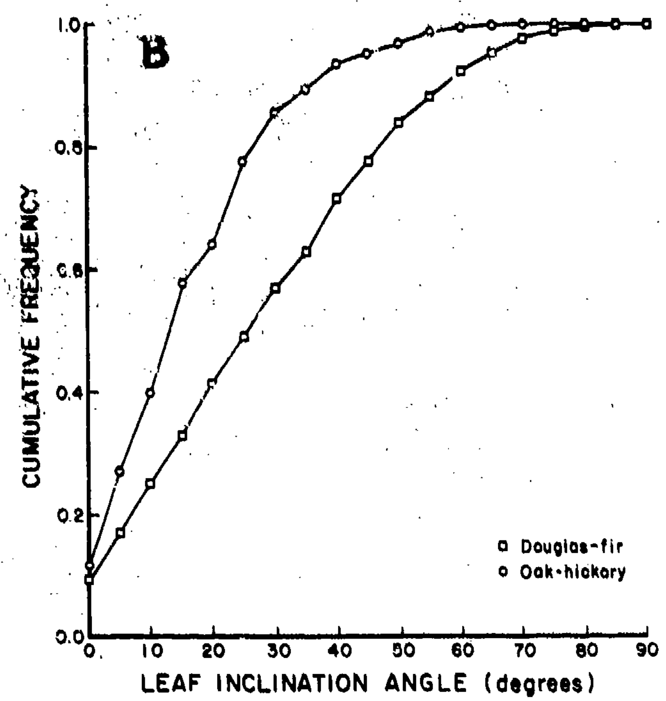
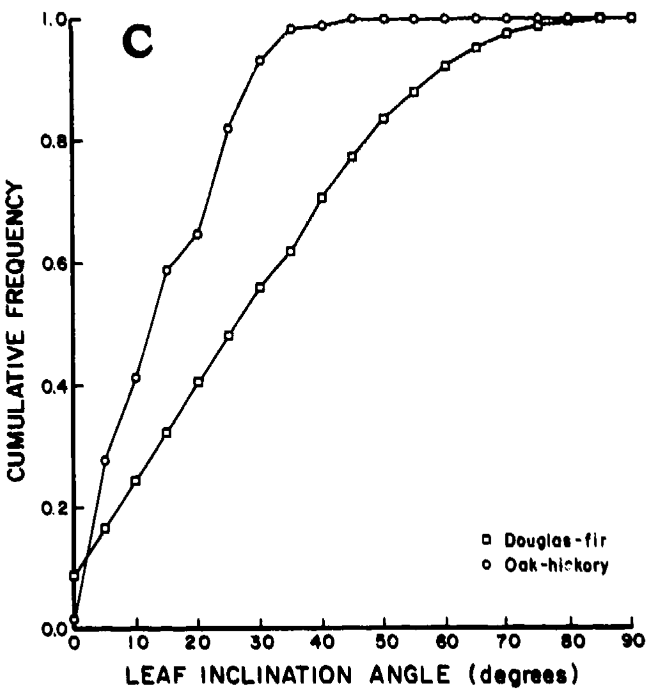


FIGURE 1. Comparative plots of foliage inclination angle vs. cumulative frequency for the three layer Douglas fir and oak–hickory canopies. A = Layer 1, B = Layer 2, C = Layer 3.


B
CUMULATIVE FREQUENCY
LEAF INCLINATION ANGLE (degrees)
Douglas-fir
Oak-hickory


C
CUMULATIVE FREQUENCY
LEAF INCLINATION ANGLE (degrees)
Douglas-fir
Oak-hickory

were derived from a graph of cumulative LAI versus height through the canopy. The graphs were generated by ATDL personnel from direct measurements. Table 2 lists the LAIs and midlayer heights used to model the Douglas fir and oak–hickory canopies and the S matrices for each canopy.

Short-wave absorption coefficients

The absorption of global short-wave radiation by canopy layers is an important component in the daytime energy budget. The radiation absorbed is a function of the global short-wave energy available, which is a measured input parameter to the model; and the short-wave interception coefficients for the canopy system, which in our case were estimated by a separate multiple scattering absorptive Monte Carlo model (Kimes and Smith, 1980). Strictly speaking these short-wave absorption coefficients for the canopy and ground layers are a function of sun angle, a result borne out by the Monte Carlo analyses. However, for the thermal model reported here our objective was to simplify the required analyses in order to facilitate the analysis of a multitude of canopy situations and reduce required input data. Extensive analyses with the complete treatment of short-wave energy absorption would be expensive and previous analyses indicate that the absorption coefficients were relatively stable within 15–20% for sun angles ranging from nadir to zenith angles of 45°. It was felt that an average absorption value calculated for each canopy for these sun angles generally would be reasonable. At large zenith solar angles the short-wave absorption coefficient becomes highly nonlinear. In our treatment of this parameter we tend to underestimate this component of the energy source term significantly at early morning and late evening, but the magnitude of the insolation is relatively small at these hours.

In order to estimate the short-wave flux absorption it is necessary to have estimates of the canopy and ground optical scattering properties, i.e., reflectance and transmittance of foliage elements and ground layer.

Canopy element transmittance values were directly measured at both sites as well as average background reflectance

TABLE 2 Canopy layer heights, LAIs and S matrices for the Douglas fir and oak–hickory canopies modeled in this study.

		Douglas fir	Oak–hickory
Mid-layer height (m)	Layer 1	23.3	18.3
	Layer 2	14.0	11.0
	Layer 3	4.7	3.7
Leaf-area index	Layer 1	1.5	3.4
	Layer 2	5.3	0.8
	Layer 3	1.0	0.4

S Matrix		To (i) Layer 1	To (i) Layer 2	To (i) Layer 3	To (i) Layer 1	To (i) Layer 2	To (i) Layer 3
From (j)	Sky	0.2722	0.0006	0.0000	0.1595	0.0281	0.0201
	Layer 1	1.4484	0.0048	0.0000	1.6741	0.7914	0.5441
	Layer 2	0.2722	1.9820	0.2946	0.0470	0.3539	0.2574
	Layer 3	0.0000	0.0047	1.4035	0.0338	0.2589	0.3496
	Ground	0.0000	0.0007	0.2946	0.0788	0.5607	0.8217

values as described in the report (Smith et al., 1981). However, it was not practical to obtain measurements of the canopy element reflectances, particularly for the Douglas fir needles. Rather, literature reflectance values for both old and new Douglas fir were obtained from Jarvis et al. (1976). Similarly, measurements by Colwell (1969) were averaged for the oak–hickory leaves. In both cases the actual site measured transmittance values were used to ensure that at least physically reasonable reflectance estimates were obtained.

Stomatal resistance

The resistance of the leaf to water vapor diffusion depends on many environmental factors. Leaf stomates open and close in response to microclimatic and soil conditions and regulate the cooling of the plant through evapotranspiration. This parameter is difficult to measure and highly variable. For our modeling purposes average values were used as constants. The value for Douglas fir was set at 0.10 min/cm. Stomatal resistances measured for the oak–hickory canopy ranged from 0.04 to 0.07 min/cm for sun leaves. The upper value was selected for use in the deciduous canopy simulations. Stomatal resistance was set to infinity during nighttime hours for both canopies. Model estimates of leaf temperatures are not very sensitive to stomatal resistance at these values and under the moderate environmental conditions encountered during the data collection (Smith et al., 1981).

Emissivity and absorptivity

The ability of a canopy element to emit and absorb long-wave radiation is expressed by the emissivity and absorptivity coefficients specified in the model. Emissivity (ε_l) and absorptivity (α_l) were set to 1.0 for all three canopy layers. Emissivity of the ground (ε_g) was also set to 1.0. Emissivity of the air (ε_a) was calculated as a function of air temperature by an empirical relationship (Hudson, 1969).

Canopy temperature measurements

Since the purpose of the experiments was to collect data sets for validation of the thermal model, actual canopy foliage temperature measurements were required.

The experimental setup at the Cedar River site included temperature measurements for a number of individual Douglas fir needles. The temperature sensors were located around the lysimeter tree at heights from 20 to 26 m. The measurements at a given height were averaged to give an average layer temperature. The 26-m measurement was assumed to represent the average canopy temperature for the top layer (Layer 1). The 20-m measurement was assumed to approximate the middle layer (Layer 2) although its location is closer to the boundary between Layer 1 and Layer 2.

No individual leaf temperature measurements were available at the Walker Branch site, so a portable thermal radiometer[1] was used to monitor the canopy temperature throughout a 24-hr period. The procedure was to position the instrument upward from the ground at the canopy and slowly move it until the maximum temperature was recorded. This was done to minimize errors due to the presence of sky or clouds in the field of view. However, the inferred measured temperature represents a value integrated over the entire depth of the canopy and

[1] Barnes Insta-Therm, Barnes Engineering Corporation

weighted most heavily toward the bottom of the canopy. It is, thus, not a precise measurement.

Environmental input parameters

In addition to the geometrical, optical and thermal parameters discussed above, a set of dynamic variables characterizing the microclimate of the target are required to drive the thermal model. These parameters consist of air temperature above the canopy, ground surface temperature, wind speed at the top of the canopy, relative humidity, and global short-wave radiation.

Environmental data were provided from the automated recording systems at the two sites. Air and ground temperatures and global short-wave radiation were measured directly. Relative humidity was determined from wet and dry bulb temperatures. All measurements were either instantaneous or short time interval averages.

Results

The data collected for the coniferous and deciduous canopies provided a good means of testing the thermal model under these diverse conditions. Three layer canopy temperature simulations were made over a 48-hr period with both data sets and the results were compared with measured temperatures.

Douglas fir canopy

The thermal model was run with environmental data acquired over the 48-hr period of 4–5 August 1979.

The Layer 1 simulated temperatures followed the trend of air temperature

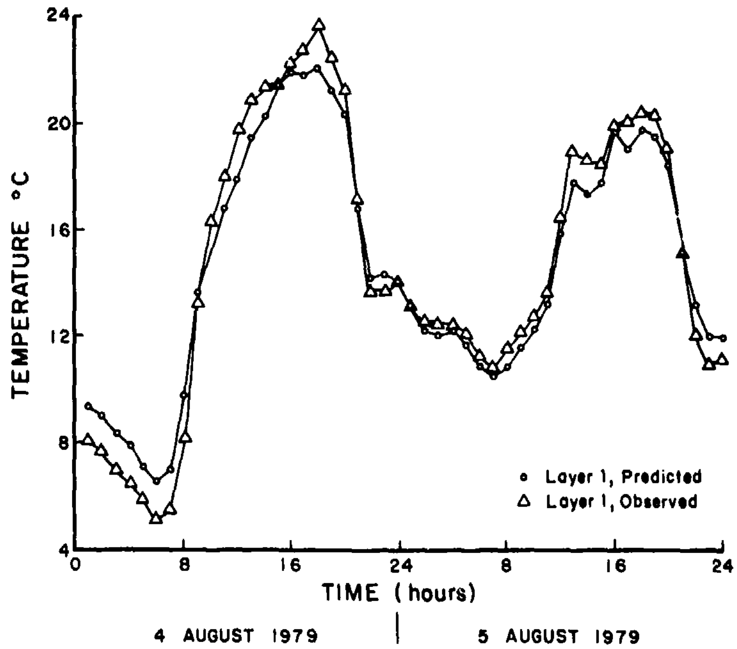


FIGURE 2. Layer 1 predicted temperatures plotted with average temperatures measured at the 26-m level in the Douglas fir canopy.

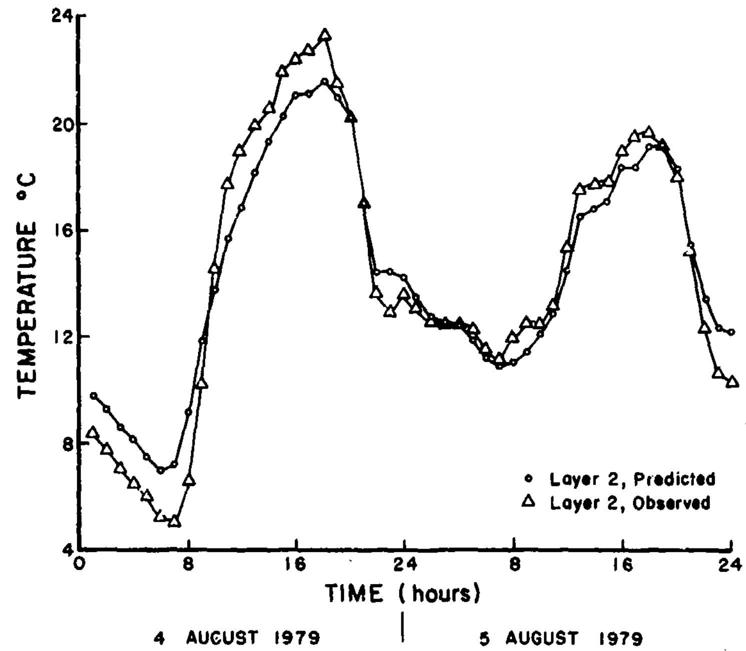


FIGURE 3. Layer 2 predicted temperature plotted with average temperatures measured at the 20-m level in the Douglas fir canopy.

throughout the 48-hr period. Comparisons of measured and predicted needle temperatures are presented as Fig. 2 and 3 for Layers 1 and 2, respectively.

The Layer 1 predicted temperatures varied from measured by a maximum of 3°C. These deviations were observed during the daylight hours under hazy skies. Nighttime predictions deviated from measured by 2°C or less with the maximum deviations occurring under conditions of fog. This leads us to conclude that the thermal model may be most valid for days with primarily direct solar radiation and clear nights where radiative cooling is occurring.

Oak–hickory canopy

Environmental data acquired at the Walker Branch site for the 48-hr period from 18–19 August 1979 were used to validate the thermal model for a deciduous oak–hickory canopy. Nighttime simulations were nearly equal to air temperature while daytime predictions varied by a maximum of 2°C over air temperature.

Measured temperatures were compared to predicted results for Layer 2 and are shown in Fig. 4. The agreement between model and measured temperatures is quite good. However, as discussed earlier an indirect measure of canopy effective radiant temperatures was made. The largest deviation (3°C) occurs in the afternoon whereas morning and nighttime predictions vary only 1°C or less.

Summary

A simplified thermal canopy model which treats the radiative flux transfers in some detail and permits the incorporation of alternative expressions for other energy

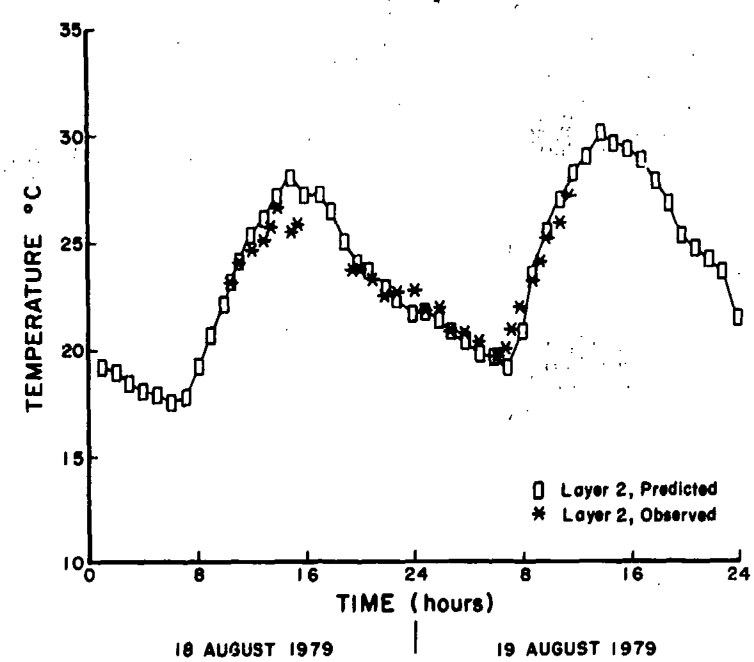


FIGURE 4. Layer 2 predicted temperature plotted measured average temperature of oak–hickory canopy. Measurements were made from the ground with a thermal IR radiometer.

components has been described and shown to give reasonable results for two forest canopy situations. The model utilized detailed canopy structure characteristics but in contrast to an earlier but more comprehensive form of the model (Kimes et al., 1981) factors the long-wave energy source terms into a product of two terms, one dependent on thermal properties only of the canopy (the Boltzmann source term) and the other on canopy geometric characteristics only. This factorization has two significant applications. First, as was done here, geometrical long-wave flux transfer matrices may be precalculated for a variety of targets and subsequently convolved with local meteorological scenarios. Secondly, the linear form of the factorization suggests the use of linear filtering theory to estimate these flux transfer matrices given measured observations. This latter suggestion is currently being intensely investigated by the authors.

The results of the model–experiment comparisons indicate that the model provides reasonable estimates of actual temperatures for nighttime periods to within 2°C for both canopies studied. Daytime simulations generally deviated from measured temperatures because, perhaps, of the simplifications assumed for the shortwave flux absorption coefficients and the treatment of stomatal resistance. The results indicate that the model may not adequately account for some of the energy transfers under more extreme environmental conditions.

Finally, it should be noted that both in measurement situations, the model predictions, air temperature, and canopy temperature measurements all agree quite closely. The thermal model, however, provides a convenient organization of the energy flow processes in a self-consistent manner which relates measured or predicted canopy temperatures to intrinsic canopy parameters. It thus permits the potential inference of canopy characteristics from measurements as suggested above.

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