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The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.
This is the final report in a series. Overall objectives of this project are concerned with developing comprehensive optical and thermal signature data bases, the development and evaluation of optical and thermal canopy radiation models, and the interpretation of these measurements. Previous technical reports in this series have described optical and thermal measurements obtained over a coniferous site (Pinus contorta) in Leadville, Colorado. This earlier (Continued)
data set served as a test bed for the development and initial evaluation of first, individual components, that is, needle and leaves, thermal models, and then a composite canopy terrain model.

The objectives of the work reported in this study were to evaluate the thermal models developed under a wider range of meteorological conditions and for different vegetation types. In this regard, experiments were performed on a second coniferous site (Pseudotsuga menziesii) near Seattle, Washington, and a deciduous community (oak-hickory) at the Oak Ridge National Laboratory, Tennessee. As part of the evaluation procedure a complete sensitivity analysis was performed for the model. The second major objective of the study reported here was a restructuring of the mathematical model which enabled a factoring of the geometrical characterization of the canopy in terms of matrices which can be convolved with the energy process terms. The newly structured model more easily permits the precalculation of these important geometrical characteristics for a wide variety of terrain elements. Finally, two parameter estimation techniques are proposed for both the static, steady-state, thermal behavior of a canopy and the dynamic or time-dependent implementation.
PREFACE

The research described in this report was conducted by personnel of the Department of Forest and Wood Sciences, College of Forestry and Natural Resources, Colorado State University (CSU) from 1 October 1978 to 1 February 1980 under contract No. DACH 39-77-C-0073 to the U.S. Army Engineer Waterways Experiment Station (WES). The study was done under Department of the Army Project No. 4A762730AT42, Task A4, Terrain/Operations Simulation, Work Unit 003, Electromagnetic Target Surround Characteristics in Natural Terrains.

Participating project personnel concerned with the tasks described in this report include Dr. James A. Smith, Principal Investigator; Mr. K. Jon Ranson, Research Associate; and Mr. Frank Croft, Graduate Research Assistant. In addition, very significant support was provided by Dr. Duong Nguyen of the Civil Engineering Department. Dr. Lee Balick, on assignment at the WES from CSU, was responsible for the technical review of the report and numerous suggestions that benefited the overall quality of this report.

Experimental data utilized in this study were obtained from a deciduous community at Oak Ridge National Laboratory in conjunction with Dr. B. Hutchison of the Atmospheric Turbulence and Diffusion Laboratory of the National Oceanic and Atmospheric Administration. Similarly, measurements were obtained over a Douglas-fir community in cooperation with Dr. Leo Fritschen of the University of Washington. Thermal imagery was obtained by the Oregon National Guard at the Washington site.

The study was conducted under the general supervision of Dr. John Harrison, Chief of the Environmental Laboratory (EL), and Mr. Bob Benn,
Chief of the Environmental Systems Division, EL. Dr. Lewis E. Link, Chief of the Environmental Constraints Group, EL, was Technical Monitor for the study.

Commanders and Directors of WES during the conduct of this study were COL. John L. Cannon, CE, and COL. Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

This report should be cited as follows:

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THERMAL VEGETATION CANOPY MODEL STUDIES

PART I: INTRODUCTION

1. This technical report is the last of a series of reports prepared on scene radiation dynamics. Earlier volumes in this series have described the development of models for optical and thermal energy interactions with forest and grassland vegetation canopies. Extensive field measurement efforts done in cooperation with the U.S. Army Engineer Waterways Experiment Station (WES) have also been separately reported. This report describes further efforts in thermal model development, evaluation, and sensitivity analysis. Measurements obtained over a Douglas-fir (Pseudotsuga menziesii) experimental site near Seattle, Washington, and an oak-hickory, deciduous site near Oak Ridge National Laboratory, Tennessee, are included. At both sites intensive ground instrumentation was employed as well as thermal overflights provided by the Oregon National Guard and the Georgia National Guard, respectively. In addition, analyses have been performed with data from Zweibrücken Air Force Base in the Federal Republic of Germany.

2. This introduction briefly summarizes the following topics which are explored more fully in the body of the report: (a) model framework, (b) sensitivity analysis, (c) experimental validation, and (d) recommendations.

Model Framework

3. The initial thermal canopy model utilized in this study is described in the report by Kimes, Smith, and Ranson (1979). The model is a plane-parallel abstraction of a vegetation canopy divided into three horizontal layers. Furthermore, steady-state conditions are assumed.
4. An energy-balance formulation of the model may be given in vector form by

\[ \mathbf{F}(\mathbf{X}, \mathbf{P}, \mathbf{U}) = 0 \]  \hspace{1cm} (1)

where:

\[ \mathbf{F} = (F_1, F_2, F_3) \] is the energy-balance equation for layers 1, 2, and 3, considering the following energy components: longwave transfers, shortwave transfers, sensible heat, and evapotranspiration

\[ \mathbf{X} = (X_1, X_2, X_3)^T \] is the average layer temperature vector for layers 1, 2, and 3

\[ \mathbf{P} = (c_i, \alpha_i, i=1,2,3 \ \epsilon_g, R_1, S, A) \] is the parameter vector characterizing the canopy layers

\[ c_i, \alpha_i = \text{emissivity and absorptivity of the vegetation layer} \]

\[ \epsilon_g, \alpha_g = \text{emissivity and absorptivity of the ground layer} \]

\[ R_1 = \text{canopy stomatal resistance to water vapor diffusion} \]

\[ S = \text{longwave flux transfer matrix calculated from geometrical properties of the canopy} \]

\[ A = \text{shortwave flux absorption coefficient vector} \]

\[ \mathbf{U} = (T_a, T_g, WS, RH, SW)^T \] is the control or input vector

\[ T_a = \text{air temperature} \]

\[ T_g = \text{ground temperature} \]

\[ WS = \text{wind speed} \]

\[ RH = \text{relative humidity} \]

\[ SW = \text{shortwave flux} \]
5. As part of the tasks of this project, $F$ was rewritten in the following form, which explicitly factors the geometrical properties of the canopy from the remaining energy terms:

$$F = \frac{1}{2} \sigma S + \sum B(X) + A \cdot H(X) + \text{LE}(x)$$

(2)

where:

- $\sigma$ = Stefan-Boltzmann constant
- $B$ = vector of longwave emission terms
- $H$ = vector of sensible heat
- $\text{LE}$ = vector of evapotranspiration term

The significance of this factorization is that a wide variety of abstract or canonical canopies may be characterized by precalculation of $S$ and $A$ matrices. These matrix tables may then be convolved with the appropriate meteorological driving variables to simulate diurnal behavior for a wide spectrum of scenarios. Five standard canopy structures of three different densities are given. These canopy structure combinations represent a spectrum of geometrical structure-indexed thermal variations. Other combinations may easily be calculated.

6. In addition a view factor matrix $VF$ is precalculated for each canopy characterization which is used to calculate thermal exitance $W$ as a function of view angle, $\theta$.

$$W(\theta) = VF(\text{Layer}, \theta) B^T$$

(3)

where:

- $W$ = the predicted canopy exitance at view angle, $\theta$
7. Finally, a new solution of the energy-balance equation was formulated utilizing the knowledge of the $F$ function which permits an explicit evaluation of the Jacobian.

8. Specifically, a modified iterative Newton-Raphson technique is employed (Burden, Faires, and Reynolds 1978).

9. Given $P$, $U$ for a given time period, $F(X,P,U)$ becomes a function of $X$ only. Expanding about an initial guess, $X_0$, and employing a minimum squared error criteria yields

$$
\delta X = X - X_0 = (J^T J)^{-1} J^T [-F(X_0)] \tag{4}
$$

where:

$J$ = the Jacobian evaluated at $X = X_0$ and the $n+1$ iteration is given by

$$
X_{n+1} = X_n + \delta X \tag{5}
$$

Convergence usually occurs within a few iterations.

10. The initial guess is taken to be air temperature; thus, the solution approach may be interpreted as determining the modification to the air temperature profile which arises when a canopy is inserted into the volume space under consideration.

**Sensitivity Analysis**

11. A sensitivity analysis was performed on the following parameters and input variables:

- $\alpha_i$ longwave absorptivity for vegetation layers 1, 2, and 3
- $\epsilon_i$ longwave emissivity for layers 1, 2, and 3
- $\epsilon_g$ ground emissivity
canopy stomatal resistance

shortwave absorption in vegetation layers 1, 2, and 3

relative humidity

ground temperature

wind speed

air temperature above the canopy

air temperature within the canopy

Sensitivity analysis was not directly performed on the $S$ matrix nor on the view factor matrix. Rather, the above analyses were repeated for two different $S$ matrix configurations. One corresponded to the Douglas-fir canopy and the second to an oak-hickory canopy.

12. Sensitivity analysis (Tomovic 1963) involves the evaluation of the sensitivity matrix:

$$\left[ \frac{\partial x}{\partial P} \right] = S_{xp}$$

(6)

where:

$X$ = layer temperature vector

$P$ = 16-component parameter/input vector

The analysis was performed in each case for $x_0, P_0$ corresponding to a daytime and nighttime representative set of conditions.

13. The first order perturbation of each of the 16 parameters was evaluated systematically, solving for the new equilibrium canopy temperature profile after each perturbation, i.e.,

$$\delta X = S_{xp} \delta P$$

(7)
The most sensitive parameter of the model was found to be the air temperature within the canopy. Next, dependence on canopy stomatal resistance was found to be highly nonlinear for the low values of $R_I$. The dependence of canopy temperature on most other parameters was found to be highly linear.

**Experimental Validation**

14. Comparison of both daytime and nighttime measurements for the Douglas-fir and oak-hickory canopies with simulation predictions were carried out. For both of the canopies, nighttime simulations deviated from measured values by $2^\circ$C or less. Daytime simulations underestimated measured Douglas-fir canopy temperatures by a maximum of $2^\circ$C; whereas, simulation of the lower canopy for oak-hickory overestimated temperatures by a maximum of $4^\circ$C. Deviation patterns could be explained in terms of macroscopic and variable environmental conditions.

**Recommendations**

15. Two broad categories of recommendations are made in the enclosed report. First, several suggestions are made relative to improvements that could be made in the thermal model itself. Secondly, some suggested approaches for estimating required parameters in the model from observed data are given.

16. Sensitivity analysis has indicated the importance of the air temperature within the canopy as an input to the model. Further, the validation experiments have indicated the importance of utilizing an appropriate wind speed measurement. Thus, it would appear to be appropriate
to review the various hypotheses concerning the variation in air temperature and wind speed with height. The model is easily modified to include a height dependence of these two variables; they are treated as constants simply because there is not a very strong rationale for choosing among the various options. In a similar vein, various authors' recommendations have been selected for analytic representations of the energy budget components. It may be useful to systematically evaluate several alternative formulations. Two further extensions to the physics of the model would include the incorporation of a ground temperature prediction module and the expansion of the steady-state formulation to a time-dependent process, that is, allowing for heat storage within the canopy.

17. Finally, further analysis of the structure of the geometrical matrices, that is, the $S$, $A$, and $VF$ matrices, relative to the intrinsic canopy structure variables should be undertaken. Specifically, the possibility of further factoring these matrices in terms of their leaf area index dependence and their dependence upon leaf slope distribution should be investigated. It may be possible to treat the density, that is the leaf area index dependence, as a simple scaling influence on precalculated structural forms. If an analytic decomposition of these matrices in terms of these two influences is not possible, numerical approaches should be investigated. A faster, more tractable, calculation of the shortwave absorption coefficient should be given high priority.

18. Two approaches are recommended for parameter estimation analysis. The first method described is based on the Kalman filtering techniques. The linearization of the model in terms of a classic state-space framework is outlined. A Kalman filtering approach on a parameter vector or an
augmented state vector is described (Friedland 1972). A second approach to parameter estimation is suggested, which is based on the use of sensitivity functions (Durando and Leondes 1976). This approach also begins with a state-space formulation of the model but then proceeds to use the sensitivity functions to calculate an unknown parameter vector by minimizing the square of the error vector between predicted and measured response.

19. The appendixes of this report include the program listings for the thermal model, the sensitivity program, the geometrical preprocessing programs, SCALC, and the SRVC absorption model. Also included in the appendixes are the geometrical matrices for 15 abstract canopies, the sensitivity results, and supporting validation data.
PART II: NEW MODEL STRUCTURE

20. This part summarizes the updated formulation and solution approach to the basic thermal canopy model developed under previous efforts. The individual expressions for the component energy budget processes are summarized and explicit expressions for the elements of the Jacobian matrix are given. The geometrical factorization of the energy budget equation, particularly for the longwave flux transfers, is derived, and the sequence of computer programs required to develop a thermal simulation is described.

Energy-Balance Framework

21. 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 or understory layer. 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. For this and subsequent sections Figure 1 may prove useful for conceptualizing the various energy flows. The sink or vegetation layers are represented by \( i = 1,2,3; \) \( j=1,2,3,4,5 \) 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 a flow of energy from source layer \( j \) to sink layer \( i \).

22. The vector expression for the energy-balance equations was given in the Part I, Equations 1 and 2 as:
\[ F = \frac{1}{2} \sigma B(X)T + B(X) + A + H(X) + LE(X) \]

23. The vector equation may be expanded in long form and the explicit dependence on parameters or input variables indicated by

\[ \frac{1}{2} \sigma a_1 [B(T_a)S_{11} + B(X_1)S_{12} + B(X_2)S_{13} + B(X_3)S_{14} + B(T_g)S_{15}] \] (8)

\[ + A_1 - \sigma B(X_1) + H(X_1; WS, T_a) + LE(X_1; WS, T_a, R_1, RH) = 0 \]

\[ \frac{1}{2} \sigma a_2 [B(T_a)S_{21} + B(X_1)S_{22} + B(X_2)S_{23} + B(X_3)S_{24} + B(T_g)S_{25}] \] (9)

\[ + A_2 - B(X_2) + H(X_2; WS, T_a) + LE(X_2; WS, T_a, R_1, RH) = 0 \]

\[ \frac{1}{2} \sigma a_3 [B(T_a)S_{31} + B(X_1)S_{32} + B(X_2)S_{33} + B(X_3)S_{34} + B(T_g)S_{35}] \] (10)

\[ + A_3 - \sigma B(X_3) + H(X_3; WS, T_a) + LE(X_3; WS, T_a, R_1, RH) = 0 \]

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

**Longwave:**

\[ B(X_i) = \varepsilon_i (X_i + 273)^4 \] (11)

\[ B(T_a) = \varepsilon_a (T_a + 273)^4 \] (12)

\[ B(T_g) = \varepsilon_g (T_g + 273)^4 \] (13)

**Sensible Heat:**

\[ H(X_i; WS, T_a) = (X_i - T_a) - 0.698(20.4 + 0.2WS^{0.97}) \] (14)

**Evapotranspiration:**

\[ LE(X_i; WS, T_a, R_1, RH) = -697.75(-0.566 X_i + 597.3) \]

\[ \times \frac{5.234 e^{0.056715 \cdot X_i - RH} 5.234 e^{0.056715 \cdot T_a} 10^{-6}}{R_1 + 1/60 (0.04 + 1.27 WS^{1/2})} \] (15)

**Shortwave absorption:**

\[ A_i = ABS(i) \cdot SW \] (16)

where:

\[ \varepsilon_{air} = 1 - 0.261 e^{-7.77 \cdot 10^{-4} T_a} \] (17)

\[ ABS(i) = \text{shortwave absorption coefficients calculated by an optical absorption model which uses a Monte Carlo Technique to include multiple scattering effects (see Program SRVC in Appendix A)} \]
Explicit Evaluation of the Jacobian

24. As indicated in Part I, the use of the iterative Newton-Raphson technique for solving the nonlinear thermal equations involves repeated evaluation of the expression

$$\delta x = (J^T J)^{-1} J^T [-F(X_0)]$$

where:

$$J = \text{system Jacobian} = \left[ \frac{\partial F}{\partial x} \right]_{X=X_0}$$

(18)

(19)

The Newton-Raphson method is employed because, in this case, there are relatively simple closed-form expressions for the elements of $F$, and the Jacobian matrix can explicitly be evaluated. Specifically,

$$J = \begin{bmatrix}
\frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_1} \\
\frac{\partial F_1}{\partial x_2} & \frac{\partial F_1}{\partial x_2} & \frac{\partial F_1}{\partial x_2} \\
\frac{\partial F_1}{\partial x_3} & \frac{\partial F_1}{\partial x_3} & \frac{\partial F_1}{\partial x_3}
\end{bmatrix}$$

(20)

The $i,j$ component of $J$ is easily derived as

$$J_{ij} = 2 \alpha_i \varepsilon_j S_{ij} \sigma (X_j + 273)^3 + \delta_{ij} (4 \varepsilon_j \sigma (X_j + 273)^3 + 0.698 T_a)$$

$$+(20.4 + 0.2 W S^{0.97}) + (697.75(0.566)(5.234)(10^{-6})(e^{0.056715 X_j - RH} e^{0.056715 T_a}) + R_1 + 1/60 (0.04 + 1.27 WS^{-0.5})$$

$$-(697.75)(-0.566 X_j + 597.3)(5.234)(0.056715) 10^{-6} e^{0.056715 X_j}$$

$$R_1 + 1/60 (0.04 + 1.27 WS^{-0.5})$$

(21)
where:

\[ \delta_{ij} = \text{Dirac delta function} \]

25. Program TMODEL, which implements the equations, is given in Appendix A. Subroutine FEVAL evaluates the function and the Jacobian derivatives and calls upon Subroutine BFUNC which calculates the long-wave energy component and derivative; Subroutine QFUNC calculates the sensible heat component and derivative. It should also be noted that two different expressions for the convection coefficient arise, depending upon the ambient wind speed. Subroutine RFUNC calculates the evapotranspiration.

Geometrical Factorization

26. A significant simplification of the thermal model employed in this study was the factorization of the geometric-dependent terms from the energy-related terms for the longwave 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 significance of the factorization is not so much in the increased efficiency in model calculation as it is in permitting the possibility of precalculating these geometrical matrices, \( S \), for a wide variety of plant canopies. These precalculated matrices may then be convolved with the appropriate driving variables as required. Program SCALC (Appendix A) performs the actual calculations for given input of geometric measurements.

27. The required input data for a three-layer canopy include

\[ f_{ik} = \text{leaf slope distribution for layer } i=1,2,3 \text{ and angle } \theta_k=5,15,\ldots,85 \]
N_i = leaf area index LAI, for layer i

Appendix B presents the S matrices calculated for five different theoretical canopies at three different LAI densities = 1, 4, and 7.

28. The five theoretical canopies are approximated by Verhoef and Bunnik (1975) as

- **Planopnile:** \[ f_{ik} = \frac{2}{\pi} (1 + \cos 2 \theta_k) \]
- **Erectophile:** \[ f_{ik} = \frac{2}{\pi} (1 - \cos 2 \theta_k) \]
- **Plagiophile:** \[ f_{ik} = \frac{2}{\pi} (1 - \cos 4 \theta_k) \]
- **Extremophile:** \[ f_{ik} = \frac{2}{\pi} (1 + \cos 4 \theta_k) \]
- **Uniform:** \[ f_{ik} = \frac{2}{\pi} \]

where \( \theta_k \) is the leaf slope angle.

The elements of the S matrix, itself, are given by

\[ S_{ij} = \sum_{k=1}^{9} f_{ik} C_{ijk} \]  

(22)

where:

\[ C_{ijk} = \int_0^{\pi/2} \int_0^{2\pi} |\hat{\mathbf{a}} \cdot \hat{\mathbf{r}}| \, \text{CONT}_{ijr} \, d\phi_r \, d\theta_r \]  

(23)

\( \hat{\mathbf{a}} \) is the orientation of the leaf at angle \( \theta_k \); and \( \hat{\mathbf{r}} \) is the direction of the energy flux described by \( \theta_r, \phi_r \) (i.e., \( \hat{\mathbf{r}} = (\sin \theta_r \cos \phi_r, \sin \theta_r \sin \phi_r, \cos \theta_r) \))

(24)

The elements of \( \text{CONT}_{ijr} \) represent the weighting coefficients which give the flux contributions from a source layer, \( j=1,2,3,4,5 \), to a sink vegetation canopy layer, \( i=1,2,3 \), from a particular source direction \( \theta_r, \phi_r \).
These elements for an arbitrary direction, \( \hat{r} \), are given in Table 1. \( P_o(i, r) \) is the probability of a gap in transversing layer \( i \) at direction \( r \). It may approximated by

\[
P_o(i, r) \approx P_o(i, \theta_r) = e^{-N(i)} g(i, \theta_r) \sec \theta_r
\]  

(25)

where \( g(i, \theta_r) \) is the mean canopy layer projection in direction \( \theta_r \). Mean canopy projection is given by

\[
g(i, \theta_r) = \int_0^{\pi/2} k(\theta_r, \theta_k) f_{ik} \, d\theta_k
\]  

(26)

where:

\[
k(\theta_r, \theta_k) = 2/\pi \cos \theta_k \cos \theta_r, \quad \theta_k < \pi/2 - \theta_r
\]

\[
k(\theta_r, \theta_k) = 4/\pi^2 \cos \theta_k \cos \theta_r (\phi_k - \pi/2 - \tan \phi_k^r), \quad \theta_k > \pi/2 - \theta_r
\]

\[
\phi_k^r = \cos^{-1} (-\cot \theta_k \cot \theta_r)
\]

Program SCALC also calculates the view factor matrix for the canopy. This matrix is used to determine the thermal flux contribution from each vegetation layer and the ground layer which is intercepted by a sensor viewing the canopy at a particular zenith angle. It is given by

\[
W(i, \theta_r) = \mathbf{VF}(i, \theta_r) = [VF(1, r) \ VF(2, r) \ VF(3, r) \ VF(4, r)]^T
\]

\[
VF(1, \theta_r) = 1 - P_o(1, r)
\]

\[
VF(2, \theta_r) = P_o(1, r) [1 - P_o(2, r)]
\]

\[
VF(3, \theta_r) = P_o(1, r) P_o(2, r) [1 - P_o(3, r)]
\]

\[
VF(4, \theta_r) = P_o(1, r) P_o(2, r) P_o(3, r)
\]
Sequence of Required Computer Runs

29. Appendix A contains a listing of all the computer programs utilized in this study. Three of these programs are directly concerned with thermal modeling or preprocessing steps that must be initiated before the thermal calculations may be made. In addition, program SENSIT has been included. This program performs the systematic and repetitive calculations necessary to complete the sensitivity calculations of many of the thermal model parameters.

30. The basic thermal model is program TMODEL. This program assumes that the geometrical characterization of the canopy has been performed and the appropriate $S$ matrix, shortwave absorption vector, and view factor matrix have been calculated. The model then performs similar calculations at discrete time intervals, given the specification of the appropriate parameter (emission and absorption characteristics of the canopy elements and the ground, canopy stomatal resistance to water vapor diffusion). Furthermore, the input information must be provided at the discrete time intervals simulated. These data consist of the air temperature, the ground temperature, the wind speed, the relative humidity, and the shortwave flux. The basic philosophy of TMODEL is that for a given type or types of vegetation canopies, one would want to simulate a multitude of scenarios for their thermal behavior based on either ambient meteorological conditions or modifications to the thermal properties of the canopy or understory. Thus, it is usually required to calculate the geometrical characteristics of the canopy type only once and then perform multiple simulations of the canopy with TMODEL.

31. The calculations of the appropriate geometrical flux transfer matrices are done by Program SCALC and Program SRVC for absorption. For both of these programs, detailed canopy geometry information is required.
This includes the leaf area index for each layer, and the leaf slope distribution by layer. In addition, to calculate the shortwave absorption coefficients, average optical properties of the canopy elements are required. The SRVC absorption model is further described in a report by Kimes, Smith, and Ranson (1979).

32. The complete set of geometrical matrices have been calculated for the lodgepole pine canopy in Leadville, Colorado, studies under earlier WES sponsorship, the Douglas-fir canopy from the Cedar River Watershed, near Seattle, Washington, and the oak-hickory deciduous community at the Walker Branch Watershed at Oak Ridge National Laboratory in Tennessee. In addition, the geometrical characterization has been performed for 15 abstract canopies of varying densities and geometrics. These data are given in Appendix B.

33. In summary, given a specific canopy to be studied and for which detailed geometrical measurements have been obtained, Program SCALC and the SRVC absorption model are first used in a preprocessing manner to calculate the appropriate flux-transfer matrices. The data generated from these runs are then used in Program TMODEL. If there is no specific geometrical measurement available for canopies of interest, then one of the 15 theoretical canopies in Appendix B may be appropriate.

34. An example of a complete analysis for the validation experiments is given in Part IV.
PART III: SENSITIVITY ANALYSIS

35. The basic analytic model described in this report may be indicated by the form:

\[ F(X,P,U) = 0 \]

To simplify notation, \( U \) will be considered to be an additional set of parameters augmenting the \( P \) vector, and it will be written that:

\[ F(X,P) = 0 \]

Further, the solution to the system of equations for a specific parameter \( P_0 \) will be indicated as \( X(P_0) \).

36. Sensitivity analysis consists of determining the change in the solution to the model for a small change or perturbation in model parameters, i.e., \( X(P_0 + \Delta P) \).

37. The sensitivity function \( S_{xp} \) is defined (Tomovic 1963) as:

\[ \lim_{\Delta P \to 0} \frac{X(P_0 + \Delta P) - X(P_0)}{\Delta P} \]

The sensitivity function may be evaluated analytically by differentiation of the system equations with respect to the parameters under consideration, yielding the following sensitivity equation:

\[ \frac{\partial F}{\partial X} \frac{\partial X}{\partial P} + \frac{\partial F}{\partial P} = 0 \]

or

\[ S_{xp} \frac{\partial F}{\partial X} + \frac{\partial F}{\partial P} = 0 \]
Alternatively, computer simulations may be employed in which the parameters are systematically and separately perturbed from nominal values and new canopy temperatures are determined.

38. As indicated in Part I, this latter approach was employed for this study. Program SENSIT was written to facilitate the calculation (Appendix A).

39. Program SENSIT requires environmental data and temperatures for each layer to initialize the analysis. In addition, geometrical factor matrices describing a particular canopy are required. The environmental data used was collected by WES personnel at Zweibrücken Air Force Base in West Germany on 4 October 1979. Data was selected at 0600 hours and 1100 hours to provide for nighttime (predawn) and daytime analysis. Initial state temperatures for each layer were determined from simulation results. The sensitivity analysis was performed for both the Douglas-fir and oak-hickory canopies resulting in a total of four analyses. Table 2 lists the initial environmental parameters and initial temperatures for each sensitivity run. Graphical results of parameter changes versus predicted temperatures are found in Appendix C.

40. The daytime sensitivity analysis showed that the predicted canopy temperatures were most sensitive to the air temperature within the canopy. A 10 percent change in canopy air temperature resulted in nearly a 10 percent change in all layers for both types of canopies. Decreasing longwave absorption coefficients by 10 percent resulted in less than a 0.5°C change in predicted temperatures and showed a layer by layer dependence for both canopies and time periods. Predicted canopy temperatures showed minimal sensitivity to changes in air and ground temperatures as input to the model. Temperature predictions were nearly equally sensitive to the shortwave absorption in all three layers.
for both canopies. Changing the canopy emissivity in the top layer for both canopies had little effect on predicted temperature for layer 1, but slightly increased sensitivity was noted for the two lower canopy layers. Decreasing ground emissivity from 1.0 to 0.9 increased predicted temperatures by less than 0.5°C. Changing relative humidity showed little effect on canopy temperatures with the daytime oak-hickory analysis exhibiting the greatest sensitivity. A linear relationship was noted between predicted canopy temperatures and the parameters discussed above. Only stomatal resistance and wind speed analyses showed nonlinear trends. Sensitivity plots of stomatal resistance for Douglas-fir and oak-hickory are shown in Figure 2. In both cases the plots are nonlinear above $R_1$ values of 0.08 min/cm. Other analyses not reported here showed a linear relationship for $R_1$ greater than 0.08 min/cm to about 1.5 min/cm. Figure 3 shows plots of wind speed versus predicted temperature for Douglas-fir daytime and nighttime analyses. The daytime plot shows an increase in temperature with decreasing wind speed; but at night, temperatures decrease slightly with decreasing wind speed.
41. As discussed earlier, the objective of the field experiments was to provide data sets from diverse targets and environmental conditions for validation of the Colorado State University (CSU) thermal canopy model. Two existing research sites were located through the efforts of WES personnel that proved to be ideal for the experiments. The Cedar River site was located in a Douglas-fir forest near Seattle, Washington. A second research site, the Walker Branch Watershed, was typical of an Appalachian deciduous forest and was located near Oak Ridge, Tennessee. Both research sites were being used for ongoing research in forest meteorology and possessed extensive instrumentation and computerized data acquisition support. The principal scientist responsible for the development of the Cedar River site was Dr. Leo J. Fritschen of the College of Forest Resources, University of Washington, while Dr. Boyd A. Hutchison of the Atmospheric Turbulence and Diffusion Laboratory (ATDL), National Oceanic and Atmospheric Administration (NOAA) was responsible for the Walker Branch site. Further descriptions of these sites are given below.

Experimental Design

42. The model validation experiments were designed by CSU and WES personnel with cooperation from Drs. Fritschen and Hutchison. The goal was to provide appropriate input and validation data for the CSU canopy models. Input data included optical, thermal, and environmental parameters for two consecutive 24-hour periods of the targets. Validation
data consisted of foliage temperatures. In addition, thermal scanner imagery was to be obtained by local National Guard units at specified times throughout the measurement periods. Characterization of the foliage angle distributions of the canopies was also required. Input data requirements and methods are discussed in a later section.

43. WES personnel were responsible for overall mission coordination, thermal radiometric measurements of ground and canopy, air temperature measurements in the lower 1.5 m of the canopies, and arranging for National Guard thermal scanner overflights of the experimental sites. CSU personnel communicated requirements for micrometeorological data to Drs. Fritschen and Hutchison, obtained foliage geometry data from the sites, and performed necessary optical measurements required to run the canopy models. Groups headed by Drs. Fritschen and Hutchison provided site access, operated and maintained the data acquisition systems, and provided assistance for interpreting the micrometeorological data. In addition, Dr. L. W. Gay of the School of Renewable Natural Resources, Arizona University at Tucson participated in the Cedar River Douglas-fir experiment to test the use of direct beam depletion measurements for determining forest biomass.

Site Descriptions

44. Two established research sites were available for this study. A site near Seattle, Washington, developed and maintained by Dr. Leo Fritschen of the University of Washington, provided data for a stand of mature Douglas-fir. Dr. Royd Hutchison of ATDL/NOAA made available an oak-hickory site near Oak Ridge, Tennessee and provided necessary
environmental data. A detailed description of these sites is provided below.

Cedar River, Washington

45. The Cedar River, Washington, study site is located on the A. E. Thompson Research Center at the western end of the Cedar River Watershed. The site lies in the Puget Sound Basin at the western foot of the Cascade Mountains 55 km southeast of Seattle, Washington, at 47°23'N and 121°56'W. The elevation is approximately 215 m above mean sea level.

46. The area was logged prior to 1924 and subsequent fires resulted in a mosaic of different aged stands (Jensen, 1976). The most common community on the site is Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). This naturally regenerated stand was approximately 41 years old with an average tree spacing of 5.8m. There were 572 trees per hectare consisting mainly of Douglas-fir, a few hemlock, and maple (Figure 4). Ground cover consisted of fern, salal, huckleberry mosses, and litter (Figure 5). Bare soil areas were minimal and occurred only on roads and other localized disturbed areas. Soil at the site consisted of Barneston gravelly, loamy sand originating from glacial outwash.

47. The specific study site was located at a micrometeorological observatory maintained and operated by the University of Washington. Average height of the Douglas-fir stand was about 28 m with an average LAI of approximately 7.8. Located at this site was a 28-m-tall Douglas-fir tree contained in a lysimeter (Fritschen, Cox, and Kinerson, 1973). The site adjacent to this tree was instrumented to provide data for
evapotranspiration studies. These data included wet and dry bulb temperatures, soil temperatures, global shortwave 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. These data were recorded at selected time intervals by a computerized data acquisition system. A 33-m walk-up tower was available adjacent to the lysimeter tree to provide access to needle temperature sensors and other measurement devices.

Walker Branch, Tennessee

48. 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, at 35°58'N and 84°15'W. An intensive forest meteorological research site operated by the ATDL of the NOAA was made available for this study. 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.

49. 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, including Quercus alba, Quercus prinus, Quercus velutina, Carya glabra and Carya ovata. Acer rubra (red maple), Prunus serotina (black cherry), Liriodendron tulipifera (yellow popular) are less frequently found. Common understory plants include Oxydendron arboreum (sour wood), Cornus florida (flowering dogwood) and Cercis canadensis (eastern redbud). The average height of the
The codominant trees forming the canopy is about 21.5 m with lower limit of the live crown being 15 m above the ground. These heights vary greatly due to the uneven age of the stand (Figure 6). Basal area was approximately 26 m² ha⁻¹. The site appeared parklike due to a fire that occurred several years ago. Understory growth, however, is abundant. The ground is covered by an accumulation of litter (Figure 7) with bare soil occurring only in disturbed areas. In addition, fragmented, grey-colored rock covered the road surfaces. A metal track was in place beneath the stand to provide all-weather access for research vehicles. This track was covered with litter by ATDL personnel during the field experiments.

50. The site is extensively instrumented to record data pertinent to forest meteorology research as well as the thermal modeling studies. Hutchison (1977) gives a detailed description of the research facility.

Modeling Input Data

51. The data collected at the two sites included foliage and background optical parameters, geometry characterization measurements, and environmental measurements. This section describes the data required for the models and the techniques or sources used to acquire it. Listings of the data values are included in Appendix D.

Foliage geometry

52. The structure of a canopy defined by the foliage inclination angles and LAI is important for characterizing the interactions of radiation with the canopy. These inputs are required by the optical SRVC
model (Oliver and Smith 1974) to estimate the shortwave absorption of a canopy and by the thermal model to describe longwave energy exchanges inside and outside of the canopy.

53. The procedure for determining foliage geometry included acquiring high-contrast black-and-white slide photography of canopy silhouettes. These slides serve as input to a laser diffractometer which characterizes the frequency of occurrence of foliage angles in terms of the resulting diffraction pattern. The diffraction patterns are optically sampled, and the results are analyzed with a series of computer programs. See Kimes, Smith, and Ranson (1979) for a discussion of the theory and procedures.

54. The walk-up towers at both sites provided an excellent platform for acquiring slides of the canopies. For the purposes of the modeling, the canopies were partitioned into three layers of equal height. Photographs were taken for each layer from several directions from the tower. This provided a larger sample size and minimized effects of azimuthal asymmetry. Ideally, the photographs should be taken with a white backdrop placed behind the target to eliminate background trees and shadows. However, this was impractical for the canopies under study. As a result, the slides were manually interpreted to delineate branches of the desired tree in the photographs. This was done by projecting the slide on white paper and tracing the appropriate branches. Earlier work by Kimes, Smith, and Ranson (1979) showed that for complex canopies, such as conifers, two interpretations are required: one with all branches represented, and a separate tracing including only branches bearing foliage. High-contrast slides of these tracings were used as input to the laser diffractometer. The branch and foliage measurements were
combined later to provide the inclination angle distributions for each layer.

55. The calculated foliage angle distributions for a Douglas-fir canopy are shown in Figure 8. For comparison purposes, distributions of lodgepole pine (Pinus contorta) reported by Kimes, Ranson, Kirchner, and Smith (1978) are included. Figure 9 shows foliage angle distributions for oak-hickory. These data were derived from direct measurements provided by Dr. Hutchison. Laser diffraction results for oak-hickory were unavailable due to equipment problems. For comparison a one-layer distribution for Russian olive (Elaeagnus angustifolia) reported by Kimes, Smith, and Ranson (1979) is included.

Leaf area index

56. LAI is defined as the total one-sided leaf area occupying the horizontally projected area of the canopy. For example, an LAI of 5 indicates that five layers of leaves could be overlayed to completely fill an area equal to the canopy projection on the ground. LAI's for this study were determined from data provided by Drs. Fritschen and Hutchison. LAI's for the Douglas-fir canopy were derived from measurements reported by Kinerson and Fritschen (1971). In this report, graphs of canopy height \( z(\text{m}) \) versus surface area density \( F(z) \) \( (\text{m}^2 \text{m}^{-3}) \) for nine sample plots are given. Integrating \( F(z) \) over height gives the needle surface area index \( \text{NSAI} \) for a particular height increment \( dz \). Data points were taken from the graphs and averaged for given heights to produce a single average surface density curve. This curve was partitioned into three layers of equal height and layer \( \text{NSAI} \)'s determined
by Simpsons Rule (Figure 10). For our modeling purposes, LAI values were determined by dividing NSAI for each layer by two.

57. LAI for the oak-hickory canopy was determined from data provided by ATDL. These data consisted of a graph of cumulative LAI versus height and graph of LAI at given heights through the canopy. A smoothed version of the latter is presented as Figure 11.

Canopy density parameter

58. This parameter ranges from 0 to 1 and describes the spatial dispersion of foliage elements within a canopy. As values approach 1, gaps in the canopy are less frequent since the foliage is more regularly dispersed. This parameter is used in the equation to determine the probability of gaps occurring in a canopy layer. A value of 0.1 was chosen for all model runs. For a detailed discussion of spatial dispersion of canopies see deWit (1965).

Canopy optical parameters

59. The shortwave transmission and reflectance of foliage elements are required as inputs for estimating average absorption coefficients as discussed below. Canopy element transmission values were measured at the study sites, but reflectance values were derived from the published literature.

60. The procedure for determining transmission consisted of placing a needle or leaf over a narrow slit on a flat plate attached to a photodiode and recording a reading of the amount of light passing through the sample. Measurements were made in four wavelength bands--at 4.8\(\mu\)m, 0.55\(\mu\)m, 0.68\(\mu\)m, and 0.80\(\mu\)m. The transmission measurements were then
ratioed to the incoming spectral irradiance measured from a BaSO₄ standard reflectance panel. The measurement procedure was repeated for several foliage samples and the results averaged. Natural illumination was used for the Douglas-fir needles; however, because of rapidly changing irradiance conditions at the Walker Branch site, a bank of fluorescent tubes was used as the irradiance source. The transmission measurements were integrated over wavelength to estimate the average shortwave transmittance from 0.48 to 0.80 μm. This wavelength interval was assumed adequate.

61. Shortwave reflectance values for Douglas-fir were obtained from data presented by Jarvis, James, and Landsberg (1976). Curves for old and new Douglas-fir needles were digitized and averaged. The resulting curve was then integrated over the wavelength interval from 0.45 μm to 1.2 μm to obtain the average shortwave reflectance coefficient. The oak-hickory canopy element reflectance was determined from data presented by Colwell (1969). Data for maple, oak, and yellow poplar were averaged and integrated over the wavelength interval 0.45 μm to 1.2 μm.

62. In addition to foliage transmission and reflectance estimates, an average background reflectance was determined at both sites. Measurements were made of various surface covers such as litter, bare soil, and ground cover vegetation. The results were weighted according to visual estimates of occurrence and then averaged and integrated.

Shortwave absorption coefficients

63. The absorption of global shortwave radiation by canopy layers is an important component in the daytime energy budget. It is, however, difficult to directly measure and must be estimated with models. These
coefficients were approximated with the SRVC model modified for absorption (Kimes, Smith, and Berry, 1980). The procedure involved running model simulations with appropriate canopy layer geometry, LAI, and optical parameters for an average zenith sun angle of 45°. The resulting absorption values represent the proportion of shortwave absorption in each canopy layer. Since the thermal model requires absorption per unit leaf area, the simulated absorption coefficients were divided by the one-sided leaf area in a given layer.

Stomatal resistance

64. 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. Thus, stomatal resistance is important when considering energy budget analysis of plants. This parameter is difficult to measure, so for modeling purposes average values were used as constants. The value for Douglas-fir was set at 0.66 min/cm as an average value for coniferous forest (Kimes, Smith, and Ranson, 1979). Stomatal resistances were determined from data provided by Hutchison*. These data ranged from 0.04 to 0.07 min/cm for sun leaves. The upper value was selected for use in all deciduous canopy simulations.

* Personal communication; B. A. Hutchison, Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee, 1979.
Emissivity and absorptivity

65. The ability of a canopy element to emit and absorb longwave radiation is expressed by the emissivity and absorptivity coefficients specified for each component in the canopy layers and for the ground layer. Available literature values or direct measurements could, consequently, be substituted. For all of the analyses reported here, the emissivity $\varepsilon_i$ and absorptivity $\alpha_i$ are set equal to 1.0 for each of the three canopy layers. Emissivity of the ground $\varepsilon_g$ was also set at 1.0. Emissivity of the air $\varepsilon_a$ was calculated as a function of air temperature by the following function (Hudson, 1969):

$$\varepsilon_a = 1.0 - 0.0261 e^{(-0.000777 T_a^2)}$$

Canopy Temperature Measurements

66. 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 experiments were designed to provide measured canopy temperatures, as well as thermal scanner images of the sites.

67. 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 average heights of 26 m and 20 m. The measurements at a given height were averaged to give an average layer measurement. The 26-m measurement was assumed to represent the average canopy temperature for layer 1. The 20-m measurement approximated layer 2, although its location was closer to the boundary between layer 1 and layer 2. These layer temperatures are plotted along with air temperature against time in Figure 12.
68. No individual leaf temperature measurements were available at the Walker Branch site, so a portable thermal radiometer* was used to monitor the canopy temperature throughout a 24-hour 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. Figure 13 shows a plot of the canopy temperature with air temperature above the canopy and ground temperature against time.

69. In addition to the geometrical, optical, and thermal parameters discussed above, a set of dynamic variables characterizing the microclimate of the target is 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 shortwave radiation.

70. Air temperature, ground temperature, and shortwave radiation are important components for energy exchange into and within the system; whereas wind speed and relative humidity are important for determining forced convection loss and evapotranspirative cooling of plants, respectively.

71. Environmental data were provided from the automated recording systems at the two sites. Air and ground temperatures and global shortwave radiation were measured directly. Relative humidity was determined from wet and dry bulb temperatures. All measurements were

* Barnes Insta-Therm, Barnes Engineering Corporation.
either instantaneous or short time interval averages. Plots of the four environmental parameters are shown in Figure 14 for Cedar River and Figure 15 for Walker Branch.

Model Validation Results

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

Douglas-fir canopy

73. The thermal model was run with environmental data acquired over the 48-hour period of 4-5 August 1979. These data plus the required geometrical factor matrices which include the longwave exchange coefficients, the sensor view angle weighting factors, and average shortwave absorption coefficients are listed in Appendix D. The emissivities and thermal absorption coefficients for each layer were set to 1.0. The total canopy resistance to water vapor diffusion was input at 0.66 min/cm.

74. A plot of the simulated three-layer temperatures with measured air temperature is shown in Figure 16. The layer 1 simulated temperatures follow the trend of air temperature, but fall below during the night and are higher during the day. The layer 2 and layer 3 predictions are nearly equal to air temperature throughout the 48-hour period. Comparisons of measured and predicted needle temperatures for layers 1 and 2 are presented as Figures 17 and 18, respectively.
75. The layer 1 predicted temperatures vary from the measured temperature by a maximum of $3^\circ$C. These deviations were observed during the daytime hours under very hazy skies. Nighttime predictions deviated from measured by $2^\circ$C or less with the maximum deviations occurring under conditions of fog. This leads to the conclusion 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

76. Environmental data acquired at the Walker Branch site for the 48-hour period from 18-19 August 1979 were used to validate the thermal model for a deciduous oak-hickory canopy. Emissivities and thermal absorption coefficients for the three canopy layers were set to 1.0. Canopy resistance to water vapor diffusion was input as 0.07 min/cm and held constant. The input environmental and geometrical factor data for this canopy simulation are presented in Appendix C.

77. Figure 19 presents the three-layer canopy temperature predictions along with measured air temperature. Nighttime simulations were nearly equal to air temperature, but daytime predictions varied by a maximum of $2^\circ$C over air temperature.

78. Measured temperatures were compared to predicted results for layer 2 and are shown in Figure 20. The agreement between model and measured temperatures was quite good. The largest deviation ($3^\circ$C) occurred in the afternoon; but morning and nighttime predictions varied by only $1^\circ$C or less.
Summary

79. The results of the model validation study indicate that the thermal canopy temperature model provided good estimates of actual temperatures for nighttime periods to within $2^\circ$C for both canopies studied. Daytime simulations generally underestimated measured temperatures for Douglas-fir and overestimated temperatures for oak-hickory. The results indicate that the model may not adequately account for energy transfers under foggy or very hazy conditions.
PART V: RECOMMENDATIONS

80. Two broad directions for further research and development are suggested in the paragraphs below. The first set of tasks represent logical extensions or improvements to the thermal model utilized in this study. Also, a not-quite-so-obvious extension to the calculation of the geometrically dependent flux transfer matrices is outlined. The second thrust recommended for further development is concerned with parameter estimation techniques which can be used to estimate model parameters, control (or input) variables, and elements of the state vector itself. Two techniques are described. The first technique based on sensitivity functions is appropriate for the steady-state version of the model. The second method, based on the Kalman filter, is more appropriate for dynamic representation of the thermal model.

Model Improvements

81. The most urgent need for model improvement is to evaluate different theories for the height dependence of air temperature within the canopy and of the vertical profile for wind speed. It is particularly appropriate to examine those techniques which would yield these temperature and wind profiles from a few limited measurements. The structure of the current thermal model can easily include vertical variations in the two parameters; they are held constant for the want of better knowledge and for simplicity.

82. The utility of the model could be extended if a ground temperature module was included. Particularly for this extension it may be appropriate to develop a time-dependent version of the model to include heat storage effects.
83. A useful exercise, but of lesser priority, would be to systematically examine the alternative formulations expressed by various authors for different components of the energy budget equation; that is, evapotranspiration, sensible heat, and so forth. There is no clear rationale for selecting one expression over another. However, the separate expressions can be programmed and sensitivity analysis performed on the individual expressions.

84. Finally, further analysis of the structure of the geometrical matrices should be carried out to determine if either an analytical decomposition of the matrices into a leaf density (leaf area index) component and leaf slope distributions can be constructed. If an analytical decomposition is not possible, then numerical interpolation techniques should be investigated.

85. As an example, consider the expressions for the view factor matrix $\mathbf{VF}(i,\theta)$ where $\theta_r$ is the zenith view angle and $i=1,2,3,4$ corresponds to contributions from the three vegetation layers and the ground surface:

$$
\mathbf{VF}(i,\theta_r) = [\mathbf{VF}(1,r) \mathbf{VF}(2,r) \mathbf{VF}(3,r) \mathbf{VF}(4,r)]^T
$$

$$
\mathbf{VF}(1,\theta_r) = 1 - P_0(1,r)
$$

$$
\mathbf{VF}(2,\theta_r) = P_0(1,r) (1 - P_0(2,r))
$$

$$
\mathbf{VF}(3,\theta_r) = P_0(1,r) P_0(2,r) (1 - P_0(3,r))
$$

$$
\mathbf{VF}(4,\theta_r) = P_0(1,r) P_0(2,r) P_0(3,r)
$$

where:

$$
P_0(i,\theta) = e^{-\text{LAI} g(i,\theta) \sec \theta}
$$

LAI (i) = the mean leaf area index for layer i

g(i,\theta) = the mean canopy projection of vegetation layer i in

the direction $\theta$, depending only on the leaf slope distributions for layer i
86. A direct factorization is not apparent. However, particularly for large LAI a Taylor series expansion would yield a more tractable form. Alternately, LAI could be varied between 0 and 10 and numerical tables generated.

Parameter Estimation

87. Two different approaches are suggested for estimation of parameters, control vector inputs, and/or selected components of the unknown state vector, that is the average canopy temperature for the three different layers. One approach is more applicable to the steady-state conditions; the second approach is more appropriate for the time-dependent version of the model. In each case it is assumed that selected measurements of canopy temperatures are available for some time periods and that some of the parameters and control vector components are also known. A typical scenario would be that the top layer canopy temperature is measured over a diurnal cycle and that all parameters and input components are known except for the $S$ matrix, the longwave flux transfer matrix. It is then desired to estimate the $S$ matrix which depends on the geometrical properties of the canopy and evaluate the fit on a second diurnal cycle. Other scenario examples can be envisioned. In this section, general development of the two-parameter estimation techniques are indicated.

88. First, consider the steady-state situation where the model is given by the following equation:

$$F(X, P, U) = 0$$

where the symbols have the same meaning as given earlier. For this situation the parameter estimation technique of nonlinear systems as described by Durando and Leondes (1976) is recommended. For simplicity
the \( U \) vector is appended to the \( P \) vector and the equation is re-expressed as:

\[
F(X, P) = 0
\]

Further, it is assumed that observation variables are the canopy temperature variable, \( x \), directly. Given a known measurement, \( X_0 \), \( F(X, P) \) becomes a function of \( P \) only. Assume an initial estimate of \( P_0 \). Then \( F(X, P) \) can be expanded about \( P_0 \):

\[
F(X, P) - F(X_0, P_0) = \frac{\partial F}{\partial P} (P - P_0) + \varepsilon
\]

For the steady-state formulation \( F(X, P) = 0 \); \( \varepsilon \) is the error vector. Iteration is continued until convergence, i.e.,

\[
P_{n+1} = P_n + \delta P
\]

89. If observations are available for more than one time interval, the optimal \( P \) is chosen which minimizes the sum of \( \varepsilon^T \varepsilon \) over all time intervals. More general formulations of this approach, including the use of a variable increment step size, are given in the paper by Durando and Leondes.

90. The second technique proposed is applicable to the time-dependent formulation of the thermal model given:

\[
M \frac{\partial X}{\partial T} = F(X, P, U, T)
\]

where:

\[
M = \text{specific heat capacity of the system}
\]

\[
T = \text{time}
\]
The general approach recommended here is the use of the Kalman filter after first linearizing the system. Specifically,

\[ X = A X + B U + W \]  \hspace{1cm} (31)

\[ Z = H X + V \]  \hspace{1cm} (32)

where \( X = \frac{\partial X}{\partial T} \) represents the dynamical equations of the system, \( A \) and \( B \) are expansion matrices, and \( W \) represents the modeling error.

91. \( Z \) is the observation vector, which now permits transformation on the state vector (canopy temperature), and \( V \) is the observation noise.

92. Kalman filtering on the state vector or on the augmented state vector, that is, after appending \( P \) or \( U \) to \( X \), is then given by the standard expressions (Friedland 1972):

\[ \hat{X}_n = \hat{X}_{n-1} + K_n (Z_n - H \hat{X}_n) \]  \hspace{1cm} (33)

\[ \hat{X}_n = \phi_{n-1} \hat{X}_{n-1} \]  \hspace{1cm} (34)

where:

\[ K_n = \tilde{P}_n H_n^T (H_n \tilde{P}_n H_n^T + V_n)^{-1} \]  \hspace{1cm} (35)

\[ \tilde{P}_n = \phi_{n-1} \tilde{P}_{n-1} \phi_{n-1}^T + B_{n-1} W_n B_{n-1}^T \]  \hspace{1cm} (36)

\[ \tilde{P}_n = (I - K_n H_n) \tilde{P}_n \]  \hspace{1cm} (37)

\( \phi \) is the transition matrix for the system, \( n \) represents the discrete time interval, and \( \hat{X} \) describes the model predictions.

93. An additional \( \hat{X}_0, \tilde{P}_0 \) is required if many time intervals are available, e.g., a diurnal cycle; however, the final estimates are insensitive to these values.
REFERENCES


Table 1

Expressions for contribution coefficients \( C_{ijkl} \) for sink layer \( i \), source component \( j \),
and leaf slope index \( r \); \( P_o(i,r) \) = probability of gap for layer \( i \) and leaf slope index \( r \).

<table>
<thead>
<tr>
<th>Source Layer</th>
<th>1</th>
<th>Sink Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>( P_o^k(1,r) )</td>
<td>( P_o(1,r) ) ( P_o^k(2,r) )</td>
</tr>
<tr>
<td>2</td>
<td>( 2(1-P_o^k(1,r)) )</td>
<td>( P_o^k(2,r) - P_o^k(2,r) ) ( P_o(1,r) )</td>
</tr>
<tr>
<td>3</td>
<td>( P_o^k(1,r) - P_o^k(1,r) ) ( P_o(2,r) )</td>
<td>( 2(1 - P_o^k(2,r)) )</td>
</tr>
<tr>
<td>4</td>
<td>( P_o^k(1,r) ) ( P_o(2,r) - P_o^k(1,r) ) ( P_o(2,r) ) ( P_o(3,r) )</td>
<td>( P_o^k(2,r) - P_o^k(2,r) ) ( P_o(3,r) )</td>
</tr>
<tr>
<td>5</td>
<td>( P_o^k(1,r) ) ( P_o(2,r) ) ( P_o(3,r) )</td>
<td>( P_o^k(2,r) ) ( P_o(3,r) )</td>
</tr>
</tbody>
</table>
Table 2
Initial environmental and initial temperature data used for sensitivity analyses for the Douglas-fir and oak-hickory canopies

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>( A_T ) ( ^\circ C )</th>
<th>( G_T ) ( ^\circ C )</th>
<th>WS ( \text{cm/s} )</th>
<th>RH</th>
<th>SWR ( \text{w/m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0600</td>
<td>10.6</td>
<td>10.7</td>
<td>136.0</td>
<td>0.72</td>
<td>0.0</td>
</tr>
<tr>
<td>1100</td>
<td>18.2</td>
<td>19.0</td>
<td>110.0</td>
<td>0.84</td>
<td>299.7</td>
</tr>
</tbody>
</table>

Initial Temperatures, \( ^\circ C \)

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas-fir</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0600</td>
<td>9.0</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>1100</td>
<td>18.4</td>
<td>18.2</td>
<td>18.2</td>
</tr>
<tr>
<td>Oak-hickory</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0600</td>
<td>10.1</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>1100</td>
<td>18.8</td>
<td>18.5</td>
<td>18.2</td>
</tr>
<tr>
<td>SINK VARIABLE</td>
<td>SOURCE VARIABLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKY</td>
<td>J=1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-1</td>
<td>VEGETATION LAYER ONE</td>
<td>J=2</td>
<td></td>
</tr>
<tr>
<td>I=2</td>
<td>VEGETATION LAYER TWO</td>
<td>J=3</td>
<td></td>
</tr>
<tr>
<td>I=3</td>
<td>VEGETATION LAYER THREE</td>
<td>J=4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GROUND LAYER</td>
<td>J=5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Diagram showing sink and source variable indices used in the model energy flow formulations.
Figure 2. Sensitivity plots of stomatal resistance versus predicted canopy temperature for Douglas-fir (top) and Oak-hickory daytime analyses.
Figure 3. Sensitivity plots of wind speed versus predicted canopy temperature for Douglas-fir day and nighttime analyses.
Figure 4. Aerial view of the Douglas-fir canopy at Cedar River, Washington, site; object in center of photograph is a greenhouse enclosure over the lysimeter tree; structure not in place at the time of the experiments (photo courtesy of Leo J. Fritschen)

Figure 5. Typical ground cover at the Cedar River site
Figure 6. Oblique view of deciduous canopy at Walker Branch site showing height variations of tree crowns

Figure 7. Ground cover at Walker Branch site consisting primarily of litter and seedling trees; the cart (center) is mounted on a tram system and measured shortwave and photosynthetically active radiation at bottom of canopy
Figure 8. Comparative plots of foliage angle frequency for Douglas-fir and lodgepole pine. A) Layer 1, B) Layer 2 and C) Layer 3 (Continued)
Figure 8. Concluded.
Figure 9. Foliage inclination angle frequency plots for the three layer oak-hickory canopy and a one-layer Russian olive canopy.
Figure 10. Leaf area index distribution for the Douglas-fir canopy
Figure 11. Leaf area index distribution for the oak-hickory canopy.
Figure 12. Measured average layer needle temperatures for Douglas-fir plotted with air and ground temperatures for a 48-hour period from August 4 to August 5, 1979; layer 1 and layer 2 needle temperatures measured at 26 m and 20 m respectively.
Figure 13. Measured average canopy temperature for oak-hickory plotted with air and ground temperatures for a 48-hour period from August 18 to August 19, 1979; canopy temperatures measured intermittently from 1100 hours on August 18 to 1200 hours on August 19 with a hand-held thermal radiometer.
Figure 14. Plots of thermal model environmental input parameters for the Cedar River site from 0000 hr 4 August 1979 to 2400 hr 5 August 1979: a) Global shortwave radiation (SWR), b) Wind speed (WS), c) Relative humidity as estimated from wet and dry bulb temperatures, and d) air temperature (●) and ground temperature (○).
Figure 15. Plots of thermal model environmental input parameters for Walker Branch Site: a) Global shortwave radiation (SWR), b) Wind speed (WS), c) Relative humidity as estimated from wet and dry bulb temperatures, and d) air temperature (●) and ground temperature (○).
Figure 16. Simulation results for the three-layer Douglas-fir canopy plotted with air temperature for the 48-hour time period from 4-5 August 1979.
Figure 17. Layer 1 predicted temperatures plotted with average temperatures measured at the 26-m level in the Douglas-fir canopy.
Figure 18. Layer 2 predicted temperature plotted with average temperatures measured at the 20-m level in the Douglas-fir canopy.
Figure 19. Simulation results for the three-layer oak-hickory canopy plotted with air temperatures for the 48-hour period from 18-19 August 1979.
Figure 20. Layer 2 predicted temperature plotted with measured average temperature of oak-hickory canopy; measurements made with a thermal infrared radiometer.
TMODEL

PROGRAM TMODEL1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,
1TAPE1,TAPE2,TAPE3)

**********TMODEL--VERSION 2.14.80**********
 COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),A(3),U(4,9),
1ALP(3),FNU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
 COMMON/PARA2/BTA,BTG,BX(3),DBX(3),DX(3),DBX(3),RX(3),DRX(3)
 COMMON/ESTIM/FX(3),DFX(3,3)
 COMMON/SENSOR/ERT(9),ERTH(3),EX(9),EXH(3)
 DIMENSION DX(3),SAIS(3)

SIG=5.6686E-8 $ TOL=.0001

--- READ CANOPY GEOMETRY MATRICES ---
 FROM TAPE 2

READ(2,203) TITLE1,TITLE2,TITLE3
WRITE(3,203) TITLE1,TITLE2,TITLE3
 READ W MATRIX: SENSOR VIEW ANGLE WEIGHTS

DO 2001 N1=1,4
 READ(2,202) (W(N,J),J=1,9)
2001 CONTINUE

--- READ S MATRIX: LW FLUX TRANSFERS

DO 2000 I=1,3
 READ(2,202) (S(I,J),J=1,3),STG(I)
2000 CONTINUE

--- READ ABS: SW FLUX

 FORMAT(9F7.4)
 READ(2,202) (SABS(N),N=1,3)
 FORMAT(1X,3A10)

--- DEFINE NOMINAL VALUES FOR MODEL PARAMETERS ---

C1000 FORMAT(I4,4F5.0,2X,F5.0)
C1000 FORMAT(I4,2F7.2,2F6.2,2X,F10.2)

ALP(1)=1.0
ALP(2)=1.0
ALP(3)=1.0
EPS(1)=1.0
EPS(2)=1.0
EPS(3)=1.0
EPSTG=1.0

A2
C --- READ-IN THE NUMBER OF SIMULATION PERIODS ---
C
PRINT 201
201 FORMAT(//,* ENTER THE NUMBER OF SIMULATION PERIODS DESIRED*/*)
READ*,NSIM
C --- READ IN CANOPY RESISTANCE ---
C
PRINT 219
219 FORMAT(//,*ENTER THE CANOPY STOMATAL RESISTANCE FOR THIS RUN*/*)
READ*,RL
WRITE(6,600)
600 FORMAT(1H ,4HTIME,4X,4HHSW,15X,1HA,31X,1HB,31X,1HH,23X,2HLE)
WRITE(6,602)
602 FORMAT(1H ,17X,1H1,7X,1H2,7X,1H3,7X,1HA,7X,1H1,7X,1H2,7X,1H3,7X,
1HG,7X,1H1,7X,1H2,7X,1H3,7X,1H1,7X,1H2,7X,1H3)
2 CONTINUE
DO 100 NTIMEwI,NSIM
READ( I,s)ITINE,TA,TG,FMU,RH,GL1
C .... CONVERT FNU IN M/SEC TO CM/SEC .....
FMU = FMU*100.
A(1)=GLB*SABS(1) $ A(2)=GLB*SABS(2) $ A(3) = GLB*SABS(3)
TAC=TA
DO 90 I=1,3
90 X(I)=TA
50 CALL FEVAL
DO 20 I=1,3
20 FX(I)=-FX(I)
CALL SOLVE(FX,3,DFX,3,DX)
DO 30 I=1,3
30 X(I)=X(I)+DX(I)
DO 40 I=1,3
40 CONTINUE
IF(ABS(DEV) .GT. 10.L) GO TO 50
40 CONTINUE
CALL UATS
WRITE(3,80) ITIHE,TA,TG,(ERTH(J),J=1,3)
80 FORMAT(1H,110,2F7.2,3F6.1)
95 FORMAT(110,4F10.5)
BTA=BTAOSIG
BX(I)=BX(I)*SIG
BX(3)=BX(3)*SIG
BTG=DTG*SIG
C
WRITE(6,604)ITIME,GLB,(A(I),I=1,3),BTA,(BX(I),I=1,3),BTG,(QX(I),
.I=1,3),(RX(I),I=1,3)
604 FORMAT(1H ,14,15F8.2)
100 CONTINUE
STOP
END
SUBROUTINE FEVAL
C
COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),A(3),U(4,9),
1ALP(3),FMU,TA,TAC,TA,EPS(3),EPS,TG,RL
COMMON/PARA2/BTA,BTG,BX(3),BBX(3),GX(3),QX(3),RX(3),DRX(3)
A3
COMMON/ESTIM/DFX(3,3),DFX(3,3)

CALL FBTAT(A,T(A))
CALL 3FUNC(EPSTG,TG,BTG,D3TG)
DO 10 I=1,3
CALL 3FUNC(EPS(I),X(I),3X(I),DBX(I))
CALL 0FUNC(X(I),TAC,FMU,DX(I),DQX(I))
CALL RFUNC(X(I),TAC,FMU,RL,RH,RX(I),DRX(I))
10 CONTINUE
DO 20 IL=1,3
FX(IL)=0.5*ALP(IL)*SIG*(STA(IL)+3X(1)*S(IL,1)+3X(2)*S(IL,2)+3X(3)*S(IL,3)+BTGSTG(IL)+A'IL)-SIG3XIL)+ALP(IL)*SIG*DBX(IL))
2+X(IL)
DO 30 I=1,3
DO 30 J=1,3
DFX(I,J)=0.
DO 40 IL=1,3
DO 40 J=1,3
IF(J.NE.I) GO TO 35
DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)-SIG*DBX(IL)+DQX(IL)+
DBX(IL)
GO TO 40
35 DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)
40 CONTINUE
RETURN
END
SUBROUTINE 3FUNC(EPSI,XI,3XI,3BXI)
BXI=EPSI*(XI+273.0)**4.
DBXI=4.*EPSI*(XI+273.0)**3.
RETURN
END
SUBROUTINE FBTAT(A,T(A))
EPSTA=1.-0.261*EXP(-7.77E-4*T(A)+TA)
CALL 3FUNC(EPSSTA,T,STA,DTSTA)
RETURN
END
SUBROUTINE 0FUNC(XI,TAC,FMU,DXI,DQXI)
IF(FMU.GT.30.) GO TO 10
HC=0.69775*20.4+0.2*FMU**0.97
GO TO 20
10 HC=0.69775*0.95*FMU**0.97
HC=(XI-TAC)*(-HC)
SUBROUTINE RFUNC(XI,TAC,FNU,RL,RH,RXI,DRXI)
C
RNU=FEX(XI)*1.0E-6-RH*FEX(TAC)*1.0E-6
RDEN=RL+(1.60)*(0.04+1.27*FHU**(-0.5))
RXI1=-697.75*(-0.566*XI+597.3)
RXI2=RNU/RDEN
RXI=RXI1+RXI2
DRXI=697.75*0.566*RXI2+RXI1*(0.056715E-6*FEX(XI))/RDEN
RETURN
END

SUBROUTINE INVERSE(A,N,D)
C
C --- INVERT A 3X3 REAL MATRIX A WHOSE DETERMINANT IS D
C THE RESULT WILL BE STORED IN A
C
DIMENSION A(3,3),B(3,3)
C
B=(1,1)*A(2,2)*A(3,3)+A(1,2)*A(2,3)+A(1,3)*A(2,1)
1A(3,2)-A(3,1)*A(2,2)*A(1,3)-A(1,1)*A(3,2)-A(2,1)*
2A(1,2)*A(3,3)
B(1,2)=-(A(2,1)*A(3,3)-A(2,3)*A(3,1))/D
B(1,3)=-(A(2,1)*A(3,2)-A(2,2)*A(3,1))/D
B(2,1)=-(A(1,2)*A(3,3)-A(1,3)*A(3,2))/D
B(2,2)=-(A(1,2)*A(3,3)-A(1,3)*A(3,1))/D
B(2,3)=-(A(1,1)*A(3,2)-A(1,2)*A(3,1))/D
B(3,1)=-(A(1,1)*A(2,3)-A(1,3)*A(2,2))/D
B(3,2)=-(A(1,1)*A(2,3)-A(1,3)*A(2,2))/D
B(3,3)=-(A(1,1)*A(2,2)-A(1,2)*A(2,1))/D
DO 10 I=1,3
DO 10 J=1,3
10 A(I,J)=B(I,J)
RETURN
END

FUNCTION FEX(XI)
C
XX=5.2342*EXP(0.056715*XI)
FEX=XX
RETURN
END

SUBROUTINE SOLVE(Y,N,A,N,X)
C
A5
C DIMENSION Y(N), A(N,M), X(N), ATA(M,M), ATY(M)
C
DIMENSION Y(3), A(3,3), X(3), ATA(3,3), ATY(3)
C
DO 10 I=1,N
DO 10 J=1,M
ATA(I,J)=0.
DO 10 K=1,N
10 ATA(I,J)=ATA(I,J)+A(X,I)*A(X,J)
CALL INVERSE(ATA,M,D)
DO 20 I=1,M
ATY(I)=0.
DO 20 J=1,N
20 ATY(I)=ATY(I)+A(J,I)*Y(J)
DO 30 I=1,M
X(I)=0.
DO 30 J=1,N
30 X(I)=X(I)+ATA(I,J)*ATY(J)
RETURN
END

SUBROUTINE WATTS
COMMON/PARA/SIG, STA(3), S(3,3), STG(3), X(3), A(3), W(4,9),
1 ALP(3), FNU, TA, TAC, TG, EPS(3), EPSTG, RH, RL
COMMON/SENSOR/ERT(9), ERTH(3), EX(9), EXH(3)
C
DO 1 M=1,3
EXH(N)=EPS(N)*SIG*(X(N)+273.)**4
ERTH(N)=( (EXH(N)/SIG)**0.25 ) - 273.
1 CONTINUE
C
DO 2 J=1,9
EX(J)=SIG*EPS(1)*W(1,J)*(X(1)+273.)**4 +
1 SIG*EPS(2)*W(2,J)*(X(2)+273.)**4 +
2 SIG*EPS(3)*W(3,J)*(X(3)+273.)**4 +
3 SIG*EPSTG*W(4,J)*(TG+273.)**4
ERT(J)=( (EX(J)/SIG)**0.25 ) - 273.
2 CONTINUE
RETURN
END
SCALC

PROGRAM SCALC(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2,
.TAPE3)
C
C***************SCALC--VERSION 2.14.80****************
C
C...THIS PROGRAM IS EXTRACTED FROM THE TCSM MODEL BY KIMES TO
C...CALCULATE THE SENSOR VIEW WEIGHTING MATRIX W AND THE LONGWAVE
C...RADIATION EXCHANGE MATRIX S FOR A GIVEN CANOPY GEOMETRY.
C...REQUIRED INPUTS ARE LEAF INCLINATION ANGLE AND CORRESPONDING
C...FREQUENCY, CANOPY DENSITY (SLAI) AND LEAF AREA INDEX (FLAI)
C...FOR EACH OF THREE CANOPY LAYERS.
C
C
COMMON /A/ WV,RH,RL,D(3)
COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
COMMON /C/ COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
COMMON /D/ CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, MUSIM, ITIME
COMMON /E/ AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
COMMON /F/ XS(9,18),ZS(9), CEDTR, B, FREQD(9,3), WA(15), EPS
COMMON /G/ NSIG,N, ITMAX
COMMON /H/ INDEX1,TITLE(8)
COMMON /I/ X(3)
COMMON /J/ THERM,THMLEX,CONVEC,TRANS
COMMON /S/ ABSOL(3)
C
C...READ AND ASSIGN THE INPUT DATA
C
NUSIM=-1
INDEX1=0
76 IF(INDEX1.EQ.NUSIM)STOP
CALL INPUTDA
IF(INDEX1.GT.1) GO TO 95
C
C...CALCULATE THE CANOPY GEOMETRY COEFFICIENTS
C
CALL CANGEOM
C
CALL WMAT(TITLE)
C
C...CALCULATE THE SIN THETA FACTORS FOR ALL SOURCE ANGLE-LEAF ANGLE
C...PERMUTATIONS.
C
CALL DEVANG

A7
C...CALCULATE THE NORMALIZING FACTOR FOR THE RELATIVE SIZES OF SOURCE SECTORS
C
CALL SECTOR
95 CONTINUE
C
C...CALCULATE THE THERMAL RADIATION COEFFICIENTS
C
CALL SETUP
C
C...CALCULATE THE AVERAGE LEAF TEMPERATURE WITHIN EACH LAYER.
C
C...DISPLAY THE OUTPUT
C
CALL OUTDAT
GO TO 76
END
SUBROUTINE INPUTDA
C
C...SUBROUTINE INPUTDA READS AND ASSIGNS THE INPUT DATA
C
COMMON/GEO/ PHIT(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
COMMON /A/ UV,RH,RL,D(3)
COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
COMMON/D/CONT(3,3,9),C(3,5,9), SUMT(3,9), KELV, GT, MUSIM, ITIME
COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREO(9,3), WA(15),EPS
COMMON/G/HSIG,N, ITMAX
COMMON /H/ INDEX1,TITLE(E)
COMMON /I/ X(3)
COMMON /J/ THERM,THMLEX,CONVEC,TRANS
COMMON /K/ STOR(3)
COMMON/S/ABSOL(3)
C
C...TEST FOR THE SIMULATION NUMBER AND SKIP TO THE APPROPRIATE INPUT DATA
C
IF (INDEX1.EQ.0) GO TO 99
IF(INDEX1.EQ.MUSIM) STOP
99 CONTINUE
C
C...ASSIGN THE STEFFAN BOLTZMANN CONSTANT WATTS/M**2*K**4
C
STEF=5.6686E-8

A8
C... ASSIGN THE CONVERSION FACTOR FOR KELVIN-DEGREES
C
E= 273.0
C
C... READ THE AVERAGE THERMAL EMISSIVITY COEFFICIENTS FOR THE 3 VEGTAION LAYERS
C (1,2,3) AND THE GROUND(4).
C
READ(1,199)(TITLE(N),N=1,8)
IF(EOF(1).NE.0.)STOP
199 FORMAT(BA10)
C
C
C
C... READ THE CANOPY GEOMETRY FREQUENCY DISTRIBUTIONS OF THE ELEMENTS
C IN LAYERS 1,2,3. AXLFA REPRESENTS THE INCLINATION ANGLES 0-90
C (5 DEGREE INTERVALS) AND AYLFA REPRESENTS THE CORRESPONDING
C FREQUENCY. SLAI AND FLAI ARE EACH LAYERS S PARAMETER AND LAI
C RESPECTIVELY.
C
DO 190 I=1,3
READ(1,*) (AXLFA(M,I),AYLFA(M,I),M=1,19)
READ(1,*) SLAI(I,1),FLAI(I,1)
190 CONTINUE
101 FORMAT (8FI0.5)
RETURN
END
SUBROUTINE OUTDAT
C
C... SUBROUTINE OUTPUT FORMATS THE DATA TO BE DISPLAYED.
C
COMMON/SENS/ ELAYT(9),ELAYH(3),ERTT(9),ERTH(3)
COMMON/6ED/ PHIT(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
COMMON /A/ WV,RH,RL,D(3)
COMMON /B/ PGAP(3,9),PHIT(3,9),PGAP2(3,9),PHIT2(3,9),STEF
COMMON/C/COSTA(9,9,16),EMISSV(4),ABSORB(3),ESKY, EGRD, SECTAR(9)
COMMON/D/CONT(3,5,9),C(3,5,9),SUMT(3,9),KELV, GT, NUSIM, ITIME
COMMON/E/AT,THETA(9),PHI(18),XLF(9),YLF(9),ZLF(9),XS(9,18)
COMMON/F/YS(9,18),YS(9),CEDTR, B, FREDD(9,3), WA(15),EPS
COMMON/G/NSIG,H, IMAX
COMMON /H/ INDEX1,TITLE(8)
COMMON /I/ X(3)
COMMON /J/ THERM,THMLEX,CONVEC,TRANS
COMMON /K/ TTI(3),TT2(3),TT3(3),TT4(3)
COMMON /L/ STOR(3)
COMMON /L/ TEMP(3)
COMMON /S/ ABSOL(3)
DIMENSION S(3,5)

C
C..WRITE THE CALCULATED GEOMETRY FOR EACH LAYER
C
    DO 319 I=1,3
    WRITE (2,320) I
320 FORMAT (///,* THE COMPONENT ANGLE COMPUTATIONS FOR LAYER */,I1,/
    WRITE (2,321) FLAI(I,1),SRAI(I,1)
321 FORMAT (* LAI = F4.2,4X, S =F4.2,/
    WRITE (2,322) XLIFA(M,I),YLIFA(M,I),M=1,19)
322 FORMAT (XLIFA,YLIFA *,,(2X,F16.3))
    WRITE (2,323) (PGAP(I,M),M=1,9)
323 FORMAT (///,* PGAP FOR 1-9 INCLINATION INTERVALS*,9F8.3)
    CONTINUE
C
C..WRITE THE CALCULATED THERMAL CONTRIBUTIONS COEFFICIENTS
C
    WRITE (2,302)
302 FORMAT (1X,/* THE PROPORTION OF RADIANCE AREA CONTRIBUTED BY
     * A SECTOR OF THE 9 BANDS(1-9) DIVIDED BY 18 (SECTORS) ARE=*,/
     WRITE (2,303) (SECTR(I),I=1,9)
303 FORMAT (10X,9F10.5,///)
    WRITE (2,40)
40 FORMAT (1X,/* THE BAND-PGAP-PHIT-COEFFICIENTS FOR THE THERMAL RA
     * DIATION TRANSFERS ARE =*,/
     DO 39 I=1,3
     WRITE (2,41) I
39 CONTINUE
41 FORMAT (1X,/* THE 9 BAND COEFFICIENTS TO LAYER */I1,* ARE=)
     DO 39 J=1,5
     WRITE (2,42) J, (CONT(I,J,M),M=1,9)
39 CONTINUE
     WRITE (2,50)
50 FORMAT (1X,///,* THE FINAL THERMAL RADIATION COEFFICIENTS ARE AS FOLLOWS
     ***,/
     DO 49 MXX=1,3
     DO 49 HXX = 1,5
     S(MXX,HXX) = 0.0
A10
CONTINUE
DO 51 I=1,3
WRITE(2,52) I
52 FORMAT (1X,* THE THERMAL RADIATION CONTRIBUTION TO LAYER *,I1,* FOR
+R EACH OF THE 9 LEAF INCLINATIONS ARE*)
DO 51 J=1,5
WRITE (2,53) J,(C(I,J,K),K=1,9)
DO 51 K=1,9
S(I,J) = S(I,J)+C(I,J,K)*FREQD(K,I)
53 FORMAT (8X,* FROM LAYER*,I1,2X,9E10.3)
51 CONTINUE
DO 55 IXX = 1,3
WRITE(3,505)(S(IXX,JXX),JXX=1,5)
505 FORMAT(5F7.4)
WRITE(4,503)(S(IXX,JXX),JXX=1,5)
503 FORMAT(1H ,5F10.4)
55 CONTINUE
RETURN
END
SUBROUTINE SETUP
C
C...SUBROUTINE SETUP PRE-CALCULATES AND PRE-ARRANGES MANY OF THE THERMAL
C COEFFICIENTS NEEDED FOR THE FINAL ENERGY BUDGETS WHICH ARE PLACED INTO THE
C ZSYSTM ROUTINE.
C
COMMON /A/ WV,RH,RL,D(3)
COMMON /B/ PGAP(3,9),PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
COMMON/D/CONT(3,5,9),C(3,5,9),SUMT(3,9), KELV, GT, MUSIK, ITIME
COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
COMMON/G/NSIG,N, ITMAX
COMMON /H/ INDEX1,TITLE(8)
C
C...FOR EACH LAYER CALCULATE THE BAND-PGAP-PHIT COEFFICIENTS NEEDED FOR EACH
C LAYERS THERMAL RADIATION CONTRIBUTION TO A SPECIFIC LAYER.
C
DO 20 I=1,9
C
C...CONTRIBUTION COEFFICIENTS TO LAYER 1
FROM SKY

CONT(1,1,I) = PGAP2(1,I)

FROM LAYER 1

CONT(1,2,I) = 2.*PHIT2(1,I)

FROM LAYER 2

CONT(1,3,I) = PGAP2(1,I)*PGAP2(1,I)*PGAP(2,I)

FROM LAYER 3

CONT(1,4,I) = 2.*PHIT2(2,I)

FROM LAYER 3

CONT(1,5,I) = PGAP2(1,I)*PGAP(2,I)*PGAP(3,I)

CONTRIBUTION COEFFICIENTS TO LAYER 2

FROM SKY

CONT(2,1,I) = PGAP(1,I)*PGAP2(2,I)

FROM LAYER 1

CONT(2,2,I) = PGAP2(2,I)*PGAP2(2,I)*PGAP(1,I)

FROM LAYER 2

CONT(2,3,I) = 2.*PHIT2(2,I)

FROM LAYER 3

CONT(2,4,I) = PGAP2(2,I)*PGAP(2,I)*PGAP(3,I)

FROM GROUND

CONT(2,5,I) = PGAP2(2,I)*PGAP(3,I)
CONTRIBUTION COEFFICIENTS TO LAYER 3

FROM SKY

\[ \text{CON}(3,1,I) = \text{PGAP}(1,1) \cdot \text{PGAP}(2,1) \cdot \text{PGAP}(3,1) \]

FROM LAYER 1

\[ \text{CON}(3,2,I) = \text{PGAP}(2,1) \cdot \text{PGAP}(3,1) - \text{PGAP}(2,1) \cdot \text{PGAP}(1,1) \]

FROM LAYER 2

\[ \text{CON}(3,3,I) = \text{PGAP}(3,1) \cdot \text{PGAP}(2,1) \cdot \text{PGAP}(2,1) \]

FROM LAYER 3

\[ \text{CON}(3,4,I) = 2 \cdot \text{PHIT}(3,1) \]

FROM GROUND

\[ \text{CON}(3,5,I) = \text{PGAP}(3,1) \]

CONTINUE

NOW FORM THE EQUATION COEFFICIENTS FOR THE CONTRIBUTED THERMAL RADIANT ENERGY TO EACH LAYER AND FOR EACH LEAF INCLINATION ANGLE WITHIN A LAYER.

CALL SET03(C,3,5,9)

THERMAL RADIATION CONTRIBUTION TO LAYER N

DO 30 N=1,3

FOR EACH LEAF INCLINATION ANGLE INTERVAL

DO 30 I=1,9

SUM EACH SECTORS RADIATION CONTRIBUTION (9 BANDS CONTAINING 18 SECTORS)

DO 30 J=1,9

DO 30 K=1,18
...ABSORBED THERMAL RADIATION CONTRIBUTED BY SKY

\[ C(N,1,I) = C(N,1,I) + \text{SECTAR}(J) \times \text{CONT}(N,1,J) + \text{COST}(I,J,K) \]

...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 1

\[ C(N,2,I) = C(N,2,I) + \text{SECTAR}(J) \times \text{CONT}(N,2,J) + \text{COST}(I,J,K) \]

...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 2

\[ C(N,3,I) = C(N,3,I) + \text{SECTAR}(J) \times \text{CONT}(N,3,J) + \text{COST}(I,J,K) \]

...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 3

\[ C(N,4,I) = C(N,4,I) + \text{SECTAR}(J) \times \text{CONT}(N,4,J) + \text{COST}(I,J,K) \]

...ABSORBED THERMAL RADIATION CONTRIBUTED BY THE GROUND

\[ C(N,5,I) = C(N,5,I) + \text{SECTAR}(J) \times \text{CONT}(N,5,J) + \text{COST}(I,J,K) \]

30 CONTINUE
RETURN
END

SUBROUTINE DEVANG

...SUBROUTINE DEVANG CALCULATES THE \cos(\text{ANGLE}) DEVIATION

...ANGLE OF ALL LEAF INCLINATIONS SOURCE ORIENTATIONS PERMUTATIONS. THE THEORY IS BASED ON THE EXISTENCE OF PLANE ELEMENTS AS USED IN THE SRVC MODEL.

COMMON /A/ WW,RH,RL,D(3)
COMMON /B/ PGAP(3,9),PHIT(3,9),PGAP2(3,9),PHIT2(3,9),STEF
COMMON /C/ COSTA(9,9,18),EMISSV(4),ABSORB(3),ESKY,EGRD,SECTOR(9)
COMMON /D/ CONT(3,5,9),C(3,5,9),SUMT(3,9),KELV,GT,NUSIM,ITIME
COMMON /E/ AT,THETA(9),PHI(18),XLF(9),YLF(9),ZLF(9),XS(9,18)
COMMON /F/ YS(9,18),ZS(9),CEDTR,B,FREDO(9,3),WA(15),EPS
COMMON /G/ WSIG,N,ITMAX
INTEGER SB,SS
CEDTR= 0.017453293
C...CALCULATE INCLINATION ANGLES IN RADIANS
C
THETA(1) = 5. * CEDTR
DO 10 I = 1, 8
THETA(I+1) = THETA(I) + 10.0 * CEDTR
10 CONTINUE
C
C...CALCULATE AZIMUTH ANGLES IN RADIANS
C
PHI(1) = 10. * CEDTR
DO 20 I = 1, 7
PHI(I+1) = 20. * CEDTR + PHI(I)
20 CONTINUE
C
C...CALCULATE ALL THE DIRECTION COSINES OF SOURCE SECTORS
C
DO 40 I = 1, 9
ZS(I) = SIN(THETA(I))
DO 40 J = 1, 18
XS(I, J) = COS(THETA(I)) * COS(PHI(J))
YS(I, J) = COS(THETA(I)) * SIN(PHI(J))
40 CONTINUE
C
C...CALCULATE THE DIRECTION COSINES FOR THE NORMAL VECTOR OF ALL PLANAR LEAF
C INCLINATION ANGLES ASSUMING THAT THE AZIMUTH ANGLE IS EQUAL TO ZERO DEGREES.
C
DO 30 I = 1, 9
XLF(I) = -SIN(THETA(I))
YLF(I) = 0.0
ZLF(I) = COS(THETA(I))
30 CONTINUE
C
C...CALCULATE THE ABSOLUTE VALUE OF THE DOT PRODUCTS OF ALL SOURCE-LEAF
C ANGLE PERMUTATIONS. THIS VALUE IS EQUAL TO THE COSINE FACTOR DESIRED.
C
DO 50 LI = 1, 9
DO 50 SB = 1, 9
DO 50 SS = 1, 18
DOT = (XLF(LI) * XS(SB, SS) + YLF(LI) * YS(SB, SS) + ZLF(LI) * ZS(SS))
COSTA(LI, SB, SS) = ABS(DOT)
50 CONTINUE
RETURN
END
SUBROUTINE CANGEOM

A15
SUBROUTINE CANGEON calculates the canopy geometry coefficients.

The subroutine CANGEON calls subroutine SRVCMOD which is a modified portion of the SRVC model that calculates the canopy geometry parameters.

COMMON/GEO/ PHIT1(3,9), FLAI(3,1), SLAI(3,1), AXLFA(19,3), AYLFA(19,3)
COMMON /A/ WU, RH, RL, D(3)
COMMON /B/ PGAP(3,9), PHIT(3,9), PGAP2(3,9), PHIT2(3,9), STEF
COMMON/C/ COSTA(9,9,18), EMISSV(4), ABSORB(3), ESKY, EGRD, SECTOR(9)
COMMON/D/ CONT(3,5,9), C(3,5,9), SUMT(3,9), KELV, ST, NUSIM, ITIME
COMMON/E/ AT, THETA(9), PHI(18), XLF(9), YLF(9), ZLF(9), XS(9,10)
COMMON/F/ YS(9,10), ZS(9), CEDTR, B, FREQD(9,3), WA(15), EPS
COMMON/G/ NSIG, ITMAX

CALL SRVCMOD
DO 10 I=1,3
DO 10 M=1,9

TRANSFER IDENTICAL ARRAYS PHIT AND PHIT1. PHIT CONTAINS THE PROBABILITY OF HIT COEFFICIENTS FOR EACH VIEW ANGLE AND LAYER PERMUTATION

PHIT(I,K)=PHIT1(I,K)

CALCULATE THE PROBABILITY OF GAP (PGAP) FOR ALL PERMUTATIONS.

PGAP(I,K)=1.-PHIT(I,K)

CALCULATE THE PROBABILITY OF GAP AND HIT FOR THE HALF LAYERS (PGAP2, PHIT2) FOR ALL PERMUTATIONS.

PGAP2(I,K)= SORT(PGAP(I,K))
PHIT2(I,K)=1.-PGAP2(I,K)

OBTAIN THE FREQUENCY OF OCCURENCE (FREQD) OF ELEMENTS IN EACH OF THE NINE INCLINATION INTERVALS FOR EACH LAYER.

DO 15 J=1,3
ADD=0.0
DO 20 M=1,9
FREQD(M,J)= AYLFA(2*M,J)
ADD=ADD + FREQD(M,J)

A16
COMMON/GEOM/PHIT1(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
DIMENSION NANGLE(3,3),FLA(3,3,10),THETA(10)
DIMENSION PHIT(3,3,10),MTP(3),OPM(10),XK(9),XLFA(19)
DIMENSION YLFA(19), DM(17), F(19), DP(9)
REAL INCLF

C ....GENERAL SIMULATION CONSTRAINTS
CEPI02 = 1.57079632
CE2PI = 6.28318530
CEPI1 = 3.14159265
CETR = 0.17453293
CEFB = 57.2957795
CETB = 0.0029088821
NBANDS = 9
WHAT = 1
MLAT = 3
BANDW = .90/NBANDS

C ....PARAMETER INITIALIZATION AND CONVERSION
MSOUR = NBANDS + 1
BANDW = BANDW * CETR

C ....COEFFICIENTS FOR DIFFUSE RADIATION VECTORS
ALPHA2 = 0.
SINA2 = 0.
DO 2 I = 1, NBANDS
   SINAI = SINA2
2 CONTINUE
ALPHA2=ALPHA2+BANDW
SINA2=SIN(ALPHA2)
XK(I)=SINA2=SINA2-SINA1*SINA1
2 CONTINUE
C
C....SOURCE DIRECTION INCLINATION ANGLES
C
TOTAL=0.
THETA(1)=(BANDW/2.)-BANDW
DO 3 I=1,NBANDS
THETA(I+1)=THETA(I)+BANDW
3 CONTINUE
C
C....CANOPY GEOMETRY. EACH CANOPY LAYER IS COMPOSED OF ONE OPTICAL MATERIAL WHICH MAY BE SPECIFIED AND UNIQUE GEOMETRICAL PROPERTIES. CANOPY GEOMETRIC PARAMETERS CONSIST OF (1)LEAF ANGLE FREQUENCY DISTRIBUTION FUNCTION DENOTED BY XLFA AND YLFA (2)LEAF AREA INDEX DENOTED BY FLAI AND (3)CANOPY DENSITY DENOTED BY SLAI. XLFA (DEG) AND YLFA MUST BE SPECIFIED AT AN ODD NUMBER (NANG) OF EVENLY SPACED POINTS. FLAI IS NON-NEGATIVE AND SLAI RANGES BETWEEN 0 AND 1.
C
DELF=10.*CEDTR
DO 350 IL=1,NLAY
NANG=19
C
C....ASSIGN THE NUMBER OF MATERIALS IN ANY GIVEN LAYER
C
IHAT=1
MTP(IL) = IMAT
IHAT=IHAT
DO 351 J=1,IMAT
IHAT = J
DO 41 MM=1,NANG
XLFA(MM)=XLFA(MM,IL)
YLFA(MM)=YLFA(MM,IL)
41 CONTINUE
C
C....INTEGRATE AND NORMALIZE THE LEAF ANGLE FREQUENCY DISTRIBUTION FUNCTION USING SIMPSONS RULE--THIS IS TEMPORARILY DENOTED BY FLA (M-1 EQUALLY SPACED INTERVALS OF F ARE THEN DETERMINED AND DENOTED BY FLA (M POINTS). THE TABLE FLA IS USED FOR RANDOMLY SELECTING LEAF INCLINATION ANGLES.
C
DO 305 I=1,NANG
305 XLFA(I)=XLFA(I)*CEPTR
\[ M = \left( \frac{NANG-1}{2} \right) + 1 \]

\[ \text{NANGLE(IL,IMAT)} = M \]

\[ \text{CALL TBLR(M,XLFA,YLFA,BK,F)} \]

\[ \text{DO 310 IANG=1,M} \]

\[ 310 \text{ FLA(IL,IMAT,IANG)=BM(IANG)} \]

**C**

**C** NORMALIZE THE INPUT LEAF FREQUENCY DISTRIBUTION FUNCTION TO OBTAIN A DENSITY FUNCTION F WHICH IS SPECIFIED AT M POINTS.

**C**

\[ \text{FTOT=0.} \]

\[ \text{DO 311 I=1,NANG} \]

\[ 311 \text{ FTOT=FTOT+YLFA(I)} \]

\[ \text{DO 312 I=1,9} \]

\[ 312 \text{ F(I)=(YLFA(2*I)+YLFA(2*I+1))/FTOT} \]

\[ \text{DO 315 I=1,NANG} \]

\[ 315 \text{ XLFA(I)=XLFA(I)*CERTD} \]

\[ M=M-1 \]

**C**

**C** CALCULATE THE MEAN PROJECTION (OP) IN THE DIRECTION OF THE SOURCE (THETA) OF ONE UNIT LEAF AREA WITH INCLINATION INCLF. THE LEAVES AT THIS ANGLE ARE ASSumed TO BE AZIMUTHALLY ISOTROPIC.

**C**

\[ \text{DO 330 IANGLE=1,MSOUR} \]

\[ \text{INCLF=-5.*CEDTR} \]

\[ \text{DO 320 I=1,9} \]

\[ 320 \text{ CALL COP(INCLF,THETA(IANGLE),OP(I),CEPI02)} \]

**C**

**C** CALCULATE THE MEAN PROJECTION (OPM) IN THE DIRECTION OF THE SOURCE (THETA) OF ONE UNIT LEAF AREA AVERAGED OVER THE CANOPY LEAF ANGLE DENSITY FUNCTION F.

**C**

\[ \text{CALL COPM(F,OP,OPM(IANGLE))} \]

**C**

**C** CALCULATE THE PROBABILITY OF A HIT (PHIT) FOR A LIGHT RAY WITH SOURCE DIRECTION THETA.

**C**

\[ \text{CALL PDENS(IL,IMAT,IANGLE,OPM(IANGLE),THETA,NANGLE,FLA,SLAI,FLAI,PHIT)} \]

\[ 330 \text{ CONTINUE} \]

\[ 350 \text{ CONTINUE} \]

\[ J=NMAT \]

\[ \text{DC 228 I=1,3} \]
DO 228 M=1,9
PHIT(I,1,1)=PHIT(I,1,1+1)
END
228 CONTINUE
RETURN

SUBROUTINE COP(ALPHA,BETA,OP,CEPI02)

C COP
C
C...
THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COP
C...
THE DIRECTION OF THE SOURCE. THE LEAF IS INCLINED AT AN ANGLE COP
C...
ALPHA AND IS ASSUMED TO BE AZIMUTHALLY ISOTROPIC.
C
C
DP=COS(ALPHA)*SIN(BETA)
IF(ALPHA.LE.BETA) RETURN

C...
THETAO IS THE LEAF AZIMUTH ANGLE AT WHICH OP BECOMES NEGATIVE AND COP
C...
IS IN THE FIRST QUADRANT. THE FUNCTION OP IS SYMMETRIC AND HENCE COP
C...
IS AVERAGED OVER LEAF AZIMUTH ANGLES OF 0 TO PI RADIANS.
C
C
THETAO=ACOS(TAN(BETA)/TAN(ALPHA))
TANTO=TAN(THETAO)
OP=OP*(I.+(TANTO-THETAO)/CEPI02)
RETURN
END

SUBROUTINE COPM(G,OP,OPM)

C COPM
C
C...
THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COPM
C...
THE DIRECTION OF THE SOURCE (OPM) FOR THE SIMULATED CANOPY. THE COPM
C...
LEAVES OF THE CANOPY ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC. THE COPM
C...
FUNCTION USED IN THE CALCULATION HAS BEEN PREVIOUSLY DETERMINED COPM
C...
FOR A GIVEN SOURCE DIRECTION FOR LEAF INCLINATION ANGLES OF COPM
C...
5, 15, ... , 85 DEGREES. G IS THE LEAF INCLINATION ANGLE DENSITY COPM
C...
FUNCTION.
C
C
DIMENSION OP(9),G(9)
OPM=O.
DO 1 I=1,9
1 OPM=OPM+OP(I)*G(I)
RETURN
END

SUBROUTINE PDENS(IL,MTYPE,IANGLE,OPM,THETA,NANGLE,FLA,SLAI,FLAI,
* PHIT

C
C----THIS PROGRAM COMPUTES THE PROBABILITY THAT LIGHT AT INCIDENT ANGLE
C THETA(IANGLE) INTERACTS WITH MATERIAL TYPE MTYPE WITHIN CANOPY
C LAYER IL.
C
C INPUT
C IL
C MTYPE
C IANGLE
C OPH
C SLAI
C FLAI
C THETA
C
C OUTPUT
C PHIT
C
C DIMENSION DUM(357), TNETA(10)
DIMENSION NANGLE(3,3), FLAI(3,3,10), SLAI(3,3), FLAI(3,3), PHIT(3,3,10)
ARG=I.-(SLAI(IL,MTYPE)*OPH/SIN(THETA(IANGLE)))
IF (ARG.LE.0.) GO TO 1
PO=ARG**(FLAI(IL,MTYPE)/SLAI(IL,MTYPE))
GO TO 2
1 PO = 0.
2 CONTINUE
PHIT(IL,MTYPE,IANGLE)=1.-PO
RETURN
END
SUBROUTINE TBLR(M, X, Y, XX, Z)

C
C....THIS PROGRAM FINDS THE INTEGRAL Z(X) OF THE FUNCTION Y(X) FROM X(1) TO X(2M-1) USING SIMPSON'S RULE. THE INTEGRAL Z(X) IS NORMALIZED TO 1.0 AT X(2M-1). THE TABLE OF Z VERSUS X IS THEN INVERTED TO DETERMINE X AS A FUNCTION OF Z AT M REGULARLY SPACED POINTS ALONG Z.
C
C INPUT VARIABLES
C M = DESIRED NUMBER OF REGULARLY SPACED POINTS ALONG Z
C X = SPECIFIED AT 2M-1 POINTS
C Y = SPECIFIED AT 2M-1 POINTS
C
C OUTPUT VARIABLES
C

A21
C  XX = THE TABLE OF X VALUES FOR M REGULARLY SPACED POINTS
C (M-1 INTERVALS) ALONG Z.
C  Z = THE NORMALIZED INTEGRAL OF Y AT X(1), X(3), ..., X(2M-1).
C  DIMENSION X(19),Y(19),Z(10),XI(10),XX(10)
C
C....SIMPSONS RULE INTEGRATION
C 10  Z(1) = 0.0
  DX = X(2) - X(1)
  20  DO 50 J = 2,M
  30   J0 = 2*J - 3
  40   J1 = 2*J - 2
  30   J2 = 2*J - 1
  40   Z(J) = Z(J - 1) + DX*(Y(J0) +4.*Y(J1) + Y(J2))/3.0
  50   XI(J) = X(J2)
  60   XI(1)=X(1)
C
C....NORMALIZE INTEGRAL Z(X)
C  60  DO 70 J = 1,M
  70   Z(J) = Z(J)/Z(M)
C
C....FIND X AT M REGULARLY SPACED POINTS ALONG Z.
C  XX(1) = X(1)
  EM = M - 1
  80  DO 120 K = 2,M
  90   ZT = K - 1
  100  ZT = ZT*F
  110  DO 110 J =JS,N
  120   IF(Z(J) - ZT) 110, 100, 100
  100  G = (ZT - Z(J - 1))/Z(J) - Z(J - 1))
  110  XX(K) = XI(J - 1) + G*(XI(J) - XI(J - 1))
  100  GO TO 115
  110  CONTINUE
  100  CONTINUE
  115  JS=J
  120  CONTINUE
  RETURN
END
SUBROUTINE SECTOR
C
SUBROUTINE SECTOR calculates the normalizing factors which account for the area of each source sector.

COMMON /A/ UV, RH, RL, D(3)
COMMON /B/ PGAP(3,9), PHIT(3,9), PGAP2(3,9), PHIT2(3,9), STEF
COMMON /C/ COSTA(9,9,18), EMISSV(4), AB3ORB(3), ESKY, EGRD, SECTOR(9)
COMMON /D/ CONT(3,5,9), C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
COMMON /E/ AT, THETA(9), PHI(18), XLF(9), YLF(9), ZLF(9), X(9,18)
COMMON /F/ HS(9,18), ZS(9), CEDIR, B, FREQD(9,3), WA(15), EPS
COMMON /G/ NSIG, N, ITMAX

ALPHA2 = 0.
SINA2 = 0.
DO 2 I = 1, 9
  SINA2 = SINA2
  SINA2 = SINA2
  SINA2 = SINA2
  CONTINUE
RETURN
END

SUBROUTINE SET02(A,I,J)

DIMENSION A(I,J)
DO 10 K = 1, I
  DO 10 L = 1, J
    A(K,L) = 0.0
  CONTINUE
RETURN
END

SUBROUTINE SET03(A,I,J,K)

DIMENSION A(I,J)
DO 10 K = 1, I
  DO 10 L = 1, J
    A(K,L) = 0.0
  CONTINUE
RETURN
END

note we must divide by SIN(THETA) since we are interested in the flux before it hits a horizontal panel.

SECTOR(I) = (SINA2**2 - SINA1**2)/(18.0*SIN(THETA(I)))
DIMENSION A(I,J,K)
DO 10 L=1,I
DO 10 M=1,J
DO 10 N=1,K
A(L,M,N) = 0.0
10 CONTINUE
RETURN
END

SUBROUTINE WHAT(TITLE)
COMMON/B/PAP(3,9), PHIT(3,9), PAP2(3,9), PHIT2(3,9), STEF
DIMENSION W(4,9), TITLE(B)

WHAT CALCULATES THE U MATRIX.

DO 10 M = 1,9
U(1,M) = PHIT(1,M)
U(2,M) = PAP(1,M) - PAP(1,M)*PAP(2,M)
U(3,M) = PAP(1,M)*PAP(2,M) - PAP(1,M)*PAP(2,M)*PAP(3,M)
U(4,M) = PAP(1,M)*PAP(2,M)*PAP(3,M)
10 CONTINUE
WRITE(6,199)(TITLE(N),N=1,8)
WRITE(3,199)(TITLE(N),N=1,8)
199 FORMAT(* THE U AND S MATRICES FOR */8A10)
WRITE(3,300)((W(M,N),M=1,9),N=1,4)
WRITE(6,300)((W(M,N),M=1,9),N=1,4)
300 FORMAT(9F7.4)
RETURN
END
SENSIT

PROGRAM SENSIT(INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2)

C

COMMON/Para1/SIG,STA(3),S(3,3),STG(3),X(3),PARAM(16),A(3),
IALP(3),FMU,TA,TAC,TB,EPS(3),EPSTG,RH,RL
COMMON/Para2/BTA,BTG,BX(3),BBX(3),DQX(3),DDX(3),DRX(3)
COMMON/Estim/FX(3),DFX(3,3)
DIMENSION PAR(16),DSTEP(16),DP(16),DX(3),TEMP(3),XO(3),XX(3),
IFSEN(3),PARMAX(16)

--- DEFINE INPUT VARIABLES ---

SIG=5.6486E-8
STA(1)=0.6107
STA(2)=0.1887
STA(3)=0.0729
STG(1)=0.0815
STG(2)=0.2482
STG(3)=0.7257
S(1,1)=0.7715 $ S(1,2)=0.4769 $ S(1,3)=0.0523
S(2,1)=0.2277 $ S(2,2)=1.1600 $ S(2,3)=0.1682
S(3,1)=0.0830 $ S(3,2)=0.5698 $ S(3,3)=0.5414

--- DEFINE NOMINAL VALUES FOR MODEL PARAMETERS ---

PAR(1)=ALP(1)=1.0
PAR(2)=ALP(2)=1.0
PAR(3)=ALP(3)=1.0
PAR(4)=FMU=10.0
PAR(5)=TA=14.6
PAR(6)=TAC=14.6
PAR(7)=TG=11.7
PAR(8)=EPS(1)=1.0
PAR(9)=EPS(2)=1.0
PAR(10)=EPS(3)=1.0
PAR(11)=EPSTG=1.0
PAR(12)=RH=0.20
PAR(13)=RL=0.66
PAR(14)=A(1)=144.
PAR(15)=A(2)=49.
PAR(16)=A(3)=46.

--- DEFINE INITIAL VALUES FOR STATE VARIABLES ---

XO(1)=20.4
XO(2)=16.6
\[ \text{XO}(3)=16.3 \]

\( \text{--- DEFINE UPPER BOUNDS FOR MODEL PARAMETERS ---} \)

\[
\begin{align*}
\text{PARMAX}(1) &= \text{PARMAX}(2) = \text{PARMAX}(3) = 1.0 \\
\text{PARMAX}(4) &= 20.0 \\
\text{PARMAX}(5) &= \text{PARMAX}(6) = \text{PARMAX}(7) = 30.0 \\
\text{PARMAX}(12) &= 0.50 \\
\text{PARMAX}(13) &= 1.20 \\
\text{PARMAX}(14) &= 150.0 \\
\text{PARMAX}(15) &= \text{PARMAX}(16) = 60.0
\end{align*}
\]

\( \text{--- DEFINE STEP-SIZES OF MODEL PARAMETERS FOR SENSITIVITY ANALYSIS ---} \)

\[
\begin{align*}
\text{DSTEP}(1) &= \text{DSTEP}(2) = \text{DSTEP}(3) = \text{DSTEP}(9) = \text{DSTEP}(10) = \text{DSTEP}(11) = 1.0 + 0.005 \\
\text{DSTEP}(4) &= -1.0 \\
\text{DSTEP}(5) &= \text{DSTEP}(6) = \text{DSTEP}(7) = -1.0 \\
\text{DSTEP}(12) &= -0.05 \\
\text{DSTEP}(13) &= -0.05 \\
\text{DSTEP}(14) &= -7.5 \\
\text{DSTEP}(15) &= \text{DSTEP}(16) = -3.0
\end{align*}
\]

\( \text{--- START SENSITIVITY ANALYSIS ---} \)

\[
\begin{align*}
\text{TOL} &= 0.0001 \\
\text{DO } 100 & \text{ IP}=1,16 \\
\text{DO } 92 & \text{ I}=1,16 \\
92 & \text{ PARAM}(1) = \text{PAR}(1) \\
\text{DO } 94 & \text{ I}=1,3 \\
XX(I) &= \text{XO}(I) \\
94 & \text{ X}(I) = \text{XO}(I) \\
\text{DO } 90 & \text{ NTIME}=1,20 \\
\text{FACTOR} &= \text{NTIME}-1 \\
\text{DP}(IP) &= \text{FACTOR} \times \text{DSTEP}(IP) \\
\text{PARAM}(IP) &= \text{PARMAX}(IP) + \text{DP}(IP) \\
50 & \text{ CALL FEVAL} \\
\text{C} & \text{ WRITE(6,1010)}(\text{FX}(I),I=1,3) \\
\text{C1010} & \text{ FORMAT(1H1,3F10.5)} \\
\text{DO } 20 & \text{ I}=1,3 \\
20 & \text{ FX}(I) = -\text{FX}(I) \\
\text{CALL SOLVE(FX,3,DFX,3,DX)} \\
\text{DO } 30 & \text{ I}=1,3 \\
\text{C} & \text{ WRITE(6,1010)} X(I), DX(I)
\end{align*}
\]
30 X(I)=X(I)+DX(I)
   DO 40 I=1,3
   DEV=DX(I)
   IF(ABS(DEV) .GT. TOL) GO TO 50
   FSEN(I)=(X(I)-XX(I))/DSTEP(IP)
   XX(I)=X(I)
40 TEMP(I)=X(I)
   WRITE(1,90) (TEMP(I),I=1,3),PARAM(IP)
90 FORMAT(3F10.5)
90 CONTINUE
100 CONTINUE
END
ENDFILE 1
REWIND 1
STOP
END

SUBROUTINE FEVAL

COMMON/ PARA1/SIG,STA(3),S(3,3),STG(3),X(3),PARAM(16),A(3),
ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
COMMON/ PARA2/STA,STG,DX(3),DBX(3),DX(3),DX(3),DX(3),DX(3)
COMMON/ ESTIM/FX(3),DFX(3,3)

C
ALP(1)=PARAM(1)
ALP(2)=PARAM(2)
ALP(3)=PARAM(3)
FMU=PARAM(4)
TA=PARAM(5)
TAC=PARAM(6)
TG=PARAM(7)
EPS(1)=PARAM(8)
EPS(2)=PARAM(9)
EPS(3)=PARAM(10)
EPSTG=PARAM(11)
RH=PARAM(12)
RL=PARAM(13)
A(1)=PARAM(14)
A(2)=PARAM(15)
A(3)=PARAM(16)
CALL F3TA(TA,STA)
CALL BFUNC(EPSTG,TG,BTG,D3TG)
   DO 10 I=1,3
   CALL BFUNC(EPS(I),X(I),XX(I),DX(I))
   CALL OFUNC(X(I),TAC,FMU,DX(I),DQX(I))
   CALL RFUNC(X(I),TAC,FMU,RL,RH,rx(I),DQX(I))
10 CONTINUE
DO 20 IL=1,3
20 FX(IL)=0.5*ALP(IL)*SIG*(BTA*STA(IL)+BX(1)*S(IL,1)+DX(2)*
    15(IL,2)+BX(3)*S(IL,3)*STG(STG(IL)))*A(IL)-SIG*BX(IL)+DX(IL)
+RX(IL)
DO 30 I=1,3
DO 30 J=1,3
30 DFX(I,J)=0.
DO 40 IL=1,3
DO 40 J=1,3
IF(J.NE.I) GO TO 35
DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)-SIG*DBX(IL)+DX(IL)*
    DBX(IL)
GO TO 35
35 DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)
40 CONTINUE
RETURN
END
SUBROUTINE BFUNC(EPSI,XI,BXI,DBXI)
    BXI=EPSI*(XI+273.0)**4.
    DBXI=4.*EPSI*(XI+273.0)**3.
RETURN
END
SUBROUTINE FBTA(TA,BTA)
    EPSTA=1.-0.261*EXP(-7.77E-4*TA*TA)
    CALL BFUNC(EPSTA,TA,BTA,DBTA)
RETURN
END
SUBROUTINE OFUNC(XI,TAC,FMU,QXI,DRXI)
    IF(FMU.GT.30.) GO TO 10
    HC=0.69775*(20.4+0.2*FMU**.97)
    GO TO 20
10    HC=0.69775*(0.95*FMU**.97)
20    QXI=(XI-TAC)*HC*(-1.0)
    DOXI=HC*(-1.0)
RETURN
END
SUBROUTINE RFUNC(XI,TAC,FMU,RL,RH,RXI,DRXI)
    RNUN=FEX(XI)*1.0E-6-RH*FEX(TAC)*1.0E-6
    RDEN=RL+(1./60.)*(0.04+1.27*FMU**(-0.5))
    RXI1=-697.75*(0.566*XI+597.3)
    RXI2=RNU/RDEN
    RXI=RXI1*RXI2
    DRXI=697.75*0.566*RXI2+RXI1*(0.056715E-6*FEX(XI))/RDEN
RETURN
END
SUBROUTINE INVERSE(A,M,D)

--- INVERT A 3x3 REAL MATRIX A WHOSE DETERMINANT IS D
THE RESULT WILL BE STORED IN A

DIMENSION A(3,3),B(3,3)

D=A(1,1)*A(2,2)*A(3,3)-A(1,2)*A(2,3)*A(3,1)+A(1,3)*A(2,1)*
A(3,2)-A(1,1)*A(2,3)*A(3,2)-A(1,2)*A(3,3)-A(1,3)*A(2,1)*
2*A(1,2)*A(3,3)
B(1,1)=-A(2,2)*A(3,3)-A(2,3)*A(3,1))/D
B(1,2)=-(A(2,1)*A(3,3)-A(2,3)*A(3,1))/D
B(1,3)=A(1,2)*A(3,3)-A(1,3)*A(3,1))/D
B(2,1)=-A(1,2)*A(3,3)-A(1,3)*A(3,2))/D
B(2,2)=A(1,1)*A(3,3)-A(1,3)*A(3,1))/D
B(2,3)=-(A(1,1)*A(3,2)-A(1,2)*A(3,1))/D
B(3,1)=A(1,2)*A(3,3)-A(1,3)*A(3,2))/D
B(3,2)=-(A(1,1)*A(2,3)-A(1,3)*A(2,1))/D
B(3,3)=(A(1,1)*A(2,2)-A(1,2)*A(2,1))/D
DO 10 I=1,3
DO 10 J=1,3
10 A(I,J)=B(I,J)
RETURN
END

FUNCTION FEX(XI)

XX=5.2342*EXP(0.056715*XI)
FEX=XX
RETURN
END

SUBROUTINE SOLVE(Y,N,A,M,X)

DIMENSION Y(N),A(N,N),X(N),ATA(M,M),ATY(N)
DIMENSION Y(3),A(3,3),X(3),ATA(3,3),ATY(3)

DO 10 I=1,N
DO 10 J=1,N
ATA(I,J)=0.
DO 10 K=1,N
10 ATA(I,J)=ATA(I,J)+A(K,I)*A(K,J)
CALL INVERSE(ATA,M,D)
DO 20 I=1,N
ATY(I)=0.
DO 20 J=1,N
20 ATY(I)=ATY(I)+A(J,I)*Y(J)

A29
DO 30 I=1,N
   X(I)=0.
DO 30 J=1,N
30 X(I)=X(I)+ATA(I,J)*ATY(J)
RETURN
END
*DECK SRVC

PROGRAM SRVC(INPUT,OUTPUT,TAPE5=OUTPUT,TAPE6=INPUT)

C.... SOLAR RADIATION - VEGETATION CANOPY REFLECTANCE MODEL
C.... THIS PROGRAM CALCULATES THE APPARENT DIRECTIONAL REFLECTANCE OF A
C.... VEGETATION CANOPY AS A FUNCTION OF CANOPY GEOMETRY, LEAF REFLEC-
C.... TANCE AND TRANSMISSION, SOIL REFLECTANCE, AND CANOPY IRRADIANCE
C.... FOR A GIVEN SOLAR POSITION.
C.... R.E. OLIVER AND J.A. SMITH COLORADO STATE UNIVERSITY JUNE, 1974
C
C.................. COMMON BLOCKS AND REFERENCES ..................

COMMON /CI/DAY,YEAR,TIME,GLAT,GLONG,DEC, BANDU,NLAM,THETS1,THETS2,
INMAT,EXTRA(4),NOP,INIT,DUNI(13),
2CEDTR,CERTD,CENTR,CEPI2,CE2PI,DUM2(14),
3SINLAT,COSLAT,SINDEC,COSDEC,COSH,SINZ,COSZ,SINAZ,COSAZ,LXS,LYS,LZS
COMMON/C2/CMRM(17),SKYIM(17),DIFIM(17),R(17),T(17),XLM(17)
1),SOURCE(10,17),THETA(10),ZENITH(10)
COMMON/C4/HANGLE(3,3),FLA,(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10)
COMMON/C6/DR(4,10,17),UR(4,10,17),THRES(10),IGOD(4,10),IGOU(4,10)
1,THRESU(10)
COMMON /KIM/ IML(3,3,2)
COMMON/C9/SINL,COSL,SIMP,COSP
COMMON/L1/DATAID(7,9),XHU(17,9),C(17,17,9),WVEC(9)
COMMON/CMAT/HTP(3),MLAY,GPM(10)
A,ENDLC
COMMON AVEC(17),XK(9),SXL,SYL,SZL,XLW,YLF,ZLF

A31
1. XS(10,18), YS(10,18), ZS(10)

COMMON /AB3/TABS(4,17)

COMMON /AB3/TABS(4,17)

DIMENSION JODID(9), VECT(17), SIG(17), V(17,17), COR(17,17)

DIMENSION COV(10,17,17), COVM(17,17)

DIMENSION XLFA(19), YLFA(19), DM(17), DM1(17), REFER(17)

DIMENSION RIT(10,17), RITBAR(10,17), RBAR(10,17)

DIMENSION F(19), OP(9)

INTEGER RORT

REAL LXS, LYS, LZS, INCLF

INTEGER DAY, YEAR, TH, TM, ZDEG

8000 CONTINUE

DO 10 I=1,10
    THETA(I)=0.
    ZENITH(I)=0.
    ZS(I)=0.
    THRESH(I)=0.
    OPH(I)=0.
    THRESU(I)=0.

DO 10 J=1,18

10 YS(I,J)=0.

DO 4 K=1,17
    CANRM(K)=0.
    SKYIM(K)=0.
    DIFIM(K)=0.
    R(K)=0.
    T(K)=0.
    RG(K)=0.
    DM(K)=0.
    DM1(K)=0.
    SIG(K)=0.
    XLAM(K)=0.

DO 4 I=1,10
    SOURCE(I,K)=0.
    RIT(I,K)=0.
    RITBAR(I,K)=0.
    RBAR(I,K)=0.

4 CONTINUE

DO 9 I=1,19
    F(I)=0.
    XLFA(I)=0.

9 YLFA(I)=0.

DO 12 I=1,9
    NVEC(I)=0.
OP(I)=0.
XK(I)=0.
DO 12 J=1,17
12 XNU(J,I)=0.
DO 7 I=1,3
MTP(I)=0.
DO 7 J=1,3
MANGLE(I,J)=0.
SLAI(I,J)=0.
FLAI(I,J)=0.
DO 7 K=1,10
FLA(I,J,K)=0.
7 PHIT(I,J,K)=0.
DO 6 I=1,3
DO 6 J=1,3
DO 6 K=1,2
6 IML(I,J,K)=0.

C....PERIPHERAL CONTROLS
IHIST = 0
ISTOH = 1
IFILE = 5

C....IFILE ASSIGNMENT COULD BE MADE THRU A READ STATEMENT.
IF(EOF(5).NE.0.) STOP
IF(IHIST.EQ.1) CALL FUN(-1,-1)

C....GENERAL SIMULATION CONSTRAINTS
READ(IFILE,100) JOBID,DAY,YEAR,TH,TL,OLAT,SLON6,DEC,RANDU,NLAM,NNAT,
MLAY=NLAY+1
1073 CONTINUE
NSOUR=NBANDS+1
NLAYP1=NLAY+1
CALL RANSET(INIT)
XT1=TH
XT2=TM
TIME=XT1+(XT2/60.)
GLAT = GLAT * CEDTR
GLONG = GLONG * CEDTR
DEC = DEC * CEDTR
BANDW = BANDW * CEDTR

C.... SUN POSITION PARAMETERS
CALL SUN
WRITE (6, 222) LXS, LYS, LZS
ZS(1) = LZS

C.... COEFFICIENTS FOR DIFFUSE RADIATION VECTORS
C.... SENSOR/BAND AREA RATIO FOR ALL DIFFUSE BANDS
ALPHA2 = 0.
SIMA2 = 0.
DO 2 I = 1, NBANDS
SIMA1 = SIMA2
ALPHA2 = ALPHA2 + BANDW
SIMA2 = SIN(ALPHA2)
XX(I) = SIMA2 * SIMA2 - SIMA1 * SIMA1
2 CONTINUE
WRITE (6, 208) (XX(I), I = 1, NBANDS)

C.... SOURCE DIRECTION INCLINATION ANGLES
TOTAL = 0.
THETA(1) = (BANDW/2.) - BANDW
DO 3 I = 1, NBANDS
THETA(I + 1) = THETA(I) + BANDW
3 CONTINUE
THETA(1) = CEPIO2 - ACOS(COSZ)
CONS = LZS * TOTAL
DO 50 I = 1, 10
50 ZENITH(I) = CEPIO2 - THETA(I)
WRITE (6, 223) THETA

C.... DIRECTION COSINES OF AZIMUTHAL SECTORS IN THE DIFFUSE BANDS
DEG2O = 20. * CEDTR
DO 60 JSOR = 2, NSOUR
ZS(JSOR) = SIN(THETA(JSOR))
PHI = 10. * CEDTR
DO 60 IPHI = 1, 18
XS(JSOR, IPHI) = COS(THETA(JSOR)) * COS(PHI)
YS(JSOR, IPHI) = COS(THETA(JSOR)) * SIN(PHI)
60 PHI = PHI + DEG20

C.... CANOPY GEOMETRY. EACH CANOPY LAYER IS COMPOSED OF ONE OPTICAL
C.... MATERIAL WHICH MAY BE SPECIFIED AND UNIQUE GEOMETRICAL PROPERTIES.
C.... CANOPY GEOMETRIC PARAMETERS CONSIST OF (1) LEAF ANGLE FREQUENCY
C.... DISTRIBUTION FUNCTION DENOTED BY XLFA AND YLFA (2) LEAF AREA INDEX
C.... DENOTED BY FLA! AND (3) CANOPY DENSITY DENOTED BY SLAI. XLFA (DEG)
C.... AND YLFA MUST BE SPECIFIED AT AN ODD NUMBER (NANG) OF EVENLY SPACED...
C. .... POINTS. FLAI IS NON-NEGATIVE AND SLAI RANGES BETWEEN 0 AND 1.
DELF = 10 * CEDTR
WRITE (6, 227)
DO 350 IL = 1, NLAY
READ (IFILE, 102) MANG
DO 350 IL = 1, NLAY
READ (IFILE, 102) IMAT
IMAT = IMAT
DO 351 J = 1, IMAT
IMAT = J
READ (IFILE, 101) (XLFA(I), YLFA(I), I = 1, NANG)
READ (IFILE, 101) SLAIIIL, IXAT, FLAI(IL, IMAT)
C. .... INTEGRATE AND NORMALIZE THE LEAF ANGLE FREQUENCY DISTRIBUTION
C. .... FUNCTION USING SIMPSONS RULE--THIS IS TEMPORARILY DENOTED BY F.
C. .... N-1 EQUALLY SPACED INTERVALS OF F ARE THEN DETERMINED AND DENOTED
C. .... BY FLA (M POINTS). THE TABLE FLA IS USED FOR RANDOMLY SELECTING
C. .... LEAF INCLINATION ANGLES.
DO 305 I = 1, NANG
305 XLFA(I) = XLFA(I) * CEDTR
M = ((NANG - 1) / 2) + 1
NANGLE(IL, IMAT) = M
CALL TBLR (M, XLFA, YLFA, DM, F)
WRITE (6, 233) (F(I), I = 1, M)
DO 310 IANG = 1, M
310 FLA(IL, IMAT, IANG) = DM(IANG)
C. .... NORMALIZE THE INPUT LEAF FREQUENCY DISTRIBUTION FUNCTION TO OBTAIN
C. .... A DENSITY FUNCTION F WHICH IS SPECIFIED AT M POINTS.
FTOT = 0.
DO 311 I = 1, NANG
311 FTOT = FTOT + YLFA(I)
DO 312 I = 1, M
312 F(I) = (YLFA(2*I) + YLFA(2*I + 1)) / FTOT
DO 315 I = 1, NANG
315 XLFA(I) = XLFA(I) * CEDTR
WRITE (6, 230) IL, IMAT, MANG, (XLFA(I), YLFA(I), I = 1, NANG)
WRITE (6, 231) NANGLE(IL, IMAT)
WRITE (6, 232) (FLA(IL, IMAT, I), I = 1, M)
M = M - 1
WRITE (6, 233) (F(I), I = 1, M)
WRITE (6, 207) FLAI(IL, IMAT), SLAI(IL, IMAT)
C. .... CALCULATE THE MEAN PROJECTION (OP) IN THE DIRECTION OF THE SOURCE
C. .... (THETA) OF ONE UNIT LEAF AREA WITH INCLINATION INCLF. THE LEAVES
C. .... AT THIS ANGLE ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC.
DO 330 IANGLE = 1, NSOUR
INCLF=-5.*CDETR
DO 320 I=1,9
INCLF=INCLF+DELF
320 CALL COP(INCLF,THETA(IANGLE),DP(I))
C....CALCULATE THE MEAN PROJECTION (OPM) IN THE DIRECTION OF THE SOURCE
C....(THETA) OF ONE UNIT LEAF AREA AVERAGED OVER THE CANOPY LEAF ANGLE
C....DENSITY FUNCTION F.
   CALL COPM(F,OP,OPM(IANGLE))
C....CALCULATE THE PROBABILITY OF A HIT (PHIT) FOR A LIGHT RAY WITH
C....SOURCE DIRECTION THETA.
   CALL PDENS(IL,IMAT,ANGLE,OPM(IANGLE))
   WRITE(6,235) OP,OPM(IANGLE),PHIT(IL,IMAT,ANGLE)
330 CONTINUE
350 CONTINUE
350 CONTINUE
WRITE(6,228)
C....REFLECTANCE AND TRANSMISSION VECTORS ARE READ FOR EACH CANOPY
C....CONSTITUENT. IN ADDITION REFLECTANCE VECTORS ARE READ FOR THE SOIL
C....BACKGROUND AND THE MEASURED CANOPY. THE MEAN VECTOR AND COVARIANCE
C....AND CORRELATION MATRICES ARE CALCULATED AS WELL AS THE SQUARE-ROOT
C....MATRIX WHICH IS SUBSEQUENTLY USED FOR MULTIVARIATE NORMAL
C....STOCHASTIC VECTOR SAMPLING.
C
C....WAVELENGTHS TO BE SIMULATED
   READ(IFILE,101) (XLAM(I),I=1,NLAM)
   WRITE(6,201) (XLAM(I),I=1,NLAM)
C....CONSTITUENT OPTICAL VECTORS
C....READ NUMBER OF CONSTITUENT OPTICAL VECTORS WHICH EQUALS 2*MTYPE
C * NUMBER OF LAYERS
   READ (IFILE,105) HOP
105 FORMAT (110)
   READ(IFILE,104)(DATAID(I),I=1,7)
   WRITE(6,5) (DATAID(I),I=1,7)
   READ(IFILE,101) (CANRM(J),J=1,NLAM)
   WRITE(6,294)
   WRITE(6,203) (CANRM(J),J=1,NLAM)
   READ(IFILE,101) (SKYIN(J),J=1,NLAM)
   WRITE(6,295)
   WRITE(6,203) (SKYIN(J),J=1,NLAM)
   READ(IFILE,101) (DIFIN(J),J=1,MLAM)
   WRITE(6,296)
   WRITE(6,203) (DIFIN(J),J=1,MLAM)
   READ(IFILE,101) (RG(J),J=1,NLAM)
   WRITE(6,297)
   WRITE(6,203) (RG(J),J=1,NLAM)
A36
DO 11 NL=1,NDP
READ(IFILE,106) NULAY,NTYP,RORT,(DATAID(I),I=1,7)
WRITE(6,202) (DATAID(I),I=1,7),NULAY,NTYP,RORT
READ(IFILE,101) (XMU(I,NL),I=1,NLAN)
INL(NULAY,MTYP,RORT)=NL
WRITE(6,204) (XMU(I,NL),I=1,NLAN)
CONTINUE

11

WRITE (6,210)

C............... BIG LOOP .................

ISTOP=0
DO 40 J=1,NLAN
SOURCE(I,J)=(SKYIN(J)-DIFIM(J))/(SKYIM(J))
DO 40 I=1,NBANDS
40 SOURCE(I+I,J)=(DIFIM(J)*XK(I))/(SKYIN(J))
WRITE(6,209)
DO 45 I=1,NSOUR
45 SOURCE(I,J),J=I,NLAM
DO 7000 ISAMP=1,NSAMP
DO 6000 ITRIAL=1,NTRIAL
C............ COMPUTE PROPORTION OF IRRADIANCE WHICH IS DIRECT AND PROPORTION WHICH IS DIFFUSE.
C............ POPULATE FIRST (TOP) DOWN DWELL LAYER (DR) WITH INCIDENT DIRECT AND DIFFUSE LIGHT. DOWN DWELL RADIATION FLUX (DR) IS INDEXED FROM 1 TO NLAY IN A DOWN GOING SEQUENCE. UPWARD DWELL RADIATION FLUX (UR) IS INDEXED FROM 1 TO NLAY+1 IN UPWARD GOING SEQUENCE. THAT IS FOR UR, LAYER 1 IS THE LAYER IMMEDIATELY ABOVE THE BACKGROUND. THE FLUX IN LAYER NLAY+1 IS THAT WHICH ESCAPES THE CANOPY AND TOGETHER WITH THE INCIDENT FLUX DETERMINES THE CANOPY REFLECTANCE.

DO 8 K=1,17
DO 8 J=1,10
DO 8 I=1,4
UR(I,J,K)=0.
DR(I,J,K)=0.
IGOU(I,J)=0.
IGOD(I,J)=0.
8 CONTINUE
DO 1003 J=1,NSOUR
DO 1003 K=1,NLAN
1003 DR(I,J,K)=SOURCE(J,K)
C............ SET FLUX LEVEL INDICATORS (DOWNWARD)
CALL ETHRES(NLAY,NSOUR,-1)
C............ FAST LOOP TRACES LIGHT ATTENUATION THROUGH CANOPY.............
C............ FLUX PASSING THROUGH LAYERS IN A DOWNWARD DIRECTION
2000 CONTINUE
DO 2600 IL=1,NLAY

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DO 2500 JSOR=1,NSOUR
C....CHECK FLUX LEVEL INDICATOR
   IF(IGOD(IL,JSOR).EQ.0.) GO TO 2500
C....DID LIGHT STRIKE LEAF
   CALL PGAP(IL,JSOR,-1,IHIT,MTYPE)
   IF(IHIT.EQ.0) GO TO 2200
   DO 2100 IPHIP=1,18
C....DIRECTION COSINES OF SOURCE SECTOR (LVLH)
   SXL = XS(JSOR,IPHIP)
   SYL = YS(JSOR,IPHIP)
   SZL = ZS(JSOR)
   CALL LAMBTNL(IL,JSOR,MTYPE,-1,NSOUR)
2100 CONTINUE
   GO TO 2400
C....GAP ENCOUNTERED IN DOWNWARD PATH
2200 DO 2250 KL=1,NLAN
2250 DR('L+1,JSOR,KL)-DR(ILG1,JSOR,XL)+DR(IL,JSOR,KL) SRVC
2400 CALL SETZ(IL,JSOR,-1)
2500 CONTINUE
2600 CONTINUE
C....BACKGROUND REACHED - REFLECTS LAMBERTIAN
   DO 3600 JSOR=1,NSOUR
   DO 3400 JJ=2,NSOUR
       IL = MLAY + 1
       DO 3400 KL=1,NLAN
           UR(J,JJ,KL)=UR(I,JJ,XL)+R6(KL)*DR(IL,JSOR,XL)*XX(JJ-1)
           TABSO(4,KL)=TABSO(4,XL)+(1.-R6(KL))*DR(IL,JSOR,KL)*XX(JJ-1)
   CALL SETZ(MLAY+1,JSOR,-1)
3600 CONTINUE
   CALL ETHRES(MLAY,NSOUR,-1)
C....FLUX PASSING THROUGH LAYERS IN AN UPWARD DIRECTION
   DO 4600 IL=1,NLAY
   DO 4500 JSOR=2,NSOUR
C....CHECK FLUX LEVEL INDICATOR
   IF(IGOD(IL,JSOR).EQ.0) GO TO 4500
C....DID LIGHT STRIKE LEAF
   CALL PGAP(IL,JSOR,+1,IHIT,MTYPE)
   IF(IHIT.EQ.0) GO TO 4200
   DO 4100 IPHIP=1,18
C....DIRECTION COSINES OF SOURCE SECTOR (LVLH)
   SXL = XS(JSOR,IPHIP)
   SYL = YS(JSOR,IPHIP)
   SZL = ZS(JSOR)
   CALL LAMBTNL(IL,JSOR,MTYPE,+1,NSOUR)
4100 CONTINUE
GO TO 4400
C.... GAP ENCOUNTERED IN UPWARD PATH
4200 DO 4250 KL=1,NLAM
4250 UR(IL+1,JSOR,KL)=UR(IL+1,JSOR,KL)+UR(IL,JSOR,KL)
4400 CALL SETZ(IL,JSOR,+1)
4500 CONTINUE
CALL ETHRES(NLAY,NSOUR,+1)
4600 CONTINUE
CALL ETHRES(NLAY,NSOUR,-1)
CALL ETHRES(NLAY,NSOUR,+1)
C.... RECYCLE THROUGH LAYERS UNTIL FLUX EXHAUSTED
DO 5000 IL=1,NLAY
DO 5000 JSOR=2,NSOUR
IF (IGOU(IL,JSOR).NE.0) GO TO 2000
5000 CONTINUE
DO 5001 IL=2,NLAY
DO 5001 JSOR=1,NSOUR
IF (IGOD(IL,JSOR).NE.0) GO TO 2000
5001 CONTINUE
C.... FLUX EXHAUSTED IN ALL SOURCES--COMPUTE REFLECTANCE FOR THIS TRIAL
DO 5200 JSOR=2,NSOUR
DO 5200 KL=1,NLAM
RIT(JSOR,KL)=UR(NLAY+1,JSOR,KL)/XK(JSOR-1)
5200 RITAR(JSOR,KL)=RITAR(JSOR,KL)+RIT(JSOR,KL)
WRITE(6,283) ISAMP,ITRIAL
DO 5300 JSOR=2,NSOUR
ZDEG=105.1*JSOR
5300 WRITE(6,284) ZDES,(RIT(JSOR,KL),KL=W,NLAN)
DO 6000 JSOR=2,NSOUR
FTRIAL=ITRIAL
6000 CONTINUE
C.... TRIALS COMPLETE FOR THIS SAMPLE POINT
FTRIAL=ITRIAL
6200 DO 6300 JSOR=2,NSOUR
DO 6300 KL=1,NLAM
6300 RITBAR(JSOR,KL)=RITBAR(JSOR,KL)/FTRIAL
WRITE(6,286) ISAMP
DO 6400 JSOR=2,NSOUR
ZDEG=105.1*JSOR
6400 WRITE(6,284) ZDES,(RITBAR(JSOR,KL),KL=W,NLAN)
DO 6600 JSOR=2,NSOUR
DO 6500 KL=1,NLAM
RBAR(JSOR,KL)=RBAR(JSOR,KL)+RITBAR(JSOR,KL)
DO 6500 KL=1,NLAM
6500 COV(JSOR,KL)=COV(JSOR,KL)+RITBAR(JSOR,KL)
DO 6600 KL=1,NLAM

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6600 RITBAR(JSOR,KL)=0.
IF (ISTOP.EQ.1) GO TO 7100
7000 CONTINUE
   FSAMP=NSAMP
   GO TO 7150
7100 FSAMP=ISAMP
7150 CONTINUE SRVC
7100 CONTINUE SRVC
FSAAPzNSAMP
GO TO 7130
7130 FSAAP=ISANP
7150 DO 7200 JSOR=2,NSOUR
   DO 7200 KL=1,MLAM
7200 RBAR(JSOR,KL)=RBAR(JSOR,KL)/FSAMP
   DO 7900 JSOR=2,NSOUR
      ZDEG=105-10*JSOR
      IF (FSAMP.LE.1.) GO TO 7600
      DO 7400 I=1,NLAM
      DO 7300 J=1,NLAM
7300 COV(JSOR,I,J)=(COV(JSOR,I,J)-FSAMP*RBAR(JSOR,I)*RBAR(JSOR,J))
   1/(FSAMP-1.)
7400 SIG(I)=SQRT(COV(JSOR,I,I))
   DO 7500 I=1,NLAM
   DO 7500 J=1,NLAM
7500 COR(I,J)=COV(JSOR,I,J)/(SIG(I)*SIG(J))
7600 WRITE(6,287) ZDEG,(RBAR(JSOR,KL),KL=1,MLAM)
WRITE(6,293) (SIG(KL),KL=1,MLAM)
   IF (FSAMP.LE.1.) GO TO 7900
WRITE(6,288)
   DO 7700 I=1,NLAM
WRITE(6,289) (COV(JSOR,I,J),J=1,NLAM)
WRITE(6,291)
   DO 7800 I=1,NLAM
   DO 8000 J=1,NLAM
WRITE(6,289) (COR(I,J),J=1,NLAM)
7900 CONTINUE
   DO 7213 IK=1,4
   DO 7213 KL=1,MLAM
   TABSO (IK,KL)=TABSO(IK,KL)/(FSAMP*FTrial)
7213 CONTINUE
   DO 7215 I=1,4
      J=I
WRITE (6,2714) JJ,(TABSO(I,J),J=1,MLAM)
7214 FORMAT (* THE LAYER IS*,I2,* THE ABSORPTIONS ARE *6(F8.5,1X))
7215 CONTINUE
   IF (IFILE.EQ.5) GO TO 8000
   STOP
C...........DATA FORMATS......................................
101 FORMAT(8F10.5)  
102 FORMAT(10F7A10)  
103 FORMAT(8E10.4)  
104 FORMAT(7A10)  
   5 FORMAT(*0*,7A10)  
106 FORMAT(3F,7W1)  

200 FORMAT(*3I,43X,*SOLAR RADIATION/VEGETATION CANOPY REFLECTANCE MODE* 
   1*,//,64X,*INPUT DATA*,,/,,1X,*DA10,,/* 
   2* JULIAN DAY *=,13*, YEAR *=,14*, TIME *=,212*, HOURS*,,,/,* 
   3* LATITUDE *=,F6.2*, DEGREES, LONGITUDE *=,F7.2*, DEGREES*,,,/,* 
   4* SOLAR DECLINATION *=,F6.2*, DEGREES*,,,/,* 
   5* BAND WIDTH OF DIFFUSE VECTORS *=,F5.1*, DEGREES*,,,/,* 
   6* NUMBER OF WAVELENGTH BANDS SIMULATED *=,12,,/,* 
   7* NUMBER OF CANOPY CONSTITUENTS *=,11,,/,* 
   8* K DIGIT ODD NO. TO INITIALIZE RANDOM SEQUENCE *=,15,,/,* 
   9* NSAMP *=,I5,,/,* 
   A* NTRIAL *=,I5,,/,* 
   B* NLAY *=,I1,* 
   C) 

201 FORMAT(*50WAVELENGTHS SIMULATED*,,/,,0*,F7.4,16F8.4)  
202 FORMAT(*0*,7A10/*,*,NUMBER OF LAYERS *=,I1/*,*, 
   1* MATERIAL TYPE *=,I1/*,*,R OR T *=,I1)  
203 FORMAT(*,F7.4,16F8.4)  
204 FORMAT(*0, MEAN*,,,/,,3X,10E12.4)  
205 FORMAT(*0, COVARIANCE MATRIX*)  
206 FORMAT(*ORANDOM VECTOR GENERATED FROM THE *,7A10,,/,,(* *,10E12.4))  
207 FORMAT(*0LAI = *,F4.2,4X,*S = *,F4.2)  
208 FORMAT(*9DIFFUSE VECTOR COEFFICIENTS*,,/,* 
   19(=K =,,/(9F8.4))  
   209 FORMAT(*0IRRADIANCE SOURCE VECTORS*)  
210 FORMAT(*I1)  
211 FORMAT(*0, CORRELATION MATRIX*)  
212 FORMAT(*0DM1 = *,9F8.4)  
221 FORMAT(*0THRESH = *,10F8.4/* THRESU = *,10F8.4)  
222 FORMAT(*0DIRECTION COSINES OF SUN *=,3F8.4)  
223 FORMAT(*0THETA = *,10F8.4)  
227 FORMAT(*//,*,25(1H.),2X,*CANOPY GEOMETRY*,2X,25(1H.))  
228 FORMAT(*//,*,25(1H.))  
230 FORMAT(*0LEAF ANGLE COMPUTATIONS - IL = *,I1, 
   1* IMAT = *,I1,*, WANG = *,12,,/* XLFA,YLFA*,  
   1/(2X,16F8.3))  
231 FORMAT(*0NANGLES(IL,IMAT) = *,I2)  
232 FORMAT(*0, FLA =*,10F9.3)  
233 FORMAT(*0, F =*,10F9.3)  
235 FORMAT(*0, OP =*,9F8.3,3X,*OPM = *,F8.3,3X,*PHIT = *,F8.3)
SUBROUTINE LAMBTN(IL,JSOR,MTYPE,IDIR,NSOUR) 
C.....FOR A GIVEN FLUX SOURCE THIS PROGRAM CALLS THE APPROPRIATE 
C.....PROGRAMS TO DETERMINE LEAF ORIENTATION AND OPTICAL PROPERTIES 
C.....AND UPDATES THE DIFFUSE SOURCES WITH SCATTERED FLUX.
C
SXL, SYL, SZL 
JSOR 
LXS, LYS, LZS 
IDIR 
NLAM 
DR(I,J,K) 
UR(I,J,K) 
MTYPE 
IL 
NSOUR 
R,T 
ZENITH 
OUTPUT VARIABLES 
DR(I,J,K) 
UR(I,J,K) 
COMMON DUMO(17),XK(9),SXL,SYL,SZL,XLF,YLF,ZLF 
COMMON/C1/DUM1(7),NLAM,DUM2(26),CE1PI,DUM3(24),LXS,LYS,LZS 
COMMON/C2/DUM4(51),R(17),T(17),RG(17),DUM5(197),ZENITH(10) 
COMMON/C6/DR(4,10,17),UR(4,10,17) 
COMMON/CMAT/MT(3),MLAY,QPM(10) 
C
COMMON /AB3/TABSO(4,17)
DIMENSION H(17),PTRP(2,17)
REAL LXS,LYS,LZS
DATA PII02/1.570796327/
C....SET DIRECTION COSINES OF SOURCE
XL=XLS
YL=YSL
ZL=ZLS
IF(JSOR.NE.1) GO TO 100
XL=LXS
YL=YS
ZL=LS
C....RANDOM LEAF ORIENTATION, DIRECTION COSINES OF NORMAL, AND
C....LEAF OPTICAL PROPERTIES
100 IF(IDIR.EQ.-1) IXL=IL
    IF(IDIR.EQ.1) IXL=WAY-IL+1
    CALL LANGLE(IXL,MTYPE,THETAL,PHIL)
C....SET SIDE OF LEAF WHICH LIGHT STRIKES. ISIDE=1 (TOP), -1 (BOTTOM).
    ISIDE=IDIR
    DOT=XL*XL+YL*YL+ZL*ZL
    IF(DOT.LT.0.) ISIDE=IDIR
    COSLA=ABS(DOT)
    IF(IDIR.EQ.1) GO TO 5
    DO 4 KL=1,NLAN
        4 H(KL)= DR(IL,JSOR,KL)/18.
    GO TO 9
    5 DO 7 KL=1,NLAN
    7 H(KL)= UR(IL,JSOR,KL)/18.
    9 CONTINUE
C....UPDATE OPTICAL PROPERTIES FOR MTYPE,LAYER,REFLECT. AND TRANS.
C....SET OPTICAL PROPERTIES WITH SCATTERED RADIATION FLUX
    DO 50 JJSOR=2,NSOUR
        IF(ISIDE.EQ.-1) CALL DFLUX(THETAL,ZENITH(JJSOR),H,T,R,NLAN,PTRP)
        IF(ISIDE.EQ.1) CALL DFLUX(THETAL,ZENITH(JJSOR),H,T,R,NLAN,PTRP)
        DO 50 KL=1,NLAN
            IF(IDIR.EQ.1) GO TO 45
            DR(IL,JJSOR,KL)=DR(IL,JJSOR,KL)+PTRP(2,KL)
            UR(NLAY+2-IL,JJSOR,KL)=UR(NLAY+2-IL,JJSOR,KL)+PTRP(1,KL)
        45 G0 TO 50
        50 CONTINUE
    DO 53 KL=1,NLAN
        TABSO(IL,KL)=H(KL)*((1.-R(KL)+T(KL)))+TABSO(IL,KL)
    53 CONTINUE
RETURN
END

*deck iflux

subroutine iflux(ta, trp, h, r, t, nlanptrp)

C.... given the irradiance h of a leaf inclined at ta this program determines the flux reflected and transmitted into a source band whose zenith angle is trp.

dimension ptrp(2, 17), h(17), r(17), t(17)

data pi/3.141592654/, pi02/1.570796327/

f1(x,y)=cos(ta)*(sin(x)**2-sin(y)**2)

f2(x)=acos(-1/(tan(ta)*tan(x)))

f3(x,y,z)=2.*sin(ta)*sin(x)*(del+.25*(sin(2.*y)-sin(2.*z)))/pi

del=.087266463

10 xf1=f1(t2, t1)

do 15 kl=1, nlan

ptrp(1, kl)=r(kl)*h(kl)+xf1

ptrp(2, kl)=t(kl)*h(kl)+xf1

15 continue

return

C.... case 1

20 xf1=f1(t2, t1)

if(ta-le.pi02-t2) go to 10

if(ta.ge.pi02-t1) go to 20

go to 30

C.... case 2

25 xf3=f3(prp, t1, t2)

do 25 kl=1, nlan

ptrp(1, kl)=h(kl)+(r(kl)+t(kl))*xf3+

1*(r(kl)+h(kl)+prp-t(kl)+h(kl)+h(kl)+prp)*xf1/pi

ptrp(2, kl)=h(kl)+(t(kl)+r(kl))*xf3+

1*(t(kl)+h(kl)+prp-r(kl)+h(kl)+h(kl)+prp)*xf1/pi

25 continue

return

C.... case 3

30 tb=pi02-ta

xf1=f1(tb, t1)

do 35 kl=1, nlan

ptrp(1, kl)=r(kl)*h(kl)*xf1

35 ptrp(2, kl)=t(kl)*h(kl)*xf1

A44
IF (TB + T2 .LE. 3.106) GO TO 36
PRP = P102
GO TO 37
36 PRP = F2((TB + T2) / 2.)
37 XF1 = F1(T2, TB)
DEL = ((TRP + TA) / 2.) - .74176493
XF3 = F3(PRPP, T9, T2)
DO 40 KL = 1, HLAM
P2R(1, KL) = PTRP(1, KL) + H(KL) * (R(KL) + T(KL)) * XF3
P2R(2, KL) = PTRP(2, KL) + H(KL) * (T(KL) + R(KL)) * XF3
40 CONTINUE
RETURN
END

*DECK LANGLE

SUBROUTINE LANGLE(IL, NTYPE, THETAL, PHIL)
C----THIS PROGRAM SELECTS A RANDOM LEAF INCLINATION (THETAL) AND AZIMUTH (PHIL) AND THEN COMPUTES ITS DIRECTION COSINES XLF, YLF, AND ZLF. THE INTERMEDIATE PARAMETERS SINL, COSL, SINP, AND COSP ARE ALSO SELECTED.
C OUTPUT. RANDOM LEAF REFLECTANCE AND TRANSMITTANCE VECTORS ARE ALSO SELECTED.
C INPUT
C IL
C NTYPE
C NANGLE
C OUTPUT
C THETAL
C PHIL
C XLF, YLF, ZLF
C SINL, COSL, SINP, COSP
C R, T
C
COMMON/C1/DUM2(31),CERTD,DUM7(3),CE2PI
COMMON/C4/MANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10)
COMMON/CB/SINL,COSL,SINP,COSP
COMMON DUM3(29),XLF,YLF,ZLF
COMMON /KIM/ INL(3,3,2)

C----DETERMINE RANDOM LEAF ORIENTATION.
FM = MANGLE(IL, NTYPE)
XT = RANF(0.)
XI = 1. + (FM - 1.) * XT
IX = XI
1F (IX .EQ. MANGLE(IL, NTYPE)) IX = IX - 1
IXP1=IX+1
THETA=FLA(IL,MTYPE,IX)+.5*(FLA(IL,MTYPE,IXP1)-FLA(IL,MTYPE,IX))
PHIL=CE2PI*RANF(0.)

C----THETAL, PHIL ARE LEAF INCLINATION AND AZIMUTH, RESPECTIVELY.
I CONTINUE
SINL=SIN(THETAL)
COSL=COS(THETAL)
SINP=SIN(PHIL)
Cosp=COS(PHIL)

C----COMPUTE LEAF NORMAL DIRECTION COSINES
XLF=-SINL*COSP
YLF=-SINL*SINP
ZLF=COSL

C----SELECT RANDOM LEAF REFLECTANCE AND TRANSMITTANCE VECTORS.
CALL OPTICAL(MTYPEIL)
RETURN
END

*DECK COP
SUBROUTINE COP(ALPHA,BETA,OP)
C
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COP
C....THE DIRECTION OF THE SOURCE. THE LEAF IS INCLINED AT AN ANGLE COP
C....ALPHA AND IS ASSUMED TO BE AZIMUTHALLY ISOTROPIC. THE SOURCE COP
C....DIRECTION IS AT AN AZIMUTH OF ZERO AND AN INCLINATION OF BETA. COP
C
COMMON/C1/DUM1(33),CEPI02
OP=COS(ALPHA)*SIN(BETA)
IF(ALPHA.LE.BETA) RETURN
C
THETAO=ACOS(TAN(BETA)/TAN(ALPHA))
TANTO=TAN(THETAO)
OP=OP*(1.+(TANTO-THETAO)/CEPI02)
RETURN
END

*DECK COPM
SUBROUTINE COPM(G,OP,OPM)
C
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COPM
C....THE DIRECTION OF THE SOURCE (OPM) FOR THE SIMULATED CANOPY. THE COPM
C....LEAVES OF THE CANOPY ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC. THE COPM
C....OP FUNCTION USED IN THE CALCULATION HAS BEEN PREVIOUSLY DETERMINED COPM
C....FOR A GIVEN SOURCE DIRECTION FOR LEAF INCLINATION ANGLES OF COPM
C....5, 15, ..., 85 DEGREES. 0 IS THE LEAF INCLINATION ANGLE DENSITY COPM
C....FUNCTION.
C DIMENSION OP(9),G(9)
CPHM
COPM
CPHM
CPHM
CPHM
CPHM
CPHM
CPHM
CPHM
CPHM
DO 1 I=1,9
1 OPM=OPM+OP(I)*G(I)
CPHM
CPHM
RETURN
CPHM
END

*DECK PDENS
SUBROUTINE PDENS(IL,MTYPE,IANGLE,OPM)
CPHM
C----THIS PROGRAM COMPUTES THE PROBABILITY THAT LIGHT AT INCIDENT ANGLE THETA(IANGLE) INTERACTS WITH MATERIAL TYPE MTYPE WITHIN CANOPY LAYER IL.
CPHM
C INPUT
CPHM
IL
CPHM
C MTYPE
CPHM
CPHM
CPHM
C IANGLE
CPHM
CPHM
C OPM
CPHM
CPHM
C SLAI
CPHM
CPHM
C FLAI
CPHM
CPHM
C THETA
CPHM
CPHM
C OUTPUT
CPHM
PHIT
CPHM
CPHM
COMMON/C2/DUM(289),THETA(10)
COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10)
ARG=1.-(SLAI(IL,MTYPE)*OPM/SIN(THETA(IANGLE)))
IF (ARG.LE.0.) GO TO 1
PO=ARG**((FLAI(IL,MTYPE)/SLAI(IL,MTYPE))
GO TO 2
1
PO = 0.
WRITE(6,100) IANGLE
FORMAT (1HO, * PO SET TO ZERO*,I5)
100 CONTINUE
PHIT(IL,MTYPE,IANGLE)=1.-PO
RETURN
END

*DECK PGAP
SUBROUTINE PGAP(IL,IANGLE,IDIR,IHIT,MTYPE)
CPHM
C----THIS PROGRAM DETERMINES IF AN INTERACTION IS BEING MADE IN LAYER IL AND SETS THE MATERIAL TYPE OF LAYER IL.
CPHM
C INPUT
CPHM
IL
CPHM
IANG
C IDIR
C NLAY
C MTP
C PHIT
C OUTPUT
C IHIT
C MTYPE

COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10)
COMMON/CMAT/MTP(3),NLAY
REAL PHIT
IF(IDIR.LT.0) GO TO 10
ILAYER=NLAY+1-IL
GO TO 20
10 ILAYER=IL
...MTP(ILAYER) GIVES THE LAST MTYPE WITHIN A LAYER WHICH CONTAINS THE COMBINED
C MTYPE DISTRIBUTION.
20 MTYPE=MTP(ILAYER)
IHIT=0
TEST=RANF(0.)
IF(PHIT(ILAYER,MTYPE,IANGLE).LT.TEST) GO TO 30
IHIT=1
IF (MTYPE.EQ.1) GO TO 30
C A HIT HAS BEEN RECORDED - NOW WHAT DID IT HIT.
C NORMALIZE THE 2 MATERIAL DISTRIBUTION TO 1.0
PHITM = PHIT(IL,1,IANGLE)/(PHIT(IL,1,IANGLE)+PHIT(IL,2,IANGLE))
TEST =RANF(0.)
IF (PHITM .LT.TEST) GO TO 40
MTYPE = 1
GO TO 30
40 MTYPE = 2
30 RETURN
END

*DECK ETHRES
SUBROUTINE ETHRES(NLAY,NSOUR,IDIR)
C-----THIS PROGRAM DETERMINES (FOR EACH LAYER AND FOR ALL LIGHT SOURCE
C DIRECTIONS) IF THE SOURCE FLUX IS ABOVE THRESHOLD REQUIREMENTS IN
C THE DIRECTION INDICATED BY IDIR. INDICATORS IGOD OR IGOU ARE SET
C ACCORDINGLY.
C
C INPUT
C NLAY
C NSOUR
C IDIR
C NLAM

A48
C    DR ETHRES
C    UR ETHRES
C    THRES ETHRES
C    OUTPUT ETHRES
C    IGOD ETHRES
C    IGOU ETHRES
C
COMMON/C1/DUMO(7),NLAM ETHRES
COMMON/C6/DR(4,10,17),UR(4,10,17),THRES(10),IGOD(4,10),IGOU(4,10) ETHRES
1,THRESU(10) ETHRES
C----DOWNWARD FLUX ETHRES
   IF(IDIR.GT.0) GO TO 10 ETHRES
   NLLAYER=NLAY+1 ETHRES
   DO 2 I=1,NLLAYER ETHRES
   DO 2 J=1,NSOUR ETHRES
   IGOD(I,J)=0 ETHRES
   DO 1 K=1,NLAM ETHRES
   IF(DR(I,J,K).LT.THRESD(J)) GO TO 1 ETHRES
   IGOD(I,J)=1 ETHRES
   GO TO 2 ETHRES
1 CONTINUE ETHRES
2 CONTINUE ETHRES
   RETURN ETHRES
C----UPWARD FLUX ETHRES
10 CONTINUE ETHRES
   DO 4 I=1,MLAY ETHRES
   DO 4 J=2,NSOUR ETHRES
   IGOU(I,J)=0 ETHRES
   DO 3 K=1,NLAM ETHRES
   IF(UR(I,J,K).LT.THRESU(J)) GO TO 3 ETHRES
   IGOU(I,J)=1 ETHRES
   GO TO 4 ETHRES
3 CONTINUE ETHRES
4 CONTINUE ETHRES
   RETURN ETHRES
END ETHRES
*DECK SETZ ETHRES
SUBROUTINE SETZ(IL,IANGLE,IDIR) SETZ
C----THIS PROGRAM SETS THE FLUX (AND ITS APPROPRIATE INDICATORS) IN THE SETZ
C    IDIR DIRECTION AT ANGLE THETA(IANGLE) IN LAYER IL TO ZERO. SETZ
C
C    INPUT SETZ
C    IL SETZ
C    IANGLE SETZ
C    IDIR SETZ
COMMON/C1/DUM1(7),NLAM
COMMON/C6/DR(4,10,17),UR(4,10,17),THRES(10),IGOD(4,10),IGOU(4,10)
IF(IDIR.EQ.1) GO TO 10
C----DOWNWARD FLUX
DO 1 K=1,NLAM
   1 DR(IL,IANGLE,K)=0.
   IGOD(IL,IANGLE)=0
RETURN
C----UPWARD FLUX
10 CONTINUE
DO 2 K=1,NLAM
   2 UR(IL,IANGLE,K)=0.
   IGOU(IL,IANGLE)=0
RETURN
END
*DECK OPTICAL
SUBROUTINE OPTICAL (MTYPE,IL)
C----THIS PROGRAM SELECTS RANDOM LEAF REFLECTANCE AND TRANSMITTANCE
C VECTORS FOR MATERIAL TYPE MTYPE.
C INPUT
C MTYPE
C NVEC
C XMU
C OUTPUT
C R,T
C
COMMON/L1/DATAID(7,9),XNU(17,9),C(17,17,9),NVEC(9)
COMMON/C2/CANRM(17),SKYIM(17),DIFIN(17),R(17),T(17),
  1R0(17),XLAM(17),SOURCE(10,17),THETA(10)
COMMON /KIN/ INL(3,3,2)
C...SELECT APPROPRIATE OPTICAL VECTOR GIVEN MTYPE,IL,AND R OR T VECTOR.
   I= INL(IL,MTYPE,1)
   J=I+1
11 CALL UTIL(XNU(1,I),R)
13 CALL UTIL(XNU(1,J),T)
RETURN
*DECK NRN
*DECK NATSOR
*DECK OLDATA

DATA CEDTR, CERTD, CEMTR /0.17453293, 57.2957795, 0.002908821/
DATA CEIPO2, CEIPI, CE2PI /1.57079632, 3.14159265, 6.29319530/

*DECK TBLR

SUBROUTINE TBLR(M, X, Y, XX, Z)

C THIS PROGRAM FINDS THE INTEGRAL Z(X) OF THE FUNCTION Y(X) FROM X(1) TO X(2M-1) USING SIMPSONS RULE. THE INTEGRAL Z(X) IS NORMALIZED TO 1.0 AT X(2M-1). THE TABLE OF Z VERSUS X IS THEN INVERTED TO DETERMINE X AS A FUNCTION OF Z AT M REGULARLY SPACED POINTS ALONG Z. 

C INPUT VARIABLES
M = DESIRED NUMBER OF REGULARLY SPACED POINTS ALONG Z
X = SPECIFIED AT 2M-1 POINTS
Y = SPECIFIED AT 2M-1 POINTS

C OUTPUT VARIABLES
XX = THE TABLE OF X VALUES FOR M REGULARLY SPACED INTERVALS ALONG Z.
Z = THE NORMALIZED INTEGRAL OF Y AT X(1), X(3), ..., X(2M-1).

DIMENSION X(19), Y(19), Z(10), XI(10), XX(10)

C SIMPSONS RULE INTEGRATION
DX = X(2) - X(1)
DO 50 J = 2, M
JO = 2*J - 3
J1 = 2*J - 2
J2 = 2*J - 1
Z(J) = Z(J - 1) + DX*(Y(JO) + 4.*Y(J1) + Y(J2))/3.0
50 XI(J) = X(J2)
C NORMALIZE INTEGRAL Z(X)
DO 70 J = 1, M
Z(J) = Z(J)/Z(M)
C FIND X AT M REGULARLY SPACED POINTS ALONG Z.
XX(1) = X(1)
EM = M - 1
F = 1.0/EM
JS = 2
SUBROUTINE SUN
C----THIS PROGRAM CALCULATES THE POSITION OF THE SUN
C
C INPUT
C TIME
C GLAT
C DEC
C
C OUTPUT
C SINLAT, COSLAT
C SINDEC, COSDEC
C CSH
C SINZ, COSZ
C SINAZ, COSAZ
C LXS, LYS, LZS
C
C TIME OF SIMULATION (HOURS)
C GLAT IS SITE GEOGRAPHICAL LATITUDE
C GLONG IS SITE LONGITUDE
C DEC IS SOLAR DECLINATION
C H IS SOLAR HOUR ANGLE
C COSZ IS COSINE OF SOLAR ZENITH ANGLE
C COSAZ IS COSINE OF SOLAR AZIMUTH
C LXS, LYS, LZS ARE SOLAR DIRECTION COSINES
C
C COMMON/C1/DAY, YEAR, TIME, GLAT, GLONG, DEC, DUM(24),
CIDTR, CERT, CEMTR, DUM2(17),
2SINLAT, COSLAT, SINDEC, COSDEC, CSH, SINZ, COSZ, SINAZ, COSAZ, LXS, LYS, LZS
REAL LXS, LYS, LZS
H=ABS(((12.-TIME)*15.)*CIDTR)
SINLAT=SIN(GLAT)
COSLAT = COS(GLAT)
SINDEC = SIN(DEC)
COSDEC = COS(DEC)
COSH = COS(H)
COSZ = SINLAT * SINDEC * COSLAT * COSDEC * COSH
SINZ = SQRT(1.0 - COSZ * COSZ)
COSAZ = (SINDEC - SINLAT * COSZ) / (COSLAT * SINZ)
SINAZ = SQRT(1.0 - COSAZ * COSAZ)
LXS = SINZ * COSAZ
LYS = SINZ * SINAZ
LZS = COSZ
RETURN
END

C
SUBROUTINE UTIL(A, B)
C ....... SET VECTOR B = VECTOR A
COMMON/C1/DUM(7), NLAM
DIMENSION A(17), B(17)
DO 1 I = 1, NLAM
  1 B(I) = A(I)
RETURN
END

C
SUBROUTINE FUN(A, B)
RETURN
END
APPENDIX B: GEOMETRICAL MATRICES FOR THEORETICAL CANOPIES
## Planophile Canopy Geometry

### Foliage Angle Distribution

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CANOPY GEOMETRY INPUT DATA FOR PLANOPHILE, LAI=1

LEAF AREA INDEX

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CANOPY DENSITY PARAMETERS

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GEOMETRICAL VIEW ANGLE FACTOR MATRIX

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LONG WAVE TRANSFER MATRIX

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CANOPY GEOMETRY INPUT DATA FOR Planophile, LAI=4

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CANOPY DENSITY PARAMETERS

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GEOMETRICAL VIEW ANGLE FACTOR MATRIX

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LONG WAVE TRANSFER MATRIX

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CANOPY GEOMETRY INPUT DATA FOR PLANOPHILE, LAI=7

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CANOPY DENSITY PARAMETERS

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GEOMETRICAL VIEW ANGLE FACTOR MATRIX

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LONG WAVE TRANSFER MATRIX

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### Erectophile Canopy Geometry

**Foliage Angle Distribution**

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CANOPY GEOMETRY INPUT DATA FOR ERECTOPHILE, LAI=1

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CANOPY DENSITY PARAMETERS

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GEOMETRICAL VIEW ANGLE FACTOR MATRIX

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CANOPY GEOMETRY INPUT DATA FOR ERECTOPHILE, LAI=4

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B9
## Plagiophile Canopy Geometry

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B10
CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE, LAI=1

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CANOPY DENSITY PARAMETERS

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GEOMETRICAL VIEW ANGLE FACTOR MATRIX

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LONG WAVE TRANSFER MATRIX

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**CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE, LAI=4**

### Leaf Area Index

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B12
CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE, LAI=7

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B13
Extremophile Canopy Geometry

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B14
CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE, LAI=1

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CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE, LAI = 4

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B16
CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE, LAI=7

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B20
CANOPY GEOMETRY INPUT DATA FOR SPHERICAL, LAI=7

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B27
APPENDIX C: SENSITIVITY ANALYSIS RESULTS
Douglas-Fir Daytime Sensitivity Plots
SENSITIVITY PLOT OF DAY

- LAYER 1
- LAYER 2
- LAYER 3

TEMPERATURE (DEGREES, CENTIGRADE)

GROUND TEMP (DEGREES C)
Douglas-Fir Nighttime Sensitivity Plots
SENSITIVITY PLOT  DF NIGHT

TEMPERATURE (DEGREES CENTIGRADE) 22.00  24.00

EMISSIVITY LAYER 3

- LAYER 1
O LAYER 2
A LAYER 3

C28
SENSITIVITY PLOT  DF NIGHT

- LAYER 1
- LAYER 2
- LAYER 3

TEMPERATURE (DEGREES CENTIGRADE)

ABSORPTION COEFFICIENT LAYER 1
SENSITIVITY PLOT OF NIGHT

- LAYER 1
- LAYER 2
- LAYER 3

TEMPERATURE (DEGREES, CENTIGRADE)
9:00 12:00 16:00

ABSORPTION COEFFICIENT LAYER 3
0.76 0.80 0.84 0.88 0.92 0.96 1.00 1.04 1.08 1.12
Oak-Hickory Daytime Sensitivity Plots
SENSITIVITY PLOT  OH DAY

- LAYER 1
- LAYER 2
- LAYER 3

TEMPERATURE (DEGREES, CENTIGRADE)  22.00  24.00

GROUND TEMP (DEGREES C)  0.00  4.00  8.00  12.00  16.00  20.00  24.00  28.00  32.00  36.00
SENSITIVITY PLOT

TEMPERATURE (DEGREES CENTIGRADE) vs.

SHORT WAVE ABSORPTION LAYER 1

- LAYER 1
- LAYER 2
Δ LAYER 3
THERMAL VEGETATION CANOPY MODEL STUDIES. (U)

AUG 81
J A SMITH, K J RANSON

DAC39=77-C=0073

UNCLASSIFIED

COLORADO STATE UNIV
FORT COLLINS DEPT OF FOREST AND ETC
F/0 17/9

MEE~h~hhEEE
Oak-Hickory Nighttime Sensitivity Plots
SENSITIVITY PLOT

TEMPERATURE (DEGREES CENTIGRADE)

AIR TEMP IN CANOPY (DEGREES C)

-12.00 -8.00 -4.00 0.00 4.00 8.00 12.00 16.00 20.00 24.00

LAYER 1
LAYER 2
LAYER 3

OH NIGHT

C51
SENSITIVITY PLOT  OH NIGHT

- Layer 1
- Layer 2
- Layer 3

TEMPERATURE (DEGREES CENTIGRADE)

GROUND TEMP (DEGREES C)
SENSITIVITY PLOT  0H NIGHT
SENSITIVITY PLOT

OH NIGHT

- LAYER 1
- LAYER 2
- LAYER 3

TEMPERATURE (DEGREES CENTIGRADE)

EMISSIVITY OF GROUND

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APPENDIX D: SUPPORTING VALIDATION DATA
Cedar River, Douglas-Fir

CANOPY GEOMETRY INPUT DATA FOR DOUGLAS-FIR

LEAF AREA INDEX

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THERMAL MODEL INPUT DATA FOR DOUGLAS-FIR

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AVERAGE SHORTWAVE ABSORPTION COEFFICIENTS

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STOMATAL RESISTANCE

.66 (MIN/CM)
ENVIRONMENTAL INPUT DATA

CEDAR RIVER, WASHINGTON 4 AUGUST 1979

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Walker Branch, Oak-Hickory

CANOPY GEOMETRY INPUT DATA FOR OAK HICKORY

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**Walker Branch, Tennessee  18 August 1979**

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