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A GENERAL MODEL FOR THE ENERGY EXCHANGE AND MICROCLIMATE OF PLANT COMMUNITIES

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Summary

The individual physical processes which define the energy exchange within and above plant canopies are described by equations derived from continuum mechanics and thermodynamics. These equations, arranged into a system of nonlinear equations, serve as a model for the energy exchange of a plant stand. An equilibrium solution for the system, under prescribed boundary conditions, can be obtained through an iterative procedure. Results for such a solution are given for a representative plant energy balance condition. A dynamic model which will evolve from the current model is also discussed.

Introduction

Energy exchange between a plant community and its environment is a complex physical phenomenon. While the individual energy exchange processes can be quantitatively expressed by physical models, the plant-atmosphere-soil system is very interactive and the effects of changes in the system can not be easily predicted. Furthermore, because of the large number of variables involved, and the impossibility of holding any of these variables constant or reproducing an experimental situation exactly, the system can not be evaluated in a meaningful way by a reasonable number of systematic experiments. However, this type of problem can be fruitfully investigated by computer simulation.

Computer models for energy exchange in a plant community are capable of answering two basic kinds of questions. They are those related to the effect of different external environments or community structure on the microclimate within the plant-atmosphere-soil system; and those related to the effect of environment or community structure on one or more of the energy fluxes. An example of the first kind would be the use of the model to predict the air temperature and humidity throughout plant stands of varying density in order to predict the microenvironments of plant leaves, or possibly of the pathogens on those leaves. An example of the second kind would be a prediction of the integrated latent heat flux from a given stand as a means of estimating the evaporative term of the stand water balance.

Ideally, the model should be able to answer the above questions for a plant community of any structure or extent and for any external environment. Currently this is not possible because the energy exchange processes are not adequately understood under all circumstances. However, it is possible to model certain cases of interest. Accordingly, we have developed a model for energy exchange in a plant community which has a homogeneous structure in the horizontal planes, and which is in equilibrium with its environment. Examples of plant stands which fit the assumptions of this model are large fields of some agricultural crops and extensive stands of evenaged or mature forests with closed canopies located on nearly flat terrain. While the model can not be utilized during periods of sudden environmental changes, gradual changes in environmental parameters will not lead to large errors.

Vegetation Energy Exchange Processes

The active energy exchange processes in vegetation stands are radiative transfer, convective transfer of sensible and latent heat, and the conduction of sensible heat in and out of soil and vegetation storage. The metabolic sink or source for energy is often ignored because of its small magnitude when compared to the other fluxes, rarely as large as 5%(1). It is also convenient to divide the radiative transfer in two parts: the short wavelength radiation, which reaches the stand directly or indirectly from the sun; and the long wavelength radiation which is emitted by the plant community itself or by certain gases in the atmosphere. With this division of the radiation fluxes we have a total of five individual fluxes that must be included in our energy exchange model.

Submodels, which describe the energy fluxes in various parts of the plant community, are the building blocks of the stand model. The vegetative stand can be described in terms of four separate regions or components which are joined

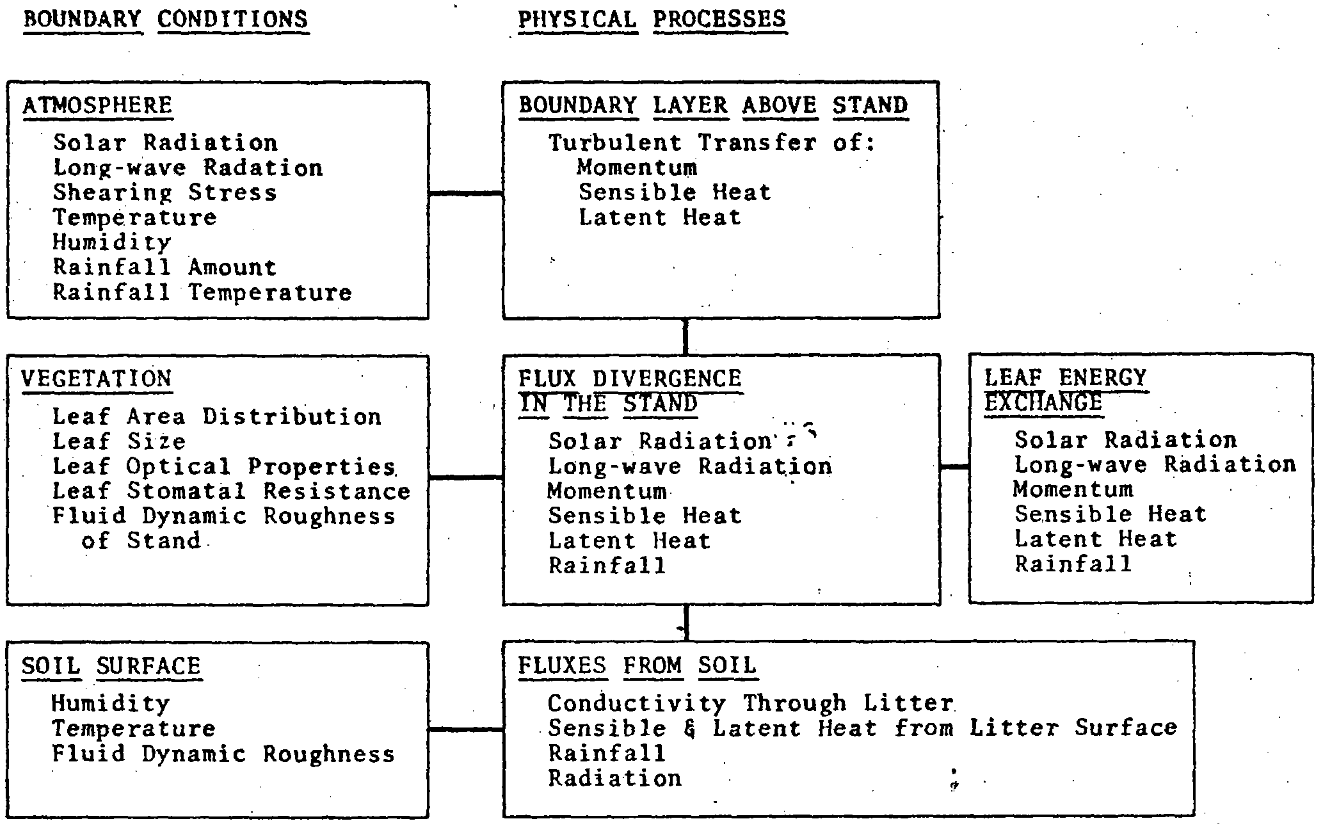

Figure 1. Boundary conditions and energy exchange processes for the Vegetation Energy Balance and Microclimate Model.

through appropriate continuity conditions. These regions are the atmospheric boundary layer above the plant canopy, the air space within the canopy, the plants which make up the vegetative stand, and the soil beneath the plants. The combination of these four regions or components and the five processes by which energy exchange occurs indicates that there should be twenty submodels within our total energy exchange model. However, certain energy transfer processes are not significant in some of the regions. Conduction is important only in the soil region. Radiative transfer is not important in the boundary layer above the vegetation or in the soil. Therefore fifteen submodels are actually required for the energy exchange modeling.

One further group of submodels is necessary to complete the total model. The convective transfers of sensible and latent heat are both determined by certain fluid dynamic characteristics of the air through which the transfers take place. Thus, in order to model the convective transfers, it is also necessary to model the fluid dynamic characteristics of the air. This need adds three other submodels to our model. A schematic representation of the model is given in Figure 1 which indicates the relationship of the plant community regions, the energy exchange processes, and the boundary conditions necessary to simulate these processes for a given plant stand under a specified environment.

Submodels for the Vegetation Energy Exchange Processes

Atmosphere Boundary Layer Submodels

The submodels used to define energy fluxes in the atmospheric boundary layer are analogies developed from theories of turbulent exchange of momentum near the surface of the earth. As we have used them, the equations are solved for the profiles of wind speed (u), air potential temperature (Θ), and air specific humidity (q) in the boundary layer. The equations utilized for these profiles are,

$$u_2 - u_1 = \frac{u_*}{k} \left[\ln \left(\frac{z_2 - D}{z_1 - D} \right) - (\Psi_2 - \Psi_1) \right]$$

$$\theta_2 - \theta_1 = T_* \left[\ln \left(\frac{z_2 - D}{z_1 - D} \right) - (\Psi_2 - \Psi_1) \right]$$

$$q_2 - q_1 = Q_* \left[\ln \left(\frac{z_2 - D}{z_1 - D} \right) - (\Psi_2 - \Psi_1) \right]$$

The subscripts refer to the values of the parameter at two heights (z_1, z_2). D is the displacement height of the profiles caused by the vegetation. The stability correction (Ψ) adjusts the profile shape for the effects of atmospheric buoyancy. The friction velocity (u_*) and the analogous variables in the temperature and specific humidity equations (T_*, Q_*) are defined by the equations

$$u_* = \sqrt{\frac{\tau}{\rho}}$$

$$T_* = - \frac{C}{\rho c_p u_*}$$

$$Q_* = - \frac{E}{\rho \Lambda u_*}$$

where the variables are air density (ρ), air specific heat (c_p), latent heat of vaporization for water (Λ), shearing stress of the wind near the surface (τ), sensible heat flux in the boundary layer (C), and latent heat flux in the boundary layer (E). Thorough treatment of these concepts can be found in references (2), (3), (4).

Vegetation Stand Space Submodels

Short Wave Radiation Transfer. In the stand space, the short wave radiation found at any height is a function of the amount of canopy intercepting this radiation above it. In a canopy where leaves are randomly positioned in the horizontal plane, Duncan (5) has shown that the short wave radiation (S) penetrating directly to a height is

$$S = S_o \exp \left(- \frac{A_\ell (F'/F) jk}{\sin k} \right) .$$

Here the extinction coefficient is related to the leaf area per ground surface area (A_ℓ) above the height, the Reeves-Wilson (6) ratio of leaf shadow area on a horizontal plane to leaf area (F'/F), and the altitude angle of origin for the radiation (k). The Reeves-Wilson ratio, in turn, is dependent on the leaf angle from horizontal (j) and the altitude angle of origin of the radiation. The altitude angle of origin for direct beam solar radiation is the solar altitude; for diffuse sky radiation it may be any angle from the horizon to a point in the sky hemisphere. In this model the sky radiation has been assumed to come from six different sky angles at identical, average values.

The short wave radiation is not completely absorbed by the leaf surfaces. A portion is reflected from and a portion transmitted through the leaves. The radiation which is transmitted once downward is added to the downward diffuse component in the model. That which is reflected once makes up an upward diffuse component which is intercepted in the same manner as the downward flux. The radiation can be followed in this manner through multiple reflections, and transmissions until all but a negligible fraction has been absorbed or reflected from the stand. The short wave flux is not interactive with the other fluxes in this or any other part of the system. That is it is not dependent on factors influenced by any of the other components. However, this condition does not hold for long wave radiation exchange.

Long Wave Radiation Transfer. Long wave radiation emitted from carbon dioxide and water vapor in the atmosphere above the vegetation is proportional to the fourth power of its absolute temperature within discrete wave length bands. These bands are rather narrow and the atmospheric emissivity varies between the bands. An approximate estimate of the downward atmospheric long wave radiation can be found from the expression

$$L_s = \sigma T^4 (.44 + .066 \sqrt{e_a}) .$$

This formulation, from Brunt (7), relates air temperature (T) and air water vapor pressure (e_a) near the ground to the long wave flux from the sky (L_s). The proportionality constant (σ) is the Stefan-Boltzmann constant. An effective radiant sky temperature can be computed as:

$$T_s = \sqrt[4]{L_s / \sigma} .$$

The net long wave exchange at any height in the stand is dependent on the radiation emitted by the leaves at that height and the amount of long wave radiation absorbed by these same leaves. The amount emitted is proportional to the fourth power of the absolute temperature. Likewise, the radiation received by the leaves is proportional to the fourth power of the absolute temperature of the emitting surfaces which contribute to the radiation flux reaching the leaf. The contribution of each source is weighted by the effective view of the receiving surface for the emitting surface. If all of the objects have emissivities near 1.0, the net long wave radiation at any height in the stand (L_n) is expressed by:

$$L_n = \sigma \sum_i V_{ji} A_{\ell j} (T_i^4 - T_j^4)$$

where V_{ji} is the view factor of the leaf (j) for the radiating object (i); $A_{\ell j}$ is the leaf area per unit ground area; and T_i, T_j the absolute temperatures of the leaf (j) and the object (i). The atmosphere can be included in the array of objects radiating toward the leaf at the effective sky temperature given above. The ground surface also maintains a radiative flux associated with it.

Sensible and Latent Heat Transfer. Fluxes of sensible and latent heat in the stand space are not solved for directly. Instead, the flux equations are solved for the air temperature and air specific humidity profile required to partition the radiation balance at a particular height in the stand between these fluxes. This approach leads to the differential equations first derived by Philip (8):

$$\frac{d}{dz}\left(K_h \cdot \frac{dT}{dz}\right) + C_h \cdot \frac{dA_\ell}{dz}(T_\ell - T) = 0$$

$$\frac{d}{dz}\left(K_w \cdot \frac{dq}{dz}\right) + C_w \cdot \frac{dA_\ell}{dz}(q_\ell - q) = 0 .$$

The total sensible heat transfer coefficient (C_h) and the total latent heat transfer coefficient (C_w) are related to the convective transfer from leaves and will be discussed below. The values of these coefficients and the leaf-air temperature (T_ℓ-T) and specific humidity (q_ℓ-q) gradients define the source strengths for sensible and latent heat transfer at any height in the stand where the leaf area per height increment is dA_ℓ/dz. The turbulent diffusivities for heat (K_h) and water vapor (K_w) in the canopy interact with the source strengths and the atmospheric source or sink for sensible heat or water vapor to produce the air temperature and air specific humidity gradients in the stand. The values of the turbulent diffusivities are determined by the velocity of air flow in the canopy. A somewhat different approach to modeling the canopy sensible and latent heat fluxes was taken by Waggoner and Reifsnyder (9) who used an electrical analog in formulating the problem.

Observations of wind flow in widely varying canopies (10, 11, and 12) show that the wind profile in the canopy can be fit by an equation of the form

$$u = u_H \exp[a(z-H)] ,$$

where the wind speed (u) at any height (z) is exponentially decreased from its value at the top of the canopy (u_H) by the depth into the canopy (z-H) times an extinction coefficient (a). While this form of equation holds in the canopy, the wind profile is of the form

$$u = \frac{u_{*g}}{k} \ln(z/z_{01}) ,$$

in the trunk space below the canopy, where the roughness length (z_{01}) is a function of the roughness of the ground surface beneath the stand, and the friction velocity (u_{*g}) is constant at the value found at the top of the trunk space.

Uchijima and Wright (13) have proposed a model for the decrease in friction velocity analogous to that for wind profile in the canopy.

$$u_* = u_{*H} \exp[b(z-H)] .$$

From the defining equation, the turbulent diffusivity for momentum (K_m) is:

$$K_m = u_*^2/(du/dz) .$$

In the canopy, the above equation is reduced to the form

$$K_m = K_{mH} \exp[(2b-a)(z-H)] .$$

By analogy, the diffusivities for heat and water vapor can be given by

$$K_H = K_{hH} \exp[(2b-a)(z-H)]$$

$$K_w = K_{wH} \exp[(2b-a)(z-H)].$$

Experiments analyzed by Wright and Brown (11) substantiate the form of these equations.

Vegetation Surface Exchange Submodels

The equations used to describe the sensible and latent heat transfer from leaves were developed from engineering approximations by Raschke (14). In terms of the source strength per leaf area they are

$$C = \frac{2\rho c_p}{r_h}(T_\ell - T) = C_h(T_\ell - T)$$

$$E = \rho\Lambda\left(\frac{1}{r_m + r_{\ell 1}} + \frac{1}{r_m + r_{\ell u}}\right)(q_\ell - q) =$$

$$C_w(q_\ell - q) .$$

All of the above parameters have been defined previously except the diffusion resistances for sensible heat (r_h) and water vapor (r_m, r_ℓ). The resistances associated with the laminar boundary layer over the leaf can be approximated by

$$r_h = C_\ell (d/u)^{1/2}$$

and

$$r_m = .889\ r_h .$$

The boundary layer resistances increase with increasing leaf characteristic dimension (d) and decrease with increasing wind speed (u). The proportionality constant (C_ℓ) varies with the leaf angle of attack to the wind. The diffusive resistance produced by the stoma ($r_{\ell u}, r_{\ell 1}$) on upper and lower leaf epidermus are physiologically controlled. They vary mainly with changes in light intensity and availability of water to the plant. For our purposes, they are given a single, average value. However, they could easily be varied with the change of light with change in depth in the stand.

The radiation environment of leaves at any height in the stand was described in a previous section. The amount intercepted in a finite layer of leaves is the difference between the amount of radiation reaching that layer and the amount reaching the layer below. The amount of short wave radiation absorbed is dependent on the absorptivity of the leaf. For short wavelengths absorptivities (α) of many leaves average about .45, while for long wave lengths the absorptivity of almost all plant leaves is very close to 1.0. In terms of the quantities that have already been defined, the net short wave radiation ($S_{n\ell}$) and net long wave ($L_{n\ell}$) per unit leaf area per increment of stand depth are

$$S_{n\ell} = \alpha(S_2 - S_1)/[(z_2 - z_1)/A_\ell]$$

$$L_{n\ell} = L_n/A_\ell$$

Ground Surface Submodels

At the soil surface the convective fluxes differ from those at the leaf surface in that they are determined by a fully developed turbulent boundary layer rather than a laminar boundary layer. The flux equations for this case are

$$C = -\rho c_p K_h \cdot \frac{dT}{dz}$$

$$E = -\rho\Lambda K_w \cdot \frac{dq}{dz}$$

Determination of the diffusivities (K_h, K_w) near the ground surface has been discussed previously. The net radiative fluxes for the ground surface can be calculated as they were for the leaf surfaces.

The remaining ground surface energy flux is heat conducted from the soil. The soil very rarely is in thermal equilibrium with the air above it. In order to model this part of the system for an equilibrium case, it is necessary to treat the soil as a short time period sink or source of sensible heat. This was done by using the equation:

$$G = k_s \frac{[T_g - T_s]}{\Delta Z}$$

As developed here, the specified temperature at depth Δz in the soil (T_s) will not remain constant for more than a short time period. The other variables are soil heat flux (G), the thermal conductivity of the soil (k_s) and the equilibrium temperature of the ground surface (T_g).

Simulation of the Energy Balance For A Plant Community

The equations developed above are those which describe the atmosphere-plant-soil system in the steady-state. Their solution is complicated by their non-linearity and in some instances by their differential form. Thus, an iterative procedure indicated below was developed to converge on values of the leaf temperature, air temperature and the air specific humidity.

Most of the submodels are equations which, at the most, need only algebraic manipulation, and direct arithmetic calculation. The exceptions are the differential equations of sensible and latent heat flux in the stand space and above the soil surface. These have been solved through finite difference approximations which result in a set of simultaneous linear equations. It is also necessary to solve the energy flux equations at the soil surface and the leaf surfaces for equilibrium surface temperatures. This has been done by expanding some of the terms and solving the resulting nonlinear equations iteratively. Figure 2 shows the step by step scheme for solution.

The first step of the computer simulation is to read in the environmental and stand input parameters. The stand parameters include the height of the stand, the zero plane displacement for wind flow over the stand, the optical properties and angles of the leaves, the leaf characteristic dimensions, and the distribution of leaf area. The environmental parameters are the friction velocity above the stand; the wind speed, air temperature, and air specific humidity at some height above the stand; the direct and diffuse solar radiation, and the solar angle; the atmospheric long wave radiation and an initial estimate of the ground surface temperature and specific humidity. The thermal properties of the soil must also be specified.

The vegetative stand is then divided into layers of equal depth, and the leaf area distribution is determined for each layer by interpolating between the points of the input information. Leaf temperature at each height is estimated, and the distribution of short wave radiation calculated. At this point the iterative loop is entered which will converge on the final answer for the system.

The wind, air temperature, and air specific humidity profiles are extrapolated from above the stand to the stand height using the boundary layer equations for turbulent transfer above the stand. Initially these profiles are assumed to be for zero sensible heat flux from the stand which results in the profile stability correction (Ψ) being zero. Later, as estimates of the sensible heat flux are obtained, the profile correction must be computed for each height. Since the stability correction term interacts with the profile, the best estimates for the profiles and the stability correction must be determined through an iterative procedure.

Using wind speed at the stand height, the wind profile through the stand space is calculated and the corresponding diffusivities determined. The total sensible heat transfer coefficients and the total water vapor transfer coefficients at each layer in the stand are calculated from the wind speed at that layer height.

All of the information to compute an initial estimate of the air temperature profile in the plant air space is now available. The differential equations previously described are reduced to a system of linear equations by finite difference approximations of the derivatives. The system of equations is solved by the subroutine SIMQ from the IBM-360 Scientific Subroutine Package (15). The leaf specific humidity is then set equal to the saturation specific humidity at leaf temperature and the same routine is used to solve for the specific humidity profile in the stand.

The calculation of the net long wave radiation by the formula previously proposed, provides all of the information necessary to define the leaf or soil environment. In order to estimate the sensible or latent heat flux from the leaf it is necessary to know leaf temperature. The leaf energy balance can be solved for equilibrium leaf temperature. This balance can be written as

$$S_{n\ell} + L_{n\ell} - C_h(T_\ell - T) - C_w(q_\ell - q) = 0.$$

Substituting the relationships

$$q = (RH)\, q_{as}$$

$$\Delta T = T_\ell - T$$

$$q_\ell = q_s(T_\ell) = q(T+\Delta T) =$$

$$q_{as} + \frac{dq}{dT}\Delta T + \frac{d^2q}{dT^2}\frac{(\Delta T)^2}{2} + \frac{d^3q}{dT^3}\frac{(\Delta T)^3}{6}$$

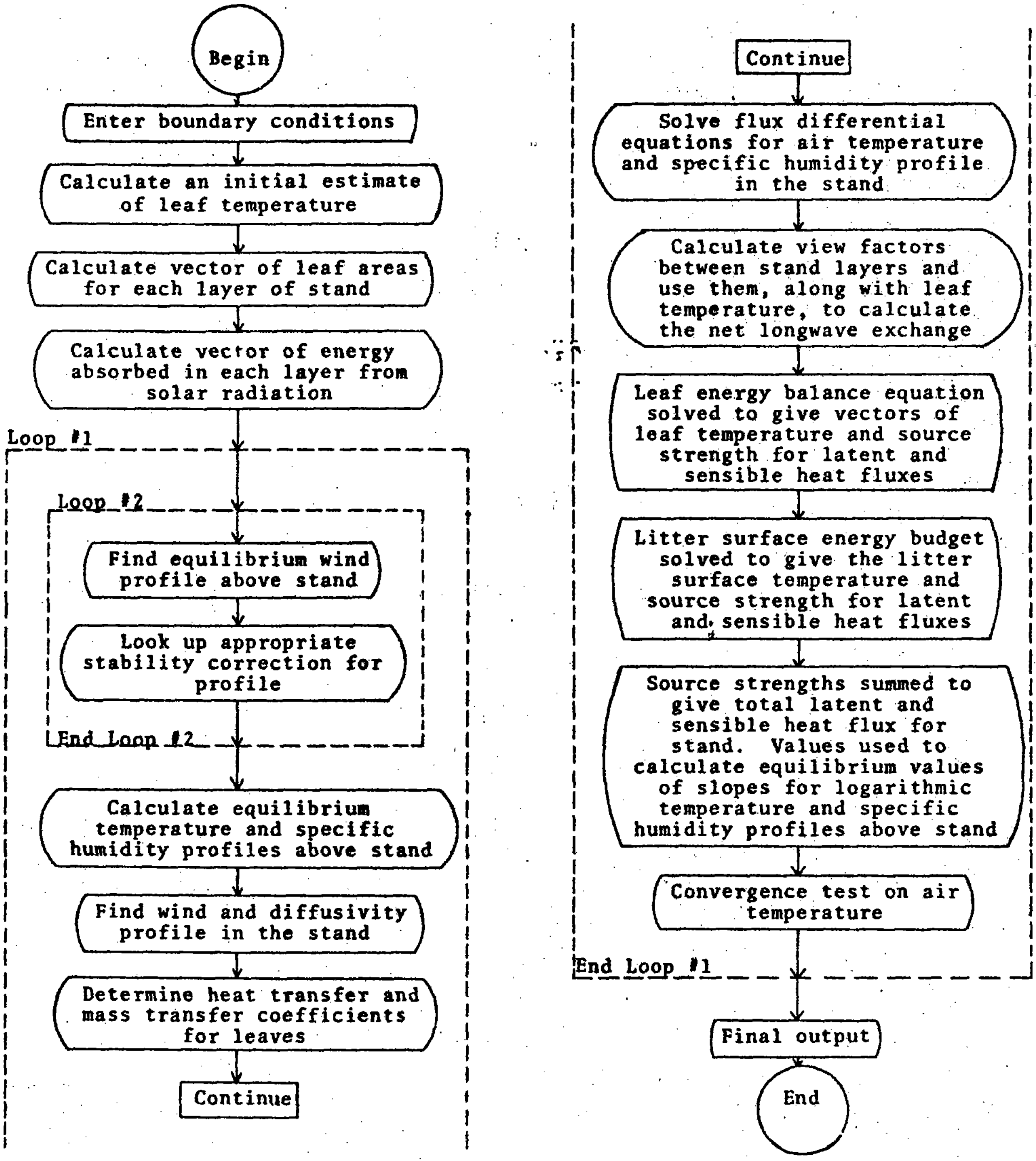

Figure 2. Logical Flow Chart for the Vegetation Energy Balance and Microclimate Simulation Model.

$$C_M = C_w/\Lambda$$

$$\Lambda = 595. - .567(T+\Delta T)$$

where RH is the relative humidity and q_{as} is the saturation specific humidity at air temperature, the equation is rearranged to give

$$S_{n\ell} + L_{n\ell} - C_M(595.-.567T)(1-RH)q_{as}$$

$$-\left[C_h + C_M(595.-.567T)\frac{dq}{dT}\right]\Delta T$$

$$+\left[.567C_M(1-RH)q_{as}\right]\Delta T$$

$$-\left[\frac{C_M}{2}(595.-.567T)\frac{d^2q}{dT^2} - .567C_M\cdot\frac{dq}{dT}\right](\Delta T)^2$$

$$-\left[\frac{C_M}{6}(595.-.567T)\frac{d^3q}{dT^3} - .567\frac{C_M}{2}\frac{d^2q}{dT^2}\right](\Delta T)^3$$

$$+ .567\frac{C_M}{6}\frac{d^3q}{dT^3}(\Delta T)^4 = 0 .$$

This equation can be solved for (ΔT) providing a basis for determining T_ℓ. A similar equation can be developed for the ground surface. The solution of both of these equations allows the computation of the source strengths for latent and sensible heat as well as the equilibrium surface temperatures.

The source strengths for the ground and the individual canopy layers can be summed to give the total sensible and latent heat fluxes from the stand. With the total fluxes, the values of T_* and Q_* can be solved for and the whole sequence restarted. This sequence is iterated until the air temperature profile has converged to an equilibrium value.

Results of a Representative Simulation

Figures 3 through 10 show the results of a simulation performed for a forest stand where wind and stand structure data were available (12). The conditions simulated had input parameters characteristic of a cloudy day preceding a rain storm. The relative humidity at 10 meters above the stand was 90%. The air temperature and wind speed at the same level were 20°C and 369 cm/sec. The short wave input was .16 ly/min. Figure 3 shows the leaf area distribution. Figures 4 through 9 demonstrate the microclimate produced in the stand, while figure 10 shows the source strengths for sensible and latent heat.

The leaf area distribution for this stand was double peaked because the forest canopy was composed of two distinct classes of trees. These classes were older, dominant, overstory trees and younger, suppressed understory trees. The energy exchange, as indicated by the short wave radiation, long wave radiation, sensible heat, and latent heat exchange components for different levels in the stand, is influenced by the leaf area distribution. In all cases, the profiles have double peaks (Figures 2,9, and 10).

However, the second maximum of the latent heat source strength profile is smaller than would be expected from the leaf area distribution alone. Moreover, the sensible heat source strength changes sign a short distance below the top of the stand canopy. The canopy acts as a sink for sensible heat above this level and a source below this level. The above profiles for the distribution of latent heat and sensible heat source strengths provide excellent examples of the value of a simulation model. The nonproportional distribution of latent heat sources with respect to leaf area distribution, or the change from a sensible heat sink to a sensible heat source between canopy regions, could not have been predicted by independently evaluating the effects of individual environmental parameters on sensible and latent heat exchange. The characteristics of the sensible and latent heat source strengths can only be predicted and understood by using a simulation model, such as the one we have described in this paper, which allows all of the energy balance processes and environmental parameters to interact in a manner approximating that found in the natural environment.

A simulation model also enables one to predict the effect of changing a single environmental parameter while all others are held constant. Figure 11 presents the results of this kind of simulation. It indicates, that for the environmental and stand conditions used for this simulation, an increase in wind speed at the top of the canopy will increase the integrated latent heat flux from the stand of vegetation. Again, this effect of wind speed on latent heat flux could not have been adequately predicted outside of the framework of a simulation model. Nor, should this single simulation imply that increasing wind speed will always have the same effect. In fact, simulations for other environmental and stand conditions indicate that increasing the wind speed

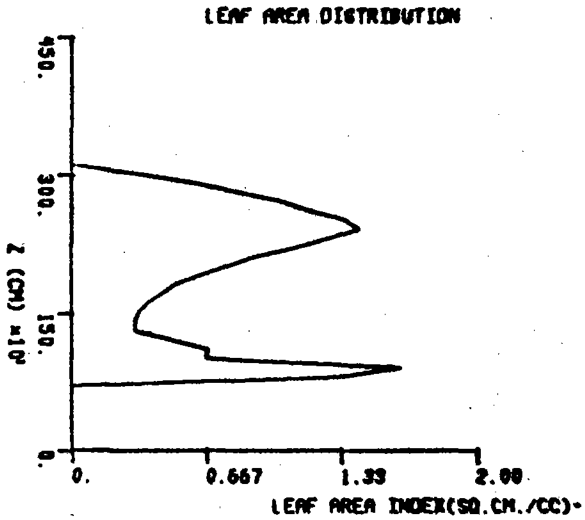

Figure 3. Leaf area per 100 cm³ of stand volume versus height from the ground.

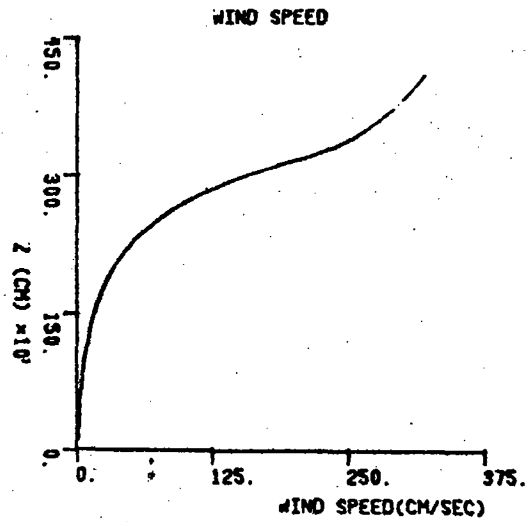

Figure 5. Wind speed versus height from the ground.

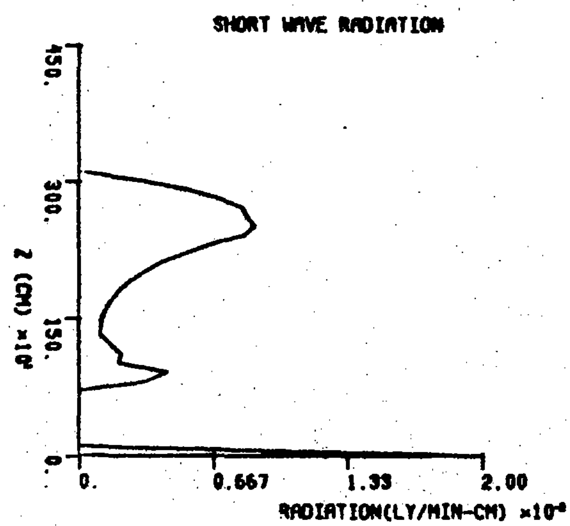

Figure 4. Short wave radiation absorbed per unit of map area for 100 cm increments of stand depth at various heights in the stand canopy.

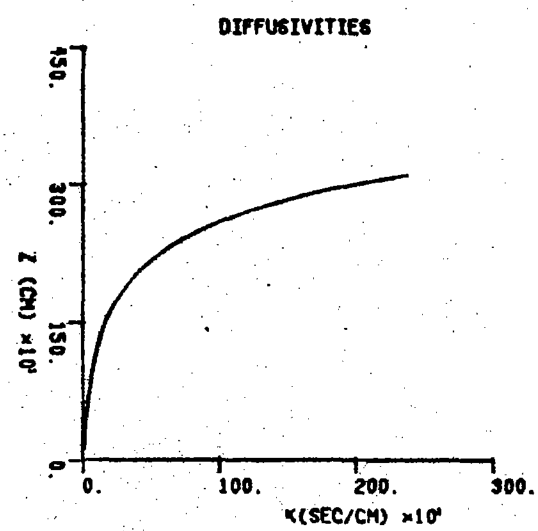

Figure 6. Turbulent diffusivities for momentum and heat transfer through the stand space. In this case they are practically identical.

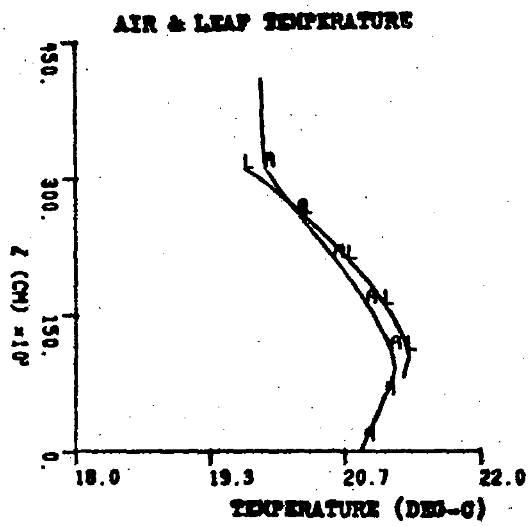

Figure 7. Air temperature (A), and leaf temperature (L) in the canopy versus height from the ground.

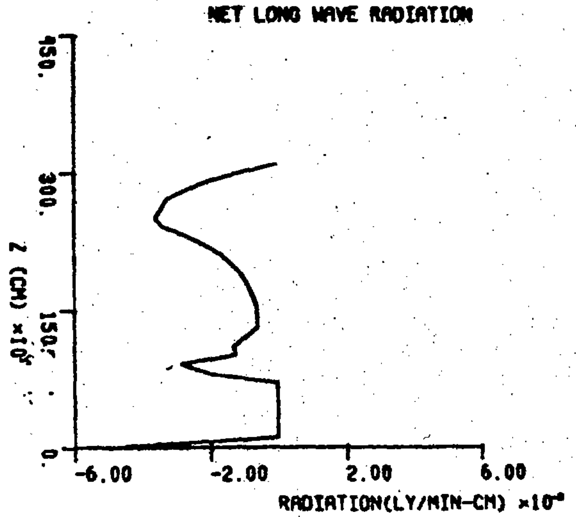

Figure 9. Net long wave radiation for a 100 cm increment of canopy, at various heights in the stand

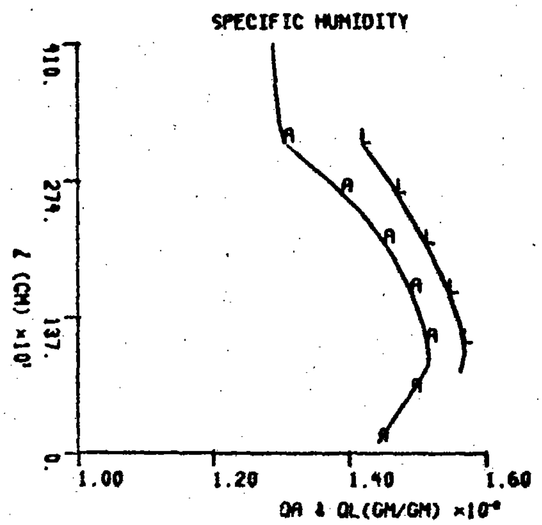

Figure 8. Air specific humidity (A), and leaf specific humidity (L) in the canopy versus height from the ground.

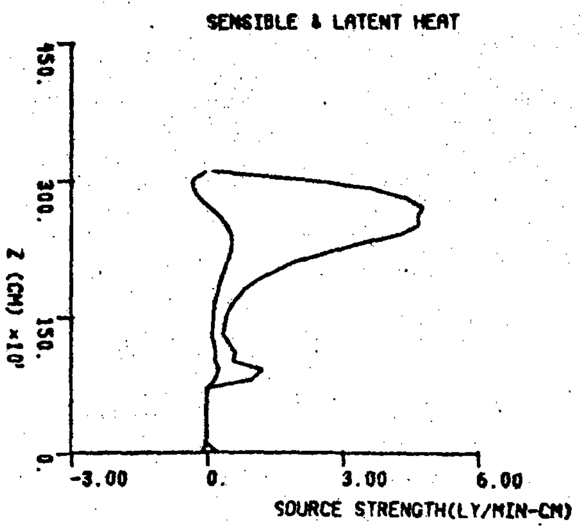

Figure 10. Source strengths for sensible heat flux (left) and latent heat flux (right) for 100 cm increments of stand depth at various heights in the stand canopy.

under some situations may actually reduce the latent heat flux.

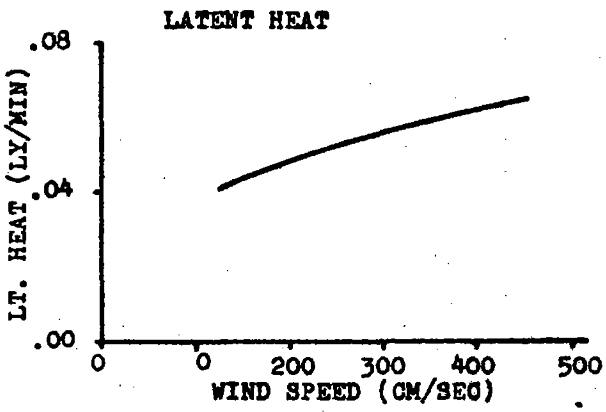

Figure 11. The effect of changing wind speed on the total latent heat transfer from the forest stand.

Future Simulation Models

There are long periods of time when a plant community is not in equilibrium with its surrounding environment. Normally this condition occurs when environmental changes take place too rapidly for the stand of vegetation to reach any equilibrium state. Thus, a dynamic model could answer a number of important questions concerning stand environment. How long does it take the plant stand to regain equilibrium from the condition imposed on it by a sudden gust of wind? What are the effects of sudden shading by clouds on the stand microclimate? What is the error involved in using a steady state model to approximate the plant community energy exchange over a period of time? These and other questions need to be answered.

There are four environmental changes which can produce nonequilibrium states in the energy exchange of a plant community. These are changes in wind speed, temperature and humidity of the air mass over the plant stand, and changes in the radiant input to the stand. Any change in the characteristics of the air mass also implies a horizontal gradient in these characteristics. In this case, horizontal homogeneity can not exist and any model for this condition must be at least two dimensional in space as well as dynamic.

The case of changing radiation load can be developed in one spatial dimension. Thus a dynamic radiation model should be more easily developed from the steady state model proposed in this paper and substantial progress has already been made in that direction. The ultimate objective for a vegetation energy exchange and microclimate model should be a four dimensional model that can be applied to large land areas, such as watersheds, and that can cope with gradients in time and space. This type of model must also be interfaced to a larger scale of meteorological motion than that developed in this paper. It will undoubtedly be the work of many people in several disciplines.

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