Working Paper

Description of a Land-Surface Scheme for Use in Vegetation Models

Philippe Martin

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IIASA

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About the Author

Philippe Martin was part of the Young Scientist's Summer Program at IIASA in 1989. The following study is one result of Mr. Martin's participation, with 22 other student and professional scientists, in the global modeling studies conducted in IIASA's Biosphere Dynamics Project throughout the summer of 1989. In addition to producing the current manuscript as an integral component of a global vegetation model, Mr. Martin also provided leadership in keeping group activities focused and on track to achievement of overall project goals. Mr. Martin is currently a PhD student at the University of California, Berkeley, and is completing his dissertation research at the National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, USA.

Foreword

IIASA's projects within the Environment Program are devoted to investigating the interaction of human development activities and the environment, particularly in terms of the sustainable development of the biosphere. The research is policy-oriented, interdisciplinary, international in scope and heavily dependent on collaboration with a network of research scientists and institutes in many countries. The importance of IIASA's Environment Program stems from the fact that the many components of the planetary life-support systems are being threatened by increasing human activity, and that these problems are not susceptible to solution by singular governments or even, international agencies. Instead, resolution of the difficulties will demand concerted and cooperative actions by many governments and agencies, based on valid understanding of the earth's environmental systems. Establishment of a basis for international cooperation, and production of accurate global environmental perceptions are both hallmarks of IIASA's Environment Program.

Foremost among the global environmental issues of concern are those involving increasing concentrations of greenhouse gases and changing climate. Problem solutions will only become apparent after collection and analysis of pertinent data, testing of relevant hypotheses, genesis of mitigation strategies and investigation of the efficacy of the strategies which are developed. All of these activities can support development of, or be supported by, the appropriate mathematical models of the biosphere. Therefore, the Biosphere Dynamics Project has been focused on the creation of models which can describe the vegetation dynamics portion of the biosphere. The models are being designed to define the biotic and ecological results of measures suggested to slow or stop increases in greenhouse gases. The models must be capable of documenting whether, and if so, by how much, vegetational communities would benefit from mitigation actions, as well as describing how the terrestrial biosphere will respond in its role as carbon source and sink.

The following report describes one important component in such a global vegetation model, the linkage between land-surface and the hydrosphere. At the scale and level of detail of other parts of the model, the land-surface routine provides a means to integrate the atmosphere-land feedbacks, through the gap or "stand" models, which are at the heart of the IIASA approach to global vegetation modeling. Martin has demonstrated a relatively elegant and direct means to solution of this non-trivial problem in global change modeling.

Bo R. Döös, Leader
Environment Program

Abstract

At the Earth's surface, two phenomena take place. Energy, water, and momentum are exchanged between the ground and the vegetation, and the atmosphere, and water is redistributed horizontally over the landscape and vertically in the soil. The exchanges of energy, water, and momentum result from specific processes, which themselves are controlled by particular surface parameters. The optical properties of the surface control the surface energy balance, which determines the energy available for the release of sensible and latent heat; the surface temperature also affects the sensible and the latent heat fluxes and modulates infrared cooling; the vegetation to a large extent determines the partitioning between the sensible and the latent heat; and, the roughness controls the transfer of momentum between the surface and the atmosphere. Conversely, the redistribution of water over the landscape is determined by topography, vegetation cover, and the physical characteristics of the soil. These processes consequently determine the quantity of water available for plant growth and cooling. Vegetation models, and in particular those with high spatial resolution, such as gap-phase forest dynamics models, should include an explicit treatment of the processes described above if they are at any point going to be used for studies of the effects of climatic changes. This paper describes a model where vegetation/atmosphere interactions are treated with greater physically and biological realism and where feedbacks are made explicit.

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1. INTRODUCTION

To study the effects of climatic changes on vegetation a various scales, models treating the exchange of energy, water, and momentum at the surface, as well as the soil hydrology, with greater realism are needed. Such models should also enable the study of the interactions between different vegetation types with different canopy geometries and contrasted root distributions. The present paper describes a model attempting to meet such requirements.

First, a short account of the context within which such an endeavor is taking place is given. Then, the computation of the evaporation from the vegetation and the ground are given. Finally, a description of the treatment of the water balance follows. So, before getting into the details of the parameterizations developed and used, let us take a look at the big picture.

2. GENERAL DESCRIPTION

The present energy and water exchange scheme is constructed to enable its coupling with ecological models of vegetation dynamics. For this reason, the inputs are on the one hand, the microclimatic parameters such as incoming solar radiation, temperature, humidity, precipitation, and a physical description of the soil profile, and on the other vegetation characteristics including height, leaf area index, optical properties of the leaves, physiological data pertaining to maximum and minimum values of the stomatal resistance, and a description of the vertical distribution of roots in the soil. The outputs are the latent and the sensible heat fluxes, the amount of moisture in the soil and the proportion of it available for plant consumption, and runoff. Feedbacks are therefore explicitly taken into account. For example, plant height determines the aerodynamic resistance of the vegetation and therefore the degree of coupling between the source of water in the vegetation and the atmospheric sink for water. For this reason, smaller plants may control the transpiration flux to a lesser extent than taller ones. If this control is lower, then those smaller plants may more likely be submitted to water stress and hence their growth impeded. Such occurrences should be registered by the present model and therefore describe seedling establishment more accurately.

3. TRANSPIRATION FROM THE VEGETATION

The evaporative flux from the vegetation, F_{veg}, is taken to be the minimum of the supply and the demand, *i.e.*, $F_{veg} = \min\{E_S, E_D\}$, where E_S is the evaporative supply of the vegetation, which is a function of root and xylem resistance, and E_D is the evaporative demand on the vegetation.

In the subsections which follow, the derivation of the evaporative demand is described. At this stage, the evaporative supply is set constant, as in Dickinson (1984). This will be ultimately changed however.

4. VEGETATION CONTROL OVER TRANSPIRATION

Vegetation determines to some extent the transpiration flux by the control it exerts on it as it diffuses through the stomata. Conceptually, the stomata may be thought of as resistances to this water flux. Stomata respond to light, temperature, air humidity, the leaf pressure potential, and other factors such as the chemical compounds which force the abscission of leaves. Here, only responses to light, temperature, and humidity will be considered. Responses to leaf pressure potential may be included at a later stage. Dickinson (1984, p. 65) proposes a purely multiplicative scheme:

$$r_s = r_{s,min}\, R_l\, S_l\, M_l\,, \tag{4.1}$$

where $r_{s,min}$ is the minimum stomatal resistance in $\mathrm{s\,m^{-1}}$(a typical value is 250 $\mathrm{s\,m^{-1}}$); R_l, a factor giving the dependence of r_s on light; S_l, a factor giving the dependence of r_s on temperature; and, M_l, a factor giving the dependence of r_s on root resistance. R_l varies between

1 for overhead sun and $r_{s,max}/r_{s,min}$ for nighttime, where $r_{s,max}$ is the cuticular resistance of the leaves (with typical values of 5,000 $\mathrm{s\,m^{-1}}$), and is expressed as,

$$R_l = \frac{1 + I_V/I_{VC}}{r_{s,min}/r_{s,max} + I_V/I_{VC}}, \tag{4.2}$$

where I_V is the flux of incoming solar radiation and I_{VC}, the visible solar flux for which R_l is about double its minimum value. Dickinson suggests values of 30 $\mathrm{W\,m^{-1}}$ for trees and of 100 $\mathrm{W\,m^{-1}}$ for grasslands and crops.

Here however, a different approach is developed. It is assumed that r_s has a lower bound equal to $r_{s,min}$ and an upper bound $r_{s,max}$. Thus, r_s is formulated as,

$$r_s = r_{s,min} + [r_{s,max} - r_{s,min}]\,\lambda_1(I)\,\lambda_2(T)\,\lambda_3(\delta e), \tag{4.3}$$

where the λ_i-functions ($i = 1,3$) give the dependence of r_s on visible light, I_V, temperature, T, and vapor pressure deficit, δe and are such that, $\forall \lambda_i$, $0 \leq \lambda_i \leq 1$. λ_1 is assumed to be of the form

$$\lambda_1(I_V) = \frac{1}{1 + k_1 I_V} \tag{4.4}$$

where

$$k_1 = \frac{1}{I_{VC}} \frac{r_{s,max}}{r_{s,min}}, \tag{4.5}$$

while λ_2 is parameterized as

$$\lambda_2(T) = 1 - \exp\{k_2\,(T - T_2)^2\}, \tag{4.6}$$

with

$$k_2 = \frac{\ln \gamma_1}{(T_1 - T_2)^2}, \tag{4.7}$$

where

$$\gamma_1 = 1 - \frac{r_s(T_1) - r_{s,min}}{r_{s,max} - r_{s,min}}, \tag{4.8}$$

and $T_1 = 273\mathrm{K}$ and $T_2 = 273 + 50 = 333\mathrm{K}$. With $\gamma_1 = 0.15$, $k_2 = -7.59\,10^{-4}$. Finally,

$$\lambda_3(\delta e) = 1 - \exp\{k_3\,\delta e\}, \tag{4.9}$$

where,

$$k_3 = \frac{\ln \gamma_2}{\delta e_1}. \tag{4.10}$$

and

$$\gamma_2 = \frac{r_s(\delta e_1) - r_{s,min}}{r_{s,max} - r_{s,min}} \tag{4.11}$$

$k_3 = -6.32\,10^{-4}$ Pa^{-1} for δe_1 = 3,000 Pa. At this point, it is assumed that the vapor pressure at the leaf surface is at saturation. Hence, λ_3 may be re-written as,

$$\lambda_3(e_s(T)) = 1 - k_4\ \exp\{k_3\, e_s(T)\}\,, \tag{4.12}$$

with

$$k_4 = \exp\{-k_3\, e\}\,, \tag{4.13}$$

where e_s is the saturation vapor pressure and e is the air vapor pressure, both in Pa.

For the derivations which follow, it is useful to compute the first and second derivatives of λ_2 and λ_3 with respect to temperature. Differentiating Eqs. (4.6) and (4.12),

$$\frac{d\lambda_2}{dT} = \lambda_2' = 2\,k_2\,(T - T_2)\,[\lambda_2(T) - 1]\,, \tag{4.14}$$

$$\frac{d^2\lambda_2}{dT^2} = \lambda_2'' = 2\,k_2\,[1 + 2\,(T - T_2)^2]\,[\lambda_2(T) - 1]\,, \tag{4.15}$$

$$\frac{d\lambda_3}{dT} = \lambda_3' = -k_4\, e_s'\,[\lambda_3(T) - 1]\,, \tag{4.16}$$

and

$$\frac{d^2\lambda_3}{dT^2} = \lambda_3'' = -k_4\,[e_s'' - k_4\,(e_s')^2]\,[\lambda_3(T) - 1]\,, \tag{4.17}$$

where e_s' is the first derivative of saturation vapor pressure and e_s'' is the second derivative of saturation vapor pressure.

5. THE ENERGY BALANCE

The energy balance for the canopy is

$$\lambda E = [R_i - \epsilon\,\Lambda\,\sigma\,T^4 - G] - H \tag{5.1}$$

where E is the evaporative flux, and here more specifically the evaporative demand on the vegetation ($E = E_D$), in W m^{-2}; R_i is the incoming solar radiation in W m^{-2}; ϵ is the emissivity of the canopy; Λ is the leaf area index defined as the surface area of leaf per unit surface area of ground in m^2 m^{-2}; σ is the Stefan-Boltzmann constant in W m^{-2} K^{-4} ($\sigma = 5.67\,10^{-8}$); G is heat flux from the canopy to the ground in W m^{-2}; and, H is the sensible heat flux in W m^{-2}. The latent and the sensible heat can be expressed specifically. The latent flux is

$$\lambda E = \frac{\rho C_p}{\gamma} \frac{e_s(T) - e}{r_a + r_c(T)} \tag{5.2}$$

where ρ is the density of dry air at reference level in kg m^3 (ρ = 1.204 at 20°C); C_p is the specific heat of dry air at constant pressure in J K^{-1}(C_p = 1,010 at 20°C); γ is the psychrometric constant evaluated at canopy temperature in Pa K^{-1} (γ = 66.1 at 20°C);and, r_a is the aerodynamic resistance of the canopy in s m^{-1}. Conversely, the sensible heat flux is

$$H = \rho C_p \frac{T - T_a}{r_a}. \tag{5.3}$$

6. COMPUTING THE LATENT HEAT FLUX

To compute the latent heat flux, the temperature of the canopy needs to be known. A solution to this problem, is to solve the system for temperature iteratively and then to compute the latent heat flux. This entails a high computer cost however and can raise non trivial convergence, as well as multiple solution, problems. An alternative is to eliminate canopy temperature, or to be more precise, the temperature gradient between the canopy and the air from the equations. Assuming that r_c is not a function of temperature, Penman (1948) first made a linear approximation of the saturation vapor pressure, $e_s(T)$, which then enabled him to eliminate the temperature gradient from Eqs. (5.1), (5.2), and (5.3). More recently, Paw U and Gao (1988) pointed out that a non-linear approximation should be used. Here, a second-order approximation of λE, as defined in Eq. (5.2), is derived. To simplify the notation, let us define $\phi(T)$ such as

$$\phi = \frac{e_s(T) - e}{r_a + r_c(T)} \tag{6.1}$$

λE can now be approximated as

$$\lambda E = \chi_0(T_a) + \chi_1 (T - T_a) + \chi_2 (T - T_a)^2 , \tag{6.2}$$

where

$$\chi_0 = \frac{\rho C_p}{\gamma} \phi(T_a) ,$$

$$\chi_1 = \frac{\rho\, C_p}{\gamma} \frac{d\phi}{dT}\bigg|_{T=T_a},$$

and

$$\chi_2 = \frac{\rho\, C_p}{\gamma} \frac{d^2\phi}{dT^2}\bigg|_{T=T_a}.$$

The function ϕ may be rewritten as

$$\phi(T) = f(T)/g(T)$$

with

$$f(T) = e_s(T) - e$$

and

$$g(T) = r_a + r_c(T) = \eta_0 + \eta_1\, \lambda_2(T)\, \lambda_3(T),$$

where $\eta_0 = r_a + r_{s,min}$ and $\eta_1 = r_{s,max} - r_{s,min}$. In what follows the reference to T is dropped for clarity, *i.e.*, $f = f(T)$ and $g = g(T)$. Hence,

$$\frac{d\phi}{dT} = \frac{f'\, g + g'\, f}{g^2}$$

and

$$\frac{d^2\phi}{dT^2} = \frac{f''\, g^2 - g'\, f\, g - 2\, f'\, g'\, g + 2\,(g')^2\, f}{g^3}$$

where

$$f' = \frac{df}{dT} = e_s', \tag{6.3}$$

$$f'' = \frac{d^2 f}{dT^2} = e_s'', \tag{6.4}$$

$$g' = \frac{dg}{dT} = \eta_1\, [\lambda_2'(T)\, \lambda_3(T) + \lambda_2(T)\, \lambda_3'(T)], \tag{6.5}$$

and

$$g'' = \frac{d^2 g}{dT^2} = [\lambda_2''(T)\, \lambda_3(T) + 2\, \lambda_2'(T)\, \lambda_3'(T)] + \lambda_2(T)\, \lambda_3(T)''] . \tag{6.6}$$

Using Eqs. (5.1), (5.2), and (5.3), approximating T^4 by $4\, T_a^3\, (T - T_a)$, defining χ_3 as

$$\chi_3 = \left[4\, \epsilon\, \Lambda\, \sigma\, T_a^3 + \frac{\rho\, C_p}{r_a}\right]^{-1}, \tag{6.7}$$

and χ_4 as

$$\chi_4 = \chi_3\, (R_i - G), \tag{6.8}$$

the following equation may be obtained:

$$a\,(\lambda E)^2 + b\,(\lambda E) + c = 0 \tag{6.9}$$

where

$$a = \chi_2\,\chi_3^2\,, \tag{6.10}$$

$$b = \chi_1\,\chi_3 + 2\,\chi_2\chi_3\chi_4 - 1\,, \tag{6.11}$$

and

$$c = \chi_0 + \chi_1\chi_4 + \chi_2\,\chi_4^2\,. \tag{6.12}$$

At this point, reevaporation from the canopy is assumed to be a fixed percentage of precipitation.

7. EVAPORATION FROM THE GROUND

Evaporation from the ground is again the minimum of a supply and a demand. It is simpler to compute than the evaporative flux from the vegetation given the absence of a stomatal resistance. The supply corresponds to evaporation at the potential rate and can be formulated as

$$\lambda E_{g,S} = \frac{\rho\,C_p}{\gamma}\,\frac{e_g - e}{r_a}\,, \tag{7.1}$$

with

$$e_g = e_s(T_g)\,\exp\left\{\frac{-g\,\Phi(0)}{R_W\,T_g}\right\}\,, \tag{7.2}$$

where T_g is the ground temperature; g is the gravitational constant; $\Phi(0)$ is the soil water suction; and, R_W is the water vapor gas constant. To compute the latent heat flux from the ground, only e_g needs to be approximated. The system is then solved in a straightforward fashion. The demand is computed as a function of soil moisture and diffusivity.

8. THE WATER BALANCE

Once the total evaporative flux from the ground and the vegetation has been determined, it is still necessary to compute the runoff to be able evaluate the soil moisture content. At this stage, the soil moisture submodel does not differ greatly conceptually from the one developed by Dickinson (1984). The simplifications and generalizations required to enable the coupling with a forest stand dynamics model constitute the main contributions in this part of the work.

The soil is divided into two layers of arbitrary depth. The soil column is assumed to be uniform, *i.e.*, the physical characteristics of the soil do not change with depth. The distribution of roots is a function of the vegetation and any configuration is possible: there can be roots in the top layer alone, in the bottom layer, or in both.

9. RUNOFF

At this point, runoff is computed as the product of the amount of water received as precipitation at the surface and a maximum infiltration rate. This maximum infiltration rate is a function of the soil moisture and the soil texture. The slope of the terrain as well as the density of the vegetation cover at the ground surface are not taken into account despite their recognized importance.

10. MOVEMENT OF WATER IN THE SOIL

Movements of water in the soil may be characterized in five different fashions: (a) capillary rise, (b) gravitational drainage, (c) infiltration from the surface, (d) uptake by the roots, and (e) supply by a water table. (a), (b), (c), and (d) are taken explicitly into account. Capillary rise is a function of the soil water potential gradient between the two layers. Gravitational drainage is a function of the soil moisture in the layer and the ability of water to diffuse through a soil with those given physical properties. Infiltration was described in the runoff section. Finally, uptake by roots is determined by the evaporative flux and the root density. Though it does not exist in the present version of the model, the supply of water from the water table should be relatively easy to include.

11. CONCLUSION

A new land-surface scheme was designed to be coupled with gap-phase and other vegetation models. It treats explicitly feedbacks between the vegetation and the atmosphere.

The next steps in the development of this scheme are to test accuracy and evaluate the physical realism of those parameterizations which have not yet been tested and evaluated. Once this work is completed, the model will be linked to a series of vegetation models of increasing complexity and the combined models will be tested again.

The projected uses of the model are varied. Its main purpose however is to examine how changes in climate may affect the vegetation of the globe. Hence, two major avenues are to be explored. On the one hand, it is desirable to understand better the dynamics taking place within ecotones and on the other to simulated the potential changes in global vegetation cover. It should be possible to use the model both with very detailed ecosystem models of gap-phase dynamics and global vegetation models simulating only vegetation functional types. Given the required data and an appropriate vegetation model, this model should provide enough flexibility to study a wide range of questions.

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