

A multilayer biochemical dry deposition model

1. Model formulation

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[1] A multilayer biochemical dry deposition model has been developed based on the NOAA Multilayer Model (MLM; *Meyers et al.* [1998]) to study gaseous exchanges between the soil, plants, and the atmosphere. Most of the parameterizations and submodels have been updated or replaced. The numerical integration was improved, and an aerodynamic resistance based on Monin-Obukhov theory was added. An appropriate parameterization for the leaf boundary layer resistance was chosen. A biochemical stomatal resistance model was chosen based on comparisons of four different existing stomatal resistance schemes. It describes photosynthesis and respiration and their coupling with stomatal resistance for sunlit and shaded leaves separately. Various aspects of the photosynthetic process in both C₃ and C₄ plants are considered in the model. To drive the photosynthesis model, the canopy radiation scheme has been updated. Leaf area index measurements are adjusted to account for stem area index. A normalized soil water stress factor was applied to potential photosynthesis to account for plant response to both drought and water-logging stresses. A new cuticle resistance model was derived based on membrane passive transport theory and Fick's first law. It accounts for the effects of diffusivity and solubility of specific gases in the cuticle membrane, as well as the thickness of the cuticle membrane. The model is designed for use in the nationwide dry deposition networks, for example, the Clean Air Status And Trends Network (CASTNet), and mesoscale models, for example, the Community Multiscale Air Quality model (CMAQ) and even the Weather Research and Forecasting model (WRF). *INDEX TERMS*: 0315

Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Atmospheric Composition and Structure: Constituent sources and sinks; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS*: multilayer, biochemical, dry, deposition, model

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1. Introduction

[2] Interest in gaseous exchanges between the biosphere and atmosphere has been increasing with recognition of their significant effects on atmospheric chemistry, ecosystem health and climate changes. Emissions of some major gases (such as oxygen and nitrogen) from biota play a crucial role in maintaining the present chemical compositions of the atmosphere. Emissions or uptake of some important trace gases (such as carbon dioxide, water vapor

and ozone) by plants also affects the atmospheric state by directly or indirectly influencing the equilibrium of the Earth climate system [*Brasseur and Chatfield*, 1991]. Meanwhile, atmospheric deposition provides biota with both pollutants and nutrition, causing crop loss and decline in many forests, particularly those growing at higher elevations in Europe and North America [*Aamlid et al.*, 1990; *Bruck*, 1989; *de Steiguer et al.*, 1990]. Deposition of NH_x, SO_x and NO_y is a major contributor to ecosystem acidification. Deposition of NH_x and NO_y to plant communities can cause loss of semi-natural grass and heathlands, as well as decrease forest vitality [*Sutton et al.*, 1996].

[3] Field measurement methods and numerical models have been developed to quantify these exchanges and assess their effects [*Bennett et al.*, 1973; *Wesely*, 1989; *Hicks et al.*, 1991; *Katul et al.*, 1996; *Meyers et al.*, 1998; *Pleim et al.*, 1999]. A common simulation method used to calculate gas

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exchange is an analog to Ohm's law, the resistance model of gas transfer, and can be expressed as:

$$F_c = \frac{C_a - C_i}{R_{Total}} \quad (1)$$

where F is the flux of a specific gas; C_a and C_i are the ambient and surface (or intercellular) gas concentrations, respectively; R_{Total} is the total resistance. Many models presented in the literature use the resistance model framework, including the *Meyers et al.* [1998] Multilayer Model (MLM) and the Regional Acid Deposition Model (RADM; *Wesely* [1989]).

[4] One of the major tasks in solving the above equation is the parameterization of the total resistance. The total resistance usually includes the aerodynamic resistance for the turbulent layer (R_A), the laminar layer resistance for the quasi-laminar layer (R_B) and the surface or canopy resistance for the receptor itself, in series. The canopy resistance includes the stomatal and cuticular resistance (R_S and R_{Cut}) as well as the soil surface resistance (R_{Soil}) in parallel. To study the gas exchange between the atmosphere and the biosphere, the parameterization of stomatal resistance and cuticular resistance is very important. The main objective of this paper is to present developments in the parameterization of the above resistances.

[5] This work started with the MLM, as an attempt to assess its strengths and weaknesses and address the latter. Since many of the components and submodels have been replaced, we propose the name "Multilayer Biochemical" model (MLBC) for the new model, presented herein. As the MLM is the reference model, we will discuss the development of the MLBC model in terms of changes to the MLM. The MLBC model framework and basic equations are described in section 2.1. An improved parameterization of the vertical distribution of Leaf Area Index is presented in section 2.2, followed by an updated canopy radiation scheme in section 2.3. Descriptions of the aerodynamic and (leaf) boundary layer resistance parameterizations follow in sections 2.4 and 2.5. A biochemical stomatal resistance scheme is detailed in section 2.6. A simplified available soil water budget is presented in section 2.6.2, and a cuticular resistance scheme in section 2.7. A soil surface resistance scheme is presented in section 2.8, followed by a short summary in section 3. Model sensitivities and validation against measured data will be shown in a companion article [*Wu et al.*, 2002].

2. Model Description

2.1. Model Framework

[6] The conservation equation for concentration of a scalar C , under steady state, horizontally homogeneous conditions, is

$$\frac{\partial F_c}{\partial z} = S(z) \quad (2)$$

Thus the vertical flux divergence is due to sources and sinks $S(z)$, accounting for emission and uptake processes below the canopy top. Integrating equation (2) from the soil

surface to the canopy top (h_c) yields the total ecosystem flux F_c [*Meyers et al.*, 1998]

$$F_c = \frac{-C_a}{\left(R_A + \frac{1}{\int_0^{h_c} S(z) dz + \frac{1}{R_{Soil} + R_{Soil}}} \right)} \quad (3)$$

where R_A is the aerodynamic resistance accounting for turbulent transfer above the canopy, and R_{Soil} accounts for turbulent diffusion near the bottom of the canopy. R_{Soil} accounts for deposition directly to the ground, the lower boundary condition of the integral. The sign convention is such that positive fluxes are upward, and the concentration of a gas species in the free air within the canopy is assumed to be equal to its value directly above the canopy (i.e. there is no sink within the air, only the plant surfaces and the ground act as sinks). This assumption may not be accurate for some gas species. The denominator of equation (3) is the reciprocal of the deposition velocity V_D .

[7] The source/sink term $S(z)$ is parameterized using terms to account for fluxes through the stomata of sun-lit and shaded leaves, and for fluxes through the cuticles of the leaves:

$$S(z) = \frac{N_S F_{SAI} F_{SL}(z) LAI(z)}{R_B(z) + R_{S,SL}(z)} + \frac{N_S F_{SAI} (1 - F_{SL}(z)) LAI(z)}{R_B(z) + R_{S,SH}(z)} + \frac{2 LAI(z)}{R_B(z) + R_{Cut}} \quad (4)$$

where $LAI(z)$ is the single-sided Leaf Area Index, F_{SAI} is the stem area correction factor, $F_{SL}(z)$ is the fraction of sun-lit leaves, R_{Cut} is the cuticular resistance, and $R_B(z)$ is the (leaf) boundary layer resistance that accounts for molecular diffusion. Equation (4) shows that the three pathways are combined in parallel and weighted by the amount of Leaf Area participating in the exchange. The factor of 2 in the last term accounts for the fact that both sides of the leaf participate in cuticular exchange; while N_S is the number of sides of the leaf that have stomata (1 or 2, and 1 was used in this study). This source term may be augmented by adding terms for additional plant types, e.g. $S(z) = S_{Plant1}(z) + S_{Plant2}(z) + \dots$ with appropriately chosen values for the resistances and the LAI for each plant type.

[8] The MLM model used rectangular integration to numerically compute the integral in equation (3) [*Meyers et al.*, 1998]. The canopy is divided into $N = 20$ equally spaced levels; $S(z)$ is evaluated at each height, and summed with appropriate normalization. The drawback of rectangular integration is that it converges slowly with increasing N . Gaussian quadrature [*Press et al.*, 1992] converges much faster, and is used in the MLBC model to numerically compute the integral in equation (3).

[9] It is important to integrate the full R.H.S. of equation (4), not the individual factors. It is tempting to use the relative conceptual clarity of rectangular quadrature, and concentrate on taking an appropriate average over each layer of the functions. However, this is tantamount to integrating each function (an "appropriate average") separately and combining them in an equation similar to

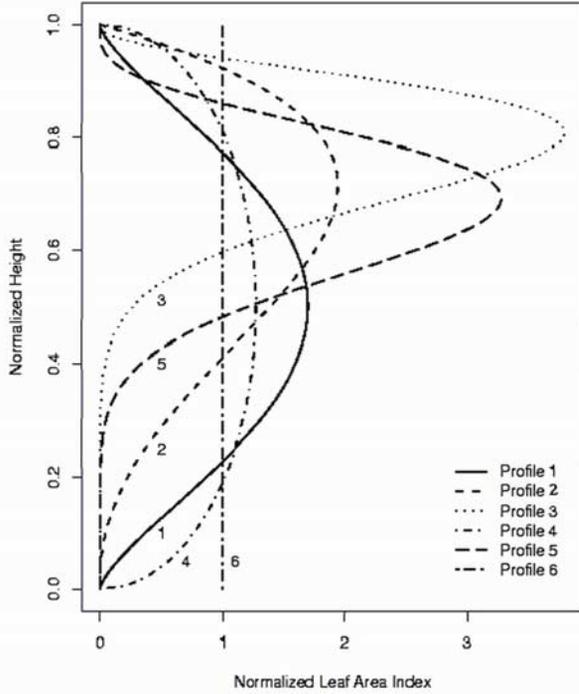


Figure 1. Profile of the (beta) distribution of $LAI(z)$ for the values listed in Table 1 plus the constant profile.

equation (4) to yield a single-layer model. If $R_B(z)$ and $LAI(z)$ were constant with height (compare sections 2.2 and 2.5) then it would be possible to find e.g. an integral-average F_{SL} for the whole canopy, and treat all the sun-lit leaves as one “big” leaf, since they all receive the same direct beam regardless of how deep in the canopy they actually are. However, the diffuse radiation falling on both sun-lit and shaded leaves would still be a function of height (a function of the amount of LAI above). There may also be other inputs to the photosynthesis model that vary with height, such as temperature. Thus there are inherent non-linearities ignored in such single-layer models, in addition to the added complexity of varying profiles of LAI and boundary layer resistance.

2.2. Leaf Area Index

[10] Following *Massman* [1982], $LAI(z)$ is assumed to be described by a beta distribution:

$$LAI(z) = a_1 \left(1 - \frac{z}{h_c}\right)^{a_2} \left(\frac{z}{h_c} - a_3\right)^{a_4} LAI_T \quad (5)$$

where a_i ($i = 1,2,3,4$) are constants, and LAI_T is the total measured (field) value, interpolated between available measurements. This form was chosen for compatibility with the roughness length and displacement height model of *Massman* [1997], which is used in our model as well. Plant canopy structures are fit by one of six profiles, shown in Figure 1. Table 1 lists the values of a_i used in this study and the companion article [*Wu et al.*, 2002]. Since a_1 is a normalizing value (such that the integral of

$LAI(z)/LAI_T$ from zero to h_c is 1) it must have many significant digits. The first three profiles were taken from *Meyers et al.* [1998]. Two more were constructed to span/increase the range of the MLM profiles, and one was constructed to be constant with height. For all varying profiles, a_3 was set to zero so that $LAI(0) = 0$, but this is not a requirement of the model and the more general $a_3 \neq 0$ is acceptable. For example, soybeans, maize, wheat and grass are assumed to be well described by profile 1, spruce and deciduous trees are assigned profile 2, and pine trees are assigned profile 3.

[11] The Stem Area Index (SAI) is the normalized area of the nonleaf portion of the plant, and consists of stems, branches, trunks, etc. The SAI can intercept light and so must be taken into account in the canopy radiation scheme. It may participate in cuticular deposition, yet it does not (generally) have stomata. Additionally, some plant species have a quasi-fixed SAI (full-grown trees) while others have a seasonally increasing SAI (annual crops). The proportion SAI/LAI will be at its minimum during the middle of the growing season, and ignoring the SAI is expected to have the smallest impact then. To account for the SAI, a correction factor is used:

$$F_{SAI} = \begin{cases} 1 - \frac{SAI_E}{LAI_T} & LAI_T < LAI_{Max} - 1 \ \& \ Jday < Jday_{Max} \\ 1 - \frac{fSAI_E + (1-f)SAI_L}{LAI_T} & LAI_T \geq LAI_{Max} - 1 \ \& \ Jday < Jday_{Max} \\ 1 - \frac{fSAI_L + (1-f)SAI_A}{LAI_T} & LAI_T \geq LAI_{Max} - 1 \ \& \ Jday \geq Jday_{Max} \\ 1 - \frac{SAI_L}{LAI_T} & LAI_T < LAI_{Max} - 1 \ \& \ Jday \geq Jday_{Max} \end{cases} \quad (6)$$

where SAI_E is the early season SAI, SAI_L is the late season SAI, $SAI_A = (SAI_E + SAI_L)/2$ is their average, $Jday$ is the Day of the Year (DOY), LAI_{Max} is the maximum LAI occurring on DOY day $Jday_{Max}$, and $f = (LAI_{Max} - LAI_T) / ((LAI_{Max} - 1) - LAI_{Max})$ is a linear interpolation factor. Thus $F_{SAI}LAI_T$ is like $(LAI_T - SAI)$ with an SAI that has been linearly interpolated between its early and late season values over the range when LAI_T was within 1 unit of its maximum value. This interpolation method preserves both the early and late season values, while performing the transition during the period of maximum LAI, when the SAI correction has the least impact. For forests, the SAI is not allowed to exceed 75% of the observed LAI. For crops, the SAI is not allowed to exceed 25% (75%) of the observed LAI during the early (late) season. This method is applicable for both forests that have a quasi-constant SAI, and annual crops that have a variable SAI. A seasonal plant growth model that partitions assimilated CO_2 between stems and leaves could have been used, but this is left for

Table 1. Parameters Used to Parameterize the (Beta) Distribution of Leaf Area Index^a

Profile Number	a_1	a_2	a_3	a_4
1	13.581218	1.5	0	1.5
2	15.749999	1.0	0	2.5
3	2204.4804	2.5	0	10.5
4	2.5464857	0.5	0	0.5
5	10009.999	4.0	0	9.0

^a Here, a_1 is a normalizing factor such that the integral of the profile is unity.

Table 2. Plant Species-Specific Parameter Used in the Model^a

Plant Species	F'_{Clump} Canopy Clumping Factor	A_{Can} Canopy Aspect Ratio	χ Ellipsoidal Leaf Angle Parameter	SAI_E Early Season SAI	SAI_L Late Season SAI	X Cuticle Thickness, 10^{-6} m
Spruce	0.4	5.5	1.0	0.5	0.5	2.2
Pond/Lodge Poll Pine	0.5	3.5	1.0	1.5	1.5	1.0
Loblolly pine	0.5	3.5	1.0	1.5	1.5	1.0
White Oak	0.9	1.0	1.0	1.5	1.5	2.5
Chestnut/Red Oak	0.9	1.0	1.0	1.5	1.5	2.5
Maple	0.95	1.0	1.0	0.5	0.5	3.0
White Birch	0.7	1.75	1.0	1.5	1.5	2.5
Beech	0.7	1.75	1.0	0.7	1.0	3.5
Aspen	0.7	1.75	1.0	1.5	1.5	2.0
Maize	1.0	1.0	1.37	0.5	2.0	3.5
Wheat	1.0	1.0	0.96	0.5	0.5	1.0
Soybean	1.0	1.0	0.81	1.0	2.0	1.0
Grass	1.0	1.0	1.0	0.5	0.5	0.5
Blue Grass	1.0	1.0	1.0	0.5	0.5	0.5

^a F'_{Clump} , A_{Can} and χ are from *Campbell and Norman* [1998]. The SAI values are from *Meyers et al.* [1998] where available. The X values are from *Kerstiens* [1996].

future work. Values of SAI_E and SAI_L for various plant species are Table 2.

2.3. Canopy Radiation

[12] The vertical profile of absorbed photosynthetically active radiation (PAR) in the canopy is calculated following *Campbell and Norman* [1998] and *de Pury and Farquhar* [1997]. Beer's law is used to calculate the attenuation (transmissivity) of both the direct beam (τ_b) coming from the sun, and the diffuse (τ_d) radiation coming from all parts of the sky. The transmissivity is given by

$$\tau_b(z, \Theta) = F_{SL}(z) = \frac{I_b(z)}{I_{b0}} = \exp\left(-\frac{\sqrt{1-\sigma}F_{Clump}K_bL_{Cum}(z)}{\cos\Theta}\right) \quad (7)$$

where I_b is the radiation intensity in the beam, F_{Clump} is a canopy clumping factor, K_b is the extinction coefficient for the direct beam, and Θ is the solar zenith angle. σ is the scattering coefficient, equal to the sum of the transmissivity τ_{leaf} and reflectivity ρ_{leaf} , and accounts for forward "scattering" by the leaves. $L_{Cum}(z)$ is the numerical integral of equation (5) from z to h_c , i.e. the cumulative LAI between the top of the canopy and the height z . I_{b0} is the intensity of the direct beam at the top of the canopy, and is calculated following *Weiss and Norman* [1985], as is the intensity of the diffuse radiation at the top of the canopy (I_{d0}). The canopy clumping factor is corrected for the solar zenith angle (Θ) following *Campbell and Norman* [1998]:

$$F_{Clump} = \frac{F'_{Clump}}{\left[F'_{Clump} + (1 - F'_{Clump})\exp(-2.2\Theta^{3.8-0.46A_{Can}})\right]} \quad (8)$$

where F'_{Clump} is the tabulated value, and A_{Can} is the aspect ratio (depth/diameter) of the canopy crown. Values for uncorrected F'_{Clump} and A_{Can} are listed in Table 2.

[13] The extinction coefficient for beam radiation (K_b) is calculated using an ellipsoidal leaf angle distribution [*Campbell*, 1986; *Campbell and Norman*, 1998],

$$K_b = \frac{\sqrt{\chi^2 + \tan^2(\Theta)}}{\chi + 1.744(\chi + 1.182)^{-0.733}} \quad (9)$$

where χ is something like an "aspect ratio" of the leaf angle distribution. $\chi = 1$ for a spherical leaf angle distribution, $\chi = 0$ for a vertical distribution, and $\chi \rightarrow \infty$ for a canopy of horizontal leaves. For example, $\chi_{soybean} = 0.81$ and $\chi_{corn} = 1.37$ [*Campbell and Norman*, 1998].

[14] To find the extinction coefficient for diffuse radiation, the radiation incident on shaded leaves is treated as if it were direct-beam radiation coming from all angles. The integral is numerically evaluated as:

$$\tau_d = 2 \int_0^{\pi/2} \tau_b(\Theta) \sin \Theta \cos \Theta d\Theta \quad (10)$$

where five Gaussian quadrature points was found to yield sufficient accuracy. The equivalent diffuse extinction coefficient is found by inverting a simplified version of equation (7):

$$K_d = -\frac{\ln(\tau_d)}{LAI_{Total}} \quad (11)$$

For a given profile $LAI(z)$, clumping factor F_{Clump} , and canopy aspect ratio A_{Can} , K_d is a smooth function of only three variables: the elliptical leaf angle distribution parameter χ , the total leaf area index LAI_T , and the scattering coefficient σ . If the sensitivity of the model to [$LAI(z)$, F_{Clump} , A_{Can}] is not too great, it would be possible to set them at a central value and parameterize K_d in terms of simple functions of [χ , LAI_T , σ]. Such a parameterization would speed computation time somewhat, which is critical for regional scale modeling where the same model is run at many grid points.

[15] Within the canopy-soil system, the reflectance for direct-beam radiation, $\rho_{b,cs}$ is found by using the reflectance of the canopy ($\rho_{b,c}$) [*Goudriaan*, 1988]

$$\rho_{b,c} = \frac{2K_b}{1 + K_b} \left(\frac{1 - \sqrt{1 - \sigma}}{1 + \sqrt{1 - \sigma}} \right) \quad (12)$$

in an equation appropriate for both dense and sparse canopies [Monteith and Unsworth, 1990],

$$\rho_{b,cs} = \frac{\rho_{b,c} + \left[\frac{\rho_{b,c} a_g}{\rho_{b,c} a_g - 1} \right] \exp(-2\sqrt{1 - \sigma} F_{Clump} K_b LAI_{Total})}{1 + \rho_{b,c} \left[\frac{\rho_{b,c} a_g}{\rho_{b,c} a_g - 1} \right] \exp(-2\sqrt{1 - \sigma} F_{Clump} K_b LAI_{Total})} \quad (13)$$

where a_g is the albedo of the ground. The diffuse reflectance of the canopy-soil system, $\rho_{d,cs}$, is found using equations (12) and (13) with K_d in place of K_b . The photosynthetically active radiation (PAR) absorbed by shaded leaves is then [de Pury and Farquhar, 1997]

$$\begin{aligned} PAR_{SH}(z) = & I_{d0} K_d (1 - \rho_{d,cs}) \exp[-K_d F_{Clump} LAI_{Cum}(z)] \\ & + I_{b0} \left(\sqrt{1 - \sigma} K_b (1 - \rho_{b,cs}) \right. \\ & \cdot \exp[-\sqrt{1 - \sigma} K_b F_{Clump} LAI_{Cum}(z)] \left. \right) - K_b (1 - \sigma) \\ & \cdot \exp[-K_b F_{Clump} LAI_{Cum}(z)] \end{aligned} \quad (14)$$

while the PAR absorbed by sun-lit leaves is

$$PAR_{SL}(z) = PAR_{SH}(z) + I_{b0} K_b (1 - \sigma) \quad (15)$$

With the specifications $\tau_{leaf} = 0.01$, $\rho_{leaf} = 0.08$, and $a_g = 0.10$, these equations fully describe the PAR absorbed by both shaded and sun-lit leaves.

2.4. Aerodynamic Resistance

[16] The aerodynamic resistance (R_A) accounts for turbulent diffusion above the canopy: the stronger the atmospheric turbulence, the smaller the aerodynamic resistance. The MLM parameterized R_A as inversely proportional to the wind speed and the square of standard deviation of the wind direction (σ_θ). The constant of proportionality was 9 during the day and 4 at night, and σ_θ was constrained to be below certain critical values. For wind speeds $< 2 \text{ m s}^{-1}$, the proportionality constant was linearly increased to 50. This parameterization is very similar to that used by the RADDM model, is discontinuous, and relies on an assumed correlation between σ_θ and stability. It was developed to be useable with simple field measurements, in nonideal conditions.

[17] In the MLBC model, R_A is parameterized using Monin-Obukhov similarity theory by assuming that the turbulent diffusion of a trace gas is similar to the turbulent diffusion of sensible heat [Wesely and Hicks, 1977]:

$$R_A = \int_{D+z_0}^z \frac{\phi_h(z/L)}{ku_* z} dz = \frac{\text{Pr}}{ku_*} \left[\ln \frac{z - D - z_0}{z_0} - \Psi_m \left(\frac{z - D}{L}, \frac{z_0}{L} \right) \right] \quad (16)$$

We use the standard definition of the atmospheric surface layer [e.g., Stull, 1988; Liu et al., 1979]

$$U_a = \frac{u_*}{k} \left[\ln \left(\frac{z_U - D - z_0}{z_0} \right) - \Psi_m \left(\frac{z - D}{L}, \frac{z_0}{L} \right) \right] \quad (17)$$

$$\theta_a - \theta_0 = \text{Pr} \frac{T_*}{k} \left[\ln \left(\frac{z_T - D - z_{0h}}{z_{0h}} \right) - \Psi_h \left(\frac{z - D}{L}, \frac{z_{0h}}{L} \right) \right] \quad (18)$$

$$q_a - q_0 = \text{Pr} \frac{q_*}{k} \left[\ln \left(\frac{z_q - D - z_{0h}}{z_{0h}} \right) - \Psi_h \left(\frac{z - D}{L}, \frac{z_{0h}}{L} \right) \right] \quad (19)$$

$$L = \frac{\theta u_*^2}{kg (T_* (1 + 0.61q) + 0.61q_* \theta)} \quad (20)$$

where Pr is the Prandtl number; k is the von Karman constant; u_* is the friction velocity; T_* and q_* are the temperature and humidity scale; z_U , z_T and z_q are the heights of the measurements of wind speed U_a , potential temperature θ_a and specific humidity q_a , respectively; D is the displacement height; z_0 and z_{0h} are the roughness lengths for momentum and sensible heat; $\Psi_{m,h}$ are the stratification correction terms; and L is the Obukhov length. We take the forms for the Ψ -functions from Högström [1988], and use the model of Massman [1997] for z_0 and D .

[18] R_B is often defined in theoretical studies as $(ku_*)^{-1} \ln(z_0/z_{0h})$ [Massman, 1999]. It is important to note that because an R_B term is included in equation (4), z_{0h} must be taken equal z_0 in the surface-layer equations (17)–(20). One should use an R_B term, or a z_{0h} different from z_0 , but not both. Using both would account for the boundary-layer effect twice. If a model for z_{0h} over vegetated surfaces were available, as is the case for over water surfaces [Liu et al., 1979], then R_B could be eliminated from equation (4) and the issues its parameterization raises (see section 2.5) could be sidestepped. It is also important to note that θ_0 and q_0 are not measurable quantities. They are the temperature and specific humidity obtained by extrapolating a constant-flux profile (strictly valid only above the canopy) to the displacement height (within the canopy). We use two measurements of θ_a taken in the constant-flux layer, evaluate equation (18), with those values along with their measurement heights $z_{1,2}$, and subtract the two equations to yield a single equation for T_* in terms of $\theta_a(z_2) - \theta_a(z_1)$. If humidity measurements are available at only one height in the constant-flux layer, eliminating equation (19) and the last term in the denominator of the Obukhov length (equation 20) will incur an error only on the order of the virtual temperature correction. Note that especially over very rough surfaces such as forests, z_0 is not necessarily negligible compared to $(z - D)$ and must be kept in the numerator of the logarithmic terms. Equations (17)–(20) must be solved iteratively, typically requiring 3–5 iterations if using an adequate iteration acceleration scheme. Required inputs include $U_a(z_U)$, $\theta_a(z_{T1})$, $\theta_a(z_{T2})$, z_U , z_{T1} and z_{T2} , with $q_a(z_{q1})$, $q_a(z_{q2})$, z_{q1} and z_{q2} if available.

2.5. Boundary-Layer Resistance

[19] The boundary-layer resistance (R_B) accounts for the molecular diffusion layer just above a stationary surface, where turbulence is suppressed and molecular diffusion dominates over turbulent diffusion. Usually, R_B is taken to be proportional to the inverse of the Stanton (Dalton) number B , and is parameterized by

$$R_B(z) = \frac{B^{-1}}{u_*} = C \frac{\text{Re}(z)^r \text{Sc}^s}{ku_*} \quad (21)$$

where Re is the Reynolds number, $\text{Sc} = (\nu/D)$ is the Schmidt number, C is a constant that must be determined

experimentally, and r and s are exponents that specify the form of the equation (see below). D is the diffusivity of the gas of interest, and ν is the kinematic viscosity of air. Substitute the Prandtl number Pr for Sc to find an R_B for heat transfer. The Reynolds number may be constructed using the wind speed in the canopy $U(z)$ and a typical leaf dimension D_L :

$$Re(z) = \frac{U(z)D_L}{\nu} \quad (22)$$

[20] The values for the exponents (r,s) in equation (21) are not clear [Brutsaert, 1979]. For aerodynamically smooth surfaces, $(r,s) = (0,2/3)$. Assuming the leaves act as flat plates horizontal to the wind and applying typical engineer arguments leads to $(r,s) = (1/5,2/3)$. The Pohlhausen model of laminar flow with weak hydrodynamic interaction between foliage elements (essentially, the wake from one leaf does not affect the turbulence near another leaf too much) leads to $(r,s) = (1/2,2/3)$. Assuming the wind speed profile near the surface is linear leads to $(r,s) = (1/3,2/3)$ while assuming it is constant due to intense mixing leads to $(r,s) = (1/2,1/2)$. Applying Brutsaert's [1975] surface renewal theory leads to $(r,s) = (1/4,1/2)$, even if Re is constructed using $(z-D)$ in place of D_L as given by Shreffler [1976]. These values are summarized in Table 3.

[21] The MLM used the Pohlhausen model and constructed R_B with $U(z)$ in place of u^* , and the RADM model used the aerodynamically smooth flow model. Even with the larger $U(z)$ (compared with u^*) in the denominator, it is found that in the MLM, R_B was often the limiting resistance during the middle of the day. This caused the model to under-predict the highest deposition velocities. Garrett and Hicks [1973] found little dependence on Re for cereal and grain crops, and concluded that fibrous roughness elements did not behave as the bluff-like roughness elements that are the basis for most of the arguments listed above. They also found that $C \sim 2$. Erisman et al. [1994] used a formula similar to (21) with $r = 0$, $C = 2$, and Sc replaced by (Sc/Pr) with $Pr = 0.72$.

[22] Due to the above controversy in the exponents and motivated to keep the number of arbitrary parameters such as D_L to a minimum, the MLBC model uses the R_B form for aerodynamically smooth flow: $(r,s) = (0,2/3)$ with $C = 2$. Since R_B is most often not the limiting resistance, model output will be somewhat insensitive to the exact formulation except during times of both very low aerodynamic and stomatal resistances. Note that by eliminating the dependence of R_B on Re , its dependence on height is also eliminated, since u^* does not depend on height in the MLBC model.

2.6. Stomatal Resistance

[23] Stomatal opening and closure is controlled by a number of internal and environmental factors. Under natural growing conditions the most important environmental factors are: incident quantum flux density (light), water supply to a leaf, humidity of ambient air, leaf temperature, and the concentration of CO_2 inside and outside a leaf. Generally, these factors have both direct and indirect effects on stomatal movement. Their effects are also tightly coupled, which makes it very difficult to distinguish their

Table 3. Values of the Exponents in the Parameterization of the Boundary Layer Resistance, for Various Assumptions Mentioned in the Text

	Smooth Flow	Flat Plate	Pohlhausen	Linear Profile	Intense Mixing	Surface Renewal
r	0	1/5	1/2	1/3	1/2	1/4
s	2/3	2/3	2/3	2/3	1/2	1/2

relative contributions. Their indirect effects are usually expressed through other biological processes, such as photosynthesis, respiration etc. The actual mechanisms by which some of the factors regulate stomatal opening are not well understood.

[24] Several different methods have been proposed to parameterize stomatal resistance. Jarvis [1976] proposed a simple explicit parameterization scheme for stomatal conductance by scaling the maximum stomatal conductance with a global radiation function, a specific humidity deficit function, an air temperature function, and a soil moisture deficit function. Such a model assumes that the various environmental factors act independently and ignores their interactions, as well as indirect effects. Tardieu and Davies [1993] proposed that stomatal conductance was controlled by an integration of hydraulic and chemical signals. They considered leaf and root water potentials, water flux, and concentration of abscisic acid (ABA) in the xylem in their model. Their parameterization is based on a comprehensive data set collected for maize plants. Some of the ideas contained therein and some empirical parameters of their model need to be tested for other species of interest.

[25] Berry and Farquhar [1978], Farquhar et al. [1980], and Collatz et al. [1991, 1992] proposed a method to calculate stomatal conductance by considering photosynthesis and respiration processes. Jacobs et al. [1996] and Calvet et al. [1998] proposed very similar methods from different approaches. Compared with the Jarvis method and the Tardieu method, this one has the advantages of: (1) providing more insights into the biochemical mechanisms governing photosynthesis and respiration, and how they are tied to stomatal conductance (resistance); (2) considering the direct and indirect effect of environmental factors on stomatal conductance; and (3) taking into account the coupled effects of environmental factors through photosynthesis and respiration processes. The Berry-Farquhar approach is adopted in the MLBC model

2.6.1. Biochemical Scheme for Stomatal Resistance

[26] The photosynthesis rate for C_3 and C_4 plants is described as the minimum of the photosynthetic CO_2 uptake rates limited by enzyme effects (Rubisco carboxylation at high irradiance), w_c ; CO_2 uptake rates limited by light, w_e ; and CO_2 uptake rates limited by carbon compound export (C_3 plants) or PEP carboxylation (C_4 plants), w_s . Equations for w_c , w_e , and w_s are the following, respectively [Berry and Farquhar, 1978; Collatz et al., 1991, 1992]:

$$w_c = I_p V_m \left[\frac{C_i - \Gamma}{C_i + K_c(1 + O_2/K_o)} \right] + (1 - I_p) V_m \quad (23)$$

where I_p is a plant type index with a value of 1 for C_3 plants and 0 for C_4 plants, C_i is the concentration of CO_2 in

the intercellular air spaces of the leaf, V_m is the maximum carboxylation rate (catalytic capacity of the CO₂-fixing enzyme), Γ is the CO₂ compensation point inside the leaf, O_2 is the concentration of oxygen inside the leaf, and K_c and K_o are the Michaelis-Menten constants for CO₂ and O₂.

$$w_e = I_p J \left[\frac{c_i - \Gamma}{c_i + 2\Gamma} \right] + (1 - I_p) J \quad (24)$$

where J is the incident flux of photosynthetically active photons.

$$w_s = I_p \frac{V_m}{2} + (1 - I_p) 10^4 \frac{V_m C_i}{P} \quad (25)$$

where P is the atmospheric pressure.

[27] To get a smooth transition from one limit to another and to allow some co-limitation between them, the gross photosynthesis rate (A) is given by the following two quadratic equations:

$$\alpha w_p^2 + w_p(w_e + w_c) + w_e w_c = 0 \quad (26)$$

$$\beta A^2 - A(w_p + w_s) + w_p w_s = 0 \quad (27)$$

where w_p is an intermediate term in the smoothing process, and α and β are two mathematical coupling coefficients.

[28] The net photosynthesis rate (A_n) is the difference between the gross photosynthesis rate and the respiration rate (R_d) from Collatz *et al.* [1991, 1992]:

$$A_n = A - R_d \quad (28)$$

[29] Finally, the stomatal conductance to water vapor is linked to the net photosynthesis by the following regression equation [Ball *et al.*, 1987]:

$$R_S^{-1} = \begin{cases} m \frac{A_n H P}{C_s} + b & \text{if } A_n \geq 0 \\ b & \text{if } A_n < 0 \end{cases} \quad (29)$$

where R_S is the stomatal resistance, H the relative humidity at leaf surface, P is the atmospheric pressure, and m and b are the stomatal conductance slope factor and minimum stomatal conductance, respectively. The stomatal resistance for specific gas of interest is given by:

$$R_{Si} = \left(\frac{D_{H_2O}}{D_i} \right) R_S \quad (30)$$

where D_{H_2O} and D_i are the molecular diffusivities of water vapor and the specified gas, respectively. For each level z_i , equations (23) through (30) are applied once using $PAR_{SL}(z_i)$ to yield $R_{S,SL}(z_i)$; and once using $PAR_{SH}(z_i)$ to yield $R_{S,SH}(z_i)$. A few iterations between equations (23) and (30) enable one to refine the estimation of R_S and R_{Si} .

2.6.2. Water Stress

[30] A water stress index is applied to the maximum carboxylation rate (V_m) to consider effects of drought and waterlogging on plant photosynthesis and stomatal opening.

The water stress index is expressed by the following empirical equation based on Wu *et al.* [1989]:

$$f_w = \begin{cases} 1 - (W_t - 0.75W_{sat})/W_{sat} & W_t > 0.75W_{sat} \\ 1 & 0.75W_{sat} \geq W_t \geq 0.75W_{fca} \\ 1 - (0.75W_{fca} - W_t)/(2.5(W_{fca} - W_{wil})) & W_t < 0.75W_{fca} \end{cases} \quad (31)$$

where f_w is the water stress factor; W_t is the available soil water content; W_{sat} , W_{fca} and W_{wil} are critical soil water contents at saturation, field capacity and the wilting point, respectively, and depend on soil type. Critical soil water contents for different soil types are available from Jacquemin and Noilhan [1990] and Schaap and Leij [1998]. The available soil water content (W_t) is calculated by the following simplified water budget equation (a so-called "bucket model"):

$$W_t = W_{t-1} - \frac{(LE_{Soil,t} + T_{P,t}) \frac{\Delta t}{\rho_a \nu} - P_{R,t}}{D_{Soil}} \quad (32)$$

where W_t is the available soil water content; the subscripts t and $t-1$ refer to the current and previous time steps, respectively; Δt is the length of the time step; D_{Soil} is the depth of the modeled soil layer; P_R the (measured) precipitation; LE_{Soil} the latent heat flux due to soil evaporation from equation (45); T_P the latent heat flux due to plant transpiration, calculated using equation (3) but with the air-leaf specific humidity difference ($q_i - q_a$) in the numerator in place of $-C_a$ and without the soil pathway (and converted to $W \text{ m}^{-2}$); q_a the specific humidity of the air measured above the canopy, and q_i the saturation specific humidity at the leaf temperature. If leaf temperature measurements are not available, the temperature corresponding to θ_0 in equation (18) can be used. If the initial value of W is not available, it can be taken to be half-way between W_{fca} and W_{sat} .

2.7. Cuticular Resistance

[31] Plant cuticles are a lipophilic polymer membrane that consists of an insoluble bipolymer cutin and waxlike lipids [Kerstiens, 1996]. The cuticular resistance (R_{cut}) includes three parts in parallel: the cuticular resistance for dry leaf surfaces (R_{cd}), the cuticular resistance for wet leaf surfaces (R_{cw}), and the surface resistance for wet leaf surfaces (R_{sfc}). The parameterizations of R_{cd} and R_{cw} are based on membrane transport theory, and can be expressed as:

$$R_{cd} = \frac{X_{cm}}{D_c K_{ca}} \quad (33)$$

where X_{cm} is the thickness of cuticle membrane (m), D_c is the diffusivity of a specific gas of interest in the cuticle ($\text{m}^2 \text{ s}^{-1}$), and K_{ca} is the cuticle/air partitioning coefficient for a specific gas; and

$$R_{cw} = \frac{X_{wm}}{D_w K_{wa}} + \frac{X_{cm}}{D_c K_{cw}} \quad (34)$$

where X_{wm} is the thickness of water film on the leaf, K_{wa} and K_{cw} are water/air and cuticle/water partitioning coefficients, respectively.

[32] The thickness of water film on the leaf, X_{wm} , is estimated by the following very simple empirical equation:

$$X_{wm} = 0.0003(H/100)^3 \quad (35)$$

where H is the relative humidity. Further research is needed for a better X_{wm} scheme, like the one described by *Xiao et al.* [2000].

[33] Assuming that the flux transferred through the water film on a leaf surface equals the flux transferred through the leaf cuticular layer, R_{cw} can also be expressed as:

$$R_{cw} = \frac{X_{wm}}{D_w K_{wa}} + \frac{X_{cm}}{D_c K_{wa} K_{cw}} \quad (36)$$

[34] The water/air partitioning coefficient (K_{wa}) for a species is the ratio of its aqueous-phase mass concentration (C_{aq}) to its gas-phase mass concentration (C_g) in equilibrium:

$$K_{wa} = \frac{C_{aq}}{C_g} \quad (37)$$

By assuming Henry's law equilibrium, we obtain:

$$K_{wa} = H_A R T_a \quad (38)$$

where H_A is the Henry's law coefficient, R the ideal gas constant, T_a the air temperature (K). According to *Seinfeld and Pandis* [1998], the Henry's law coefficient can be expressed as:

$$H_A(T_2) = H_A(T_1) \exp \left[\frac{\Delta H_A}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right] \quad (39)$$

where ΔH_A is the reaction enthalpy at constant temperature and pressure.

[35] Unfortunately, no similar equations are available for K_{wc} and K_{ca} for any chemicals. Octanol-water partitioning has been studied extensively, and the octanol-water partitioning coefficients for many organic compounds can be found in the published literature [*Leo et al.*, 1971; *Sangster*, 1997]. However, little information is available on the interaction of airborne compounds and plant cuticles. Several empirical (regression) methods have been proposed, such as utilization of octanol-water partitioning coefficients and molecule structure fragment values [*Vaes et al.*, 1998; *Meylan and Howard*, 1995], computation from molecular connectivity and water solubility [*Sabljic et al.*, 1990; *Chiou et al.*, 1982], and computation from boiling point temperatures [*Lendzian and Kerstiens*, 1991]. Following the method of *Sangster* [1997], *Sabljic et al.* [1990] and *Chiou et al.* [1982], the water/cuticle partitioning coefficient for a gas species in this study is estimated from its solubility by the following empirical equation:

$$\log K_{cw} = m_{cw} \log(S) + b_{cw} \quad (40)$$

By assuming that the air-water-cuticle-air system is in equilibrium, the cuticle/air partitioning coefficient can be estimated by:

$$K_{ca} = K_{cw} K_{wa} \quad (41)$$

[36] The presence of water on the cuticle plays a very important role in pollutant deposition. Water on a leaf surface acts as intermediate medium or a temporary sink for water-soluble gases, while it acts as a barrier for insoluble gases. Water on a leaf surface may also play an active role in influencing chemical processes on the leaf surface. *Fowler and Unsworth* [1979], and *Schuepp* [1989] found that the deposition velocity for SO_2 was several times higher when the plant was covered by dew than for dry conditions. *Weseley* [1989] reported that dew increased the deposition of SO_2 and decreased the deposition of O_3 . Observations by *Finkelstein et al.* [2000] also show that dew increases the deposition of SO_2 . Plant leaf surfaces exposed to the atmosphere are continuously exposed to water vapor, so the potential for the formation of molecular films is always present. According to *Flechard et al.* [1999], the sink strength of leaf surface is largely dependent on surface humidity and temperature. Dry deposition to leaf surface for most gas species is reversible. For example, thin water films on plant surface may behave as perfect sinks for NH_3 for a limited period of time, in wet conditions after rain or during dewfall. However, as a dew layer or intercepted rainwater evaporates from the leaf surface, NH_3 could be released from the evaporating water drops since the NH_3 molecule is not immediately 'destroyed.' *Mikhail and Robens* [1983] reported that a thin water film in the nanometer range was always present on surfaces at normal humidities in their investigation of a range of different hydrophilic materials. Depending on the air humidity, water on a leaf surface may exist as a thin film trapped in surface structures, as discrete droplets, or as a continuous liquid layer which overlays the detailed fine structure of leaf surface. Therefore, it is very important to consider the role of water when parameterizing cuticular resistance. An empirical equation based on dimensional analysis is used to compute wet leaf surface resistance R_{sfc} :

$$R_{sfc} = \left(\frac{1}{D_a K_{wa} X_{wm}} \right) \left(\frac{1}{(0.5 + |7.0 - pH|)} \right) \quad (42)$$

where pH is the pH value of leaf surface water. This equation needs further work in the future.

[37] Finally, the cuticular resistance (R_{cut}) which includes three parts in parallel: the cuticular resistance for dry leaf surface (R_{cd}), the cuticular resistance for wet leaf surface (R_{cw}), and the surface resistance for wet leaf surfaces (R_{sfc}), is expressed as

$$\frac{1}{R_{cut}} = \frac{1 - W_F}{R_{cd}} + \frac{W_F}{R_{cw}} + \frac{W_F}{R_{sfc}} \quad (43)$$

where W_F is a weighting factor for wet leaf surface area, and is given by the following empirical equation:

$$W_F = \begin{cases} 0 & (H < H_1) \\ \frac{H - H_1}{H_2 - H_1} & (H_1 \leq H \leq H_2) \\ 1 & (H > H_2) \end{cases} \quad (44)$$

where H_1 and H_2 are critical humidities. But, using humidity to define wet leaf portions is not accurate and thus equation (44) is only a tentative approach.

2.8. Soil Surface Resistance

[38] The soil surface resistance for water vapor is related to the length of the diffusion pathway through the soil [Stewart, 1984]. Wu *et al.* [1995] reported on four different kinds of methods for calculating soil surface resistance, and found that the theoretical analysis method gave the best estimate in their studies. The method is expressed as:

$$LE_{Soil} = \frac{(q_s - q_a)\rho_a L_v}{R_A + R_B + R_{Asoil} + R_{Soil}} \quad (45)$$

where LE_{Soil} is the latent heat flux from soil, ρ_a the air density (kg m^{-3}), L_v latent heat of evaporation (J/kg), q_s and q_a are the soil and air specific humidities (kg/kg), and R_{Asoil} is the aerodynamic resistance between the canopy and soil surface, following Meyers *et al.* [1998].

[39] Latent heat flux from the soil surface (LE_{Soil}) is calculated following Uchijima [1976]. The net radiation (R_n) measured at the top of the canopy is attenuated to the ground ($z = 0$) using equation (7), and a crop coefficient ($f = 0.75$) is applied:

$$LE_{Soil} = f\tau_b(0, \theta)R_n \quad (46)$$

[40] Ritchie [1972] proposed that there are two stages of soil evaporation. During stage 1, actual soil evaporation is limited by energy available for evaporation at the soil surface. During stage 2, soil evaporation declines with time. Therefore, when the soil is very dry, soil evaporation computed from the above equation is multiplied by a zero-to-one factor based on the water stress index. Rearranging equation (45),

$$R_{Soil} = \frac{(q_s - q_a)\rho_a L}{LE_{Soil}} - R_A - R_B - R_{Asoil} \quad (47)$$

The soil surface resistance for a specific gas of interest is calculated using a method similar to that of the stomatal resistance for that gas (compare equation (30)):

$$R_{Soil,i} = \left(\frac{D_{H_2O}}{D_i} \right) R_{Soil} \quad (48)$$

3. Summary

[41] We have presented a Multilayer Biochemical (MLBC) model for estimating chemical dry deposition using only routine meteorological and chemical concentration measurements. Our work is an attempt to build on the Multilayer Model (MLM) of Meyers *et al.* [1998]. We have updated many features of the original model, including the numerical integrations, the calculation of aerodynamic resistance, and the canopy radiation scheme. Several other features have been changed entirely, including the calculation of the (leaf) boundary layer resistance, aerodynamic resistance, and soil

surface resistance. Additionally, several biochemical sub-models have been added, to calculate the stomatal resistance and the cuticular resistance. These have been used in a traditional resistance-theory framework to allow the calculation of the vertical flux of various gaseous species, which can be easily divided by their ambient concentrations to calculate the deposition velocity. The new model accounts for the direct, indirect and tightly coupled effects of environmental factors on stomatal regulation of gaseous exchanges between plants and their environment. Only half-hourly to hourly averaged meteorological and chemical concentrations are required to find valid estimations of flux or deposition velocity.

[42] In the accompanying paper [Wu *et al.*, 2002] we explore the sensitivities of the model to parameter specifications and errors in the measured input variables. We also assess the overall performance of the MLBC model, using data gathered from several field studies over a variety of crops and forests.

[43] This model is immediately applicable to data gathered under several on-going programs, e.g. the Clean Air Status and Trends Network (CASTNet) and the Atmospheric Integrated Research Monitoring Network (AIRMoN-Dry). With a few modifications to minimize computational requirements, it would also be useful in regional scale air quality models, e.g. the Community Multiscale Air Quality (CMAQ) portion of the U.S. EPA's Models-3 package, and the new Weather Research and Forecasting model (WRF).

Notation

- a_g albedo of the ground, equal to 0.1.
- a_i LAI profile definition constants ($i = 1 \dots 4$, see Table 1).
- b minimum stomatal conductance.
- b_{wc} regression coefficient for K_{WC} (3.16).
- A gross photosynthesis rate, $\mu\text{mol m}^{-2} \text{s}^{-1}$.
- A_{Can} canopy crown aspect ratio, depth/diameter.
- A_n net photosynthesis rate, $\mu\text{mol m}^{-2} \text{s}^{-1}$.
- B Stanton number.
- C constant used in the R_B parameterization, equal to 2.0.
- C_a gas concentration in air above the canopy, ppb or ppm.
- C_{aq} aqueous-phase mass concentration of a chemical species, ppm.
- C_g gas-phase mass concentration of a chemical species, ppm.
- C_i gas concentration inside a leaf, ppb or ppm.
- C_s gas concentration at the surface of a leaf, ppb or ppm.
- D displacement height, m.
- $D_{Cut,i}$ molecular diffusivity in the cuticle, for a specific gas of interest, $\text{m}^2 \text{s}^{-1}$.
- D_{H_2O} molecular diffusivity of H_2O , equal to 0.2174×10^{-4} , $\text{m}^2 \text{s}^{-1}$.
- D_i molecular diffusivity in air, for a specific gas of interest, $\text{m}^2 \text{s}^{-1}$.
- D_L typical leaf dimension, m.
- D_{Soil} depth of the soil layer in simplified W budget, equal to 0.6, m.
- E_{Soil} evaporation from soil surface, W m^{-2} .

f	crop coefficient used in E_{Soil} parameterization (0.75).	$R_B(z)$	(leaf) boundary layer resistance, $s\ m^{-1}$.
f_w	water stress factor.	R_{Cut}	cuticular resistance, $s\ m^{-1}$.
F_c	Flux of a chemical species, positive upward, ppb $m\ s^{-1}$.	R_d	photorespiration rate ("dark respiration"), $\mu\text{mol}\ m^{-2}\ s^{-1}$.
F_{Clump}	canopy clumping factor.	$Re(z)$	Reynolds number.
F_{SAI}	Stem Area Index correction factor.	R_n	net radiation above the canopy, $W\ m^{-2}$.
$F_{SL}(z)$	fraction of sun-lit leaves.	R_S	stomatal resistance, $s\ m^{-1}$.
g	acceleration due to gravity, $m\ s^{-2}$.	$R_{S,SH}(z)$	stomatal resistance for shaded leaves, $s\ m^{-1}$.
h_c	height of the canopy, m .	$R_{S,SL}(z)$	stomatal resistance for sun-lit leaves, $s\ m^{-1}$.
H	relative humidity.	R_{Soil}	soil (ground) resistance, $s\ m^{-1}$.
H_A	Henry's law coefficient, $\text{mol}\ L^{-1}\ \text{atm}^{-1}$.	R_{Total}	total resistance, $s\ m^{-1}$.
H_1, H_2	critical humidities used in R_{Cut} parameterization, equal to 0.4 and 0.98, respectively.	s	exponent of the Schmidt number in R_B parameterization.
$I_b I_d$	intensity of beam and diffuse radiation, $W\ m^{-2}$.	$S(z)$	source or sink within the canopy, $m\ s^{-1}$.
I_p	plant type index, equal to 1 for C_3 and 2 for C_4 .	SAI_E, SAI_L	early and late season Stem Area Index.
J	incident flux of photosynthetically active photons, $\mu\text{mol}\ m^{-2}\ s^{-1}$.	Sc	Schmidt number.
k	von Karman's constant, equal to 0.4.	S_i	solubility of the chemical species of interest.
K_i	partitioning coefficient for the chemical species of interest.	$t, \Delta t$	time and averaging time of measurements above the canopy, s .
K_b, K_d	extinction coefficient for beam, diffuse radiation.	T_a	air temperature above the canopy, K .
K_c, K_o	Michaelis-Menten constants for CO_2, O_2 , Pa.	T_P	plant transpiration, $W\ m^{-2}$.
K_{ca}	cuticle/air partitioning coefficient.	T^*	log-layer temperature scale, K .
K_{wa}	water/air partitioning coefficient.	U_a	wind speed above the canopy, $m\ s^{-1}$.
K_{cw}	cuticle/water partitioning coefficient.	u^*	friction velocity, log-layer wind speed scale, $m\ s^{-1}$.
L	Obukhov length, m .	V_D	deposition velocity, $m\ s^{-1}$.
L_v	latent heat of vaporization for H_2O , $J\ kg^{-1}$.	V_m	maximum carboxylation rate, $\mu\text{mol}\ m^{-2}\ s^{-1}$.
$LAI(z)$	profile of (single-sided) Leaf Area Index.	w_i	weights used in Gaussian quadrature, with corresponding z_i .
LAI_T, LAI_{Max}	total and Maximum observed (measured) Leaf Area Index.	w_c, w_e, w_s	CO_2 uptake rate limited by enzyme capacity, light, and product export, $\mu\text{mol}\ m^{-2}\ s^{-1}$.
L_{Cum}	cumulative (integrated) $LAI(z)$, starting from canopy top.	W	available soil water content, $m^3\ m^{-3}$.
m	stomatal conductance slope factor.	$W(z)$	weighting function in Gaussian quadrature.
m_{wc}	regression coefficient used in K_{wc} parameterization (-0.68).	W_L	volume liquid water mixing ratio in air.
N	number of layers in a multilayer model.	W_F	humidity weighting factor used in R_{Cut} parameterization.
N_S	number of sides of leaves with stomata, equal to 1 or 2.	W_{fca}	soil water content at field capacity, $m^3\ m^{-3}$.
P	atmospheric pressure, kPa .	W_{sat}	soil water content at saturation point, $m^3\ m^{-3}$.
P_R	precipitation, m .	W_{wil}	soil water content at wilting point, $m^3\ m^{-3}$.
PAR_{SH}	photosynthetically active radiation absorbed by shaded leaves, $W\ m^{-2}$.	X	thickness of the leaf cuticle membrane, m .
PAR_{SL}	photosynthetically active radiation absorbed by sun-lit leaves, $W\ m^{-2}$.	z	height above the ground, m .
Pr	Prandtl number.	z_0, z_{0h}	roughness lengths for momentum and sensible heat, m .
q_a	specific humidity above the canopy, $kg\ kg^{-1}$.	z_U, z_T, z_q	height of wind speed, temperature and humidity measurements, m .
q_s	specific humidity at the leaf surface, $kg\ kg^{-1}$.	α	hyperbolic photosynthesis coupling coefficient.
q^*	log-layer humidity scale, $kg\ kg^{-1}$.	β	hyperbolic photosynthesis coupling coefficient.
r	exponent of the Reynolds number in R_B parameterization.	χ	ellipsoidal leaf angle distribution parameter.
R	ideal gas constant, equal to 287.04, $J\ deg^{-1}\ kg^{-1}$.	ΔH_A	Henry's law reaction enthalpy at constant temperature and pressure, $kcal\ mol^{-1}$.
R_A	aerodynamic resistance, $s\ m^{-1}$.	ϕ_h	nondimensional sensible heat structure function.
R_{Asoil}	aerodynamic resistance near the ground, $s\ m^{-1}$.	Γ	CO_2 compensation point inside a leaf, ppm .
		ν	kinematic viscosity of air, equal to $1.46 \times 10^{-5}, m^2\ s^{-1}$.
		θ_a	potential temperature, calculated from T_a , K .
		Θ	solar zenith angle, deg .

ρ_a	density of the air as above the canopy, kg m ⁻³ .
ρ_{leaf}	reflectivity of individual leaves, equal to 0.08.
$\rho_{b,c}$	reflectivity of the canopy for beam radiation.
$\rho_{b,cs}, \rho_{d,cs}$	reflectivity of the canopy-soil system for beam and diffuse radiation.
σ_θ	standard deviation of the wind direction, deg.
σ	Scattering coefficient for leaves, equal to $\tau_{leaf} + \rho_{leaf}$.
τ_b, τ_d	canopy transmissivity for beam and diffuse radiation.
τ_{leaf}	transmissivity of individual leaves, equal to 0.01.
ψ_m, ψ_h	stability correction for momentum, heat.

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