A CANOPY STOMATAL RESISTANCE MODEL FOR GASEOUS DEPOSITION TO VEGETATED SURFACES

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Abstract—A gaseous deposition model, based on a realistic canopy stomatal resistance submodel, is described, analyzed and tested. This model is designed as one of a hierarchy of simulations, leading up to a "big-leaf" model of the processes contributing to the exchange of trace gases between the atmosphere and vegetated surfaces. Computations show that differences in plant species and environmental and physiological conditions can affect the canopy stomatal resistance by a factor of four. Canopy stomatal resistances to water vapor transfer computed with the present model are compared against values measured with a porometer and computed with the Penman-Monteith equation. Computed stomatal resistances from a soybean canopy in both well-watered and water-stressed conditions yield good agreement with test data. The stomatal resistance submodel responds well to changing environmental and physiological conditions. Model predictions of deposition velocities are evaluated for the case of ozone, transferred to maize. Calculated deposition velocities of O₃ overestimate measured values on the average by about 30%, probably largely as a consequence of uncertainties in leaf area index, soil and cuticle resistances, and other modeling parameters, but also partially due to imperfect measurement of O₃ deposition velocities.

Key word index: Dry deposition, stomatal conductance, environmental physiology, micrometeorology.

1. INTRODUCTION

The consequence of deposition of gaseous pollutants to vegetated surfaces is perceived by many to be one of the major environmental problems of our time. Gaseous deposition is popularly identified as a major factor damaging forests in eastern North America and Europe, and as a possible contributor to the elimination of aquatic life in some Adirondack and Scandinavian Lakes. Assessments of area-wide deposition budgets are presently hindered by the inability to compute (or model) trace gas exchange with specific kinds of vegetation; the ability to decide on the comparative adequacy of potential emission control strategies is correspondingly limited. An important task confronting the atmosphere-surface exchange community is therefore to develop better methods to quantify flux densities of gaseous pollutants to landscapes, both for inclusion in larger scale numerical models and for use in interpreting air chemistry observations made in areas of special interest.

The flux density of a gaseous pollutant that is known to be depositing at the surface can be expressed as the product of the mean concentration of the pollutant (C) and an appropriate deposition velocity (υ). For many chemical species of interest, mean concentrations can be measured using available technology. The deposition velocity, on the other hand, is difficult to determine, since it depends on the chemical species and is a function on many meteorological, biological and surface variables (see Sehmel, 1980; Hosker and Lindberg, 1982; Hosker, 1986).

Most efforts to model and parameterize υ employ a "big-leaf", multiple-resistance analog model (Wesely and Hicks, 1977; O'Dell et al., 1977; Unsworth, 1980; Sehmel, 1980; Hosker and Lindberg, 1982; Hicks, 1984). Such big-leaf models are one-dimensional and are most applicable over relatively flat, horizontally homogeneous terrain. The most important individual resistances to pollutant transfer are usually identified as an aerodynamic resistance ($R_\text{a}$) associated with atmospheric turbulence, a quasi-laminar boundary layer resistance ($R_\text{b}$) which is influenced by the diffusivity of the material being transferred, and a net canopy resistance ($R_\text{c}$) which is dominated by surface factors (mainly biological, see Fig. 1).† To a large extent, it is the uncertainty surrounding specification of the canopy resistance which has limited abilities to infer dry deposition rates from air concentration data. Although this uncertainty is often large, big-leaf models are being applied to infer rates of pollutant uptake in a trial dry deposition monitoring network presently operational in North America (Hicks et al., 1985). The inclusion of simple ecophysiological con-

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† For clarity, upper case symbols will be used to signify resistances associated with the whole canopy, as in a big-leaf model. Lower case symbols are used for the corresponding quantities expressed as an individual-leaf basis.
cept into such models is needed to make them adaptable to different vegetated surfaces and regions.

The canopy resistance is a function of environmental and physiological conditions, surface wetness and chemistry, leaf area index, and diffusivity of the pollutant (Jarvis, 1971, 1976; Turner et al., 1973; Sehmel, 1980; Unsworth, 1980; Hosker and Lindberg, 1982). In comparison, the aerodynamic and quasi-laminar components are relatively simple products of factors not strongly influenced by the physiology of the surface. For a gas such as \( \text{SO}_2 \), \( R_c \) is known to be influenced by stomatal \( (R_s) \) and (somewhat less certainly) mesophyll \( (R_m) \) resistances, which are in series with each other, and are in parallel with resistances exerted by the leaf cuticle \( (R_{cut}) \), the soil \( (R_{soil}) \), surface wetness \( (R_{wet}) \), and any other surface material \( (R_{misc}) \) (Unsworth, 1980; Hosker and Lindberg, 1982; Hicks, 1984; Hosker, 1986). High ambient pollutant concentrations can also influence the canopy resistance to pollutant uptake by increasing or decreasing stomatal resistance (Black, 1982).

Many measurements of canopy resistance to gaseous deposition are available in the literature (e.g. Bennett and Hill, 1973; Fowler, 1978; Fowler and Unsworth, 1979; Wesely et al., 1978, 1982; Leuning et al., 1979a, 1979b; Lenschow et al., 1982; Hicks et al., 1982; Fowler and Cape, 1983; Greenhut, 1983). A much greater level of attention has been focused on the resistance components at the individual-leaf level; the way in which these detailed resistances can be combined to represent the behavior of an entire vegetated canopy are still not well understood. All studies have shown, however, that stomatal resistance is the most dynamic and most influential resistance to \( O_3 \), \( \text{SO}_2 \), and \( \text{NO}_x \) transfer, when the canopy is dry.

Most gaseous deposition models (e.g. Turner et al., 1974; Waggoner, 1975; Belot et al., 1976; Fowler and Unsworth, 1979; Unsworth, 1980) treat the role of foliar-element stomatal resistance \( (R_s) \) without considering the detailed role of radiation and other controlling factors, most of which vary with height within a canopy. In concept, it appears preferable to compute canopy stomatal resistance \( (R_s) \) on the basis of the irradiance on both sunlit and shaded leaves and weighting these resistances according to the fraction of sunlit and shaded leaf area (Murphy et al., 1977; Norman, 1982). This approach is preferred because the stomatal resistance responds non-linearly to light (Turner and Begg, 1974; Jarvis, 1976). Since the light environment within a vegetated canopy is quite complex, the canopy stomatal resistance to gaseous deposition should be computed by coupling a leaf resistance model with a canopy radiation transfer model.

To our knowledge the only gaseous deposition model which estimates canopy stomatal resistance on the basis of sunlit and shaded leaf area is that of Murphy et al. (1977), for loblolly pine. The generality of their model, however, is limited by its dependence on empirically derived, species-specific, attenuation coefficients for beam and diffuse radiation. The model also does not consider the effects of other environmental and physiological variables on stomatal resistance.

Here, we develop a canopy stomatal resistance submodel which couples a canopy radiative transfer model (see Norman, 1979, 1982) with a leaf stomatal resistance model (see Jarvis, 1976), and incorporate the submodel into a "big-leaf", resistance-analog, gaseous deposition model. The objectives of this paper are: (1) to present and discuss this gaseous deposition model and canopy stomatal resistance submodel; (2) to examine the effects of environmental, physiological and structural variables and plant species on the canopy stomatal resistance of several pollutant gases; and (3) to compare computed deposition velocities, based on this model, against measured values.

2. THEORY

It is usual to take the canopy-level aerodynamic, quasi-laminar boundary layer and canopy resistances to be in series. Thus, \( v_z \) is computed as:

\[
v_z = 1/(R_a + R_s + R_c). \tag{1}
\]

The aerodynamic resistance is the resistance to mass or energy transfer exerted by the turbulent internal boundary layer between a height \( z \) and the surface,
characterized by a displacement height \( (d) \) and a roughness length \( (z_0) \). This resistance is a function of wind speed, surface properties and atmospheric stability. It can be expressed as:

\[
R_c = (k u_*)^{-1} \left[ \ln \left( \frac{z_0}{d} \right) - \psi_a \right] \tag{2a}
\]
or under near neutral conditions as:

\[
R_c = u/u_*^2 \tag{2b}
\]

where \( u \) is windspeed, \( u_* \) is friction velocity, \( k \) is von Karman’s constant \( (k = 0.40) \), and \( \psi_a \) is the integral form of the diabatic stability correction for heat and mass transfer.

The quasi-laminar boundary layer resistance is an “excess” resistance which is introduced because the resistance to mass and energy transfer is different from that for momentum (see Thom, 1975; Hicks, 1984; Hosker, 1986). In the immediate vicinity of a surface, mass and energy transfer are controlled by the molecular properties of the fluid, whereas the rate of momentum transfer is influenced by bluff-body effects of the surface elements—a process which has no precise analog in cases of heat and mass transfer. The “excess” resistance is a function of wind speed and surface properties and can be conveniently written as:

\[
R_c = \left[ \frac{1}{(k u_*)} \right] \ln \left( \frac{z_0}{z_c} \right) \tag{3}
\]
where \( z_c \) is the roughness length for the pollutant or entity under investigation.

Since the roughness length, \( z_c \), is difficult to evaluate, the quasi-laminar resistance is often expressed in terms of the inverse Stanton number \( (B) \) (Owen and Thompson, 1963; Chamberlain, 1966):

\[
k u_* R_c = k B^{-1} = \ln \left( \frac{z_0}{z_c} \right). \tag{4}
\]

Empirical evidence indicates that \( kB^{-1} \) can be estimated in terms of the surface roughness, Reynolds number and the Schmidt number (see Garratt and Hicks, 1973; Brutsaert, 1975).

The canopy resistance \( (R_c) \) is computed as:

\[
1/R_c = \left[ 1/(R_c + R_m) \right] + 1/R_{soil} + 1/R_{canopy} \tag{5}
\]

where \( R_c \) is the canopy stomatal resistance, \( R_m \) is the canopy mesophyll resistance, and the remaining subscripts are self-explanatory.

Stomatal resistance of a leaf is primarily a function of photosynthetically active radiation \( (PAR) \), air temperature \( (T) \), leaf water potential \( (\psi) \) and vapor pressure deficit \( (D) \). To a lesser extent it is dependent on CO\(_2\) concentration and the concentrations of many trace gases in the atmosphere.

Jarvis (1976) presents a model for the computation of the stomatal resistance \( (r_s) \) to water vapor transfer of a leaf that is biologically and physically realistic. It is a multiplicative model which is expressed in terms of stomatal conductance \( (g_s) \), the inverse of \( r_s \), stomatal conductance for a leaf is computed as the product of the functional relationships for \( PAR, T, D \) and \( \psi \):

\[
g_s = g(PAR) g(T) g(D) g(\psi) D_s/D_i. \tag{6}
\]

\( D_c \) and \( D_i \) are the molecular diffusivities for water vapor and the pollutant gas, respectively, and are incorporated into Equation (6) to extend the standard formulation to the case of a general trace gas that is transferred via stomata. Values of the functions \( g(T), g(\psi) \) and \( g(D) \) range from 0 to 1. Equation (6) can be expanded to incorporate additional effects (such as the physiological effects of other pollutants) by introducing further multiplicative factors.

The response of stomatal resistance to \( PAR \) is estimated using a rectangular hyperbola relationship (Turner and Begg, 1974):

\[
r_s(PAR) = r_s(min) + b_s r_s(min)/PAR \tag{7a}
\]

\[
g_s(PAR) = 1/r_s(PAR) \tag{7b}
\]

where \( r_s(min) \) is the minimum stomatal resistance and \( b_s \) is a constant equal to the \( PAR \) flux density at twice the minimum stomatal resistance. Korner et al. (1979) and Pospilova and Solarova (1980) provide a comprehensive survey of minimum stomatal resistances of many native and cultivated plants.

The canopy stomatal conductance \( (G_c) \) is computed as a function of \( PAR \) according to the fractions of sunlit and shaded leaf area and the \( PAR \) flux densities on those leaves:

\[
G_c(PAR) = \int_0^f d f_s(\psi) g[PAR_{sun}(\psi)] \tag{8}
\]

In order to compute \( f_{sun} \), \( f_{shade} \), \( PAR_{sun} \), \( PAR_{shade} \), a canopy radiative transfer model must be introduced. Sunlit leaf area is a function of solar elevation, the leaf orientation distribution and cumulative leaf area. The functional relationship for sunlit leaf area is derived on the assumption that the foliage in a canopy is randomly distributed in space and that the distribution of leaf inclination angles is spherical. This assumption is reasonable for many agricultural and forest canopies (Lemeur, 1973; Jarvis and Leverenz, 1983). Based on this assumption the cumulative sunlit leaf area between the top of the canopy and a level inside the canopy \( (f) \) is computed as:

\[
f_{sun}(f) = [1 - \exp \left(-0.5 f/(\sin(\beta)) \right)] 2 \sin(\beta) \tag{9}
\]

where \( \beta \) is the solar elevation angle. The shaded leaf area is expressed as:

\[
f_{shade}(f) = f - f_{sun}. \tag{10}
\]

The flux density of \( PAR \) incident on a sunlit leaf is a function of direct and diffuse radiation penetrating through the canopy and scattered radiation generated by the transmission and reflection of intercepted
radiation. $PAR_{sun}$ is also dependent on the mean angle between leaves and the sun. $PAR$ flux densities within the canopy are computed with the radiation transfer model reported by Norman (1979, 1982). The flux density of $PAR$ on the sunlit leaves is:

$$PAR_{sun}(f) = PAR_{dir} \cos(\alpha)/\sin(\beta) + PAR_{shade}(f)$$

(11)

where $PAR_{sun}$ is the flux density of direct $PAR$ above the canopy and $\alpha$ is the angle between a leaf and the sun. For a canopy with a spherical leaf inclination distribution $\alpha$ can be assumed constant at 60 degrees.

$PAR_{shade}$ is computed semi-empirically using Norman (1982):

$$PAR_{shade}(f) = PAR_{dir} \exp \left( -0.5f^{0.7} \right) + 0.07 PAR_{dir}(1.1 - 0.1f) \times \exp\left[ -\sin(\beta) \right].$$

(12)

Equations (9)-(12) are generally evaluated for differences in $f$ ($df$) of less than 0.25 to minimize the influence of leaf overlap.

Stomatal conductance increases with increasing temperature until a threshold temperature, after which it decreases. This dependence on temperature is the result of energy balance feedbacks between humidity and transpiration of the leaf (see Schulze and Hall, 1982) and the influence of temperature on enzymes associated with stomatal operation (Jarvis and Morison, 1981). The response of stomatal conductance to temperature ($T$) is computed using the relationship presented by Norman (1982):

$$g(T) = \left[ (T - T_{min})/(T_0 - T_{min}) \right] \left[ (T_{max} - T) / (T_{max} - T_0) \right]^b.$$  

(13)

where $T_{min}$ and $T_{max}$ are the minimum and maximum temperatures at which stomatal closure occurs, $T_0$ is the optimum temperature and $b$, is defined as $b = (T_{max} - T_0)/(T_{max} - T_{min})$.

Stomatal conductance is linearly related to vapor pressure deficit ($D$):

$$g(D) = 1 - b \cdot D$$

(14)

where $b$, is a constant.

Water stress can be quantified in terms of leaf water potential ($\psi$), a thermodynamic quantity. Stomatal conductance is relatively independent of $\psi$ until it drops below a threshold value ($\psi_0$), after which the stomata close rapidly. The function $g(\psi)$ is computed using a discontinuous linear model (Fisher et al., 1981) since parameters for this model are readily available in the literature (e.g. Pospisilova and Solarova, 1980). This function is expressed as:

$$g(\psi) = 1, \quad \text{if } \psi > \psi_0$$

(15a)

and as:

$$g(\psi) = a\psi + b_w, \quad \text{if } \psi < \psi_0$$

(15b)

where $a$ and $b_w$ are constants.

We assume that temperature, vapor pressure deficit and leaf water potential are constant with height in the canopy. The canopy stomatal resistance is thus computed by combining Equations (8), (13), (14) and (15):

$$R_c = 1/[g(T)g(\psi)D_c/D].$$

(16)

After a pollutant gas diffuses through a stomatal pore it comes into contact with the moist environment of the leaf mesophyll. The resistance to uptake of soluble gases by the mesophyll cells is influenced by the surface area of the mesophyll and the solubility of the gas (Hill, 1971; O’Dell et al., 1977; Hosker and Lindberg, 1982). The magnitude of this resistance is usually small on a leaf basis, 10 to 50 s m$^{-1}$ (Hosker and Lindberg, 1982). On a canopy basis, this resistance is usually evaluated as ratio between the leaf value and the canopy leaf area index.

The cuticular resistance is associated with gaseous uptake at the surface of the leaf. This resistance will depend on the chemical characteristics of the trace gas under consideration, but will also be influenced by the amount of leaf surface area, leaf pubescence and waxes and exudates on the leaf surface. The cuticular resistance of a dry leaf is typically quite large for many pollutant gases, exceeding 1000 s m$^{-1}$. However, leaf surface uptake is a significant pathway for HNO$_3$ and liposoluble HCs. The degree of leaf wetness also affects the cuticle resistance. For example, leaf wetness caused by condensation (i.e. dewfall and distillation) enhances SO$_2$ uptake (Fowler and Unsworth, 1979) and inhibits O$_3$ and NO$_2$ uptake (Wesely et al., 1982).

The soil resistance to pollutant uptake of a particular species is influenced by soil moisture, soil type and texture and soil litter (Turner et al., 1973). There are no models available in the literature for estimating the cuticle and soil resistances to pollutant uptake. Consequently, we must rely on published values reported in the literature.

3. RESULTS

Canopy stomatal resistance

In terms of the canopy resistances, gas transport through the stomata generally provides the path of least resistance for the uptake of SO$_2$, O$_3$ and NO$_2$, assuming the canopy is dry and transpiring. In this section we will discuss the influence of varying environmental and physiological variables on canopy stomatal resistance in order to illustrate the magnitude of the role that the stomata have on the uptake of gaseous pollutants.

Figure 2 shows the relationship between calculated canopy stomatal resistance [R$_c$, as specified by Equation (16)] and $PAR$ for SO$_2$, O$_3$ and NO$_2$ uptake. Curves for soybean, maize (corn), oak and spruce are presented since these plant species represent some of the different classes of vegetation growing in the eastern U.S. The data used to generate these curves are
based on clear-day (10% diffuse radiation), non-stressful ($\psi > \psi_0$), summertime conditions ($T = 25^\circ C$) for fully developed canopies ($LAI = 5$). The modeling parameters used in the computations of $R_c$ are listed in Table 1.

Canopy stomatal resistances for each species decrease curvilinearly with increasing $PAR$ (Figs 2a and 2b). A factor of 2-4 decrease in $R_c$ is observed as $PAR$ increases from low light levels (50 W m$^{-2}$) to high light levels (400 W m$^{-2}$). A pronounced difference in $R_c$ among plant species is also evident. Based on the parameters used in these computations, a factor of 8 difference between the extremes (soybeans and maize) at high $PAR$ levels is observed even though the respective minimum stomatal resistances differ by only a factor of 4. This is due in part to differences in the $g_{s,PAR}$ curvature coefficient, $b_c$. Actual differences in $R_c$ among these species may vary from that presented in Fig. 2 since the minimal stomatal resistance can vary by an order of magnitude for herbaceous plants (Korner et al., 1979).

Greater canopy stomatal resistances are found for $SO_2$ than for $NO_2$ and $O_3$ (Fig. 2). This is a consequence of the differences in molecular diffusivities. Pollutants with greater molecular weights have lower molecular diffusivities, and correspondingly greater canopy stomatal resistances.

Cloudiness affects the relationship between $R_c$ and $PAR$ since it influences the distribution of light inside a canopy. Under low $PAR$ levels, $R_c$ for $O_3$ transfer to a soybean crop is reduced by 50% as the percentage of diffuse radiation increases from 10 to 80% (Fig. 3). Under high $PAR$ levels, $R_c$ is reduced by only 25% as the percentage of diffuse radiation increases from 10 to 80%. This reduction is less at higher $PAR$ levels since a greater proportion of shaded and sunlit leaves are exposed to $PAR$ levels exceeding light saturation ($PAR > b_c$).

Table 1. A list of the parameters used to compute canopy stomatal resistance

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</thead>
<tbody>
<tr>
<td>$\min r_c$</td>
<td>s m$^{-1}$</td>
<td>232</td>
<td>1</td>
<td>145</td>
<td>5.6</td>
<td>242</td>
<td>10</td>
<td>65</td>
<td>3</td>
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<tr>
<td>$b(PAR)$</td>
<td>W m$^{-2}$</td>
<td>25</td>
<td>2</td>
<td>22</td>
<td>6</td>
<td>66</td>
<td>10</td>
<td>10</td>
<td>12</td>
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<tr>
<td>$T_{\text{min}}$</td>
<td>C</td>
<td>-5</td>
<td>1</td>
<td>10</td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>17*</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>C</td>
<td>35</td>
<td>1</td>
<td>45</td>
<td>7</td>
<td>45</td>
<td>8</td>
<td>45</td>
<td>17*</td>
</tr>
<tr>
<td>$g_{s,PAR}$</td>
<td>k Pa$^{-1}$</td>
<td>0</td>
<td>1</td>
<td>24-32</td>
<td>5.7</td>
<td>22-25</td>
<td>8</td>
<td>25</td>
<td>16*</td>
</tr>
<tr>
<td>$b(\text{vpd})$</td>
<td>k Pa$^{-1}$</td>
<td>-0.0026</td>
<td>1.14</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>13</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>$\psi_0$</td>
<td>MPa</td>
<td>-2.1</td>
<td>2.11</td>
<td>-2.0</td>
<td>5.7</td>
<td>-0.8</td>
<td>15.9</td>
<td>-1.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Canopy stomatal resistance is strongly linked to the amount of vegetation covering the surface, expressed in terms of leaf area index (LAI). At a given PAR level, $R_s$ for ozone deposition to a soybean canopy decreases proportionally with increasing LAI (Fig. 4). For example, at high PAR levels $R_s$ decreases by a factor of 5 as LAI increases from 1 to 5.

Often $R_s$ is estimated from porometer measurements as $r_s/LAI$, where $r_s$ is the average of stomatal resistances of individual leaves within the canopy. Superimposed on Fig. 4 is a plot of $(R_s = 1)/LAI$, a surrogate for $r_s/LAI$. It is evident that this ratio underestimates values of $R_s$ computed with the canopy radiative transfer model. For example, when the canopy LAI is 5 ($R_s = 1)/LAI$ can lead to a 25% underestimation in canopy stomatal resistance. The relative difference is smaller at lower leaf area indices. Differences between the two estimates of $R_s$ reflect the importance of considering stomatal resistance in terms of the sunlit and shaded leaves.

The model suggests that canopy stomatal resistance for soluble trace gas transfer to a soybean canopy decreases as $T$ increases up to about 35°C at all levels of PAR (Fig. 5). At higher temperatures $R_s$ decreases since these temperatures cause high transpiration rates, which may trigger plant water stress (Schulze and Hall, 1982), and denature enzymes, which control stomatal operation (Jarvis and Morison, 1981). Theoretically, $R_s$ should be smallest at the optimal temperature ($T_0 = 25°C$), not at 35°C. The functional form presented
A canopy stomatal resistance model for gaseous deposition to vegetated surfaces

by Jarvis (1976) for $R_s$ appears to be in error; a better form is $R_s = (T_{max} - T_0)/(T_0 - T_{min})$.

The model indicates that plant water stress, quantified by leaf water potential, does not affect ozone deposition to soybeans when $\psi$ values exceed the threshold level for stomata closure (Fig. 6). However, $R_s$ increases rapidly when $\psi$ drops below the threshold level. For example, a factor of 4 increase in $R_s$ results as $|\psi|$ drops 0.3 MPa below the threshold level of -1.1 MPa.

A test of the canopy stomatal resistance model

As yet, there are no comprehensive data sets on trace gas exchange with enough supporting biological information to test predictions of the canopy stomatal resistance model developed here. Generation of such data is a major goal of experimental programs presently under way, with initial focus on $SO_2$ and $O_3$. In this context, it should be noted that $O_3$ data are considered relevant even though $O_3$ is poorly soluble in pure water. Field experiments have invariably shown that $O_3$ dry deposition rates are stomatically controlled during daytime and over surfaces that are biologically active (see Hicks, 1984). However, some confidence in model performance can be generated by testing it against observations of water vapor exchange. For this purpose, independent estimates of canopy stomatal resistance have been derived from: (a) measurements of $R_s/LAI$, made with a steady-state porometer; and (b) computations based on the Penman-Monteith model for latent heat exchange.

Fig. 6. Influence of $PAR$ on the soybean canopy stomatal resistance for ozone transfer under different levels of leaf water potential.

Fig. 7. Comparison between canopy stomatal resistance for water vapor ($R_s$), computed with Equation (16) ($y$ axis), against two estimates of canopy stomatal resistance derived from measurements ($x$ axis). The measured estimates are: (a) $R_s = \bar{r}_s/LAI$, where $\bar{r}_s$ is the mean stomatal resistance measured with a steady-state diffusion porometer; and (b) $R_s$ derived from the Penman–Monteith equation (17). The measured and computed canopy stomatal resistance values were derived from physiological and micrometeorological measurements made over a soybean canopy near Mead, NE and are reported in Baldocchi et al. (1985).

\begin{equation}
LE = \frac{(s \cdot A + \rho \cdot C_p \cdot D/(R_s + R_b))}{[s + \gamma \cdot R_s/(R_s + R_b)]}
\end{equation}

where $s$ is the slope of the relationship between saturation vapor pressure and temperature, $\gamma$ is the psychrometric constant, $\rho$ is air density, $C_p$ is the specific heat of air at constant pressure and $A$ is the available heat energy ($A = R_n - G$, where $R_n$ is net radiation and $G$ is transfer into the ground). The data used for this test were obtained in a field study of the energy budget of a soybean canopy, as reported by Baldocchi et al. (1985). These data represent a wide range of canopy conditions, ranging from well-watered to water-stressed ($\psi$ ranged between -0.6 and -1.9 MPa).

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There is a tendency for the computed values of $R_s$...
using Equation (16)] to overestimate $R_i/LAI$ by about 5 s m$^{-1}$, or 5-30%. This overestimate, however, appears acceptable since it is consistent with the results presented in Fig. 4 and because the measured values of canopy stomatal resistance were derived from only sunlit leaves in the upper canopy. On the other hand, this difference is expected, considering the theoretical arguments of Thorn (1975) and Finnigan and Raupach (1987), who show that the canopy stomatal resistance in the Penman-Monteith equation does not equal the parallel, area-weighted sum of the stomatal resistance of individual leaves in the canopy. Instead, the Penman-Monteith canopy resistance $R_{PM}$ is a function of the stomatal and aerodynamic resistance of the leaves in the canopy and net radiation incident on those leaves (Finnigan and Raupach, 1987) or it can be expressed, after Thorn (1975), as:

$$R_{PM} = R_s + (1 - \frac{R_s}{R_o}) R_o$$

where $B_o$ is the Bowen ratio, the ratio of sensible heat to latent heat flux. In view of Equation (18), $R_s$, derived from the Penman-Monteith equation, can overestimate canopy stomatal resistance computed as the parallel, area-weighted sum of the individual leaves in the canopy. The data used in the present comparison permit the second term on the right hand side of Equation (18) to be evaluated. Under well-watered conditions, $B_o$ was typically less than 0.1 and $R_o$ was of the order of 20-30 s m$^{-1}$. Hence, the second term on the right hand side of Equation (18) was about 20 s m$^{-1}$, thus accounting for part of the factor of two difference observed between $R_s$ and $R_{PM}$ under well-watered conditions. The errors involved in determining the model parameters and in measuring the input variables used to compute $R_{PM}$ also account for differences between $R_s$ and $R_{PM}$. Callander and Woodhead (1981) report that typical errors associated with canopy conductances, computed with the Penman-Monteith equation, are of the order of ±25-35%.

A comparison of calculated and measured deposition velocities

Deposition velocities computed using Equation (1) have been tested against measured values of O$_3$ deposition velocities measured values over a mature maize canopy (Wesely et al., 1978).

Deposition velocities for ozone transfer to maize were computed assuming that the leaf area index of the canopy was 4. The parallel resistances due to the soil and cuticle were assumed to be constant at 400 s m$^{-1}$, as given by Wesely et al. (1978). The mesophyll resistance was assumed to be zero (Leuning et al., 1979a, 1979b). Canopy stomatal resistance was computed using the parameters listed for maize in Table 1.

Calculated and measured deposition velocities are well correlated for conditions with $u_*$ values ranging between 0.3 and 0.7 cm s$^{-1}$ (Table 2); the correlation coefficient is 0.76. This high correlation suggests that much of the variation in measured $u_*$ values can be accounted for by variations in $R_s$, $R_o$ and $R_{PM}$. However, calculated $u_*$ values overestimate measured values by an average of about 0.11 cm s$^{-1}$, or about 27%—a relatively small difference considering measurement and modeling errors.

One possible explanation for the differences between measured and predicted O$_3$ deposition velocities is the assumption used for the canopy leaf area index. An overestimation of LAI can account for some of the underestimate in the calculated $u_*$ values; no measurement of LAI was made in the experiment from which these data were derived. Other sources of error are doubtlessly associated with both the measurement of $u_*$ and with the specification of inputs and parameters used in the model computations. For example, Wesely and Hart (1985) show that measured values are subject to experimental error and large run-to-run variability due to sensor noise.

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<th>Day</th>
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<th>$u_*$ calculated (cm s$^{-1}$)</th>
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r, paired = -0.66
r, 0.05 = -1.67

Table 2. Deposition velocities of ozone measured over a well-watered, mature corn canopy (Wesely et al., 1978) and computed with the deposition velocity model
A canopy stomatal resistance model for gaseous deposition to vegetated surfaces

4. DISCUSSION

The hierarchy associated with canopy-atmosphere mass and energy transfer models involves three distinct levels of detail. These correspond to single-layer "big-leaf" resistance-analog models, multilayer resistance-analog or K-theory models (e.g. Waggoner, 1975; Norman, 1979; Unsworth, 1980) and higher order closure models (e.g. Finnigan and Raupach, 1987). The model presented here is designed to provide a link between a simple "big-leaf" model and a multi-layer resistance model, and is intended to permit detailed data on plant physiology to be utilized in practical applications concerning the determination of pollutant dry deposition.

The practical utility of a more complicated model is often limited by the need for complex parameters, which are often unknown or difficult to obtain. These parameters include vertical variations in leaf area index, canopy drag coefficients, the wind profile attenuation coefficient, and coefficients used to close higher order moment equations (see Waggoner, 1975; Finnigan and Raupach, 1987). Complex models are also limited somewhat by the incomplete theoretical understanding of within-canopy turbulent exchange processes. For example, K-theory models are based on the assumption that within-canopy turbulent transfer is dominated by eddies which have length scales similar to the length scales associated with the canopy and its elements. Recently, this has been shown not to be the case; within-canopy turbulent transfer is dominated by eddies much larger than the length scale of the canopy (see Finnigan and Raupach, 1987).

The present computation of canopy stomatal resistance is based on the assumption that the leaf inclination distribution is spherical and the foliage distribution is uniform in space. In reality, these assumptions are not always appropriate. Leaf orientation can be planophile, plagiophile, spherical or erectophile, among other distributions. Alterations in leaf orientation influence the probability of beam penetration and the irradiance incident on the leaf (see Lemeur, 1973; Norman, 1979). Spatial distribution of leaves can also vary. For example, individual leaves can be clumped or the plant stand can be clumped or in rows. Recently, Baldocchi and Hutchison (1987) examined the influence on clumped foliage on the penetration of PAR in a deciduous forest and its impact on the estimation of canopy stomatal conductance. It was found that clumping of the foliage increases PAR penetration and leads to greater values of $G_c$.

The model computations also assume that parameters and variables used to compute $R_c$ are constant with height inside the canopy. Values of such parameters as $r_c$ (min) and leaf scattering coefficients vary with leaf age and position in the canopy (see Jarvis et al., 1976; Jarvis and Leverenz, 1983), so canopy air and leaf temperatures and vapor pressure deficits. Computations of canopy stomatal resistance can doubtlessly be improved by including computations of the net radiation balance of leaves to estimate leaf temperature and the vapor pressure deficit between the leaf and air (e.g. Waggoner, 1975; Norman, 1979), and by accounting for the vertical variation of some of the more sensitive parameters.

5. CONCLUSIONS

A multilayer canopy stomatal resistance model has been developed, with the intent to provide more realistic descriptions of biological processes than are presently included in "big-leaf" models of trace gas dry deposition processes. The model is based on the leaf stomatal resistance model of Jarvis (1976) and incorporates the canopy radiative transfer model of Norman (1979, 1982).

Computations of canopy stomatal resistance show a strong dependence on $PAR$, leaf area index, temperature and leaf water potential. Diffuse radiation and the distribution of plant and chemical species also affect $R_c$. Variations in these environmental and physiological variables can affect $R_c$ by a factor of 2-4, and could cause corresponding "errors" if such factors are omitted from models of trace gas deposition velocity.

The canopy stomatal resistance model was tested for water vapor against values derived from data obtained over soybeans. Predictions of canopy stomatal resistances differed from field observations by an average that could be explainable in terms either of errors in measurement (or in the interpretation of field observations) or of erroneous model assumptions. In general, predictions are well correlated with test values, for water vapor exchange.

The model has been used to predict deposition velocities for $O_3$. Comparisons with field data obtained over maize show that measured and computed deposition velocities are well correlated and agree, on the average, within 27%.

Major limitations of the present model lie with its omission of within-canopy turbulent exchange processes, its inherent inability to address questions concerning the flux of bi-directional pollutants such as NH$_3$, CH$_4$ and NO, and its lack of detail concerning transfer with soil, mesophyll and cuticle. Development of a complete multi-layer model is under way at this time.

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A canopy stomatal resistance model for gaseous deposition to vegetated surfaces


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