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3.5

AERIAL AND CROP RESISTANCES AFFECTING ENERGY TRANSPORT*

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INTRODUCTION

Energy transport (latent and sensible heat flux) models which consider the effects of both plant and meteorological variables have been used by various investigators (e.g. Raschke, 1960; Monteith, 1963; Wiegand and Bartholic, 1970; Brown and Rosenberg, 1973; Heilman and Kanemasu, 1976;. Verma et al., 1976). These models take into account the resistance to flow of water vapor through stomates of plant leaves and resistance to heat and/or water vapor transport across the turbulent boundary layer. The subject of aerial resistances is introduced in chapter 3.2. Since the concepts are used frequently in theoretical analyses of energy fluxes associated with environmental modification, more detailed coverage with examples is given in this chapter.

When a temperature difference exists between a cropped surface and the free air above the surface, a transfer of sensible heat takes place. The rate of transfer of sensible heat depends on the temperature difference as well as the impedence (resistance) of the atmosphere to movement of sensible heat. Sensible heat flux, H_s, to (or from) crop surfaces can be described as,

$$H_s = \frac{\rho_a C_p (T_s - T_a)}{r_{as}} \quad \text{[3.5-1]}$$

where ρ_a is the air density, C_p is the specific heat at constant pressure, T_s is the mean surface temperature of the crop, T_a is the air temperature at a given elevation, and r_{as} is the aerial diffusion resistance to the transport of heat.

Latent heat transfer occurs when a difference in water vapor concentration occurs between the cropped surface and free air. A relationship similar to equation [3.5-1] can be written for latent heat as,

$$H_\ell = \frac{\rho_a \lambda (\chi_{vs} - \chi_{vz})}{r_{av} + r_c} \quad \text{[3.5-2]}$$

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where λ is the latent heat of vaporization, χ_{vs} is the saturation humidity ratio at the surface temperature, χ_{va} is the humidity ratio of the free air, r_{av} is the air resistance to movement of water vapor and r_c is the crop resistance to movement of water vapor. In the case of water vapor transport, a diffusion resistance, r_c, exists to transport from inside the leaf stomata to the leaf surface as well as a resistance to transport through the air, r_{av}.

The drag imposed by airflow over a surface results in horizontal momentum being transported from the air to the surface. An expression similar to equation [3.5-1] can be written for momentum flux, τ, as,

$$\tau = \frac{\rho_a u}{r_{am}} \qquad [3.5\text{-}3]$$

where u is the mean wind speed at a given elevation, r_{am} the aerial resistance to momentum transport and $\rho_a u$ is the momentum per unit mass of the air. The rate of transport of momentum to the surface is also equal to the shearing stress. A term known as the shear velocity is defined as,

$$U_* = \sqrt{\tau/\rho} \qquad [3.5\text{-}4]$$

Using this definition, r_{am} can be written as

$$r_{am} = \frac{u}{U_*^{\,2}} \qquad [3.5\text{-}5]$$

From equations [3.5-5] and [3.5-3], if measurements of U_* are available, it is possible to predict the rate of momentum transfer to the cropped surface for a given windspeed. Also, if r_{am} can be related to r_{as} and r_{av}, it will be possible to predict sensible heat transfer from equation [3.5-1] for a given temperature difference and latent heat transfer from equation [3.5-2] for a given crop resistance and water vapor concentration difference. Much of the discussion in this chapter is devoted to the relationships between r_{am}, r_{as}, and r_{av} as well as to characterizing crop resistance, r_c.

If measurements of U_* are not available, estimates can be made from the log velocity profile given in chapter 3.2.

$$u = \frac{U_*}{k}\left[\ln\frac{z-d}{Z_o} + \psi_m\right]$$

or

$$U_* = \frac{ku}{\ln\dfrac{z-d}{Z_o} + \psi_m} \qquad [3.5\text{-}6]$$

where k is von Karman's constant, d is crop displacement height, Z_o is crop roughness height, and ψ_m is the diabatic stability correction parameter given in chapter 3.2 which accounts for the effects of buoyancy on mixing. Attention is also devoted in this chapter to characterizing d, Z_o, and the stability correction parameter.

RELATIONSHIP BETWEEN AERIAL (BOUNDARY LAYER) RESISTANCE TO TRANSPORT OF HEAT, WATER VAPOR AND MOMENTUM

The rate of heat (or water vapor) transport in the immediate neighborhood of a vegetated surface is primarily controlled by a purely molecular property of the fluid—its thermal conductivity, D_C (or molecular diffusion coefficient, D_V for water vapor). In other words, no matter how much the heat (or water vapor) transfer capacity of the air away from the surface is increased by the roughness-generated turbulence, heat (or water vapor) cannot be transferred at a rate greater than conduction (or molecular vapor transfer) away from (or into) the surface will allow. In this respect the transport of heat and water vapor differs from that of momentum. Momentum is destroyed at a surface by pressure forces (the bluff body effect acting on individual leaves and stems) which have no analog in heat and water vapor transfer. In aerodynamically rough flows, by definition, the bluff body effect is large enough to render the transfer of momentum independent of the molecular viscosity, ν, of the fluid. Reynolds analogy between the transport of heat (or water vapor) and momentum, therefore, may or may not apply above the canopy, but it can never apply right up to the crop surface (Owen and Thomson, 1963; Chamberlain, 1966 and 1968; Thom, 1972).

The transfer of heat or water vapor to or from vegetated surfaces encounters greater aerodynamic resistance than does the transfer of momentum. Owen and Thomson (1963) developed a dimensionless parameter B^{-1} to measure the discrepancy between the transport of heat (or mass) and momentum to the surface as,

$$B^{-1} = r_{as}^{+}(z) - r_{am}^{+}(z) \quad \text{[3.5-7]}$$

where $r_{as}^{+}(z)$ and $r_{am}^{+}(z)$ are non-dimensional resistances defined by:

$$r_{as}^{+}(z) = r_{as}\, U_* = \frac{\rho_a C_p (T_a - T_s)\, U_*}{H_s}$$

and

$$r_{am}^{+}(z) = r_{am}\, U_* = \frac{\rho_a u\, U_*}{\rho_a U_*^2} = \frac{u(z)}{U_*} \quad \text{[3.5-8]}$$

B^{-1} can also be expressed in terms of the effective roughness parameter for heat (or water vapor) and momentum (Chamberlain, 1966 and Thom, 1972) as

$$e^{k/B} = Z_o/Z_s \quad \text{(heat transfer)}$$

$$= Z_o/Z_v \quad \text{(water vapor transfer),} \quad \text{[3.5-9a]*}$$

or

$$kB^{-1} = \ln Z_o/Z_s \quad \text{(heat transfer)}$$

$$= \ln Z_o/Z_v \quad \text{(water vapor transfer).} \quad \text{[3.5-9b]*}$$

A further discussion of Z_o is given in a subsequent section.

Relationships have been proposed by several investigators for B^{-1} (Owen and Thomson, 1963; Chamberlain, 1966 and 1968; Thom, 1968, 1971, and 1972). The most comprehensive analysis presented to date is that of Garratt and Hicks (1973). Their analysis includes the data of the foregoing investigators.

Garratt and Hicks analyzed atmospheric and wind tunnel heat and mass transfer data for various kinds of surfaces: (a) water, snow, soil, grass, vineyard and pine forest (atmospheric) and (b) towelling, rough

*Equations [3.5-9a] and [3.5-9b] are strictly valid only for neutral stability.

glass, artificial grass and several arrays of cylinders and spheres (wind tunnel) (overall behavior given in Fig. 1). They found little difference in values of kB^{-1} obtained for heat and water vapor transfers. While systematic differences were apparent between the results of various experiments, the data for $RE_* = U_* Z_0/\nu < 100$ were generally found to be consistent, showing a gradual increase with Re_*. Above $Re_* = 100$, the situation was less apparent: there was overall consistency within particular experiments but the values of kB^{-1} deduced from various experiments differed by an order of magnitude. Garratt and Hicks interpret the separation of data at large Re_* (fully rough flows) in terms of different bluff body contributions because of differences in surface structure. The data contributing to the upper band of Fig. 1 were obtained over vineyard (atmospheric measurements). The former may be considered to be similar to an array of horizontal cylinders arranged in well-spaced paralled rows (Hicks, 1973), thus being similar in structure to the wind tunnel models. The vineyard data suggest considerable enhancement of the bluff body effect when wind blows at right angles to the rows. The individual leaves of the vines play little part in the determination of the bulk aerodynamic resistance to heat and momentum transfer. In every case, the surface contributing to the upper band in Fig. 1 was comprised of relatively solid geometrical arrays of well-spaced roughness elements. The surfaces over which the data in the lowerband in Fig. 1 were obtained, however, consisted of natural vegetation—grass, bean, crops and pine forest. It seems likely, Garratt and Hicks suggest, that for such surfaces the aerodynamic characteristics of individual elements (leaves, twigs, etc.) determine the bulk aerodynamic properties. The bluff body effect was considered to be minimal. These surfaces were characterized by closely-packed, complex roughness elements of a "fibrous character".

Heilman and Kanemasu (1976) computed B^{-1} values from their field measurements over soybeans and sorghum grown at Manhattan, KS. Their esults compared well with the lower band in Garratt and Hicks' Fig. 1 (for large $U_* Z_0/\nu$).

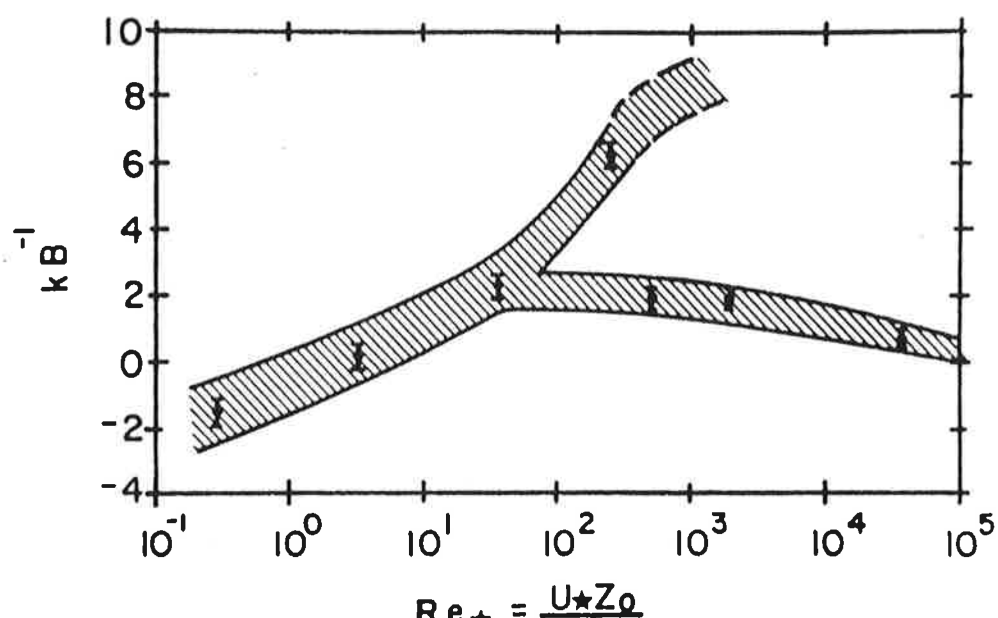

FIG. 1 The overall behavior of kB^{-1}. The bands of data are drawn by eye to represent the probable 95 percent confidence limits of the present body of observations [from Garratt and Hicks, 1973].

When using B^{-1} values for mass transfer other than water vapor, corrections must be made for diffusivity differences. A discussion of this correction is given in Chapter 3.2.

It must be pointed out that the use of B^{-1} is a gross simplification of a complicated micrometeorological process. The concept, however, is very useful.

ATMOSPHERIC STABILITY EFFECTS

Air resistance is essentially the inverse of the ability of the atmosphere to diffuse a given constituent (i.e. momentum, heat, water vapor) from (to) the leaf surface to (from) the free air. As diffuse capability increases, air resistance decreases. Since diffusion is enhanced by buoyancy forces, air resistance as a function of atmospheric stability is an important consideration. This has been addressed in chapter 3.2. A further discussion on atmospheric stability is deferred to examples later in the chapter.

CROP ROUGHNESS AND DISPLACEMENT HEIGHTS

As indicated earlier, aerial resistance to heat and mass transfer depends on mixing (as defined by shear velocity, U_*) as well as momentum roughness height Z_o and crop displacement height d. Szeicz et al. (1969) summarized the available data on fully developed canopies. For wind speeds of approximately 2.5 m/s they found that

$$Z_{o,2.5} = 0.105H \quad [3.5\text{-}10]$$

for crops other than maize and sorghum and

$$Z_{o,2.5} = 0.03H^{1.3} \quad [3.5\text{-}11]$$

for maize and sorghum where H is crop height in cm. There was a very good fit to the data available. Brutsaert (1975) used a semi-empirical approach to show that the coefficient of equation [3.5-10] should be approximately 0.12.

The variation of Z_o with windspeed is the subject of considerable controversy, primarily over the magnitude of the variation. Z_o over most crops decreases with increasing windspeed; however, Z_o over rice increases with increasing windspeed. Rijtema (1966) proposed relationships between Z_o and u. Szeicz et al. (1969) present data as shown in Fig. 2, showing significant variation of Z_o with windspeed over potatoes, lucerne and pine forest. Since the Szeicz et al. data were not stability corrected, the possibility exists that a significant portion of the variation of Z_o with windspeed could have possibly been an artifact. At this point no definitive statement can be made about the Z_o-windspeed relationship until further data is collected.

Little data are available for roughness height prediction for discrete crop canopies. Lettau (1969) proposed that

$$Z_o = 0.5\, H\frac{s}{S} \quad [3.5\text{-}12]$$

where s/S is the ratio of projected silhouette area of the object to total area. Norman† proposed the relationship shown in Fig. 3 for Z_o and d. A direct comparison between Norman's curves and Lettau's relationship is not possible. More complex models have been proposed (e.g. Seginer et al., 1972) but do not lend themselves simple calculations.

†Unpublished data furnished by J. Norman, Dept. Agron., Univ. of Nebraska, Lincoln, NE.

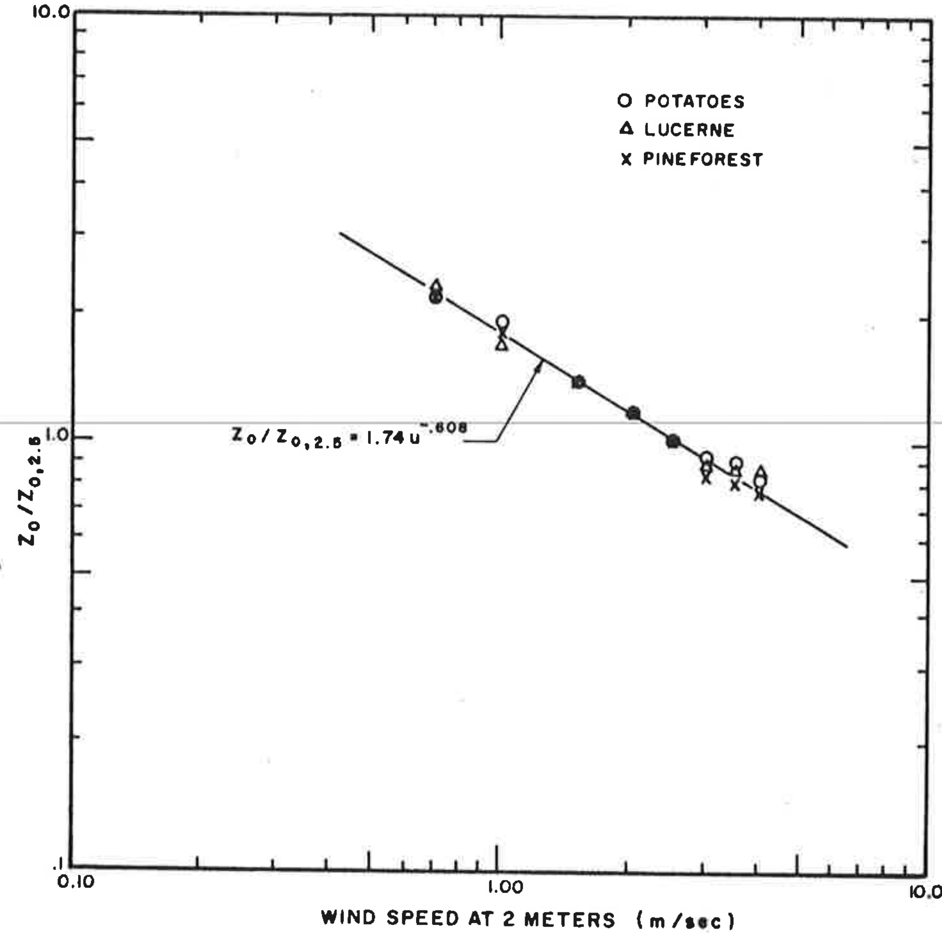

FIG. 2 The effect of windspeed on roughness height as proposed by Szeicz et al. [1969].

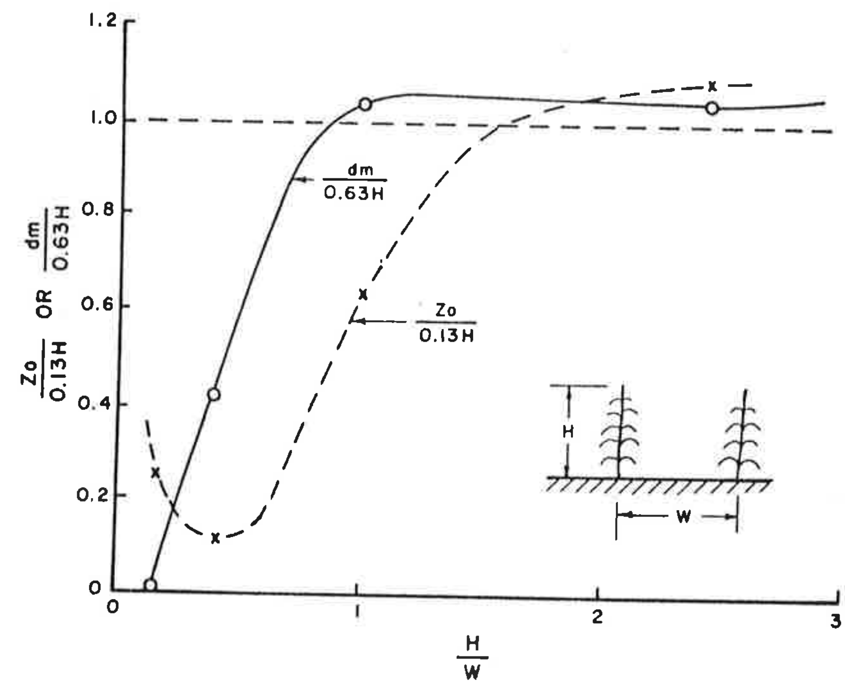

FIG. 3 Aerodynamic roughness height and displacement height versus dimensionless plant height for corn. [Data and analysis graciously furnished by J. Norman, Dept. of Agronomy, Univ. of Nebraska, Lincoln.

Several investigators have propôsed that zero displacement height was a constant for a given crop and independent of windspeed (Thom, 1971; Stanhill, 1969; Szeicz and Long, 1969). The best predictor consistent with experimental results in that of Stanhill, or

$$d = 0.64\ H \qquad [3.5\text{-}13]$$

The assumption is usually made that the zero displacement height for heat, mass, and momentum is equal. This assumption is supported by simulations by Thom (1972), but experimental support would be desirable. Relationships for d in a developing canopy as given by Norman are shown in Fig. 3.

It should be pointed out that the use of Z_0 and d is gross simplification of a complex process at best. They probably are profile and not canopy properties. They can serve, however, as estimates.

STOMATAL AND CROP RESISTANCES

The Concept of Stomatal Resistance

The surface of a plant leaf is covered with cuticle cells which are coated with a relatively impervious waxy surface. Small openings known as stomata are scattered at random on the surface through which gaseous exchange between the plant and atmosphere occur. On some species stomata occur primarily on the lower (abaxial) leaf surface and on some species they are approximately equally distributed on both lower (abaxial) and upper (adaxial) surfaces.

Stomatal openings are enclosed by guard cells as shown in Fig. 4 which control the size of the opening. This size of opening controls the impedence to movement of gases into and out of the leaf. The opening and closing of the guard cells responds to many environmental parameters as will be discussed subsequently.

Using the concept of stomatal resistance as defined by Raschke (1960) the movement of water per unit area of leaf is

$$E = \frac{\rho_a\,(\chi_{v\ell} - \chi_{vl})}{r_s} \qquad [3.5\text{-}14]$$

where E is the flux of vapor per unit area of leaf surface, $\chi_{v\ell}$ is saturation humidity ratio‡ at the leaf temperature, χ_{vl} is the humidity ratio at the leaf surface, and r_s is "stomatal resistance to gaseous diffusion". Similar relationships could be written for fluxes of carbon dioxide and other gases. Stomatal resistance as used in this context is actually the sum of stomatal, pore, mesophyll cell wall, and internal pore resistance. Using the concept of a leaf boundary layer, the vapor flux can alternately be written as

$$E = \frac{\rho\,(\chi_{v\ell} - \chi_{va})}{r_s + r_{av}} \qquad [3.5\text{-}15]$$

where χ_{va} is the humidity ratio of the free air outside the leaf mass boundary layer and r_{av} is the resistance of the individual leaf boundary layer. Numerous researchers have proposed relationships for r_{av}. A summary is given by Westerman et al. (1976).

‡Humidity ratio and water vapor concentration are used interchangeably in this chapter.

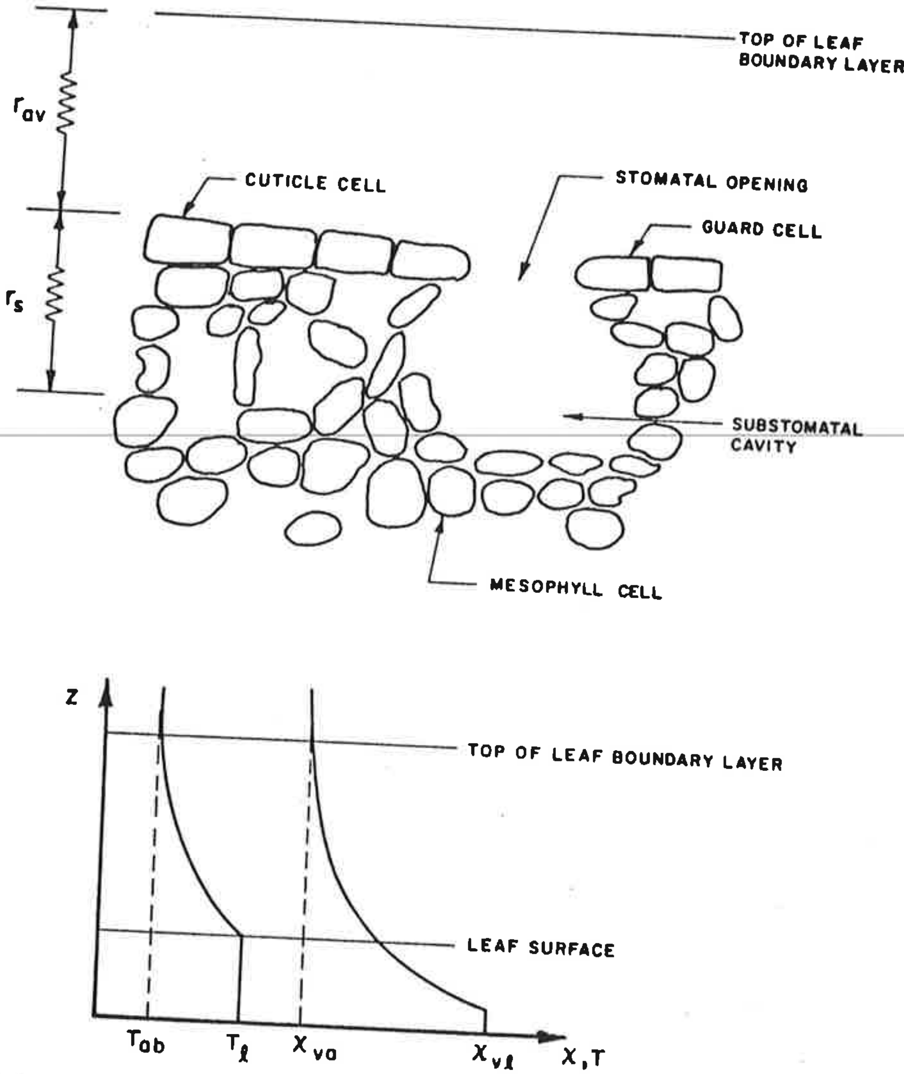

FIG. 4 Schematic of leaf showing stomatal cavity, stomatal resistance air resistance, and assumed temperature and water vapor concentration profiles. Stomatal resistance as used here is actually the sum of stomatal pore, mesophyll cell wall, and internal air pore resistance.

To use equation [3.5-15] it is necessary to characterize stomatal resistance. Brown and Escombe (1900) originally related stomatal resistance to stomatal density, radius, and depth of opening. This relationship, as later modified by others (Milthorpe and Penman, 1967; Parlange and Waggoner, 1970), is difficult to use due to the necessity of making measurements on individual stomatal openings. Early measurements, which were time consuming, were made with impressions with a silicone rubber compound (Zelitch, 1961) and similar materials. In recent years, the development of diffusion parameters has made possible the rapid measurement of stomatal resistance in the field. From these measurements, it has been found that stomatal resistance is very much a function of environmental parameters. Due to space limitations, the coverage given in this chapter to environmental responses of stomata will be limited to a brief discussion and several examples. The reader is referred to several excellent reviews for detailed coverage of the subject (eg., Raschke, 1975; Meidner and Mansfield, 1968; Allaway and Milthorpe, 1976; Burrows and Milthorpe, 1976).

Relationship between Environmental Parameters and Stomatal Resistance

Stomatal resistance is a strong function of light intensity at weak light intensities and relatively constant at normal light levels. The literature abounds with examples of the relationship. A typical curve is shown in Fig. 5 along with the equation proposed by Waggoner et al. (1968) for the relationship between light intensity and stomatal resistance; or

$$r_s = r_{sm}/\mathrm{erf}(R_{s,n}/C) \quad \ldots\ldots\ldots\ldots \quad [3.5\text{-}16]$$

where r_{sm} is the minimum stomatal resistance obtained when radiation is great and C is an empirical parameter (0.21 for the curve in Fig. 4). The implication of equation [3.5-16] is that the presence of absorbed light demands stomatal opening. In reviewing the literature on stomatal movement, however, Raschke (1975) points out that stomatal action actually responds to CO_2 concentration inside the substomatal cavity. DeMichele and Sharpe (1973) developed a complex model to define this movement. Under normal CO_2 field conditions the complex model is no more accurate than equation [3.5-16]. Under modified CO_2 conditions, the use of equation [3.5-16] would be questionable.

The effects of water potential on stomatal resistance have been studied extensively in recent years with the development of instrumentation for measuring water potential§. Early researchers theorized that stomata closed slowly in response to decreasing water potential. Recent research as summarized by Hsiao (1973) and Raschke (1975) has shown that stomata remain open until some critical value of water potential and then close rapidly to prevent water potential from becoming any more negative. A

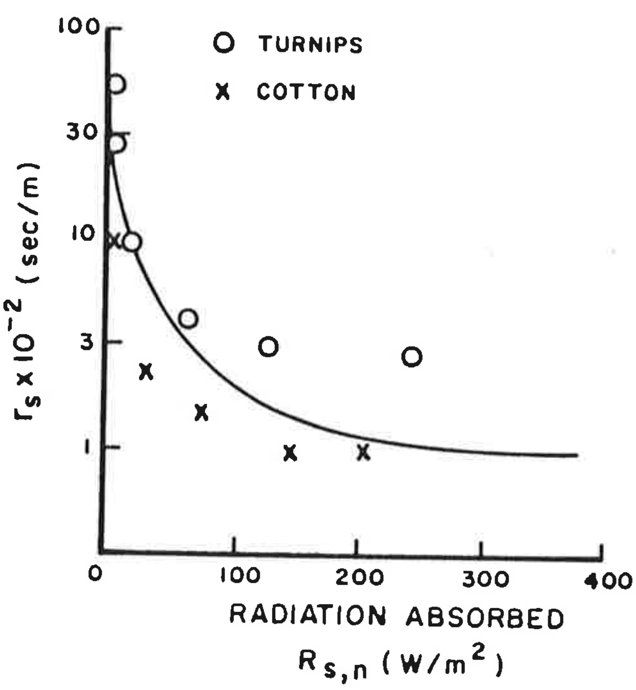

FIG. 5 Typical relationship between stomatal resistance and radiation absorbed [after Waggoner, 1968].

§Water potential is a measure of the tenacity with which plants hold water. The more negative the water potential, the more "tightly" water is held.

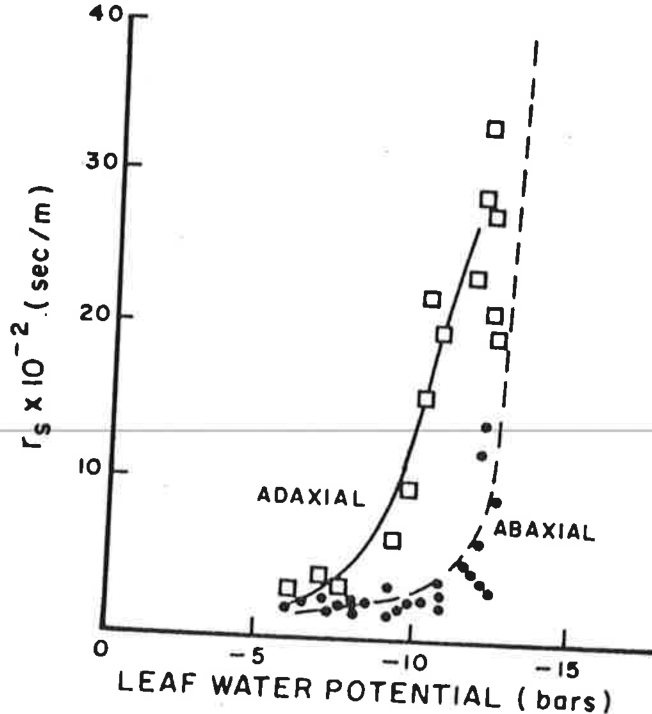

FIG. 6 Effect of water stress on stomatal resistance of snap beans. Data from Kanemasu and Tanner [1969] and curves from simulations by DeMichele and Sharpe [1973].

typical relationship is given in Fig. 6. The earlier-mentioned complex model of DeMichele and Sharpe (1973) can also be used to simulate this relationship.

Air temperature is another important parameter affecting stomatal resistance. Raschke (1975) indicates that stomatal resistance decreases with temperature up to about 35 °C and increases at higher temperatures. Values for cotton taken by Sharpe (1973) are shown in Fig. 7. Similar results have been found for other crops (Hofstra and Hesketh, 1969; Stalfelt, 1962). The result of this temperature response, when coupled with the non-linearity between air temperature and saturation vapor deficit, is

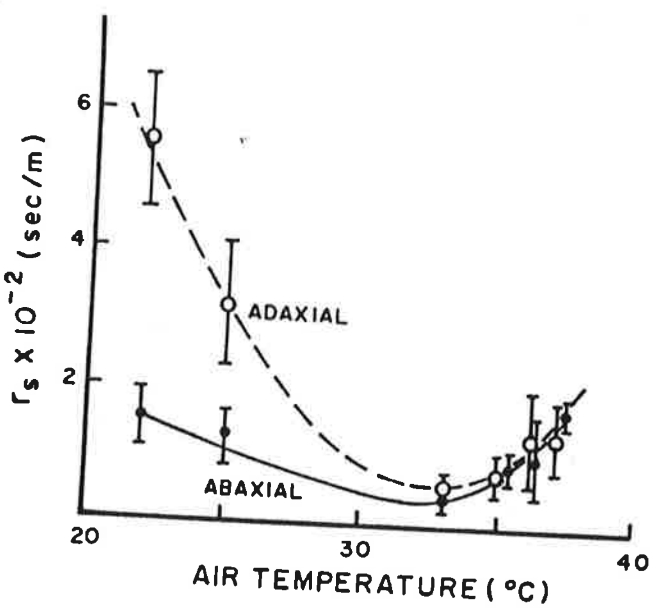

FIG. 7 Temperature response of stomatal resistance for cotton. Measurements were made in full sunlight at approximately equal values of solar radiation [after Sharpe, 1973].

that plants tend to be warmer than air at temperatures below 35 °C and cooler than air at temperatures above 35 °C. This is a fortunate coincidence since the optimum temperature for photosynthesis is near 35 °C.

Stomata also display a certain amount of circadial rhythm in their opening and closing (Raschke, 1975). This rhythm is ill defined but should be considered in simulations of mass and heat transfer with light-dark modifications.

The Use of Stomatal Resistance in Computing Energy Fluxes

The energy budget of an individual plant leaf can be written as

$$R_{N,a} = \frac{2\rho\, c_p\, (T_\ell - T_{ab})}{r_{as}} + \frac{2\rho\, \lambda\, (\chi_{v\ell} - \chi_{va})}{r_s + r_{av}} \quad \text{[3.5-17]}$$

where $R_{N,a}$ is the net radiation absorbed by the plant leaf, T_ℓ is leaf temperature, T_{ab} is air temperature above the leaf boundary layer and λ is the latent heat of vaporization. Gates (1966) used equation [3.5-17] to predict the energy budget of a plant leaf and to propose its response to various environmental parameters. Westerman, et al. (1976) used a similar relationship to predict the effects of leaf weting on leaf temperatures. In both studies, it was only possible to make generalizations about the response for an entire crop canopy.

By using equation [3.5-17] and functional relationships between plant water potential, light intensity, and stomatal resistance, Waggoner et al. (1968) and Stewart et al. (1969) have built complex micrometeorological models which can be used to define crop response to environment. These models are useful research tools, but are too complex to be used as operational tools at the present time.

Crop Resistance

An alternative to using stomatal resistance in a complex micrometeorological model of a plant canopy is to consider the canopy as a source or sink at $d + Z_v$ for vapor or $d + Z_s$ for sensible heat and to define a canopy resistance r_c for vapor. This was essentially the approach of Monteith (1963) and others (Edling et al., 1971) assuming that Z_v, Z_s and Z_o were all equal.

In order to use this approach it is necessary to determine stomatal resistance from environmental parameters and relate this to a crop resistance. Evaporative flux could then be determined for the entire canopy from equation [3.5-2].

Monteith (1963) proposed that crop resistance could be predicted from

$$\log_{10} r_c = 1.40 - 2\,\lambda\, E/(R_n - G) \quad \text{[3.5-18]}$$

Szeicz and Long (1969) showed that equation [3.5-18] was inaccurate and proposed that

$$r_c = r_s/LAI_e \quad \text{[3.5-19]}$$

where r_s is the average stomatal resistance of the crop and LAI_e is the effective leaf area index. Szeicz and Long proposed that

$$LAI_e = LAI \qquad LAI \leq \tfrac{1}{2}\, LAI_{max} \quad \text{[3.5-19a]}$$

$$LAI_e = \tfrac{1}{2}\, LAI_{max} \qquad LAI > \tfrac{1}{2}\, LAI_{max} \quad \text{[3.5-19b]}$$

where LAI_{max} is the maximum LAI the crop will develop. Thom (1972) proposed that LAI_e was equal to LAI. This question does not appear to be resolved at this point.

It must be pointed out that a LAI weighted stomatal resistance is a gross simplification of a very complex process. It is such a useful concept, however, that it is worth the effort required to make it tractable.

APPLICATION OF AERIAL AND CROP RESISTANCES FOR PREDICTING ENERGY FLUXES

Resistance-Energy Balance Method

Accurate estimates of energy fluxes over a large area are needed for estimating energy fluxes associated with environmental modifications. One approach is to use a resistance-energy model of the type

$$R_N + G + H_s + H_\ell = 0 \qquad [3.5\text{-}20]^{***}$$

or using the aerial resistance concept,

$$R_N + G = \frac{\rho\, c_p\,(T_s - T_a)}{r_{as}} + \frac{\rho\, \lambda\,(\chi_{vs} - \chi_{va})}{r_{av} + r_c} \qquad [3.5\text{-}21]$$

where G is soil heat flux, and R_N is net radiation flux. Three specific examples will be given of the use of equation [3.5-21] to calculate energy fluxes.

Case I: Surface temperature measured. R_N, G, and T_a are routinely measured environmental parameters. T_s can be measured by remote sensing or thermal imagery and r_{as} can be estimated from wind speed and air temperature profile measurements. With these parameters available, sensible heat flux is given by equation [3.5-1] and latent heat fluxes by,

$$H_\ell = -\left(\rho_a\, c_p\, \frac{(T_a - T_s)}{r_{as}} + R_N + G\right) \qquad [3.5\text{-}22]$$

Heilman and Kanemasu (1976) tested this model over sorghum and soybeans at Manhattan, Kansas. The resistance to heat transfer, r_{as}, was evaluated by

$$r_{as} = (k U_*)^{-1}\left[\ln \frac{z - d}{Z_s} + \psi_s\right] \qquad [3.5\text{-}23]$$

where Z_s = roughness length for heat transfer, d = displacement length which was assumed to be the same for heat as well as momentum transfer, ψ_s = diabatic influence function (integral form) for heat transfer. Values of Z_s were obtained from intercepts of linearized relationships of $(T_s - T_a)$ vs ln(z−d) (Chamberlain, 1966). ψ was evaluated in terms of Richardson's number using relationships presented by Lettau (1962), Dyer and Hicks (1970) and Webb (1970). Figs. 8 and 9 (from Heilman and Kanemasu, 1976) show their r_{as} values for soybeans and sorghum at two growth stages and the resulting LE fluxes compared with lysimetrically measured evapotranspiration data.

An alternative method of computing r_{as} is given below. The sensible heat flux term in equation (3.5-22] can be expressed as,

$$H_s = \rho_a\, C_p\, \frac{T_a - T_s}{r_{as}} = \rho_a\, C_p\, K_s \frac{\partial T}{\partial z} \qquad [3.5\text{-}24]$$

***The convention used here is that heat flow to the surface is positive.

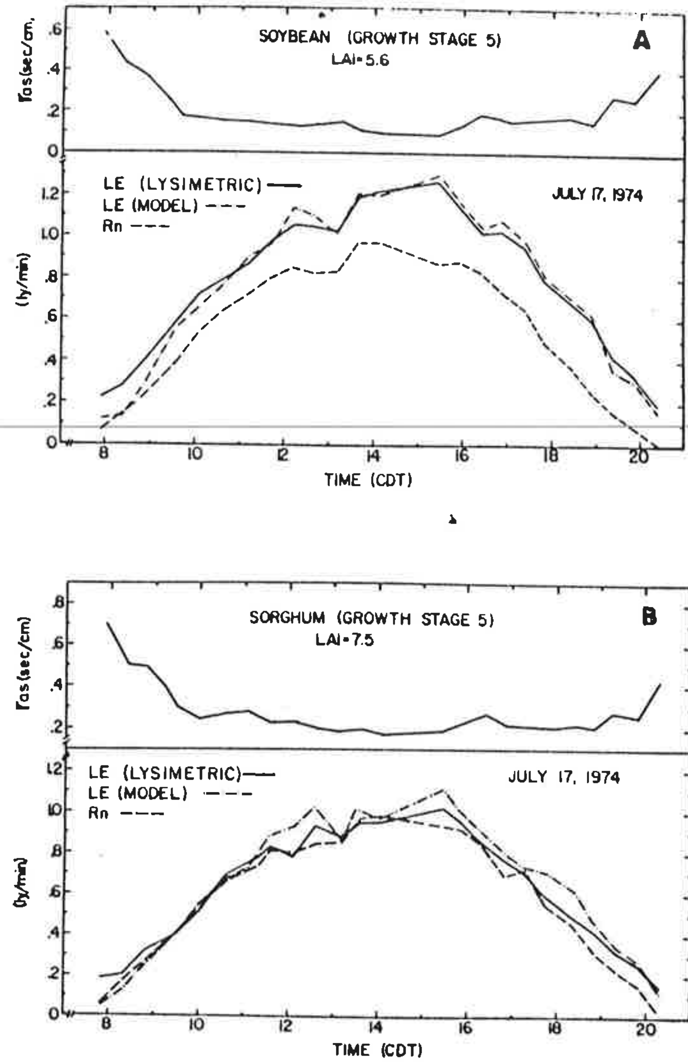

FIG. 8 Estimates of r_{as} and comparisons of model LE, lysimetric LE, and Rn for soybean [A] and sorghum [B] on July 17, 1974 [from Heilman and Kanemasu, 1976].

or

$$r_{as} = \frac{(T_s - T_a)\left(\frac{\partial u}{\partial z}\right)}{\left(\frac{K_s}{K_m}\right) U_*^{\ 2} \left(\frac{\partial T}{\partial z}\right)} \quad \text{[3.5-25]}$$

Following Thom's (1972) analysis, a representative surface temperature can be obtained by extrapolating T(z) vs ln(z−d) to $z = d + Z_S$ (In other words, $T = T_S$ where $u = -B^{-1} U_*$). Equation [3.5-25] can, therefore, be rewritten as

$$r_{as} = \frac{(u + B^{-1}\ U_*)}{\left(\frac{K_H}{K_m}\right) U_*^{\ 2}} \quad \text{[3.5-26]**}$$

**Verma et al. (1976) used a similar approach in estimating ET from sorghum at Mead, Nebraska except that they extrapolated $T = T_S$ to $u = 0$ instead of $u = -B^{-1} U_*$.

Rn for soybean [A]

. . . . . [3.5-25]

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sorghum at Mead.
β^{-1} U_*.

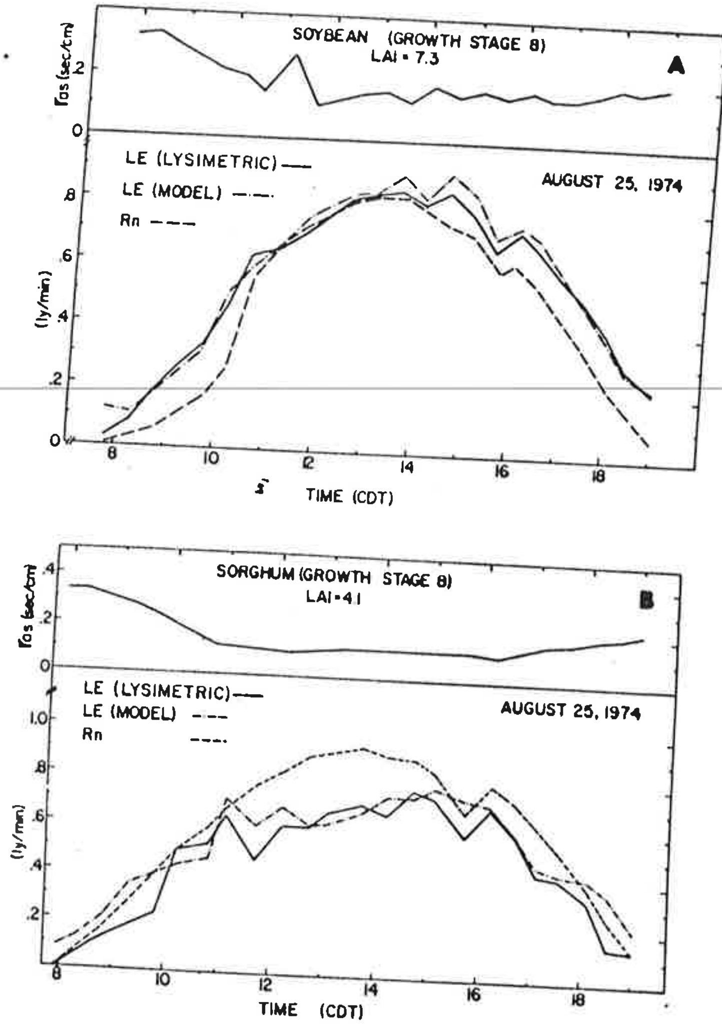

FIG. 9 Estimates of r_{as} and comparisons of model LE, lysimetric LE, and Rn for soybean [A] and sorghum [B] on August 25, 1974 [from Hellman and Kanemasu, 1976].

B^{-1} can be estimated from results reported by Thom (1972) and by Garratt and Hicks (1973) (e.g. Fig. 1). Reasonably accurate values of friction velocity can be obtained by employing Deacon-Swinbank's low level drag coefficient approach (Deacon and Swinbank, 1958; Bradley, 1972; Pierson and Jackman, 1975 and Verma et al., 1976). Results from recent micrometeorological investigations (e.g. Dyer and Hicks, 1970); Pruitt et al., 1973) can be used to estimate K_s/K_m.

Case II: Surface temperature predicted. χ_{vs} in equation [3.5-21] is a function only of surface temperature. Over a range of −54 to +54 °C a reasonably accurate estimate of χ_{vs} has been proposed by Bosen (1960) as

$$\chi_{vs} = \frac{21.07}{P}\,[(0.00738\,T_s + 0.8072)^8 - 0.0019\,(T_s + 48) + 0.001316] \quad \ldots\ldots [3.5\text{-}27]$$

where P is atmospheric pressure and T is measured in degrees F. Denoting χ_{vs} as $f(T_s)$, equation [3.5-21] becomes

$$R_N + G = \frac{\rho\, C_p\,(T_s - T_a)}{r_{as}} + \frac{\rho^2\,(f(T_s) - \chi_{va})}{r_{av} + r_c} \quad \ldots\ldots [3.5\text{-}28]$$

If profile data are not available for estimating r_{as} and r_{av} estimates can be made from crop parameters. Assuming that $r_{as} = r_{av}$, equation [3.5-23] can be written in terms of roughness heights as

$$r_{as} = r_{av} = \frac{[\ln \frac{z-d}{z_o}]\,[\ln \frac{z-d}{z_s}]\,\phi_m^2}{k^2 \frac{K_s}{K_m} u} \qquad [3.5\text{-}29]$$

Values of Z_o and d can be estimated from equations [3.5-11] and [3.5-13]. Knowing Z_o, an estimate of U_* can be obtained from

$$U_* = \frac{ku}{\ln(\frac{z-d}{Z_o})\,\phi_m} \qquad [3.5\text{-}30]$$

Z_s can be estimated from Z_o using the parameter B^{-1} and equation [3.5-9a]. If Garratt and Hicks (1973) data on crops is used, kB^{-1} can be estimated rather roughly from Fig. 1.

Relationships by Dyer and Hicks (1970) were proposed in Chapter 3.5-2 for ϕ_m and K_s/K_m. Alternate relationships are given by Businger et al. (1971) and Pruitt et al. (1973). The problems with the use of the stability relationships by Businger et al. is that they are in terms of the Monin-Obukhov stability length given in Chapter 3.2. In the absense of profile data one normally needs a diabatic correction in terms of Richardson number,

$$R_i \simeq \frac{g}{T}\,\frac{(T_s - T_a)(z-d)}{u^2} \qquad [3.5\text{-}32]$$

This relationship is an approximation only and should be limited to situations where the reference height z is close to the surface. It is also necessary to measure or estimate T_s for its use. A formula is necessary to relate z/L to R_i. Binkowski (1975) proposed relationships as a simplification of the more complex forms proposed by Businger et al. (1971).

A test of the model given by equation [3.5-27] to [3.5-32] using Businger's stability correction was conducted by the authors on data collected by Ehrler and van Bavel (1967) over grain sorghum in which evapotranspiration, leaf stomatal resistance, and leaf temperature were measured. The effects of windspeed in Z_o was accounted for by using the relationship shown in Fig. 2 based on the Szeicz et al. (1969) data. As mentioned earlier, the Szeicz et al. data probably overestimate the effects of wind on Z_o. Predicted leaf temperatures and evapotranspiration are shown in Fig. 10 under assumptions that LAI_e is equal to one-half LAI and to LAI. Based on the results indicated, it appears that the procedure has merit. A similar approach was used by Edling et al. (1971) and Barfield et al. (1974) to predict the effects of irrigation on crop cooling.

The Brown-Rosenberg model. The Brown-Rosenberg model is a slight modification of Case II. A resistance mass-transfer method (e.g. Monteith, 1963) for estimating evapotranspiration is given by:

$$LE = \frac{\rho_a \lambda\, M_w/M_a}{P}\,\frac{(e_s - e_a)}{r_{av} + r_c} \qquad [3.5\text{-}33]$$

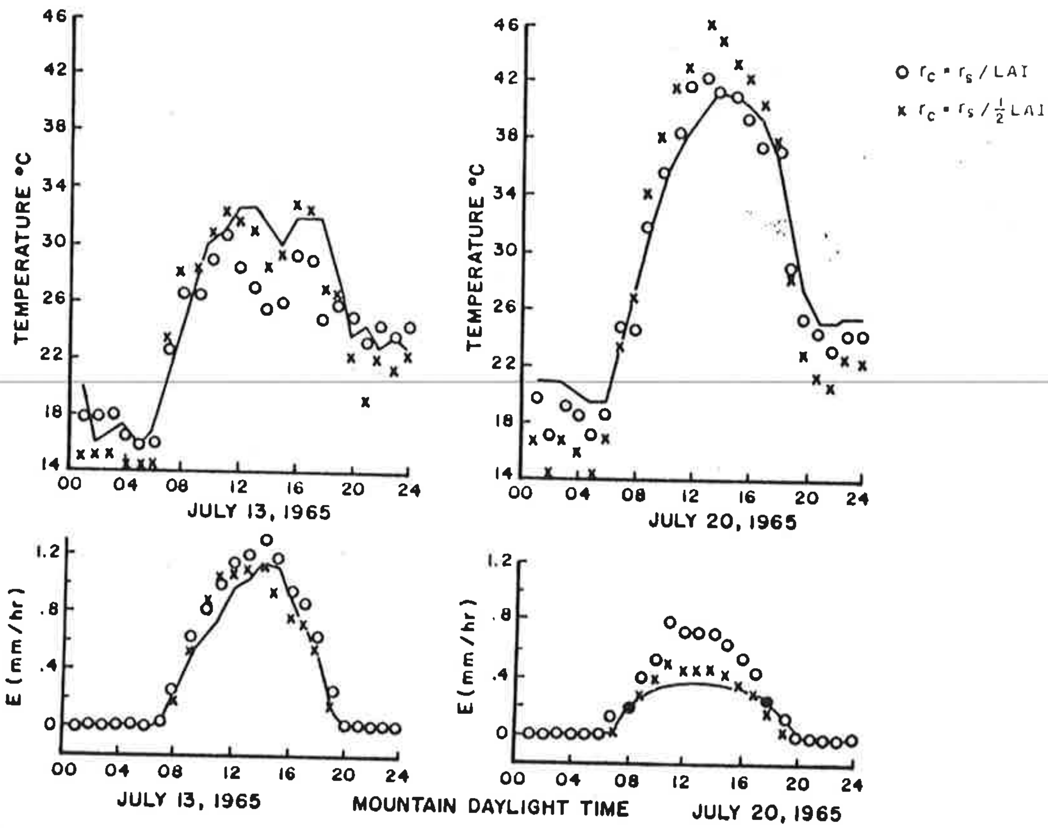

FIG. 10 Comparison of predicted and observed crop temperatures and evaporation for Arizona sorghum data using Case II model [data from Ehrler and van Bavel, 1967].

where e_s is the saturation vapor pressure at the crop surface temperature, T_s, e_a is the vapor pressure in the ambient air, P is the atmospheric pressure, r_{av} is the aerial resistance to the transport of water vapor, r_c is the plant canopy resistance, M_w and M_a are the molecular weights of water and air, respectively. Saturation vapor pressure e_s can be obtained from crop surface temperature measurements by using an integrated version of the Clapeyron-Classius equation [$e_s = f_1 (T_s)$], assuming the air space within the leaves (the sub-stomatal cavities) to be at or very near a relative humidity of 100 percent.

Brown and Rosenberg (1973), employing energy-balance consideration, eliminated e_s in equation [3.5-33] to obtain

$$LE = -(\rho_a C_p \frac{T_a - T_s}{r_{as}} + R_N + S) \qquad [3.5\text{-}34]$$

or

$$T_s = \frac{(LE + R_N + S)\, r_{as}}{\rho_a C_p} \qquad [3.5\text{-}35]$$

Therefore, e_s can be written as

$$e_s = f_1 (T_s) = f_1 \left[\frac{(LE + R_N + S)\, r_{as}}{\rho_a C_p} + T_a\right] \qquad [3.5\text{-}36]$$

Combining equations [3.5-33] and [3.5-36] results in

$$LE = \frac{\rho_a L\, M_w/M_a}{P} \; \frac{[f_1 \left(\frac{(LE + R_N + S)\; r_{as}}{\rho_a\, C_p} + T_a \right) - e_a]}{r_{as} + r_c} \quad \ldots\ldots\ldots\ldots \; [3.5\text{-}37]\dagger\dagger$$

Using R_N, S, T_a, e_a and aerial and crop resistance measurements in equation [3.5-37] and employing an iteration technique, Brown and Rosenberg (hereafter called B-R model) obtained ET estimates which agreed closely with measurements made in a sugar beet field. The B-R model has been used to evaluate windbreak, antitranspirant and reflectant influences on ET and gave results consistent with experimentation (Hales, 1970, unpublished; Brown and Rosenberg, 1972; Miller et al., 1973 and Baradas et al., 1976). The B-R model is useful when neither direct nor remotely sensed canopy temperature data are available and when there is need to evaluate the impact on evapotranspiration of the several aforementioned environmental and crop parameters.

SUMMARY AND CONCLUSIONS

A discussion is given of the factors affecting aerial and crop diffusion resistance to heat, mass, and momentum transport. Examples are given of the use of these concepts to predict heat and mass transfer from crop canopies. The limitations of these approaches are pointed out.

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