RADIATIVE SURFACE TEMPERATURE AND CONVECTIVE FLUX CALCULATION OVER CROP CANOPIES

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Abstract. The analysis presented in this paper aims at a better understanding of the potential role of radiative temperature, as measured by a radiometer over crops, in sensible heat flux calculation. Defining radiative temperature as the mean temperature of the surfaces viewed by the radiometer (leaves and soil surface) and assuming that an Ohm's law type formula can be used to express sensible heat flux as a function of the difference between air temperature and radiative temperature, the aerodynamic resistance which divides this temperature difference has been analytically defined. The parameters which appear in the resistance expression depend essentially on wind velocity and canopy structure but also on the inclination angle of the radiometer. Finally an experimental verification is presented with data obtained over a potato crop.

1. Introduction

Infrared thermometry is a common technique for measuring surface temperature in environmental studies. Radiometers mounted on a mast, in an aircraft or on a satellite provide a good estimate of the so-called radiative temperature on both local and regional scales. In the scientific literature, many papers deal with the use of radiative temperature as input in energy balance models for estimating sensible and latent heat fluxes (Brown, 1974; Seguin *et al.*, 1982; Hatfield *et al.*, 1983; Choudhury *et al.*, 1986) or for evaluating crop water stress (Jackson *et al.*, 1977).

The sensible heat flux density emanating from natural surfaces is commonly expressed as:

$$C = \rho c_p (T_S - T(z_r))/r_a \,, \tag{1}$$

where $T(z_r)$ and T_S are respectively the air temperature at a reference height above the surface and at the surface level, r_a is the aerodynamic resistance to convective heat transfer between the two levels, c_p is the specific heat of air at constant pressure and ρ the mean air density. In the case of vegetation stands, the surface temperature is taken at level $z = \mathrm{d} + z_0$ above the soil surface, d being the zero plane displacement and z_0 the roughness length for heat transfer (Huband and Monteith, 1986; Thom, 1975). $T(\mathrm{d} + z_0)$ is estimated from temperature and wind velocity profiles above the canopy extrapolated down to that level and is recognized to be the temperature of the apparent source or sink of heat. It is

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frequently referred to as the canopy aerodynamic temperature. Many workers assume implicitly crop radiative temperature as measured with a radiometer to be equal to the aerodynamic temperature calculated as indicated above. But an experimental discrepancy between the two temperatures has been observed (Choudhury *et al.*, 1986; Huband and Monteith, 1986) and the relationship between them, from a theoretical point of view, has not yet been clearly explored.

In this paper, we present a model which provides a modified version of Equation (1) to be used when radiative temperature T_R is substituted for surface temperature T_S. In this case, the resistance term of the modified equation differs in nature and definition from the original one. The purpose of the paper is to specify the nature of this difference by linking radiative temperature with wind characteristics, canopy structure and energy balance components.

2. A Simple Interpretation of Canopy Radiative Temperature

The radiometer measuring the surface temperature of a crop canopy takes into account the elementary radiative fluxes emitted by all surfaces viewed by the instrument. These surfaces are essentially leaves at different levels within the canopy and a part of the soil surface. Radiative temperature T_R given by the instrument is the result of the integration of all these elementary fluxes. But expressing mathematically these elementary fluxes becomes rather complicated because of shape factors. The correct expression of T_R is thus not easily accessible in practice. For this reason, we intend to simplify the problem by considering an approximate expression of T_R based on a one-dimensional model.

We shall define T_R as the mean temperature of the surfaces viewed by the radiometer. If $v(z)$ and $T_v(z)$ are respectively the functions giving the viewed surface and the surface temperature at each level z within the canopy, we can write:

$$T_R = \int_0^{z_h} v(z)\, T_v(z)\, \mathrm{d}z \Big/ \int_0^{z_h} v(z)\, \mathrm{d}z\,, \tag{2}$$

where z_h is the canopy height.

Two functions linked with canopy architecture are used to express $v(z)$. The first one is leaf area density $l(z)$ related to downward cumulative leaf area index $L(z)$ by:

$$L(z) = \int_z^{z_h} l(z)\, \mathrm{d}z\,; \tag{3}$$

$L(0) = LAI$ represents canopy leaf area index. The second one is function $s(z)$ which represents the fraction of surface viewed by the radiometer at any (horizontal) level z within the canopy. This function is the same as the one used by several authors to express the sunlit horizontal area within the vegetation (Chartier, 1966; Monteith, 1969). For a given canopy, this function depends essentially upon the inclination angle of the sensor to the vertical.

Assuming that leaves display a random distribution and that the radiometer viewing angle is small so that the variation of $s(z)$ around the viewing direction can be neglected, the leaf area viewed by the sensor can be written as:

$$v(z) = s(z)l(z) \tag{4}$$

and the soil surface viewed by the radiometer is $s(0)$. $T_L(z)$ is the leaf temperature at level z and T_0 is the ground surface temperature. The radiative temperature expression then becomes:

$$T_R = \frac{\int_{0+}^{z_h} s(z)l(z)T_L(z)\,\mathrm{d}z + s(0)T_0}{\int_{0+}^{z_h} s(z)l(z)\,\mathrm{d}z + s(0)} \tag{5}$$

3. Convective Fluxes Expressed as a Function of T_R

We shall assume that the Ohm law type formula (1) used to express sensible heat flux remains valid if T_S is replaced by T_R as defined above. But the aerodynamic resistance r_a has to be modified to take into account the difference existing between aerodynamic temperature T_S and radiative temperature T_R. Sensible heat flux will be written as:

$$C = \rho c_p(T_R - T(z_r))/re_c \tag{6}$$

and a similar formula will be used for latent heat flux:

$$\lambda E = (\rho c_p/\gamma)(e_S(T_R) - e(z_r))/re_v, \tag{7}$$

where γ is the psychrometric constant, $e(z_r)$ the water vapour pressure of the air and $e_s(T_R)$ the saturated vapour pressure at temperature T_R. The problem then is to derive correct expressions for the new resistances re_c and re_v.

In the appendix, the following expression is derived. It relates leaf temperature $T_L(z)$ to air characteristics at canopy height (temperature $T(z_h)$ and saturation deficit $D(z_h)$):

$$T_L(z) - T(z_h) + \frac{D(z_h)}{\Delta+\gamma} = \frac{\gamma/\rho c_p}{\Delta+\gamma}[(R_n - S)r_A(z) + \lambda E\, r_S(z)], \tag{8}$$

where Δ is the slope of the saturated vapour pressure curve as defined in the appendix, R_n the net radiation, S the soil heat flux; λE is the latent heat flux,

$r_A(z)$ and $r_S(z)$ are two resistive terms defined in the appendix (A10, A11). Three familiar functions appear in $r(z)$. The first, $a(z)$ gives the available energy extinction with depth within the canopy, which for the purpose of this study is considered as independent of leaf temperature and approximated by a Beer's law function of the downward cumulative leaf area index. The other two, eddy diffusivity $K(z)$ and boundary-layer resistance $rb(z)$, as a first approximation neglecting buoyancy forces, are considered independent of temperature and only related to wind velocity and canopy structure. In $r_S(z)$ the stomatal resistance profile $rs(z)$ appears, as well as the function $g(z)$ which gives the distribution profile of water vapour sources.

Substituting Equation (8) in Equation (5), with $T_0 = T_L(0)$, gives:

$$T_R - T(z_h) + \frac{D(z_h)}{\Delta+\gamma} = \frac{\gamma/\rho c_p}{\Delta+\gamma}[(R_n - S)rc_A + \lambda E rc_S],$$

where parameters rc_A and rc_S, which have the dimensions of a resistance, are defined as:

$$rc_A = \frac{\int_{0+}^{z_h} s(z)l(z)r_A(z)\,dz + s(0)r_A(0)}{\int_{0+}^{z_h} s(z)l(z)\,dz + s(0)}, \tag{10}$$

$$rc_S = \frac{\int_{0+}^{z_h} s(z)l(z)r_S(z)\,dz + s(0)r_S(0)}{\int_{0+}^{z_h} s(z)l(z)\,dz + s(0)}. \tag{11}$$

The saturation deficit at the top of the canopy $D(z_h)$ is linked with the same entity taken at the reference height $D(z_r)$ by means of the following classical formula (Monteith, 1981):

$$\lambda E = [\Delta(R_n - S) + \rho c_p(D(z_r) - D(z_h))/r_a]/(\Delta+\gamma), \tag{12}$$

where r_a is the aerodynamic resistance calculated between levels z_h and z_r. This equation together with Equation (1) enable one to modify Equation (9) as:

$$T_R - T(z_r) + \frac{D(z_r)}{\Delta+\gamma} = \frac{\gamma/\rho c_p}{\Delta+\gamma}[(R_n - S)(r_a + rc_A) + \lambda E rc_S]. \tag{13}$$

Linearizing the saturated vapour pressure curve, Equation (7) can be rewritten in the form:

$$\lambda E = \rho c_p(\Delta/\gamma)(T_R - T(z_r) + D(z_r)/\Delta)/re_{v^-}. \tag{14}$$

From Equations (6) and (14), advanced as hypotheses, and the energy balance equation:

$$R_n - S = C + \lambda E, \tag{15}$$

it is possible to derive the same kind of equation as (13):

$$T_R - T(z_r) + \frac{D(z_r)}{\Delta + \gamma} = \frac{\gamma/\rho c_p}{\Delta + \gamma}[(R_n - S)re_c + \lambda E(re_v - re_c)]. \tag{16}$$

Matching Equations (13) and (16) yields:

$$(R_n - S)[re_c - (r_a + rc_A)] + \lambda E[(re_v - re_c) - rc_S] = 0, \tag{17}$$

where re_c and re_v are the unknown variables. For this equation to be valid, it is necessary that:

$$re_c = r_a + rc_A, \tag{18}$$

$$re_v - re_c = rc_S. \tag{19}$$

If not, the ratio $\lambda E/(R_n - S)$ would be independent of energetic conditions such as air temperature and humidity, since the resistances defined above do not depend upon them as a first approximation (free convection excepted).

Resistances to heat transfer re_c and to vapour transfer re_v are now clearly defined by Equations (18) and (19). re_c is the sum of two resistances: the aerodynamic resistance r_a calculated between heights z_h and z_r above the canopy; and the crop aerodynamic resistance rc_A defined by Equation (10). rc_A takes into account the resistances of the air to heat transfer within the canopy and depends directly on wind velocity and canopy structure. re_v is the sum of these two resistances, r_a and rc_A, and of an additional resistance rc_S which allows for the proper resistances of exchange surfaces to vapour transfer. Due to function $s(z)$, the two canopy resistances rc_A and rc_S depend on the inclination angle of the radiometer to the vertical.

4. Practical Calculation of Resistance rc_A and Experimental Validation

Resistance rc_A is theoretically defined by Equation (10) completed by Equation (A10) of the appendix. All functions which occur in these equations can be expressed in terms of leaf area density and wind velocity.

We shall assume available energy $A(z) = R_n(z) - S$ to decrease as an exponential function of the cumulative leaf area index:

$$A(z)/A(z_h) = a(z) = \exp[-\alpha L(z)]. \tag{20}$$

Coefficient α has to be slightly different from the one used in the familiar exponential decrease of net radiation because of the soil heat flux term.

A numerical value for the boundary-layer resistance of the leaves $rb(z)$ (in s/m) can be related to local wind velocity $U(z)$ (in m/s) by means of a relation of the form:

$$rb(z) = rb_0/U(z)^a, \tag{21}$$

where rb_0 and a are two parameters considered to be respectively equal to 50 and 0.8 (Perrier, 1968).

As to wind velocity and eddy diffusivity profiles within the canopy, analytical expressions given by Perrier (1967, 1976) are used:

$$U(z) = U(z_h)\exp[-BL(z)]\,, \tag{22}$$

$$K(z) = [A/l(z)^2]\,\mathrm{d}U(z)/\mathrm{d}z\,, \tag{23}$$

where coefficients A and B are theoretically derived ($A = 0.4$ and $B = 0.6$).

The function generally used to calculate the horizontal sunlit area within the canopy is an exponential function of the cumulative leaf area index (Monteith, 1969):

$$s(z) = \exp[-bL(z)]\,. \tag{24}$$

The same kind of function can be used to indicate the fraction of horizontal surface viewed by the radiometer provided the viewing angle is small. Coefficient b depends on leaf angle distribution and on sensor elevation. Lemeur (1973), using mathematical models, calculated the values of b for different types of canopy.

All these analytical functions set in Equation (10) allow one to calculate rc_A.

In order to validate the theory presented above, the values of rc_A, calculated from Equation (10) with the functions indicated above, were compared to those estimated directly from the flux equation (6). For this purpose, a field experiment was carried out at a site in the Paris area. On several days in July and August 1986 over a potato stand (Solanum tuberosum), the radiative temperature of the canopy together with wind velocity and air temperature gradients were measured. The crop height was 0.7 m and the leaf area index 3. Air temperatures and wind speeds above the canopy were measured by shielded thermocouples and cup anemometers (MCB) set at different heights (0.7, 1.1, 2.1 and 3.0 m for the thermocouples and 1.1, 2.1 and 3.0 m for the anemometers, with heights measured from the soil surface). Radiative temperature was measured by an AGA infrared radiometer (type TPT80) equipped with a band-pass filter which limited the optical response to 8–14 micrometers. The radiometer field of view was 2°. The radiometer, previously calibrated with an AGA black body, was set on a mast 6 m above the soil surface. The angle of inclination to the vertical (θ) was maintained constant at 70°, pointing southward. All data were logged automatically as quarter-hour averages.

The sensible heat flux C was calculated from the temperature gradient between 1.1 and 2.1 m, the corresponding aerodynamic resistance being calculated by a technique described by Itier and Katerji (1983). This technique, based on assumed logarithmic profiles above the canopy, takes into account the instability of the lower atmospheric layer (conditions prevailing during the tests). An

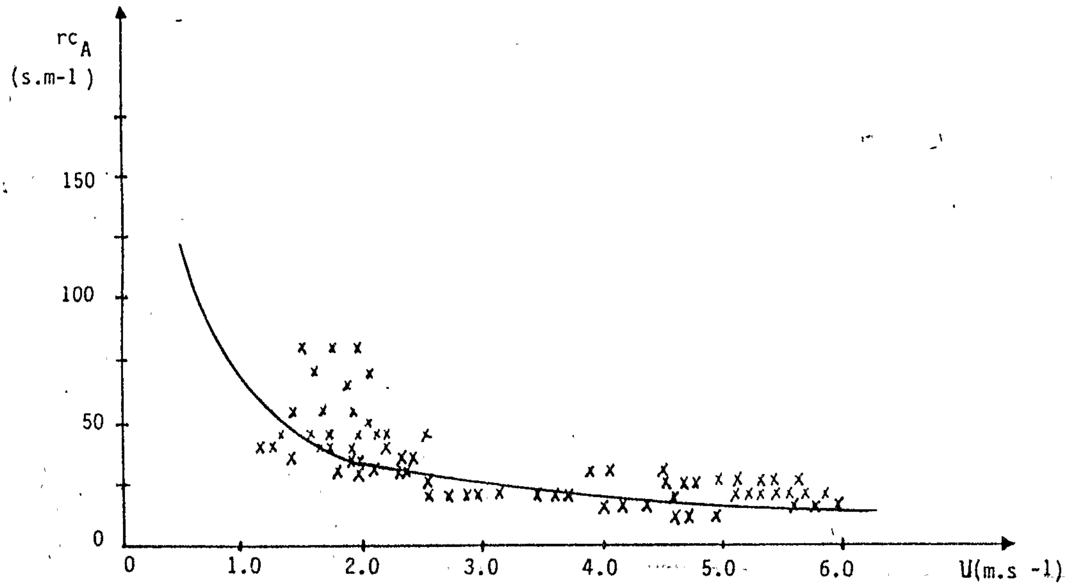

Fig. 1. Canopy aerodynamic resistance rc_A of a potato crop (LAI = 3) as a function of wind velocity at 3 m above the soil surface (—: theoretical results; × experimental results).

experimental value of rc_A was derived from the following equation:

$$C = \rho c_p (T_R - T(3\ \mathrm{m}))/(r_a + rc_A)\,, \tag{25}$$

where C is the calculated sensible heat flux, $T(3\ \mathrm{m})$ the air temperature at a height of 3 m, T_R the radiative temperature measured by the AGA radiometer and r_a the aerodynamic resistance calculated between the canopy height and 3 m by the same technique mentioned above. In Figure 1, the values of rc_A calculated from this equation are plotted against wind velocity at 3 m. Only the values corresponding to sensible heat fluxes greater than 50 W m^{-2} have been retained. The theoretical values of rc_A were calculated by means of relations 20 to 24 (coefficient b was taken to be equal to 1.3 according to Lemeur's results for this type of canopy). The curve plotted in Figure 1 represents the theoretical variation of rc_A as a function of wind velocity at the 3 m height. A rather satisfactory agreement exists between theory and the experimental data.

5. Conclusion

The theory presented here provides a way of using canopy radiative temperature as input in sensible heat flux calculation. If radiative temperature is used as surface temperature, the flux must be written as:

$$C = \rho c_p (T_R - T(z_r))/(r_a + rc_A)\,, \tag{26}$$

where r_a is the classical aerodynamic resistance calculated above the canopy between the canopy height and the reference height and rc_A is a so-called canopy aerodynamic resistance, mathematically defined by Equation (10). All the functions occuring in this expression can be parameterized in terms of wind velocity, leaf area index and radiometer inclination angle, which permits the practical calculation of rc_A. For a given canopy and a given inclination angle, rc_A is a decreasing function of wind velocity as shown in Figure 1.

Finally it should be pointed out that the theoretical approach presented in this paper rests on a number of simplified assumptions. Among them is the use of K-theory within the canopy. In one-dimensional canopy models, flux estimates based on K-theory (Equations (A2) and (A3)) must be accepted with a degree of scepticism. Turbulent diffusivity should only be used in cases where sources or sinks are at least one length scale removed from the point for which the convective flux is being specified, which is often not the case in most real canopies. But it is hard to quantify, in a general way, the errors this assumption brings into the model.

Appendix. Theoretical Expression for the Surface Temperature Profile

In this appendix an analytical expression of $T_L(z)$ is derived from a simple one-dimensional model of transfers. The basic equations used are the following:
—the energy balance equation applied to a vegetation layer located between the soil surface ($z = 0$) and height z ($0 \leq z \leq z_h$):

$$A(z) = C(z) + \lambda E(z)\,, \tag{A.1}$$

where $A(z)$ is the available energy at height z (equal to net radiation $R_n(z)$ minus soil heat flux S); $C(z)$ and $\lambda E(z)$ are respectively the sensible and latent heat fluxes at the same height. Storage and advection terms are neglected.
—the local expressions of vertical convective fluxes within the canopy:

$$C(z) = -\rho c_p K(z)\,\mathrm{d}T(z)/\mathrm{d}z\,, \tag{A.2}$$

$$\lambda E(z) = -(\rho c_p/\gamma) K(z)\,\mathrm{d}e(z)/\mathrm{d}z\,, \tag{A.3}$$

where $K(z)$ is the eddy diffusivity, assumed to be the same for heat and water vapour; $T(z)$ and $e(z)$ are respectively the temperature and the vapour pressure of the air.
—the expressions giving the elementary fluxes exchanged between the leaves and the air at height z:

$$\mathrm{d}C(z) = \rho c_p \left[\frac{T_L(z) - T(z)}{rb(z)}\right] 2l(z)\,\mathrm{d}z\,, \tag{A.4}$$

$$\mathrm{d}\lambda E(z) = (\rho c_p/\gamma) \left[\frac{e_S(T_L(z)) - e(z)}{rb(z) + rs(z)}\right] 2l(z)\,\mathrm{d}z\,, \tag{A.5}$$

where $l(z)$ is the leaf area density at height z; $rb(z)$ is the leaf boundary-layer resistance at height z assumed to be the same for heat and water vapour; $rs(z)$ is the mean stomatal resistance. The air within the substomatal cavities is assumed to be saturated by water vapour at the corresponding leaf temperature $e_S(T_L(z))$.

Combining Equations (A1), (A2) and (A3) and integrating between z and z_h we obtain:

$$T(z) - T(z_h) + \frac{1}{\gamma}[e(z) - e(z_h)] = \frac{1}{\rho c_p} \int_z^{z_h} \frac{A(z)}{K(z)} \mathrm{d}z . \tag{A.6}$$

Expressing $T(z)$ and $e(z)$ in Equation (A6) as a function of $T_L(z)$ by means of Equations (A4) and (A5) and taking into account the energy balance equation (A1) yield:

$$T_L(z) - T(z_h) + \frac{1}{\gamma}[e_S(T_L(z)) - e(z_h)] =$$

$$= \frac{1}{\rho c_p}\left[\frac{\mathrm{d}\lambda E(z)}{\mathrm{d}z}\frac{rs(z)}{2l(z)} + \frac{\mathrm{d}A(z)}{\mathrm{d}z}\frac{rb(z)}{2l(z)} + \int_z^{z_h} \frac{A(z)}{K(z)} \mathrm{d}z\right]. \tag{A.7}$$

We shall define:

$$a(z) = A(z)/A(z_h) \tag{A.8}$$

$$g(z) = \lambda E(z)/\lambda E(z_h) \tag{A.9}$$

$$r_A(z) = \frac{\mathrm{d}a(z)}{\mathrm{d}z}\frac{rb(z)}{2l(z)} + \int_z^{z_h} \frac{a(z)}{K(z)} \mathrm{d}z \tag{A.10}$$

$$r_S(z) = \frac{\mathrm{d}g(z)}{\mathrm{d}z}\frac{rs(z)}{2l(z)} . \tag{A.11}$$

Equation (A.7) then becomes:

$$T_L(z) - T(z_h) + \frac{1}{\gamma}[e_S(T_L(z)) - e(z_h)] =$$

$$= \frac{1}{\rho c_p}[A(z_h) r_A(z) + \lambda E(z_h) r_S(z)] . \tag{A.12}$$

Linearizing the saturated vapour pressure versus temperature curve between $T_L(z)$ and $T(z_h)$ yields:

$$e_S(T_L(z)) - e_S(T(z_h)) \approx \Delta[T_L(z) - T(z_h)] , \tag{A.13}$$

where Δ is the slope of the curve determined at a temperature close to $T(z_h)$. Then Equation (A12) can be rewritten as:

$$T_L(z) - T(z_h) = \frac{\gamma/\rho c_p}{\Delta + \gamma}\left[A(z_h) r_A(z) + \lambda E(z_h) r_S(z)\right] - \frac{D(z_h)}{\Delta + \gamma}, \qquad \text{(A.14)}$$

where $D(z_h)$ is the vapour pressure deficit of the air at the top of the canopy: $e_S(T(z_h)) - e(z_h)$.

The equations written so far are not defined at $z = 0$. However, it is possible to extrapolate by defining for the soil surface a resistance to water vapour transfer denoted by rs_0 and by considering that vapour originates from a saturated zone at the temperature of the ground T_0. If rb_0 is the boundary-layer resistance of the soil surface, we shall write:

$$r_A(0) = a(0) rb_0 + \int_{0+}^{z_h} \frac{a(z)}{K(z)}\,dz\,, \qquad \text{(A.15)}$$

$$r_S(0) = g(0) rs_0\,. \qquad \text{(A.16)}$$

Thus Equation (A.14) is valid from $z = 0$ to $z = z_h$ and $T_0 = T_L(0)$.

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