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RESISTANCE FOR SENSIBLE HEAT FLUX OF VEGETATION AS DERIVED FROM RADIOMETRICALLY MEASURED CROP TEMPERATURES

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C O N T E N T S

1. LIST OF SYMBOLS

Symbol	Description	Units
a_m	extinction coefficient for momentum transport	-
a_ϕ	extinction coefficient for incoming radiation from direction ϕ	-
a_θ	extinction coefficient of sources of radiation going to direction θ	-
a_H	extinction coefficient for sensible heat transport	-
c	empirical constant for heat transport from a surface	-
C_d	drag coefficient of leaves and stems	-
c_p	specific heat per unit mass of air	$J.kg^{-1}.K^{-1}$
D	zero displacement	m
E	evapotranspiration flux	$kg.m^{-2}.s^{-1}$
G	heat flux into the soil	$W.m^{-2}$
h	height of the canopy	m
H(z)	sensible heat flux at height z	$W.m^{-2}$
$H_1(z)$	sensible heat flux, generated per unit area of leaf	$W.m^{-2}$
K	von Karman's constant	-
K(z)	exchange coefficient at height z	$m^2.s^{-1}$
l(z)	leaf area density at height z	m^{-1}
l_ϕ	projection of leaf area density in the direction ϕ	m^{-1}
L(z)	downward cumulative leaf area index	-
$L_\phi(z)$	projection of L(z) in the direction ϕ	-
Nu	Nusselt number	-
p	pressure of the air	Pa
Pr	Prandl number	
P_2	stability correction for heat transport	-
r_a	atmospheric resistance inside the canopy	$s.m^{-1}$
r_{aH}	resistance for heat transport from the canopy to a certain place above the canopy	$s.m^{-1}$

Symbol	Description	Units
r_H	resistance for heat transport inside the canopy	$s.m^{-1}$
r_1	leaf resistance per unit area of leaf	$s.m^{-1}$
R_e	Reynolds number	-
R_n	net radiation	$W.m^{-2}$
$R(z)$	radiation at height z	$W.m^{-2}$
s	relative source strength of observed radiation	-
T_a	air temperature	K
T_c	crop surface temperature	K
T_1	leaf temperature	K
T_s	average recorded surface temperature	K
$u(z)$	wind velocity at height z	$m.s^{-1}$
u_*	friction velocity above the canopy	$m.s^{-1}$
w	average length of the air stream across the leaf	m
x	distance in the direction of wind velocity	m
z	height above the soil	m
z_0	roughness length of the canopy	m
κ	thermal diffusivity of air	$m^2.s^{-1}$
ν	kinematic diffusivity of air	$m^2.s^{-1}$
σ_1	scattering coefficient of leaves	-
ρ	density of air	$kg.m^{-3}$
$\tau(z)$	momentum flux at height z	$N.m^{-2}$
θ	angle between direction of observation and the vertical	-
ϕ	average angle between incident radiation and the vertical	-

2. INTRODUCTION

Several methods exist to estimate evapotranspiration of a certain field (lysimetry, Bowen-ratio, eddy correlation, etc.). However for extensive areas the use of remote sensing techniques seems more promising. In particular the use of infrared detected surface temperature has often been suggested (BARTHOLIC et al., 1972; STONE and HORTON, 1974; HEILMAN et al., 1976; SOER, 1977; MILLARD et al., 1978). In this method evapotranspiration is estimated from the energy balance at the earth surface

$$LE = R_n - G - H \tag{1}$$

where L is latent heat of vaporization ($J.kg^{-1}$)
E is evapotranspiration flux ($kg.m^{-2}.s^{-1}$)
R_n is net radiation ($W.m^{-2}$)
G is ground heat flux ($W.m^{-2}$)
H is sensible heat flux ($W.m^{-2}$)

In order to estimate the sensible heat flux from the temperature difference between the surface and the lower atmosphere the energy balance may be written in a resistance form:

$$H = \rho c_p \frac{T_c - T_a}{r_H} \tag{2}$$

where ρ is density of air ($kg.m^{-3}$)
c_p is specific heat of air ($J.kg^{-1}.K^{-1}$)
T_c is crop surface temperature (K)
T_a is air temperature at some reference height (K)
r_H is resistance for sensible heat transport ($s.m^{-1}$)

In this equation T_c is the temperature of the crop at the height where according to the logaritmic wind profile wind velocity is zero. With infrared thermometry however the whole canopy is scanned, resulting in an average surface temperature T_s. As crop temperature is often strongly dependent upon height the measured temperature T_s may deviate from T_c.

The resistance for sensible heat transport is mostly set equal to the resistance for momentum transport. Inside the canopy however the exchange processes for momentum and sensible heat transport are different. Therefore a leaf resistance term should be included which generally will be dependent of height in the canopy.

In this paper leaf resistance as well as atmospheric resistance for sensible heat transport are calculated as a function of height. A weighted average resistance is then calculated which may account for the prevailing temperature distribution inside the canopy.

3. THE CANOPY MODEL

The canopy is assumed to be built up in horizontal and vertical leaves only (SUITS, 1972). The ratio between horizontal and vertical leaves is assumed to be constant and should be seen as a measure for leaf orientation. The vertical leaves are assumed to have a homogeneous azimuthal leaf angle distribution.

In a horizontal plane the canopy is supposed to be homogeneous. In a vertical plane however the leaf area density may vary with height.

Inside the canopy the amount of radiation occuring inside the canopy is calculated as a function of total leaf area above the place of measurement (cumulative leaf area index). This leaf area is characterized by a so-called cumulative leaf area index. Then calculation of radiation is made independent of leaf area density. The distribution of wind velocity inside the canopy is calculated from a theory assuming a constant leaf area density. For varying leaf area densities, LANDSBERG and JAMES (1971) found that wind velocity can be expressed best as a function of cumulative leaf area index. This procedure is applied in this paper.

The influence of the soil is neglected in the calculations by taking the limit of leaf area index to infinity (SOER, 1978). Therefore the model should only be used for canopies approaching 100% soil cover.

4. DISTRIBUTION OF WIND VELOCITY INSIDE THE CANOPY

4.1. Basic equations

As the exchange of sensible heat appears to be dependent on wind velocity, the wind velocity distribution inside the canopy should be known. Wind velocity inside the canopy at some distance from the leaves will be calculated from the equations for momentum flux and divergence of momentum flux. The flux of momentum is defined by

$$\tau(z) = \rho\, K(z)\, \frac{du}{dz} \tag{3}$$

where $\tau(z)$ is momentum flux at height z ($N.m^{-2}$)
- z is height above the soil surface (m)
- $K(z)$ is exchange coefficient at height z ($m^2.s^{-1}$)
- u is wind velocity ($m.s^{-1}$)

Divergence of momentum is caused by molecular viscosity and pressure gradients from the Coriolis force:

$$\frac{d\tau}{dz} = \rho\, C_d\, l(z)\, u(z)^2 - \frac{dp}{dx} \tag{4}$$

where C_d is drag coefficients of the leaves, stems, etc.
- $l(z)$ is leaf area density at height z ($m^2.m^{-3}$)
- p is air pressure (Pa)
- x is distance in the direction of wind velocity (m)

Generally the second term of eq. (4) may be neglected as the Coriolis force is perpendicular to wind velocity and therefore has hardly any influence on the magnitude of the wind velocity.

4.2. General solution

For solving eqs. 3 and 4 C_d, $l(z)$ and $K(z)$ must be known as a function of height. Generally C_d and $l(z)$ are assumed to be constant. A solution of eqs. 3 and 4 was first presented by INOUE (1965) and CIONCO (1965). These authors postulated a constant mixing length in order to calculate K as a function of crop height h. However the magnitude of this mixing length is not quite clear. Therefore in this paper the solution as first described by COWAN (1968) will be used, who assumed K(z) to be proportional to u(z). Wind velocity is then expressed as

$$\frac{u(z)}{u(h)} = \left[\frac{\sinh\ (a_m z)}{\sinh\ (a_m h)}\right]^{\frac{1}{2}} \qquad (5)$$

where $a_m = \left(\frac{C_d\ l(z) u}{K}\right)^{\frac{1}{2}}$ (6)

For large values of leaf area index eq. (5) may be simplified, giving

$$u(z) = u(h)\ \exp\left[-a_m (z-h)\right] \qquad (7)$$

4.3. Evaluation of the general solution

A basic assumption in this theory is the proportionality between K(z) and u(z), i.e. an exponential decrease of K(z) with depth in the canopy. Several investigators have measured K(z) inside the canopy. Most of them found a decrease of K(z) with depth in the canopy with a secondary maximum at about half of the canopy height (UCHIJIAMA and WRIGHT, 1964; BROWN and COVER, 1966; DRUILHET et al, 1971 and JOHNSON et al., 1976). Other investigators found the exchange coefficient to be constant (THOM, 1971) or exponentially decreasing (STEWARD and LEMON, 1969). Fortunately, theoretical investigations show that the shape of K(z) has only little influence on wind velocity distribution inside the canopy, so that the exponential decrease as used in COWAN's model may be adapted.

The solution of the eqs. 5 and 7 is given for the condition of a constant leaf area density. As stated in section 3 for varying leaf area densities wind velocity can better be expressed as a function of total leaf area above the place of measurement, so

$$u(z) = u(h)\ \exp\left[-\left(\frac{C_d\ u}{l(z)\ K}\right)^{\frac{1}{2}} L(z)\right] \qquad (8)$$

where $L(z) = \int_z^h l(z)dz$ is the cumulative leaf area index

4.4. Re-expression of wind velocity distribution in more simple measurable quantities

The terms u/K, C_d and u(h) in eq. (8) will now be rewritten:

- u/K. This ratio may be found from the equations for momentum flux and wind velocity at the top of the canopy. Combining eqs. (3) and (7) gives

$$\tau(h) = \rho\ K(h)\ u(h)\left(\frac{C_d\ l(z)\ u}{K}\right)^{\frac{1}{2}}$$

or with $u_* \equiv (\tau/\rho)^{\frac{1}{2}}$, the friction velocity ($m.s^{-1}$)

$$u/K = C_d\ l(z)\ u(h)^4/u_*^4 \qquad (9)$$

- u(h). The ratio $u(h)/u_*$ may then be found from the logarithmic wind profile:

$$\frac{u(h)}{u_*} = \frac{1}{k}\ \ln\left(\frac{h-D}{z_o}\right) \qquad (10)$$

where k is von Karmen's constant
D is zero plane displacement (m)
z_o is crop roughness length (m)

By using a constant ratio $z_o/(h-D) = 0.36$ as suggested by THOM (1971) and taking k = 0.4, eq. (10) may be solved numerically, giving

$$u(h) = 2.55\ u_* \qquad (11)$$

Allthough it seems more obvious to express u(h) as a function of z_0 and wind velocity at some reference height, for the sake of simplicity u_* is assumed to be the known quantity.

- C_d. The drag coefficient may be found from measurement of THOM (1968). He found for $u > 0.3\ m.s^{-1}$ a constant value of C_d may be used. Furtheron the drag coefficient is about proportional to the leaf area perpendicular to the air stream:

$$C_d = 0.4\ l_u/l \qquad (12)$$

where l_u is leaf area density perpendicular to the airstream (m^{-1}). For a horizontal wind and a homogeneous azimuthal leaf angle distribution, l_u may be calculated from

$$l_u = \frac{2\ l_v}{\pi} \qquad (13)$$

where l_v is vertical leaf area density (m^{-1})

The expressions for u/K, u(h) and C_d may now be filled in eq. (8) giving

$$u(z) = 2.55\ u_* \exp\left[-\ 1.17\ L_v(z)\right] \qquad (14)$$

where $L_v(z) = \frac{l_v}{l}$. L(z) is cumulative leaf area index of vertical leaves.

In this equation relative windvelocity inside the canopy is found to be a function of $L_v(z)$ only. Some computed wind velocities inside the canopy are shown in fig. 1. It is seen that the boundary condition

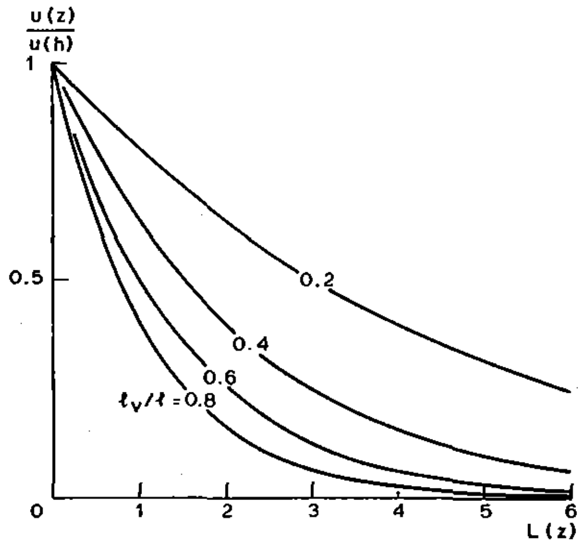

Fig. 1. Relative wind velocity as a function of downward cumulative leaf area index for some values of the percentage of vertical leaves

u = 0 at the soil surface is rather well met for crops with high soil coverage. For instance with L(z) = 4 and l_v/l = 0.5 wind velocity at the soil surface u(0) = 0.15 u(h).

5. RESISTANCE FOR SENSIBLE HEAT TRANSPORT

As shown in fig. (2) the resistance for sensible heat transport can be written as the sum of leaf- and atmospheric resistance:

$$r_H = r_l + r_a \tag{15}$$

where

r_l = leaf resistance ($s.m^{-1}$)
r_a = atmospheric resistance ($s.m^{-1}$)

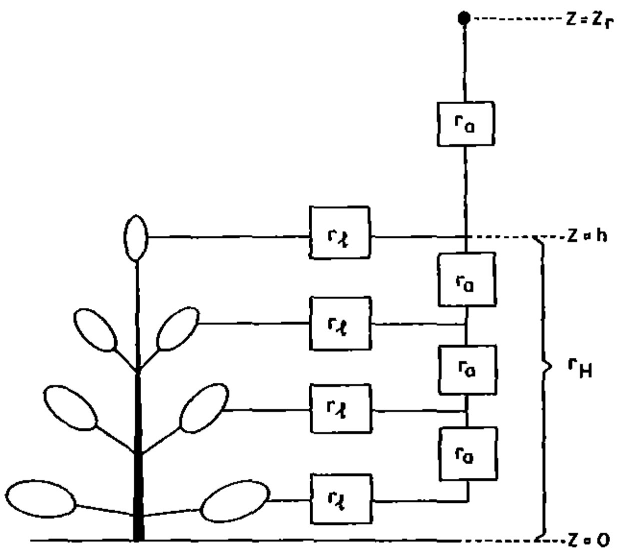

Fig. 2. Resistance model for the exchange of heat from a plant canopy. r_l is leaf resistance, r_a is atmospheric resistance, h is height of the canopy and z_r is height of measurement of air temperature

This resistance will be calculated as a function of depth in the canopy and will be compared with the resistance as calculated from the logarithmic wind profile. Inside the canopy stability corrections will be neglected. In order to get a dimensionless quantity, all resistances will be multiplied with the friction velocity.

5.1. Resistance according to the logarithmic wind profile

The resistance may be calculated from (KLAASSEN and NIEUWENHUIS, 1978)

$$u_* r = \frac{1}{k} \ln \left(\frac{z-D}{z_0}\right) \tag{16}$$

where r is the resistance according to the logarithmic wind profile. By taking the constant ratio $z_0/h\text{-}D = 0.36$ (see eq.11) eq.(16) can be expressed as

$$u_* r = 2.55 \tag{17}$$

5.2. Atmospheric resistance inside the canopy

The sensible heat flux inside the canopy may be expressed in a similar way as the momentum flux in eq. (3), so

$$H(z) = \rho \; c_p \; K(z) \; \frac{dT_a}{dz} \tag{18}$$

where H(z) is sensible heat flux at height z ($W.m^{-2}$)
c_p is specific heat per unit mass of air ($J.kg^{-1}.K^{-1}$)
T_a is air temperature (K)

from eq. (18) the average atmospheric resistance over the entire canopy may be expressed as

$$r_a = H(h)^{-1} \int_{z'}^{h} H(z) \; K(z)^{-1} \; dz \tag{19}$$

In this paper it will be assumed that the exchange coefficients for momentum and sensible heat are equal. Then K(z) may be calculated from eqs. (9, 11, 12, 13 and 14) giving

$$K(z)^{-1} = 2.12 \; l_v/u_* \; \exp\left[1.17 \; L_v(z)\right] \tag{20}$$

so

$$u_* r_a = \int_{L_v}^{0} 2.12\, H(L)/H \exp\left[1.17\, L_v\right] dL_v \qquad (21)$$

5.3. Leaf resistance

According to MONTEITH (1973) the sensible heat flux from a leaf may be expressed as

$$H_l = \rho\, c_p \frac{\kappa\, N_u (T_l - T_a)}{w} = \rho\, c_p \frac{T_l - T_a}{r_l} \qquad (22)$$

where

H_l is sensible heat flux, generated per unit area of the leaf ($W.m^{-2}$)
κ is thermal diffusivity of air ($\kappa = 18.10^{-6}\ m^2.s^{-1}$)
N_u is Nusselt number
T_l is leaf temperature (K)
w is average length of the air stream across the leaf, commonly expressed as leaf width (m)
r_l is leaf resistance ($s.m^{-1}$)

The generated sensible heat flux H_l can be found from the divergence of sensible heat flux inside the canopy and can be expressed as

$$H_l = \frac{1}{l}\frac{dH}{dz} = \frac{dH}{dL} \qquad (23)$$

From eq. (22) it follows for the leaf resistance:

$$r_l = \frac{w}{\kappa N_u} \qquad (24)$$

The Nusselt number is found to be almost independent of leaf orientation and is usually expressed as a function of the Reynolds number R_e, defined as:

$$R_e = \frac{u\ w}{v} \qquad (25)$$

where v is the kinematic viscosity of the air ($v = 15.10^{-6}\ m^2.s^{-1}$)

For relatively low Reynolds numbers (laminary flow) and forced convection (mainly caused by differences in wind velocity) the Nusselt number may be expressed as:

$$N_u = c.R_e^{0.5}\ Pr^{0.33} \tag{26}$$

where c is an empirical constant
Pr is Prandtl number (Pr = 0.71 in air)

WIGLEY and CLARK (1974) compared several measurements and concluded that c = 1.0 is an appropriate value for R_e < 7000. Then eq. (24) may be rewritten as

$$r_1 = \frac{v^{0.5}\ w^{0.5}}{c\ \kappa\ u^{0.5} Pr^{0.33}}$$

or, combining with eq. (14):

$$u_* r_1 = 151\ (w\ u_*)^{0.5}\ \exp\ [0.59\ L_v(z)] \tag{27}$$

6. RADIATION INSIDE THE CANOPY

In chapter 5 leaf and atmospheric resistance are calculated as a function of depth inside the canopy. In chapter 7 these resistances will be integrated to get an average resistance for the canopy.
In that integration the following subjects must be taken into account.

- The distribution of sensible heat flux (for r_a) and its divergence (for r_1) inside the canopy
- The source distribution of observed thermal radiation.

Sensible heat flux will be calculated from the distribution of net radiation inside the canopy (section 6.1). Because of reciprocity of light the source distribution of radiation can be calculated from the extinction of incoming radiation (section 6.2).

6.1. Distribution of net radiation

Net radiation inside the canopy will be calculated from the extinction of incident radiation.

On black leaves the extinction of radiation may be calculated from Beer's law, yielding an exponential decrease of radiation with leaf area index

$$R(z) = R(h) \exp\left[- L_{\phi}(z)/\cos\phi\right] \qquad (28)$$

where $R(z)$ is radiation at height z ($w.m^{-2}$)

$L_{\phi}(z)$ is projection of cumulative leaf area index in the direction ϕ

ϕ is angle between incident radiation and the vertical axis

The projected leaf area index may be expressed as a function of horizontal and vertical leaf area index, giving

$$L_{\phi} = \cos\phi\, L_h + \frac{2}{\pi}\sin\phi\, L_v$$

or

$$L_{\phi} = L + L_v\left(\frac{2}{\pi}\operatorname{tg}\phi - 1\right) \qquad (29)$$

For green leaves with non-zero transmission and reflection, the radiation extinction coefficient may be approximated by multiplying it with a factor $(1 - \sigma_1)^{0.5}$ (GOUDRIAAN, 1977) so

$$R(z) = R(h) \exp\left[- a_{\phi}\, L(z)\right]$$

$$\text{with } a_{\phi} = (1-\sigma_1)^{0.5}\,\left(1 + 1/1_v\left(\frac{2}{\pi}\operatorname{tg}\phi - 1\right)\right) \qquad (30)$$

where σ_1 is the scattering coefficient (sum of transmission and reflection coefficient) of leaves

a_{ϕ} is extinction coefficient for radiation in the direction ϕ

For average green leaves scattering coefficient values are presented in table 1 (according to ROSS, 1975).

Table 1. Scattering coefficient for green leaves

Wavelength	Scattering coefficient
visible light (0.4 - 0.7 μm)	0.15
near infra red (0.7 - 1.1 μm)	0.85
thermal infra red (3 - 30 μm)	0.05

6.2. Source distribution of observed radiation

As mentioned before, the distribution of observed radiation must be of equal shape as the distribution of incident radiation. Therefore the source distribution of observed radiation may be calculated from the divergence of incident radiation. This divergence may be calculated by differentiating eq. (30), giving

$$\frac{dR}{dL} = - R(h)\ a_\theta \exp\left[- a_\theta\ L\right] \qquad (31)$$

where θ is angle between observation and the vertical axis.

For the source distribution a relative value will be used, so that $\int_0^h s(z)\ dz = 1$. Then

$$s(L) = a_\theta \exp\left[- a_\theta\ L\right] \qquad (32)$$

where s is the relative source strength of observed radiation.

7. CANOPY RESISTANCE FOR SENSIBLE HEAT TRANSPORT AS A FUNCTION OF THE PLACE OF HEAT GENERATION

The average canopy resistance will be calculated by integrating eq. (15), i.e. the eqs. (21) and (27):

$$r_H = \int_\infty^0 r_a \cdot s(L)\ dL + \frac{1}{H} \int_\infty^0 r_1 \frac{dH}{dL}\ s(L)\ dL \qquad (33)$$

The factor $\frac{1}{H}\frac{dH}{dL}$ in eq. (33) is introduced because leaf temperatures are caused by the divergence of sensible heat flux in stead of the sensible heat flux itself.

In order to investigate the dependence of r_H on the distribution of sensible heat flux, the resistance will be calculated as a function of the place, where the heat is generated by setting

$$H(z) = H \quad \text{for } z > L$$
$$H(z) = 0 \quad \text{for } z < L + \Delta L$$
$$\frac{dH}{dz} = H/\Delta L \text{ for } L + \Delta L < z < L \qquad (34)$$

It will be simulated that all sensible heat flux originates from the same height inside the canopy by taking the limit $\Delta L \to 0$. For observation perpendicular to the earth, eq. (33) is solved from the eqs. (21), (27), (32) and (34). The results shown in fig. 3. The following remarks can be made:

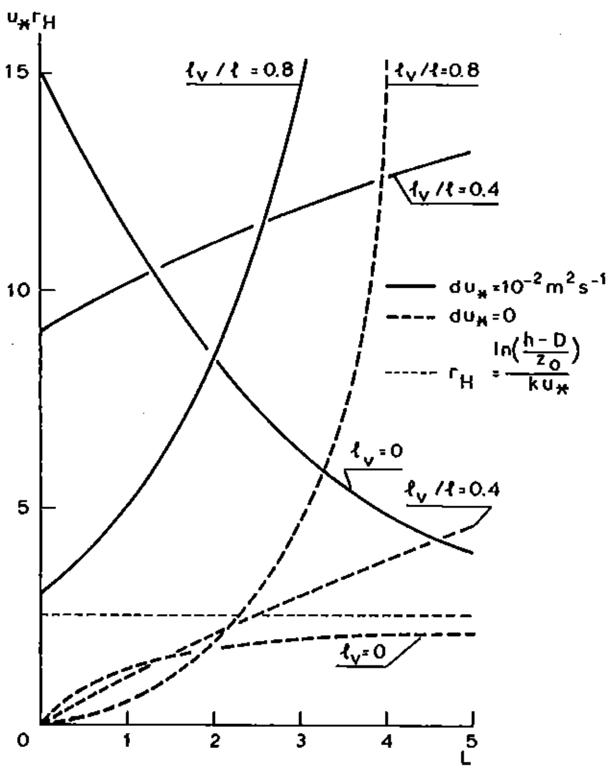

Fig. 3. Resistance for heat transport inside the canopy as a function of the place where the heat is generated for some values of the percentage of vertical leaves and two values of the leaf width compared with the usual canopy resistance

- The observed resistance is dependent on depth in the canopy. So, when the resistance model is used the distribution of heat sources inside the canopy must be known.
- Mostly the leaf resistance may not be neglected as the resistances for $wu_* = 10^{-2}\ m^2 s^{-1}$ are definitely higher than for $wu_* = 0$
- When leaf resistance is included, the resistance for heat transport inside the canopy is obviously higher than the commonly used value $r = \ln\left(\frac{h-D}{z_0}\right)/ku_*$
- For canopies with a predominantly vertical structure the observed resistance is increasing fast with depth. In that case radiometrically detected canopy temperature will be much more sensitive for drying of the lower leaves than for drying of the upper leaves.

8. AVERAGE CANOPY RESISTANCE

8.1. General solution

As stated in section 7.1 an average canopy resistance for sensible heat transport may only be used when the distribution of heat sources is known. This distribution may be calculated from the energy balance at the leaf surface.

In this paper sensible heat transport is assumed to be proportional to net radiation inside the canopy. This might be acceptable as stomatal conductance is proportional to net radiation (DENMEAD and MILLAR, 1976). So both stomatal and heat resistance are exponentionally increasing with depth in the canopy.

Because of the assumed proportionality between sensible heat transport and net radiation, sensible heat transport will be calculated from eq. (30) by setting $\sigma_1 = 0.5$. This is an appropriate average for the scattering coefficient for visible and near infrared radiation. Then the sensible heat flux inside the canopy may be written as

$$H(L) = H(h) \exp\left[- a_H L \right]$$

where $a_H = 0.71 \left[1 + (\frac{2}{\pi} tg\phi - 1) . l_v/l\right]$ (35)

being the extinction coefficient for sensible heat flux. By substituting eqs. (32) and (35) in eq. (33) the following analytical expression is found:

$$u_* r_H = 151 \, (du_*)^{0.5} . \frac{a_\theta \, a_H}{a_\theta + a_H - 0.59} + \frac{2.12 \, a_\theta}{a_\theta + a_H - 1.17 \, l_v/l} \quad (36)$$

The resistance $u_* r_H$ is shown for vertical observation as a function of leaf orientation l_v/l in fig. 4. It is seen that the solution of eq. (36) can be divided into two parts: for most leaf

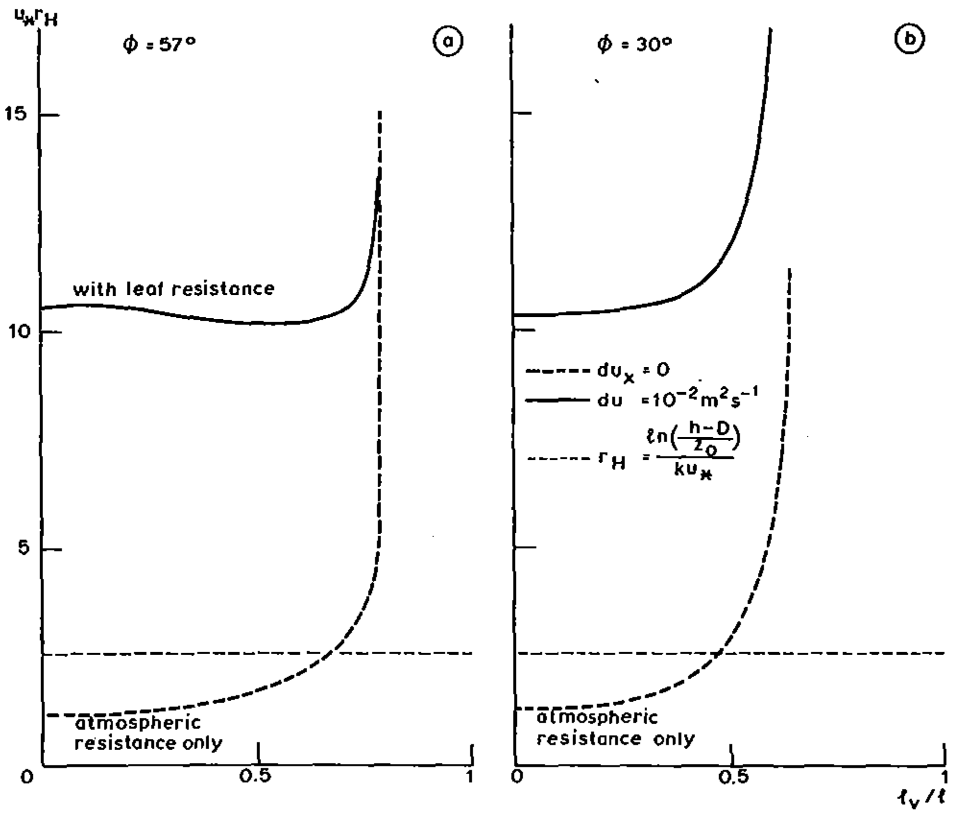

Fig. 4. Average canopy resistance for sensible heat transport as a function of the percentage of vertical leaves for vertical observation
a: solar elevation 57° from vertical
b: solar elevation 30° from vertical

orientations ($l_v/l < 0.7$) an almost constant resistance is found. With predominantly vertical orientated leaves the resistance is strongly increasing and the solution of eq. (36) gets unstable. Both solutions will now be analysed in more detail.

8.2. U n s t a b l e s o l u t i o n

As shown in fig. 4 the canopy resistance is increasing with both more vertically orientated canopies and more vertical observation. Then observation is deeper inside the canopy. As shown in fig. 3 the resistance is strongly increasing with depth inside the canopy. By taking the limit of total leaf area an index to infinity fig. 4 shows that, theoretically, even an unstable situation may occur. For actual canopies with limited leaf area index this means that observation includes a large amount of soil, which might have a strongly deviating temperature. For example a well developped vertical orientated canopy with L = 4 and l_v/l = 0.7 will show a soil coverage of only 70%. Therefore vertically orientated canopies should be viewed oblique for a reliable interpretation of the observed temperature. The unstable solution of eq. (36) is found when the denominator of the last term of eq. (36) gets zero or negative, so the condition must be set that

$$a_\theta + a_H - 1.17\ l_v/l \leq 0$$

or, with eqs. (30) and (35):

$$l_v/l\ (0.45\ \mathrm{tg}\phi + 0.62\ \mathrm{tg}\theta - 2.86) \leq -1.69 \qquad (37)$$

from eq. (37) a stable solution of eq. (36) for all solar elevations can be found by setting $\phi = 0$. By setting $\phi = 0$, eq. (37) may be rewritten as

$$\mathrm{tg}\theta \leq 4.6 - 2.7\ l/l_v \qquad (38)$$

The result of eq. (38) is shown in fig. 5. It is seen that for an accurate interpretation of radiation temperatures vertically

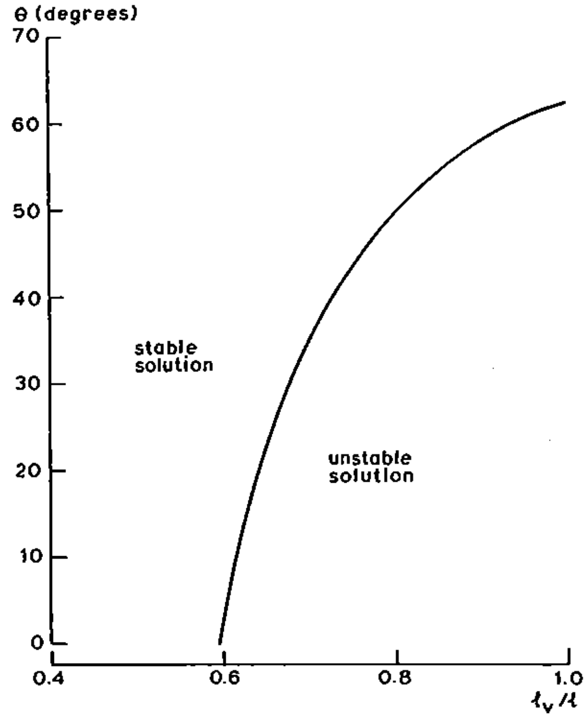

Fig. 5 . Minimal angle between direction of observation and the vertical to get a reliable temperature interpretation as a function of the percentage of vertical leaves

orientated canopies with $1_v/1 > 0.6$ should be viewed oblique. Leaf orientation is estimated from values given by ROSS (1975) (table 2).

Table 2. Leaf orientation

Type of canopy	Relative amount of vertical leaves $1_v/1$
Ryegrass	0.2 - 0.6
Maize	0.2 - 0.6
Wheat	0.5
Sugar beets	0.3
Potatoes	0.2

From table 2 it is seen that $1_v/1 > 0.6$ is seldom reached, so that also with vertical observation an accurate interpretation of radiation temperatures is possible for almost all canopies.

8.3. Stable solution

Canopy resistance was calculated for vertical observation (fig. 4). In order to find the influence of the angle of observation upon canopy resistance, calculations have also been made for $\theta = 57^o$ (fig. 6). As to be expected from section 7.3 a stable solution is

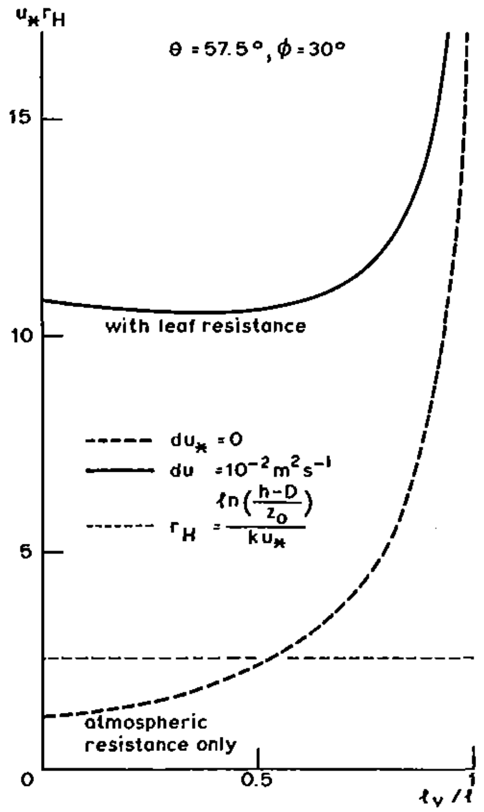

Fig. 6. Average canopy resistance for sensible heat transport as a function of the percentage of vertical leaves for observation under an angle of 57.3^o with the vertical

found for a larger range of leaf orientations. From comparison with fig. 4 it is seen that for the stable solution the average canopy resistance is almost equal to the resistance obtained with vertical observation. So it is shown for $wu_* = 10^{-2} m^2 s^{-1}$ that the stable solution of eq.(36) is almost independent of angle of observation, solar elevation and leaf orientation!

Average canopy resistance has also been calculated as a function of wu_* (fig. 7). It is seen that for low values of wu_* canopy resistance

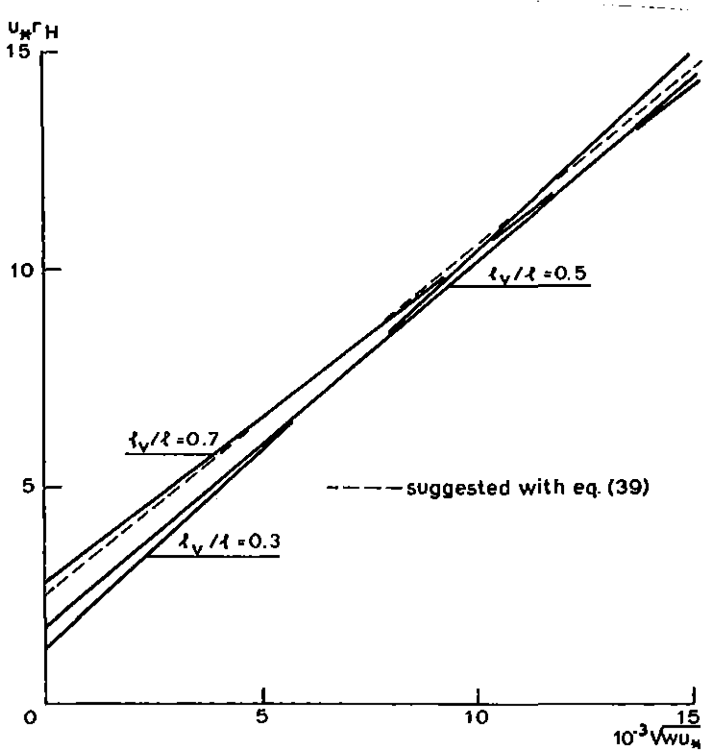

Fig. 7. Average canopy resistance for sensible heat transport as a function of wu_*

is somewhat dependent on leaf orientation. This influence is diminished as for the calculation of sensible heat flux average canopy resistance must be added to atmospheric resistance above the canopy. Therefore it is believed that only small errors will be made when average canopy resistance for $wu_* = 0$ is set equal to $\ln(\frac{h-D}{z_0})/ku_*$. Then eq. (36) may strongly be simplified and can be expressed as:

$$u_* r_H = 2.55 + 80\ (wu_*)^{0.5} \qquad (39)$$

Eq. (39) may be used in equations dealing with the calculation of sensible heat fluxes from radiometrically measured temperatures. Then total resistance for heat transport from the canopy to a certain reference height in the atmosphere r_{aH} (see KLAASSEN and NIEUWENHUIS, 1978) can be rewritten with eq. (39) as

$$r_{aH} = \frac{\ln(\frac{z-D}{z_0}) - P_2 + 32 \,..\, (wu_*)^{0.5}}{ku_*} \qquad (40)$$

9. SOME FIRST RESULTS

The resistance for sensible heat flux, expressed according to eq. (39) has been used to calculate canopy temperatures by introducing this resistance in the TERGRA model (SOER, 1977). These calculated temperatures are compared with canopy temperatures as measured with a thermal infrared radiometer. For this purpose measurements have been used from the KNMI in Cabauw on grassland (NIEUWENHUIS and KLAASSEN, 1978) as well as measurements on potatoes (experimental set up described by KLAASSEN and NIEUWENHUIS, 1978).

The results for grassland are shown in fig. 8. Without leaf resistance the agreement between measurements and simulation is rather poor. Some improvement is found by introducing the leaf resistance term 80 $(w/u_*)^{0.5}$.

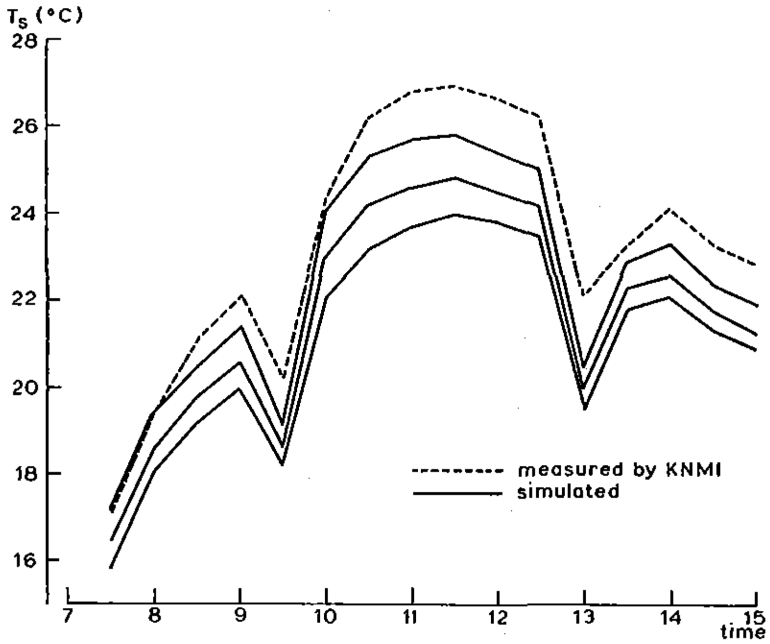

Fig. 8. Measured and calculated canopy temperatures for grassland, Cabauw 30-9-1977. For the simulated temperatures the lowest line represents the common simulation, the middle the simulation with leaf resistance term and the highest with leaf resistance and corrected z_0

Unfortunately no crop roughness length measurements were available. Therefore crop roughness was estimated from MONTEITH (1975), giving z_0 = 0.13 h. At the time of measurement the grass was just cut and had a high leaf area density. So if crop roughness was calculated from leaf area density as proposed by SOER (not yet published) and SEGINER (1972), a lower crop roughness length might be expected at the time of these measurements. Calculations have also been performed by halving the crop roughness length. Fig. 8 shows that this procedure gives a considerable improvement in the simulation of the temperature. It appears that an experimental check of the theory will only be possible when the crop roughness length is measured.

Simulations have also been performed for measurements on potatoes on a sunny day (July 12, 1978). Crop roughness length was calculated from measured wind profiles, yielding z_0 = 0.10 h with D = 0.4 m. The resulting temperatures are shown in fig. 9 . It is seen that:

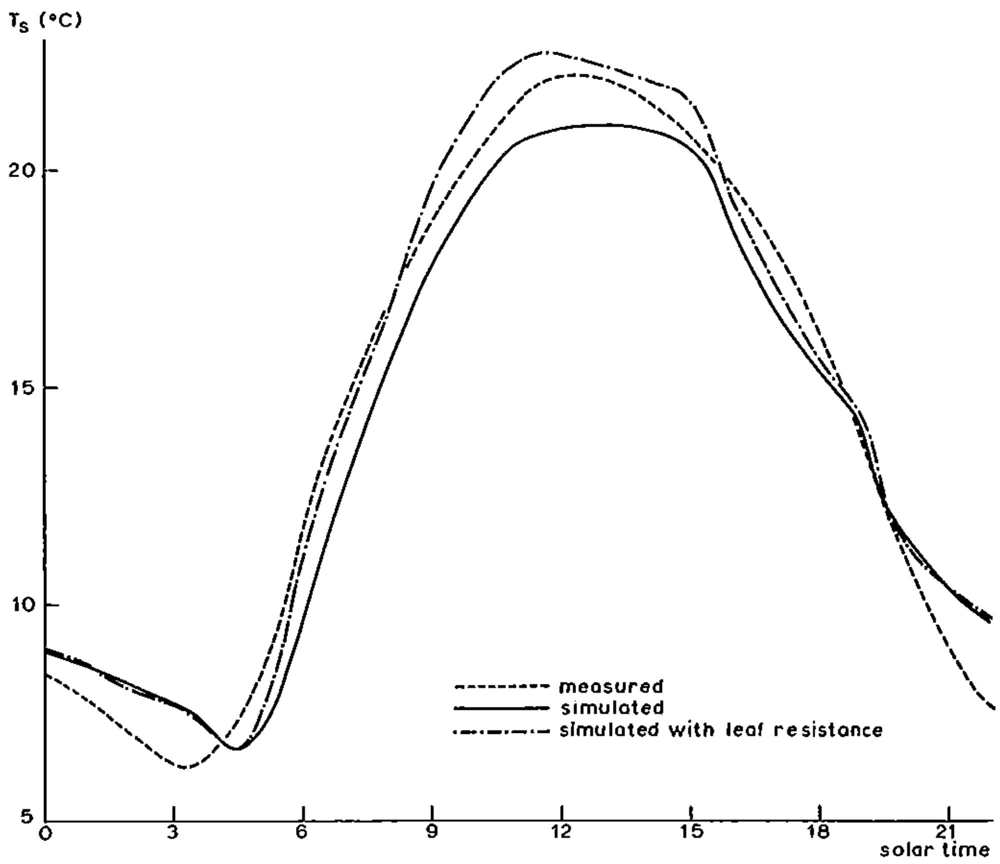

Fig. 9. Measured and calculated canopy temperatures for potatoes, ROSWINKEL, 12-7-1978

- At night the leaf resistance is relatively unimportant. Then simulations are rather poor, probably because of errors in the simulation of heat exchange between soil and plants.
- During both morning and afternoon the introduction of the leaf resistance term improves the results of the simulation. Also around noon some improvement is found.

However, the uncertainties in the temperatures, shown in fig. 9 are quite big: partly because of a restricted accuracy in measurement, partly because of uncertainties in the simulation with the TERGRA model.

The measurements indicate that the introduction of the leaf resistance term is a valuable completion for the interpretation of radiometically measured crop surface temperatures. Unfortunately the uncertainties in measurements and simulations are too large to control the magnitude of the derived leaf resistance term.

10. SUMMARY

In order to calculate the exchange of sensible heat flux of a vegetated surface from radiometrically determined crop temperature a resistance model has been set up.

Inside the canopy vertical conductance of sensible heat has been set proportional to wind velocity. Furthermore a leaf resistance has been used that is proportional to the square root of loaf width divided by wind velocity (eq. 27).

For remote sensing purposes the source distribution of observed thermal radiation has been calculated from the extinction of radiation. As canopy resistance is strongly dependent on the place where the heat is generated, the source distribution of sensible heat must be known.

In this study calculations are performed assuming the sensible heat flux to be proportional to the distribution of net radiation inside the canopy.

The calculation of average canopy resistance appeared to be unstable for canopies with mainly vertically oriented leaved and

approximately vertical observation. The reason for this behaviour is that than too much of the lower leaves and the soil are scanned. Therefore canopies showing a dominant vertical structure should be viewed oblique.

In the case of a stable solution average canopy resistance r_H appeared to be almost independent of leaf orientation, solar elevation and angle of observation. A simple approximation for most canopies is found by adding to the common resistance for sensible heat a leaf resistance term 80 $(w/u_*)^{0.5}$ (see eq. 39 and 40).

From measurements on grassland and potatoes it was found that introduction of the leaf resistance term gives a more close agreement between measured and calculated canopy temperatures. Unfortunately the measurements were not that accurate that the magnitude of the leaf resistance term could be checked.

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