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Instituut voor Cultuurtechniek en Waterhuishouding
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ESTIMATION OF THE REGIONAL EVAPOTRANSPIRATION FROM REMOTELY SENSED CROP SURFACE TEMPERATURES

I. GRASSLAND

ir. G.J.A. Nieuwenhuis and drs. W. Klaassen

C O N T E N T S

SUMMARY

With the aid of surface temperatures remotely sensed by Infra Red Line Scanning (IRLS), regional instantaneous evapotranspiration can be calculated. The Tergra-model (SOER, 1977) translates these data in daily evapotranspiration rates. Physical relations in the Tergra-model have been tested for grassland on heavy clay soil in the Lopikerwaard, which data from the Royal Meteorological Institute of the Netherlands (KNMI), that is performing energy balance- and evapotranspiration measurements in the same area (DE BRUIN and KOHSIEK, 1976).

Simulated crop temperature, net radiation, soil heat flux and evapotranspiration as calculated with the Tergra-model have been compared with actual field data.

For a potentially transpiring crop a relation has been determined between the crop temperature and the reflection ratio of orange/infrared. Investigations have been performed to see in how far this relation can be used for a qualitative analysis of IRLS data from grassland.

1. INTRODUCTION

During various dry summer periods there are many agricultural regions in Europe which lack adequate water supply and are suffering from drought. For an optimal management of available water supplies it is important to obtain information about the actual evapotranspiration of these regions. In areas, where the actual evapotranspiration is below the potential evapotranspiration, crop surface temperatures increase. These temperatures may be measured with scanners from airplanes or satellites. From the crop surface temperatures and meteorological ground observations, actual evapotranspiration can be calculated for a certain region (HEILMAN et al., 1976; SOER, 1977a).

In april 1978 the HCMM-satellite will be launched. Then each 5 days reflection-(0.5 - 1.1 μm) and heat maps (8-14 μm) over nearly whole Western Europe will be obtained. These data offer the possibility to find out quickly when and where drought damage occurs, when the obtained maps can be converted to actual evapotranspiration map.

2. THEORY

2.1. Calculation of evapotranspiration from the Bowen-ratio

The exchange of energy at the crop surface can be determined with the energy balance equation:

$$R_n + G + H + L.E = 0 \qquad (W.m^{-2}) \qquad (1)$$

where, R_n is the net radiation flux, G is the ground heat flux, H is the sensible heat flux, L is the latent heat of vaporization of water

($J.kg^{-1}$) and E is the evapotranspiration flux ($kg.m^{-2}.s^{-1}$).
The transfer of heat and water vapour in the atmosphere may be described as:

$$H = -\rho C_p \; K_H \frac{\partial \bar{T}}{\partial Z} \qquad (W.m^{-2}) \tag{2}$$

$$L.E = \frac{-\rho C_p}{\gamma} K_E \frac{\partial \bar{e}}{\partial Z} \qquad (W.m^{-2}) \tag{3}$$

where

ρ = the density of air ($kg.m^{-3}$)

C_p = the specific heat of moist air ($J.kg^{-1}.K^{-1}$)

γ = the psychrometric constant ($Pa.K^{-1}$)

K_H and K_E are eddy transfer coefficients for heat- and water vapour transport ($m^2.s^{-1}$)

$\bar{T}$ = the mean air temperature (K)

$\bar{e}$ = the mean water vapour pressure in the air (Pa)

Z = the height above the surface (m)

It is difficult to determine the eddy transfer coefficients for water vapour and heat transport. As $K_H \simeq K_E$, the ratio between H and LE (the Bowen-ratio, β) can be written as:

$$\beta = \gamma \frac{\partial \bar{T}/\partial z}{\partial \bar{e}/\partial z} \simeq \gamma \frac{\Delta \bar{T}}{\Delta \bar{e}} \tag{4}$$

where

$\Delta\bar{T}$ = the mean temperature difference

$\Delta\bar{e}$ = the mean vapour pressure difference (Pa)

both measured at the same heights above the crop.

Combining eqs. (1), (2), (3) and (4) gives:

$$L.E = \frac{R_n - G}{1 + \beta} \qquad (W.m^{-2}) \tag{5}$$

2.2. The Tergra-model

Temperatures of crop and soil surfaces can be determined by means of scanners from air planes or satellites over large areas. Actual evapotranspiration of the crop may be calculated from these surface temperatures by expressing in eq. (1) R_n, G and H as functions of the surface temperature, leaving L.E as the only unknown. The daily course of evapotranspiration can be determined from the instantaneous values using the Tergra-model developed by SOER (1977b).

In the Tergra-model the water- and heat transport in the soil-plant-atmosphere system is considered as a resistance model (fig. 1).

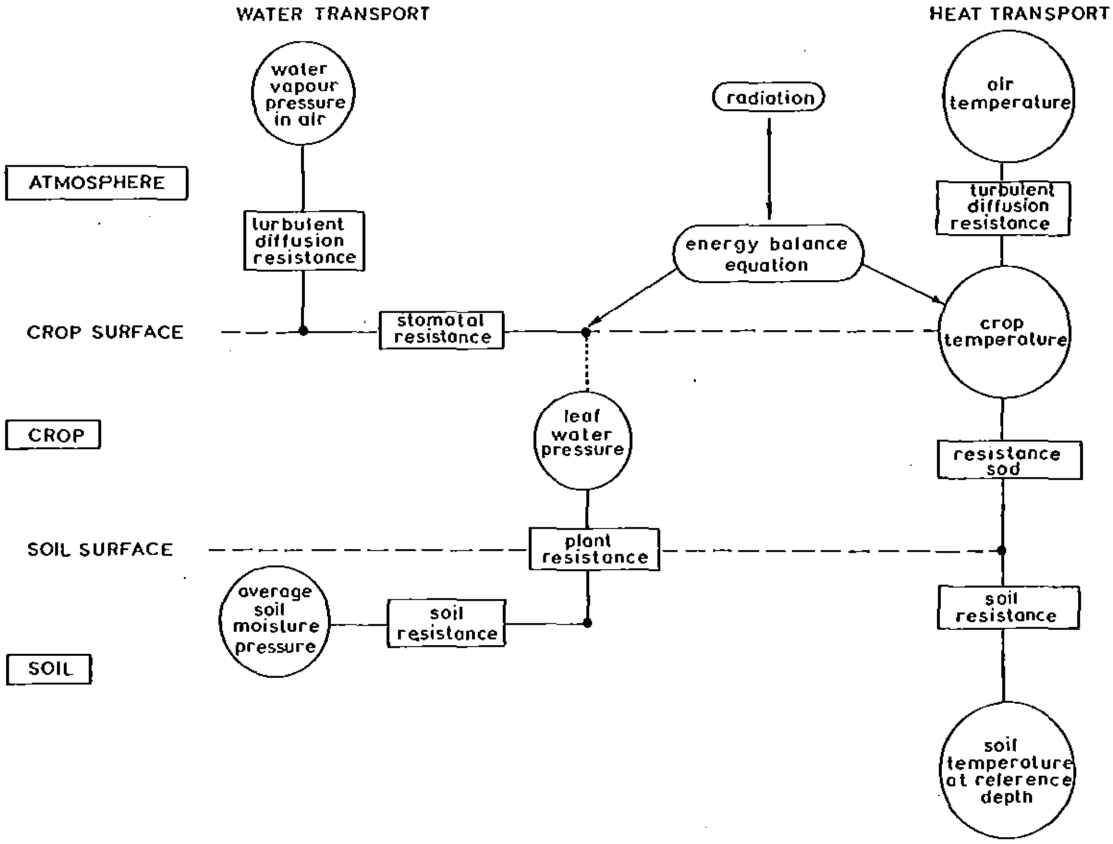

Fig. 1. Resistance model of water- and heat flux in the soil-plant-atmosphere continuum (after SOER, 1977b)

The various resistances for water vapour- and heat transport are briefly discussed below.

The transport equations for the sensible heat flux and the water vapour flux can also be written as:

$$H = \rho C_p \frac{T_c - T_a}{r_{ah}} \qquad (W.m^{-2}) \qquad (6)$$

$$L.E = \frac{\rho C_p}{\gamma} \frac{e_c^* - e_a}{r_{av}+r_s} \qquad (W.m^{-2}) \qquad (7)$$

where

T_c = the crop temperature (K)

T_a = the air temperature (K) measured at reference height Z_a

e_c^* = the saturated vapour pressure (Pa) at temperature T_c

e_a = the water vapour pressure (Pa) in the air measured at reference height z_a

r_{av} and r_{ah} are the turbulent diffusion resistances for water vapour and heat respectively ($s.m^{-1}$)

r_s = the crop diffusion resistance for vapour transport ($s.m^{-1}$)

Under conditions of neutral stability ($T_c \approx T_a$) the turbulent diffusion resistance for momentum (r_{am}) may be simply expressed as a function of wind velocity and roughness of the surface:

$$r_{am} = \left[{}^{e}\log\left(\frac{z_a - d}{z_o}\right)\right] / k^2 u \qquad (s.m^{-1}) \qquad (8)$$

where

z_a = the reference height (m) in the atmosphere, where wind velocity is recorded

z_o = the roughness length for momentum (m)

k = von Karman's constant (here taken as 0.4)

u = the wind velocity ($m.s^{-1}$)

According to MONTEITH (1973) z_o may be written as:

$$z_o = 0.13\ h \qquad (9)$$

where

h = the crop height (m).

Transport of momentum and mass occur by means of diffusion as well as by turbulence.

Over the crop turbulent transfer dominates, and an analogy between the transfer of momentum and mass is present. This is known as the Reynolds analogy concept.

Within the canopy, however, diffusion transfer may not be neglected with regard to turbulent transfer (PEARMAN et al., 1972). The layer of the canopy where this phenomenon occurs is called the interfacial sub-layer (BRUTSAERT, 1977). The numerical value of the diffusion coefficients for water vapour and heat, and the analogous value of the viscosity for momentum are different. Moreover the thickness of the interfacial sub-layer is different for momentum- and for mass transfer.

In addition to the above, transfer of momentum is also induced by local pressure differences, which are caused by the resistance of the separate plants for wind velocity. This transfer of momentum has no analogy with the transfer of heat and water vapour (BUSINGER, 1975). The consequence of all this is, that the resistances for mass transfer in the canopy are higher than that for momentum transfer. THOM (1971) has accounted for the extra resistance for heat transfer as compared to the resistance for momentum transfer by means of:

$$r_{ah} = r_{am} + 6.26 \left[ku / {}^{e}\log\left(\frac{z_a - d}{z_o}\right) \right]^{-2/3} \qquad (s.m^{-1}) \qquad (10)$$

Eq. (10) has been derived for beans. THOM assumes, that this relation can be used as a first approximation for many other types of vegetation as well.

In eq. (10) the diffusion resistance have been determined under conditions of neutral stability, but corrections for stable- (see WEBB, 1969) and unstable (see PAULSON, 1971) conditions in the atmosphere are available.

The stomatal resistance r_s in eq. (7) is a function of the water potential in the leaves and the shortwave radiation intensity.

In the Tegra-model SOER (1977b) used:

$$r_s = h^{-0.5}\left(0.05\,F^{2.1} + \frac{400}{R_s+1.5}\right) \qquad (s.m^{-1}) \qquad (11)$$

$$F = 7 \qquad \text{if} \qquad \psi_{leaf} \geq -7.10^5 \text{ Pa}$$

$$F = 10^{-5}.\psi_{leaf} \quad \text{if} \quad -50.10^5 \leqslant \psi_{leaf} \leq -7.10^5 \text{ Pa}$$

$$F = 50 \qquad \text{if} \qquad \psi_{leaf} \leq -50.10^5 \text{ Pa}$$

where

h = the canopy height (m)

R_s = the shortwave radiation ($W.m^{-2}$)

ψ_{leaf} = the leaf water pressure (Pa)

Water transport in a soil - plant system may be expressed as (e.g. FEDDES and RYTEMA, 1972):

$$E = \frac{1}{g}\,\frac{\psi_{leaf} - \psi_{soil}}{r_{plant}+r_{soil}} \qquad (kg.m^{-2}.s^{-1}) \qquad (12)$$

$\cancel{m}\ \cancel{s^2}\ s^{-1}\ kg\ \cancel{m}\ s^{-2}\ m^{-2}$

$kg.m^{-2}.s^{-1}$

where

ψ_{soil} = the soil matric potential (Pa)

r_{plant} = the resistance for liquid water flow in the plant (s)

r_{soil} = the resistance for water flow in the soil (s)

g = the acceleration of gravity ($m.s^{-2}$).

The resistance r_{plant} is taken to be constant: for grassland it is about 12 000 days (RYTEMA, 1965).

The value of r_{soil} is according to FEDDES and RYTEMA (1972):

$$r_{soil} = b/k(\psi_{soil}) \qquad (s) \qquad (13)$$

$$b = 0.0013.z_{eff}^{-1} \qquad (m) \qquad (14)$$

where

b = a root density parameter (m)

z_{eff} = the depth above which 95% of the total root weight is found (m)

$k(\psi_{soil})$ = the hydraulic conductivity ($m.s^{-1}$)

Acoording to LALIBERTE et al. (1968) the soil moisture retention curve can be described as:

$$\frac{S-S_r}{1-S_r} = \left(\frac{\psi_{soil}}{\psi_a}\right)^{-m} \qquad (15)$$

where

S = the saturation

S_r = the imaginary residual saturation

ψ_a = the air entry value (Pa)

m = the pore size distribution factor

The values of ψ_a and m are derived from linear regression of log $[(S-S_r)/(1-S_r)]$ on $\log(\psi_{soil}/\psi_a)$. The relation between permeability and soil water pressure is then (BROOKS and COREY, 1964):

$$k = k_s.(\psi_{soil}/\psi_a)^n \quad (m.s^{-1}) \qquad (16)$$

where

n = $-(1.4+3m)$

k_s = is the saturated hydraulic conductivity ($m.s^{-1}$).

Because of hysteresis in general two relations between k and ψ_{soil} will exist. An example is given in fig. 2, where curve A holds for drying and curve C for wetting.

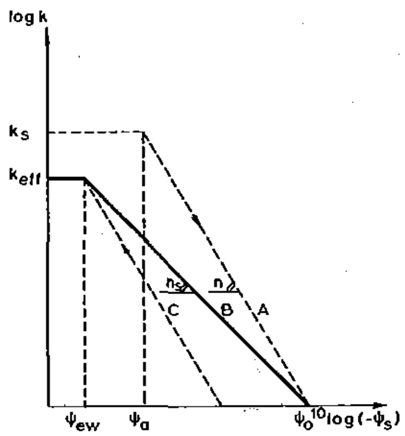

Fig. 2. Relation between the hydraulic conductivity k and the soil water pressure ψ_s. A-C is the hysteresis-loop

In this study an average-type relation as represented by curve B is used. This relation can be found by replacing k_s, ψ_a and n in eq. (16) by (BLOEMEN, 1977):

$$k_{eff} = 0.5\ k_s$$
$$\psi_{ew} = 0.3\ \psi_a \qquad (17)$$
$$n_s = \left[\log\ 2(\psi_a/\psi_o)^n\right]/\log(\psi_{ew}/\psi_o)$$

The soil heat can be calculated by multiplying the temperature change in the soil with the heat capacity. The temperature profiles are calculated by solving the diffusion eq. (18)

$$\rho_s c\ \frac{\partial T}{\partial t} = \lambda\ \frac{\partial^2 T}{\partial_z 2} \qquad (18)$$

with a finite difference method. In this equation

λ = the thermal conductivity ($W.m^{-1}.K^{-1}$)
T = the temperature (K)
z = the depth (m)
t = the time (s)
$\rho_s c$ = the heat capacity ($J.m^{-3}.K^{-1}$)

The numerical approximations for $\partial T/\partial z$ and $\partial^2 T/\partial z^2$ are

$$\frac{\partial T}{\partial t} = \frac{T(z_i, t + \Delta t) - T(z_i, t)}{\Delta t} \qquad (19)$$

$$\frac{\partial^2 T}{\partial z^2} = \frac{T(z_i - 1, t) - 2T(z_i, t) + T(z_{i+1}, t)}{(\Delta z)^2} \qquad (20)$$

Combining eqs. (18), (19) and (20) results in:

$$T(z_i, t + \Delta t) = T(z_i, t) + \zeta\{T(z_{i-1}, t) - 2T(z_i, t) + T(z_{i+1}, t)\} \qquad (21)$$

where

ζ = $\lambda\Delta t/\{\rho_s c(\Delta z)^2\}$
Δt = the time step between two iterations
Δz = the distance between two grid points in vertical direction.

Starting with a known temperature profile at time t_o the temperature profile at time $t_o + \Delta t$ may be calculated from eq. (21) and the following boundary conditions:

$-T\ (z_o,t) = T_c$
$-T\ (z_n,t) = T_n$

where T_c is equal to the crop temperature and T_n is a temperature at a reference level in the soil, where the daily amplitude of the temperature is supposed to be zero.

The heat capacity $\rho_s c$ may be expressed as (DE VRIES, 1975):

$$\rho_s c = 10^6(2\ X_{sm} + 2{,}5\ X_{so} + 4{,}2\ X_w) \qquad (J.m^{-3}.K^{-1}) \qquad (22)$$

where X_{sm}, X_{so} and X_w are the volume fractions of the mineral-, of the organic- and of the water components respectively.

The factor ζ can be calculated by measuring X_{sm}, X_{so}, X_w and the temperature profiles during different days. Re-arranging eq. (21) gives:

$$\zeta = \frac{T(z_i,t + \Delta t) - T(z_i,t)}{T(z_{i-1},t) - 2T(z_i,t) + T(z_{i+1},t)} \qquad (23)$$

The thermal conductivity $\lambda(X_w)$ of the soil and an imaginary value in the atmosphere can be calculated with eqs. (22) and (23).

3. FIELD MEASUREMENTS AND FLIGHTS

The study area in the Lopikerwaard is situated at $51^o38'$ north and $4^o55'$ east. It is a polder with mainly grass on clay soil. The grass-fields are seperated by ditches. In the middle of the study area an experimental field of 100 x 100 metres of the Royal Meteorological Institute of the Netherlands (KNMI) is situated. Incoming short wave radiation was measured by a Kipp CM5 solarimeter, net radiation by a Suomi net radiometer, and incoming longwave radiation by an Epply radiometer. Wind velocity was measured by a KNMI 0,31 m ϕ

anemometer at a height of 2 m. Dry and wet bulb air temperatures were obtained from ventilated copper-constantan thermocouples at 1.10 m and 0.45 m height. From these data the actual evapotranspiration according to the Bowen ratio method was derived.

For the period May 1 until September 1 soil matric suction was measured with tensiometers at 0.30 and 0.50 m depth. Soil water content was measured with aid of the γ-attenuation method at 0.10 m depth intervals down to 1.10 m.

In the summer of 1977 three IRLS flights were performed on May 15, June 14 and August 31, respectively. Because of cloudy weather conditions during the first two flights only the pictures of the August 31 flight appeared to be suitable for a quantitave analysis. This flight was taken after a relatively wet period, so the crops had been well supplied with water.

Crop surface temperatures were measured on August 31 at 12.04 Middle European Time (M.E.T.) by an airborne multiband scanner (Daedalus), flown at 1200 m with a resolution of about 2.5 x 3 m. The blackbody temperatures were set equal to 10 and 34 $^{\circ}$C respectively. On August 30 crop surface temperatures were measured both with a Heimann K 24 and a Barnes PRT 5 radiation thermometer from 7.30 to 15.30 M.E.T. On August 31 measurements were taken from 9.30 to 13.30 M.E.T. Heimann and Barnes measurements were taken from a height of 1.5 m and 200 m respectively. This implies that with the Heimann about a half square metre was seen, while with the Barnes the whole testfield of 100 x 100 m was seen.

4. RESULTS OBTAINED WITH THE TERGRA-MODEL

Results obtained with the Tergra-model have been compared with measurements of the KNMI. The data of August 30 and 31 have been elaborated using M.E.T. as time basis.

Table 1 shows the soil physical parameters, which have been used. The simulations have been performed for two values of the saturated conductivity k_s. For the pore size distribution m also two values have been derived from linear regression of $\log\{(s-s_r)/(1-s_r)\}$

on $\log(\psi_{soil}/\psi_a)$: one value for ψ_{soil} more than -100 kPa and one value for ψ_{soil} less than -100 kPa.

Table 1. Soil physical parameters used in the Tergra-model

- pore size distribution	m = 0.04 for ψ_{soil} > -100 kPa
	m = 0.34 for ψ_{soil} < -100 kPa
- residual saturation	s_r = 0.2
- saturated conductivity	k_s = 1 and 10 cm.day^{-1}
- air entry value	ψ_a = -1 kPa
- capillary rise	0.5 mm.day^{-1}

Table 2 shows the plant physical parameters, which have been used.

Table 2. Plant physical parameters used in the Tergra-model

crop height	h	= 0.07 m
plant resistance	r_{plant}	= 12 000 days
effective rooting depth	z_{eff}	= 0.20 m
emission coefficient	ε	= 0.95

Fig. 3 shows the net radiation R_n and the soil heat flux G as calculated with the Tergra-model together with the measured data.

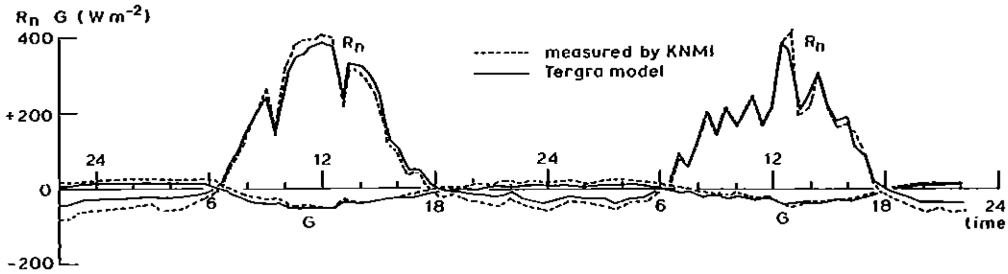

Fig. 3. Daily course of the net radiation R_n and the soil heat flux G calculated with the Tergra-model and measurements for August 30 and 31

During daytime G appears to be small as compared with R_n. From 18.00 hr untill 10.00 hr there is a difference between simulated and measured G of 10 to 20 $W.m^{-2}$. For the remaining part of the day simulated and measured values agree rather well. Simulation of R_n shows similar effects. The difference with the measurements is about 20 to 30 $W.m^{-2}$ during the evening and night. It can be concluded that the simulated values for the crop temperature are too high during the evening and night. During these periods, however, evapotranspiration is small and hence the mentioned difference will be of minor importance for the total daily evapotranspiration flux.

Fig. 4 shows the simulations and measurement of the evapotranspiration L.E. During the first night the difference between simulation and measurements is 20 to 30 $W.m^{-2}$, while during the second night the difference is much smaller. Moreover there is a phase shift between simulation and measurement. By that the difference between

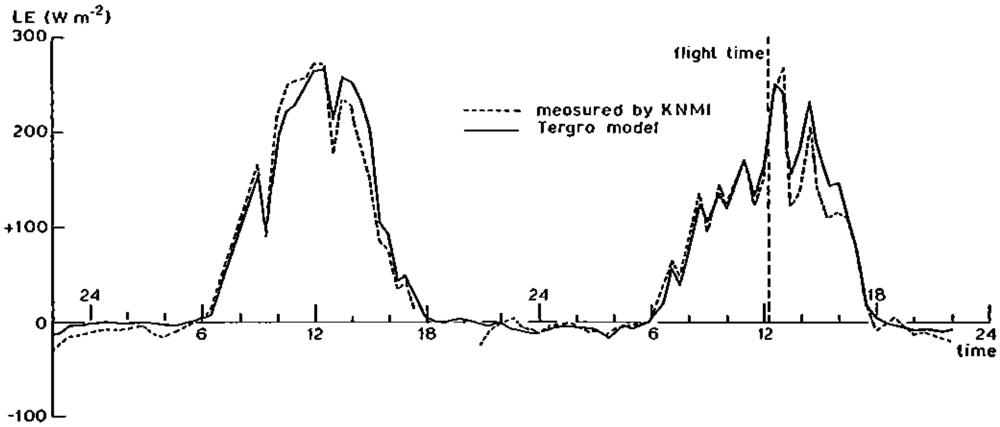

Fig. 4. Daily course of the evapotranspiration L.E calculated with the Tergra-model and measurements according to the Bowen ratio-method for August 30 and 31

computed and measured total daily evapotranspiration is only 4%, while the maximum difference for the instantaneous evapotranspiration can be 25%.

A comparison between simulated and measured crop temperatures is given in fig. 5. Crop temperatures have been calculated with the

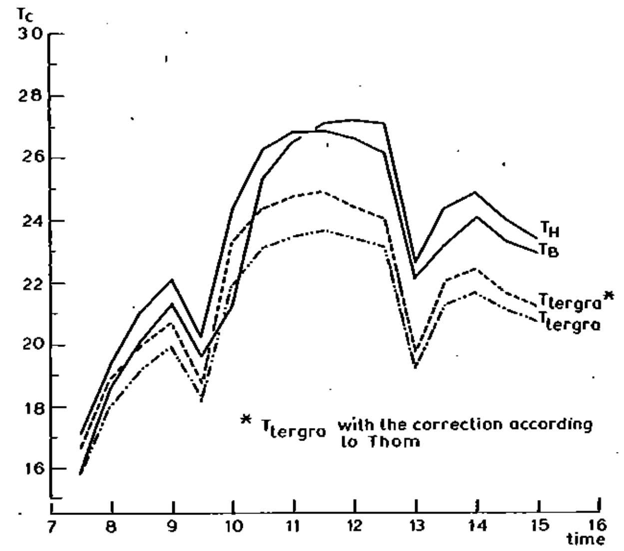

Fig. 5. The simulated crop temperature with and without the correction according to THOM and the radiation temperature measured by the KNMI with the Barnes (T_B) and the Heimann (T_H) for August 30

Tergra-model starting from the measured soil matric suction ψ_s = 10 kPa. Then L.E and the crop temperature T_c have been determined iteratively with eqs. (1), (6), (7) and (12). Although the calculated L.E agrees rather well with the measured value (fig. 4), the calculated T_c differs some degrees from the measured radiation temperature T_c. Applying a correction for the atmospheric resistance according to eq. (10) the difference between calculation and measurement reduces. So an important error may be due to the difference in roughness length for momentum - and mass transfer.

Another error may be caused by the different physical meaning of the measured and calculated T_c. A radiation thermometer generally measures a mean radiation remperature of the crop canopy as a whole. In the model an air temperature is calculated, which is valid for a reference height z_o in the crop under the assumption of a logarithmic temperature profile. The canopy temperature is compared with this air temperature, if z_o is corrected for the difference in resistance for momentum - and heat transport. This temperature need not necessarily agree with the mean radiation temperature.

The variation of T_c with time as calculated with the Tergra-model is in better agreement with that measured with the Barnes than measured with the Heimann (fig. 5). With the Barnes, the total experimental field of 100 x 100 metres is seen, with the Heimann only 0.5 m^2. Consequently a different average surface temperature was observed. Except for this deviation, differences between the Barnes and the Heimann may have been caused also by a difference in observation angle with respect to the direction of sun radiation.

The relation between evapotranspiration L.E and soil matric suction ψ_{soil} is shown in fig. 6 for two values of the saturated permeability k_s of the root zone. For the heavy clay soil in the Lopikerwaard the resistance r_{soil} for water transport causes a reduction in L.E if ψ_{soil} is above about -60 kPa (pF = 2.8). Evapotranspiration is called potential, $L.E_{pot}$, if ψ_{soil} is over -60 kPa (for both curves).

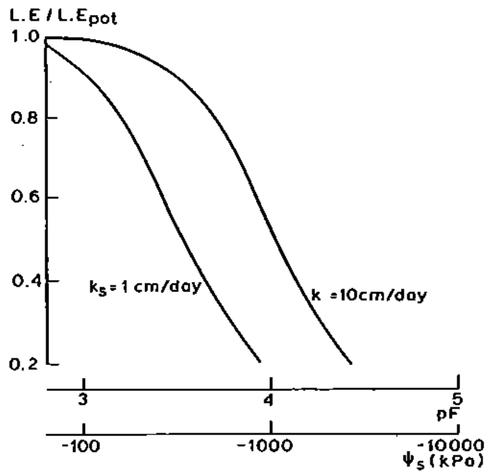

Fig. 6. The relation between soil water pressure ψ_s and relative evapotranspiration $L.E/L.E_{pot}$ for two values of the saturated hydraulic conductivity k_s for August 31

If the relation between ψ_{leaf} and r_s of eq. (11) is used, then L.E is constant for ψ_{soil} below -2000 kPa (pF = 4.3). In that case L.E is equal to 0.3 $L.E_{pot}$. This effect is caused by the minimum value of -5000 kPa for ψ_{leaf} in eq.(11). The minimum value of ψ_{leaf} is according to steady state calculations of RYTEMA (1965) a mean value for a period of some days. During the daily course the value of ψ_{leaf} around midday may be considerable less than -5000 kPa. Therefore no minimum value of ψ_{leaf} has been accepted, but L.E has been calculated as a function of ψ_{soil} until L.E is equal to 0.2 $L.E_{pot}$ (DE HEER, 1974). In this study it is assumed, that for lower values of L.E the plant dies and that eq. (11) is not valid anymore.

In Table 3 the sensitivity of the model for a change of 20% in the atmospheric (r_a)-, stomatal (r_s)-, plant (r_{plant})- and soil (r_{soil}) resistance is shown.

Table 3. Influence of a 20% increase of r_a, r_s, r_{plant} and r_{soil} on evapotranspiration E as calculated by the Tergra-model with two different values of ψ_{soil}. As reference case the values given in table 1 and 2 are used

	ψ_{soil} = -100 kPa ('wet')				ψ_{soil} = -1000 kPa ('dry')			
	Aug. 30		Aug. 31		Aug. 30		Aug. 31	
	E $mm.day^{-1}$	ΔE %	E $mm.day^{-1}$	ΔE %	E $mm.day^{-1}$	ΔE %	E $mm.day^{-1}$	ΔE %
reference case	2.48	0	2.16	0	1.19	0	1.15	0
r_{soil} + 20%	2.48	0	2.15	-0.5	1.11	-6.7	1.09	-5.2
r_{plant} + 20%	2.41	-2.8	2.12	-1.9	1.17	-1.7	1.15	0
r_s + 20%	2.43	-2.0	2.13	-1.4	1.12	-5.9	1.10	-4.3
r_a + 20%	2.42	-2.5	2.08	-3.7	1.20	+0.8	1.17	+1.7

If ψ_{soil} = -100 kPa, r_{soil} is negligible with respect to r_{plant}. In this moisture region the model is not sensitive for errors in r_{soil}. A 20% error in r_{plant} and r_s causes an error in E of the same order.

If ψ_{soil} = -1000 kPa, r_{soil} is higher than r_{plant}. Consequently in this moisture region the model is not sensitive for an error in r_{plant}. A 20% error in r_{soil} and r_s causes an error in E of the same order.

A change in r_a may cause either a decrease or an increase of E (KLAASSEN and NIEUWENHUIS, 1978). If ψ_{soil} = -100 kPa, ('wet'), r_s is small with respect to r_a. Then the resistance for heat- and vapour transfer change more or less proportional. At the same time the temperature- and vapour pressure gradients change. It is evident, that in this case the temperature gradient increases more rapidly than r_a. Hence the sensible heat flux H increases and E decreases. If ψ_{soil} = -1000 kPa ('dry'), r_s is higher than r_a. Then the resistance for sensible heat transfer (= r_a) increases more rapidly than the resistance for latent heat transfer (= r_a+r_s). The consequence is that H decreases and E increases.

5. INTERPRETATION OF REFLECTION AND HEAT MAPS

Certain crop structure parameters may be eliminated by combining special bands in the electromagnetic spectrum (BUNNIK, 1978). The reflection ratio between orange (0.60 - 0.65 μm) and infrared (0.80 - 0.89 μm) provides information about the soil cover percentage and the crop structure parameters. For example if the average leaf inclination does not change too much this ratio provides information about the leaf area index. It may be assumed that with an increase of the leaf area index, surface roughness increases too. Then the atmospheric resistance will be lowered, by which the crop temperature will decrease. So for a potentially transpiring crop the reflection ratio orange/infrared may also be correlated with the temperature of the crop.

The scanner measurements have been drawn in Fig. 7 for different grass fields at flight time. On August 31, the flight was carried out after a relatively wet period. The soil matric suction ψ_s at the experimental field was about -10 kPa (pF = 2). From Fig. 6 it is seen, that for this soil moisture pressure the grass field is transpiring potentially. Only two points differ about 3 K from the determined relationship. The explanation for this behaviour is that the two points are situated on the KNMI experimental field, where a large biomass was present in proportion to crop height (5 to 10 cm).

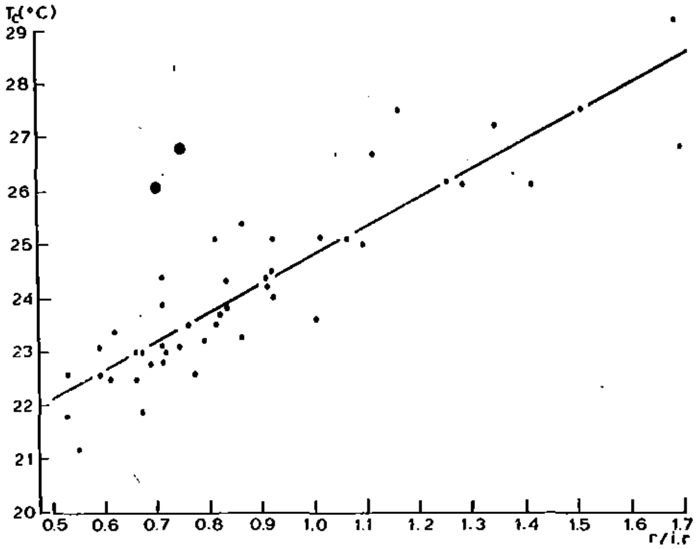

Fig. 7. The relation between reflection ratio orange/infrared (r/i.r) and crop temperature T_c measured at August 31 with a Daedalus scanner for different grassfields in the Lopikerwaard

The experimental field was mowed frequently and this resulted in a more closed sod, then in the fields in the surrounding. For that reason the reflection in orange was low and the reflection in the infrared was high. Therefore the reflection ratio is relatively low for the experimental field.

From the HCMM-satellite only one reflection map will be obtained with a wave length range of 0.5 to 1.1 μm. It may be expected, that the relation between this band and the crop temperature is rather poor. Therefore it must be decided on 'quick looks' from the HCMM-satellite, what areas can be analysed quantitatively with the Tergra-model. In the beginning of the eighties satellites will be launched from which reflection maps are obtained in the visible-, near infrared- and middle infrared band e.g. Landsat-D and SPOT. Especially the two bands in the middle infrared (1.50-1.75 and 2.10-2.35 μm) constitute an important completion. In these bands absorption to water molecules occurs, by which information about the water content of the leaves of a crop can be obtained. It can be expected, that with the heat maps and the combined reflection maps from such satellites areas, where drought damage occurs, may be spotted rather fast.

6. CONCLUSIONS

The following conclusions can be drawn:

- Daily evapotranspiration as calculated with the Tergra-model is in good agreement with those obtained with the Bowen-ratio method. Only a small phase shift exists between simulation and measurement.
- Simulated crop surface temperatures may differ some degrees from the temperature measured with a radiation thermometer. If one wants to calculate evapotranspiration from the latter, then one has to apply a correction for these temperatures depending on crop height, crop structure and observation angle.

- The crop temperature can be calculated with the Tergra-model using measured matric suction or by measuring the evapotranspiration of the crop with an independent method like the Bowen-ratio method. The assumption, however, that the roughness lengths for momentum- and mass transfer are equal, may cause a considerable error. For that reason the calculated- as well as the measured crop temperature have to be corrected. The relation between the two temperatures has to be investigated by measuring tempereture profiles inside the crop.
- At this moment calculation of evapotranspiration only from measured crop surface temperatures is unreliable. A better approach is to calculate regional evapotranspiration from measurements of the evapotranspiration at one place and by measuring temperature differences of the whole area obtained with a scanner.
- If the soil matric potential in heavy clay soils is above -60 kPa (pF = 2.8) evapotranspiration of grassland is mainly determined by the resistance in the atmosphere and not by the resistance in the soil. If the soil matric potential is below this value, stomatal resistance rapidly increases. In this case soil matric potential largely determines the rate of evapotranspiration.
- For a potentially transpiring crop a relation between crop temperature

and reflection ratio orange/infrared has been found. From this relation one may find out, where special hydrological situations leading to drought may appear. Then it may be decided upon, which areas are important to analyse quantitatively with the Tergra-model.

- As only one reflection map is obtained from the HCMM satellite, it must be decided on the basis of the 'quick-looks', which areas have to be analysed quantitatively with the Tergra-model.
- In the beginning of the eighties satellites will be launched from which reflection maps in the visible-, near infrared- and middle infrared band are obtained. It is to be expected, that with the heat maps and the combined reflection maps from such satellites, areas, where drought damage occurs, may be spotted rather fast.

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