A Proposed Technique to Measure Evapotranspiration Using Micrometeorological Methods

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Abstract

A technique to provide measurements of crop evaporation of accuracy acceptable for agricultural purposes is described. Of the equipment used two sets of recording wet- and dry-bulb thermometers and an anemometer are durable, and can be installed and maintained by untrained personnel. A net radiometer is used in this study, but when the technique is applied in practice, this could be replaced by a sunshine duration recorder. The data collected are used as inputs to the surface energy budget equation, and a reiterative method employed to determine that surface temperature which balances the energy budget equation. Once the equation has been balanced, the evaporation is obtained by conversion of the latent heat flux term to volumetric evaporation. An inexpensive programmable calculator could be used to carry out the computations.

Results of initial field work carried out on wheat over a six day period (12—17 October 1978) are presented and crop evaporation compared to pan evaporation. Furthermore computed 'surface' temperatures agree accurately with the temperatures measured at the momentum exchange surface (height d + zo).

Introduction

The accurate assessment of crop evaporation (evapotranspiration) is important to managers of irrigation projects and research workers in the field of plant water relations. Equipment required by present day techniques is either extremely expensive (lysimeters) or intricate and vulnerable (aerodynamic sensors). The proposed technique described in this paper makes use of the minimal amount of simple and durable equipment. This makes possible installation and maintenance by untrained personnel.

The theory for this proposed technique is derived from the balance of momentum, mass and heat energy in plant communities. Assuming no advective energy input, this budget provides a complete account of how energy is partitioned at a surface and hence makes possible an accurate analysis of the environment at the surface. This could be used to explain the interaction between the physical driving forces and the growth and behaviour of the biological system.

The objective of the work has been to develop a technique for evaluating each term of the energy budget equation and particularly λE for use in agricultural research.

General Theory

The energy budget at any natural surface can be described by the implicit energy balance equation of six terms, namely, net radiation (R_N), latent heat flux (λE), sensible heat flux (C), soil heat flux (G), photosynthetic flux (P) and heat storage (J). The latter two terms are usually omitted as over whole days they are negligibly small when compared to the other terms (Monteith 1973, Thom 1975).

The energy budget can thus be expressed as:

$$-R_N = G + C + \lambda E$$

where

R_N is the net radiation reaching the canopy surface (Wm^{-2}),
C is the sensible heat flux (Wm^{-2}),
λ is the latent heat of vapourization ($J\ kg^{-1}$),
E is the evaporation ($kg\ m^{-2}s^{-1}$),
λE is the latent heat flux (Wm^{-2}), and
G is the soil heat flux (Wm^{-2}).

Fig. 1 shows the canopy surface of a plant community and the radiative and soil heat flux directions for day and night time conditions. By convention, fluxes arriving at the surface are considered negative and those leaving the surface positive.

In this study R_N and G are measured quantities and C and λE are unknowns. To solve this single equation for two unknowns a reiterative method (De Jager and Harrison, 1979) is used to compute the canopy surface temperature T_0 which balances the equation. To express the latent heat flux λE and sensible heat flux C as functions of T_0, an aerodynamic treatment of momentum, mass and heat exchange is followed. This theory is adapted from Thom (1975) and is based on several major assumptions, namely:

1. The canopy surface is assumed to occur at the momentum exchange level, d + zo, at which wind speed is theoretically zero (d = 0,63h, zo = 0,13h (see Monteith, 1973) where h is the crop height).

2. The relative humidity measured at this height is assumed to indicate the magnitude of the source or sink of the vapour from which exchange with the atmosphere is taking place.

3. The similarity hypothesis is valid in the case of the crop under observation.

4. The "conglomerate" hypothesis is applied to the crop assuming it to behave as a conglomerate entity of uniform temperature and relative humidity.

For conditions over vegetation, where λE and C are independent of height, equations expressing aerodynamic resistance to the flow of these entities in terms of the change of wind u, vapour pressure e, and temperature T, at two levels only can be derived from the definition of aerodynamic resistance (aero-

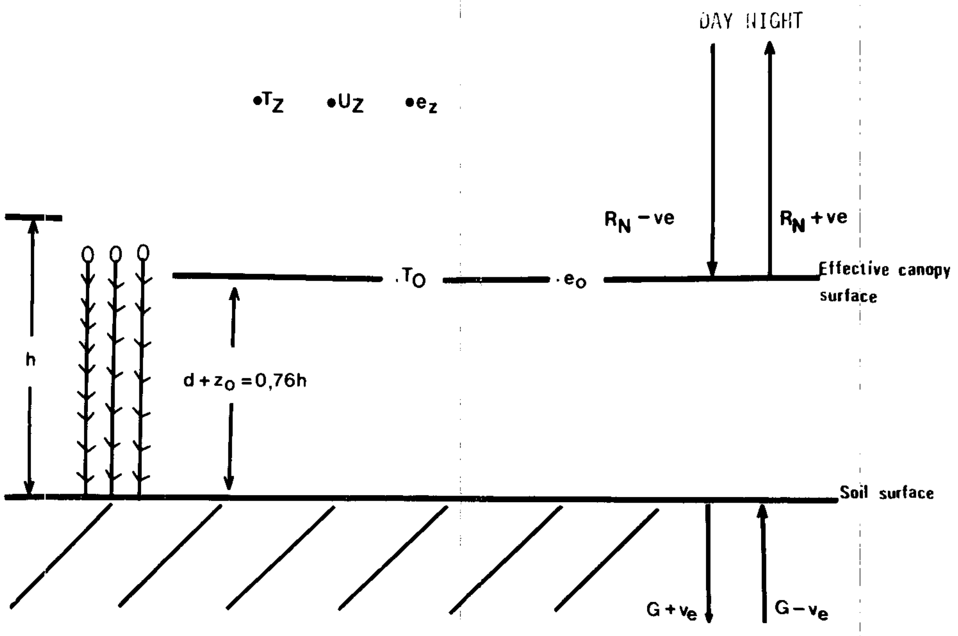

Figure 1
The plant community showing the canopy surface, the various measuring positions and the adopted sign convention.

dynamic resistance $= \frac{\text{concentration difference}}{\text{flux}}$). These equations can be written as:

$$r_{aV} = \frac{\rho C_p}{\gamma} \frac{(e_o - e_z)}{\lambda E}$$

and

$$r_{aH} = \rho C_p \frac{(T_o - T_z)}{C}$$

where,

r_{aV} is the aerodynamic resistance to the transter of water vapour (sm^{-1}),

r_{aH} is the aerodynamic resistance to the transfer of heat (sm^{-1}),

ρ is the density of air (kg m^{-3})

C_p is the specific heat of air (J kg^{-1} $°C^{-1}$),

γ is the psychrometric constant (mbar $°C^{1}$),

e_o is the surface vapour pressure (mbar),

e_z is the vapour pressure at the reference height z (mbar),

T_o is the surface temperaure (°C), and

T_z is the temperature at the reference height z(°C).

Use of the similarity hypothesis for fully forced convection yields

$$r_{zM} = r_{aV} = r_{aH} = \frac{\ln\left(\frac{z-d}{z_o}\right)^2}{k^2 u(z)}$$

where

r_{aM} is the aerodynamic resistance to the transfer of momentum (sm^{-1}),

k is von Karman's constant (= 0,41),

u(z) is the wind speed at height z (ms^{-1}),

z is the reference height at which measurements are made (m),

d is the zero plante displacement level (m), and

z_o is the roughness parameter.

This relationship permits latent heat flux (λE) and sensible heat flux (C) terms of the energy budget equation to be written as:

$$\lambda E = \frac{\rho C_p k^2 u(z)}{\gamma} \frac{(e_o - e_z)}{\left[\ln\left(\frac{z-d}{z_o}\right)\right]^2}$$

and

$$C = \rho C_p k^2 u(z) \frac{(T_o - T_z)}{\left[\ln\left(\frac{z-d}{z_o}\right)\right]^2}$$

The mean value of the vapour pressure at the effective canopy surface e_o, can be expressed as $RH_o\ e_o\ (T_o)/100$ where RH_o is the mean value of relative humidity and $e_s(T_o)$ is the saturation vapour pressure.

$e_s(T_o)$ can be expressed as a function of T_o via an integrated form of the Clausius Clapeyron equation (Hess, 1959), namely:

$$-e_s\,(T_o) = 6{,}11 \exp \left[5347{,}61\left(\frac{1}{273.16} - \frac{1}{273{,}26 + T_o}\right)\right] \text{(mbar)}$$

This means that if RH_o is measured using the wet- and dry-bulb thermometers, then λE can be expressed as a function of T_o.

It should be noted that both the evaporative and convective flux terms given here apply to neutral conditions and are not valid when temperature gradients associated with stable and unstable conditions exist. To correct for the effects of instability and stability the flux terms λE and C for neutral conditions are corrected by multiplying by the stability factor F, where

$F = (1 - 5R_i)^2$ if R_i is positive,

and $F = (1 - 16R_i)^{3/4}$ if R_i is negative (Thom, 1975)

R_i is the prevailing Richardson number and is easily calculated from the recorded temperature and wind data (Thom, 1975).

The energy budget equation,

$$-R_N = \lambda E + C + G$$

can now be written in an expanded form as

$$-R_N = G + \rho C_p k^2 u(z) \frac{(RH_o\, e_s\,(T_o)/100 - e_z)}{\gamma \left[\ln\left(\frac{z-d}{z_o}\right)\right]^2} + \frac{\rho C_p k^2 u(z)\,(T_o - T_z)}{\left[\ln\left(\frac{z-d}{z_o}\right)\right]^2}$$

It is evident from this equation that should R_N, G, z, u(z), RH_o, e_z and T_z be given, then the equation is solely a function of T_o and unique physical constants and is therefore solvable for T_o by reiteration.

To follow the daily variations in the atmospheric driving forces hourly mean values of the weather elements are inserted into the equation and an initial T_o value selected. Once the energy budget equation balances, it is assumed that the resulting T_o is the 'effective' surface temperature and required values such as λE, E and C may be computed.

In addition to the latent heat flux (λE), the equilibrium (λE_e) and potential latent heat flux (λE_p) as defined below, were computed and compared. The equilibrium latent heat flux or the latent heat flux from an infinitely large, freely transpiring vegetated surface where the air is saturated, and the potential latent heat flux were computed using the equations

$$\lambda E_e = \frac{H\Delta}{\Delta + \gamma}$$

and

$$\lambda E_p = \frac{H\Delta + \rho C_o\, \delta e/r_a}{\Delta + \gamma} \qquad \text{(Thom, 1975)}$$

In these equations

H = $R_N - G\ (Wm^{-2})$,

△ = the slope of the saturated vapour pressure curve at the temperature of the system (mbar $°C^{-1}$), and

δe = the saturation deficit of the atmosphere lat the reference level (mbar).

Experimental Procedure

Initial field work to test this proposed technique has been carried out on approximately one hectare of wheat cultivated at the Agrometeorological Observatory of the U.O.F.S.

A net radiometer and soil heat flux plates were sited near the centre of the land and their outputs connected to strip chart recorders to provide continuous records of net radiation and soil heat flux. Two ventilated psychrometers were constructed and their wet- and dry-bulb temperatures recorded continuously on a multi-channel recorder. The psychrometers, which employed resistance thermometer transducers, were both shielded and aspirated. One psychrometer was situated at the momentum exchange height 0,76h (Monteith, 1973) to monitor conditions at the canopy surface. The other psychrometer, monitored conditions above the canopy surface at height z = (d + 0,5) m. This was known as the reference level. Wind speed was recorded continuously at a height of 2 m above the short grass surface at the standard meteorological weather station. The latter was situated alongside the 1 ha experimental plot.

By means of various digitizing programs, all weather charts were digitized on the HP 9845 desktop calculator system and the respective hourly mean values stored on magnetic tapes. These hourly mean values were then used as inputs in the computer program which balanced the surface energy budget equation by a reiterative method. Before the wind data was used in the program, it was corrected to its equivalent value at the reference level by means of the logarithmic wind profile equation (Monteith, 1973). Once the energy budget equation balanced to within ± 1 Wm^{-2}, the hourly evaporation was calculated. The closeness of agreement between the measured and computed surface temperature was taken as a test of the accuracy of the technique. Although the HP9845 desktop system was used it is possible to carry out all computations on small programmable hand calculators such as the HP97.

Results and Discussion

To test the technique experimentally, the results of a six day period from 12 to 17 October 1978, were analysed in detail. Table 1 is an example of the HP 9845 print-out which gives the hourly mean values once the energy budget equation has been balanced by the reiterative method. In Table 1, R_N is the net radiation reaching the canopy surface (Wm^{-2}), G is the soil heat flux (Wm^{-2}), C is the sensible heat flux (Wm^{-2}), Le is the latent heat flux (Wm^{-2}), computed by the reiterative method, Leq is the equilibrium latent heat flux (Wm^{-2}), Lep is the potential latent heat flux (Wm^{-2}) calculated using the penman type equa-

TABLE 1

AN EXAMPLE OF THE HP 9845 COMPUTER PRINT OUT SHOWING THE MEAN HOURLY VALUES OF THE VARIOUS TERMS USED TO ESTIMATE CROP EVAPORATION. SEE TEXT FOR EXPLANATION OF THE SYMBOLS USED. 12 October 1978. Crop height: 0,49 m.

Time	Rn	G	C	Le	Leq	Lep	F	To	T M	Tair	B	E
09h00	−335	012	53	270	193	466	1,12	12,7	13,0	11,9	0,2	0,40
10h00	−587	018	170	398	370	655	1,18	19,4	17,2	16,2	0,4	0,58
11h00	−727	062	239	425	453	687	1,38	23,3	19,7	18,4	0,6	0,62
12h00	−782	018	228	536	537	970	1,20	23,1	21,4	19,7	0,4	0,79
13h00	−782	029	141	613	534	1207	1,09	22,3	22,0	20,6	0,2	0,90
14h00	−713	040	141	531	477	1213	1,07	22,3	22,0	20,7	0,3	0,78
15h00	−587	073	130	383	360	1179	1,04	21,9	21,3	20,5	0,3	0,56
16h00	−433	040	95	299	269	1025	1,03	20,4	19,8	19,3	0,3	0,44
17h00	−251	054	16	288	198	730	0,95	17,9	17,1	17,6	0,1	0,42
18h00	−084	059	34	108	85	460	0,79	15,3	12,9	14,3	0,3	0,16

COMPUTED DAILY EVAPORATION (mm) 5,65
MEASURED A-PAN EVAPORATION (mm) 7,43

$ET/E_p = 0,76$

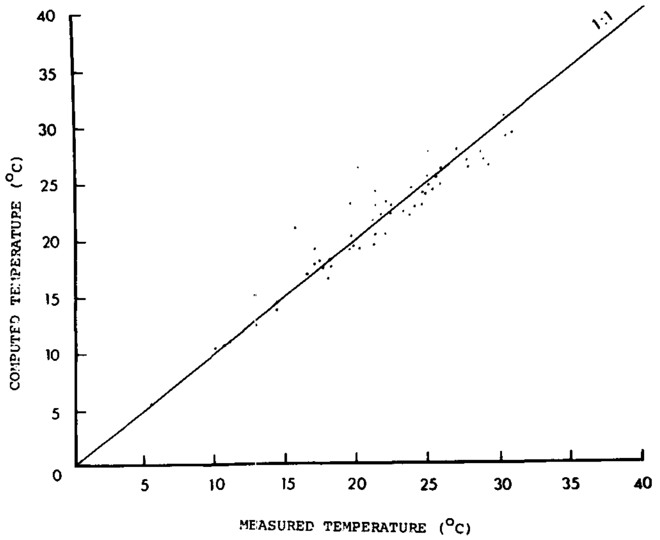

Figure 2
Computed hourly mean surface temperatures versus the hourly mean temperature measured at the momentum exchange level for the six day period (12 to 17 October 1978).

tion, F is the stability factor, To is the computed surface temperature (°C), T M is the measured surface temperature (°C). Tair is the air temperature at the reference level (°C), B is the Bowen ratio ($= \frac{C}{Le}$) and E is the evaporation (mm/h).

The agreement between the measured and computed surface temperature may be used to test the validity of the technique and Fig. 2 shows a graphical representation of the computed hourly mean surface temperature versus the temperature measured at the momentum exchange level over the six days. The straight line illustrates the 1:1 relation. This data fitted a linear relationship with a coefficient of determination of 0,917.

The computed and measured surface temperature for the six days were subjected to the students t test for paired observations (Steel and Torrie, 1960). The analysis yielded $t = 0,44$ for 63 df ($P < 0,05$), implying no significant difference between the computed and measured surface temperature and an indication of the validity of the technique.

The computed daily crop evaporation (ET) was compared to the class-A pan evaporation (E_p) and ET/Ep ratios for the six days were found to be 0,76; 0,97; 0,72; 0,72; 1,05 and 1,03 respectively. These ratios lie well within the range for wheat quoted by Streutker (1978) and Meyer, Walker and Green (1979), providing further verification of the method. It is interesting, and in agreement with Meyer *et al.* (1979) that, for the prevalent stage of crop development, it is possible during times of high atmospheric demand for the crop to transfer more water to the atmosphere than will evaporate from an open pan.

Fig. 3 shows the temporal variation in the computed mean hourly equilibrium and potential latent heat flux for the six days. The evaporation corresponding to the total heat fluxes represented under the curves λE λE_e and λEp, are 7,3; 4,9 and 17,9 mm, respectively. The mean A-pan evaporation for the six days was 8,2 mm.

Of interest is the high Penman evapotranspiration. In calculating λE_p it was assumed that the bulk canopy resistance r_{sT}, was negligible. r_{sT} might in fact have been double r_{aV} and double r_{aH}. If $r_sT = 2r_{aV} = 2r_{aH}$ then λE_p would decrease by approximately 50% which is only ± 25% higher than λE. It is however virtually impossible to measure r_{sT}.

Instead of replacing e_o by $RH_o\ e_e(T_o)/100$ it is also possible to use measured e_o. The evaporative term would then be known and the expanded energy budget equation could be solved for To algebraically. Assumptions 2 and 4 improve the sensitivity of the evaporative term to To. It is felt that this dependence and the reiteration ensure that a more accurate solution will be obtained and hence a more reliable estimate of evaporation. Furthermore, in practice, reliable measurements of relative humidity using commercially available humidity sensors are possible. This reduces the number of measurements required

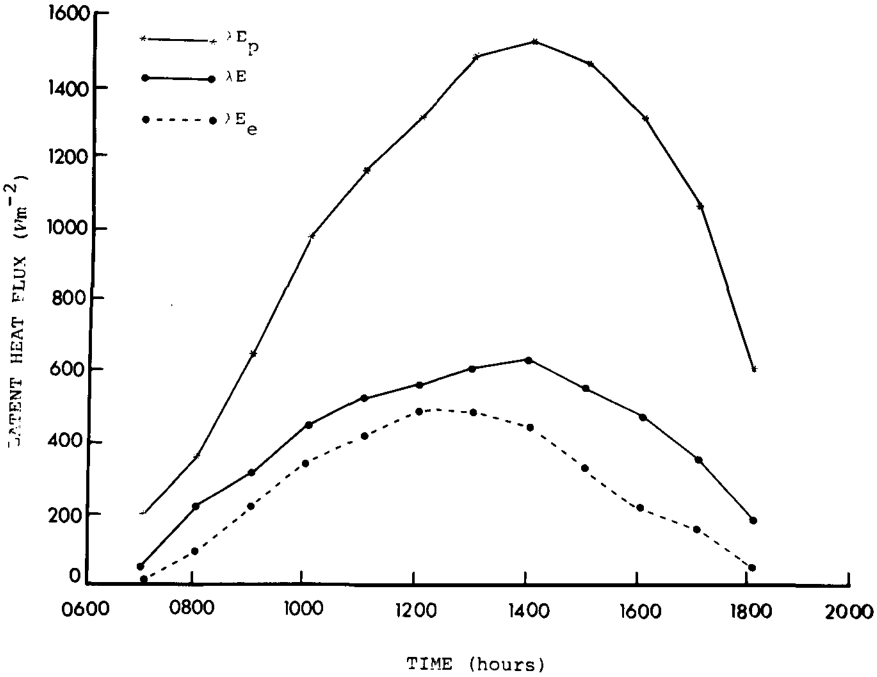

Figure 3
Mean hourly values of computed latent heat flux (λE), equilibrium latent heat flux (λEe) and potential latent heat flux (λEp) for 12, 13, 14, 15, 16 and 17 October 1978.

and saves time in data analysis.

In the preliminary work carried out to test the technique (as reported in this paper) the net radiation was measured directly by means of a net radiometer. Reliable empirical methods which involve standard macroclimate observations and sunshine duration (Selirio, Brown and King, 1971) will be substituted when the technique is applied in the field.

Conclusions

The main advantages of the proposed reiterative energy budget for measuring crop evaporation include:

1. Large gradients are measured and thus less sensitive and cheaper equipment is required.

2. The aerodynamic exchange coefficients may be calculated using a single anemometer as the surface value is assumed zero.

3. A reasonably small calculator such as the HP97 can be used for all computations.

4. The technique provides measurements of crop evaporation of accuracy acceptable for agricultural purposes.

5. The results describe in detail the surface energy budget, and thus the environment at the canopy surface. Such analyses are invaluable in agronomic experiments.

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