Errors in micro-meteorological estimates of reference crop evaporation due to advection

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Abstract

Micro-meteorological methods including the Bowen ratio, infrared thermometry, the Penman-Monteith equation and eddy correlation measurements were used to determine reference crop evaporation, Eo, under conditions of limited fetch. The accuracy of these methods was compared with lysimetrically measured values of Eo.

Advected heat flux density was determined from measurements of net radiation, soil heat flux density, the Bowen ratio and reference crop evaporation Eo.

It was shown that the experimental site was subject to advective influences brought about by limited fetch. A mean hourly advection of 301 $W \cdot m^{-2}$ was obtained from 75 hourly sets of experimental data.

The index of agreement, SI, was used to determine the accuracy of estimates of Eo using micro-meteorological techniques under limited fetch conditions. The Penman-Monteith equation compared best with lysimeter observations, with an SI value of 0,95 when daylight values were considered. This is followed by SI values of 0,77; 0,88; 0,70 and 0,49 respectively for the Bowen ratio; the energy balance equation (EBE) and infrared thermometry; the EBE and sensible heat measurements and eddy correlation measurements.

Introduction

Accurate estimation of atmospheric evaporative demand, AED, is indispensable for crop-related evaporative studies. De Jager and Van Zyl (1989) formulated AED mathematically as:

$$AED = kc\,Eo \qquad (1)$$

where:

kc = evaporation coefficient (dimensionless) composed of soil and plant components
Eo = evaporation from a reference crop ($mm \cdot h^{-1}$)

Reference crop evaporation, Eo, is defined by Doorenbos and Pruitt (1977) as the rate of total evaporation of an extended surface of an 80 mm to 150 mm tall grass cover of uniform height actively growing, completely shading the ground and not deficient of water or nutrient.

AED is defined as the water vapour transfer to the atmosphere required to sustain the energy balance of a given vegetative surface (crop), in its present growth stage, when the water status of its root zone permits unhindered plant evaporation and the water status of the top 150 mm of soil equals its current value (De Jager and Van Zyl, 1989).

It is clear from Eq. 1 that the accuracy of AED depends entirely upon the accuracy of the evaporation coefficient for the relevant crop growth stage and the value of Eo.

Numerous climatological methods of estimating Eo exist in the literature (Bowen, 1926; Thornthwaite and Holzman, 1939; Penman, 1948; Thornthwaite, 1948; Blaney and Criddle, 1950; Swinbank, 1951: Makkink, 1957; Slatyer and McLlroy, 1961; Jensen and Haise, 1963; Monteith, 1963, 1964; Van Bavel, 1966; Tanner, 1967; Priestley and Taylor, 1972; Caprio, 1974; Hargreaves, 1974; Idso et al., 1975; Idso et al., 1977; Linacre, 1977; Allen, 1986; Choudhury et al., 1986; Van Zyl and De Jager, 1987).

Perhaps the most fundamental methods of determining Eo are those derived directly from the surface energy balance equation, EBE, and the eddy correlation technique, EC.

Methods derived from the EBE relevant to this study are:

- EBE and Bowen ratio (Bowen, 1926)
- EBE and infrared thermometry, IRT (Choudhury et al., 1986)
- Penman-Monteith equation, PME (Thom, 1975)
- EBE and sensible heat flux density, C (Thom, 1975). C can be obtained from eddy correlation measurements.

In many applications in arid to semi-arid regions Eo is measured in a lysimeter over small grass-covered areas. The question therefore arises: how does advected energy influence the above-mentioned methods in such limited fetch situations. This formed the overall object of this investigation.

Specific objectives were to:

- determine the accuracy of Eo estimated using the Bowen ratio, IRT, PME, C, and EC by comparison with lysimeter observations; and
- determine advected heat flux density using surface energy balance, Bowen ratio and lysimeter observations.

Materials and methods

Method

It was decided to investigate the influence of advection upon micro-meteorological estimates of Eo under limited fetch conditions. The latter were produced by making measurements near the middel of a short grass-covered area, which was approximately 80 m x 80 m in size (see Fig. 1). Four of the micro-meteorological techniques examined involved modifications of the energy balance equation. These were derived using:

- the Bowen ratio;
- an infrared thermometer for determining sensible heat, IRT;
- a combination method (Penman-Monteith equation, PME); and
- a sonic anemometer and fine-wire-thermocouple for determining sensible heat flux, C.

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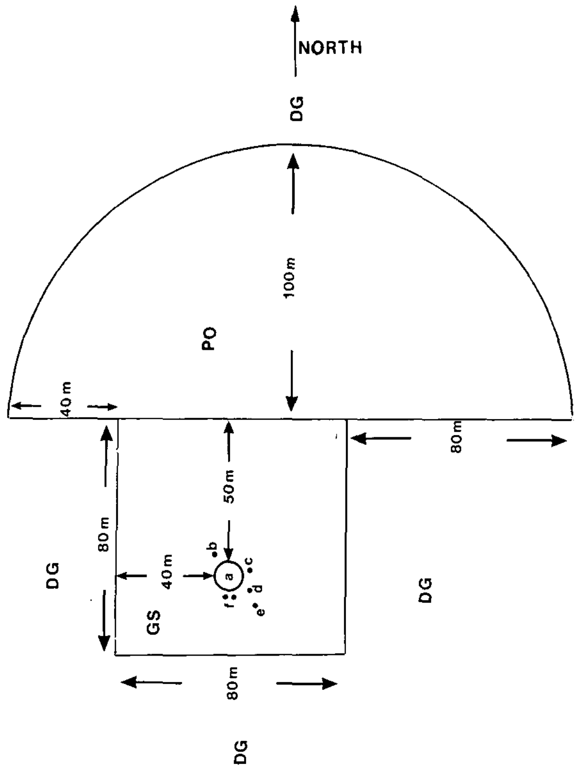


Figure 1

a : Grass lysimeter
b : Net radiometer
c : Soil heat flux sensor
d : Aspirated psychrometer
e : Three-cup anemometer
f : Sonic anemometer, fine-wire-thermocouple and Krypton hygro meter
GS : Grass site
DG : Dry grassland
PO : Potato field

The fifth method entailed direct measurement of eddy fluctuations in water vapour pressure. The theory and instrumentation are described in the appropriate sections which follow. The accuracy of these methods was compared against measurements made in a short grass lysimeter.

The IRT and PME methods exhibited little advective response while the eddy correlation techniques correlated poorly with measured Eo. Correlation coefficients of less than 0,62 (see Table 1) were obtained. Hence, these four techniques were not used to estimate advection. The Bowen ratio method correlated well and responded to advection. Thus, this technique in the method proposed by Lang (1973) was used to investigate advection.

Theory

Following the derivation of Lang (1973) the EBE for a grass surface is given by:

$$Rn + G + C + A + LEo = O \qquad (2)$$

where:

Rn = net radiation ($W{\cdot}m^{-2}$)
G = soil heat flux density ($W{\cdot}m^{-2}$)
C = sensible heat flux density ($W{\cdot}m^{-2}$)
A = advected heat flux density ($W{\cdot}m^{-2}$)
L = latent heat of evaporation ($J{\cdot}kg^{-1}$)
Eo = reference crop evaporation ($kg{\cdot}m^{-2}{\cdot}s^{-1}$)

Advection A is defined as the transport of energy or mass in the horizontal plane in the downwind direction (Rosenberg et al., 1983). This is synonamous with the deviation from measured closure in the energy balance equation and is due to mixing of horizontal and vertical air flows.

The sign convention of Houghton (1985) was used in Eq. 2 viz. all incoming energy (including advection) was denoted positive and all outgoing energy negative.

TABLE 1
RESULTS OF STATISTICAL TESTS CARRIED OUT BETWEEN Eo MEASURED LYSIMETRICALLY AND Eo CALCULATED FROM EQS. 6, 9, 11, 12 AND 13 RESPECTIVELY, USING HOURLY MICRO-METEOROLOGICAL DATA. RESULTS WERE OBTAINED FROM TWO-HOURLY (2h) EVAPORATING RATES

Statistical parameter	Parameter values				
	Eq. 6 (Bowen ratio)	Eq.9 (IRT)	Eq. 11 (PME)	Eq. 12 (C)	Eq. 13 (EC)
n	102	106	109	61	61
Slope through origin	0,74	1,13	0,92	0,89	0,49
r	0,71	0,78	0,83	0,51	0,62
SI	0,77	0,85	0,89	0,70	0,57
MAD	0,34 mm·2h⁻¹	0,37 mm·2h⁻¹	0,27 mm·2h⁻¹	0,44 mm·2h⁻¹	0,63 mm·2h⁻¹
RMSE	0,45 mm·2h⁻¹	0,48 mm·2h⁻¹	0,34 mm·2h⁻¹	0,54 mm·2h⁻¹	0,77 mm·2h⁻¹
S. RMSE	0,36 mm·2h⁻¹	0,24 mm·2h⁻¹	0,21 mm·2h⁻¹	0,39 mm·2h⁻¹	0,75 mm·2h⁻¹
U. RMSE	0,09 mm·2h⁻¹	0,24 mm·2h⁻¹	0,13 mm·2h⁻¹	0,15 mm·2h⁻¹	0,02 mm·2h⁻¹

n : number of observations
r : correlation coefficient
SI : simulation index
MAD: mean absolute difference
RMSE : root mean square error
S. RMSE : systematic root mean square error
U. RMSE : unsystematic root mean square error

Equation 2 was modified in several ways enabling determination of LEo using the different micro-meteorological techniques (see Eqs. 6, 9, 11, 12 and 13).

Fetch requirements

The thickness, $\delta(\chi)$ of an equilibrium boundary layer (see Brutsaert, 1982), as measured above the zero displacement level, d, is approximated by Munro and Oke (1978) as:

$$\delta(\chi) = 0{,}1\, x^{0{,}8}\, z_o^{\,0{,}2} \qquad (3)$$

where:

z_o = 0,13 h, the roughness parameter (m)
h = height of the reference crop (here equal to 0,05 m)
x = distance downwind of the edge of the site, covered by reference crop, and the measuring point (see Fig. 1).

The thickness of the equilibrium boundary layer in this experiment for the minimum distance, x = 40 m (see Fig. 1), was, according to Eq. 3, equal to 0,60 m. It is therefore evident that when measurements are made above 0,60 m, advective effects would prevail.

When micro-meteorological measurements are made at the surface (grass cover in this case) or within the boundary layer, A in Eq. 2 equals zero. However, when micro-meteorological measurements are made outside this boundary layer, A cannot be ignored in Eq. 2.

Determination of LEo using the Bowen ratio

Equation 2 can be rewritten (see also Lang, 1973) as:

$$Rn + G + A = -C - LEo \qquad (4)$$

Dividing both sides of Eq. 4 by LEo, resulted in:

$$\frac{Rn + G + A}{LEo} = -\left[\frac{C}{LEo} + 1\right] \qquad (5)$$

Rearranging Eq. 5 gives:

$$LEo = -(Rn + G + A)/(\beta + 1) \qquad (6)$$

where:

ß, the Bowen ratio (Bowen, 1926), is equal to $\frac{C}{LEo}$

Application of aerodynamic theory then yields:

$$\beta = \frac{\rho C_p (T_{a1} - T_{a2})\, r_e}{L\,(e_1 - e_2)\, r_c} \quad \text{(Campbell, 1977)} \qquad (7)$$

where:

ρ = density of moist air (kg.m^{-3})
C_p = specific heat of air (J.kg^{-1} °C^{-1})
T_a = ambient temperature (°C)
e = water vapour pressure (Pa)
r_e = resistance to water vapour transfer (s.m^{-1})
r_c = resistance to heat transfer (s.m^{-1})

The subscripts 1 and 2 refer to measurements of T_a and e at heights z_1 and z_2 above ground level.

Assuming that $r_e = r_c$, from the similarity hypothesis (Campbell, 1977), Eq. 7 can be rewritten as:

$$\beta = \gamma \frac{\Delta T_a}{\Delta e} \quad \text{(dimensionless)} \qquad (8)$$

where:

γ = psychrometric constant (= $\frac{\rho Cp}{L}$ = 66 Pa °C^{-1})
ΔT_a = $T_{a1} - T_{a2}$ (°C)
Δe = $e_1 - e_2$ (Pa)

Thus, in this application, LEo may be determined by substituting into Eq. 6 measurements of Rn, G, LEo, together with T_a and e measured at two different heights.

Determination of LEo using the energy balance equation and IRT

LEo may be obtained by substituting C, calculated from Eq. 9 into Eq. 2, where:

$$C = \rho\, C_p\, \phi_a\, (T_o - T_a) \qquad (9)$$

In Eq. 9:

ρ = density for moist air (kg.m^{-3})
T_o = grass canopy surface temperature (°C), measured with the infrared thermometer
ϕ_a = aerodynamic conductance (m.s^{-1})
$= k^2 u_z / \{\ln(z - d)/z_o\}^2 \qquad (10)$

where:

k = Von Karman's constant
u_z = wind speed at measuring height z (m·s^{-1})
d = 0,63 h, the zero displacement level (m)
z = height of anemometer above ground surface in the area covered with short grass (= 1,00 m)

Determination of LEo using the Penman-Monteith equation

Utilisation of Eqs. 2 and 9 to estimate LEo requires measurement of canopy surface temperature, To. The latter is difficult to measure (Berliner et al., 1984). Penman (1948) however, solved the problem by eliminating T_o. This, together with the introduction of crop canopy conductance (Monteith, 1964) and aerodynamic conductance terms (Thom, 1975) and assuming A = 0 resulted in the Penman-Monteith equation, which expresses LEo as:

$$LEo = \frac{sH}{s + \gamma^*} + \frac{\rho\, C_p\, \delta e\, \phi_a}{s + \gamma^*} \qquad (11)$$

where:

H = available energy to evaporate water (W·m^{-2})
s = slope of the saturated water vapour pressure temperature curve (Pa·°C^{-1})
γ^* = $(1 + \phi_a/\phi_{ca})$
ϕ_a = aerodynamic conductance (=$^1/r_a$)(m·s^{-1})
r_a = bulk aerodynamic resistance (s·m^{-1})
ϕ_{ca} = canopy surface conductance (=$^1/r_{ca}$)(m·s^{-1})

ϕ_{ca} = 0,03 m s^{-1} (Russel, 1980)
r_{ca} = canopy surface resistance ($s \cdot m^{-1}$)
δe = water vapour pressure deficit (Pa)

The aerodynamic resistance was determined using the logarithmic wind profile without correction for atmospheric stability as described by Thom (1975).

Determination of LEo using the energy balance equation and sensible heat

The sensible heat term in Eq. 2 can also be obtained from sonic anemometer and fine wire thermocouple observations, using:

$$C = \rho\, Cp\, \overline{W'T'} \tag{12}$$

where:
W' = vertical wind speed fluctuation ($m \cdot s^{-1}$)
T' = vertical temperature fluctuation (°C)

Determination of LEo using eddy correlation measurements

For a horizontal surface, such as a reference crop, and with an upwind fetch adequate to ensure measurements representative of the surface, the vertical transport of water vapour can be determined from:

$$LEo = L\, \overline{W'q'} \tag{13}$$

where W' (measured in $m.s^{-1}$) and q' (measured in $kg.m^{-3}$) are instantaneous departures from the mean vertical wind speed and mean water vapour density respectively.

Experimental site

The study was carried out on a 0,64 ha square grass site (Fig. 1) during the spring (beginning September till end of November 1990) on the West Campus of the University of the Orange Free State, situated at latitude 26°15' S and longitude 29°6'E.

Reference evaporation, Eo, was measured on the grass site, labelled GS in Fig. 1, utilising a weighing lysimeter with an exposed area of 5 m^2, resolution 0,05 mm, depth 0,7 m and accuracy of 0,02 mm, when moderate wind speeds prevail. Micro-meteorological instrumentation used during the study was installed in the immediate vicinity of the grass lysimeter (Fig. 1). The entire grass site (GS) was irrigated frequently throughout the growing season so as to prevent moisture stress. This ensured that evaporation proceeded at the maximum atmospherically limited rate throughout the experiment.

The area surrounding the site consisted of dry grassland (DG) extending infinitely as indicated in Fig. 1, and a section which happened to be planted to potatoes, which was also kept well watered throughout the study. This area is labelled PO in Fig. 1.

The minimum and maximum distances from the centre of the lysimeter to the edge of the grass site were 40 and 50 m respectively (see Fig. 1).

Micro-meteorological observations

The following mean two-hourly micro-meteorological elements (approximately 200 data sets) were measured from October to November during 1990, viz:

- Net radiation (calculated from 3 000 instantaneous observations per hour) using a Funk type net radiometer installed 1,00 m above ground level.
- Soil heat flux density (calculated from three observations per hour) using a soil heat flux sensor embedded at a depth of 50 mm below the reference crop surface.
- Ambient and wet bulb temperatures (calculated from 720 observations per hour) utilising self-designed and constructed aspirated psychrometers. Water vapour pressure and ambient temperature were measured at 0,50; 1,00 and 2,00 m above ground level. The psychrometers were calibrated on the day prior to measurements, using a sling psychrometer.
- Wind speed (calculated from 3 000 observations per hour) using a three-cup anemometer installed at a height of 1,00 and 2,00 m above ground level.
- Reference crop surface temperature (calculated from three observations per hour) using a teletemp infrared thermometer. It was installed at 1,00 m above ground level and directed towards the grass at an angle of 45° with respect to ground level.

Instantaneous measurements at 2,00 m (Kaimal, 1975) above ground level of the following were made:

- Vertical fluctuations in wind speed W' using a Campbell sonic anemometer.
- Vertical fluctuations in ambient temperature T' using a Campbell fine-wire-thermocouple.
- Fluctuations in water vapour pressure, q' using a Campbell krypton hygrometer.

The sampling rate in the latter three cases was 5 Hz, with a 10-min sub-interval averaging period (i.e. 3 000 obserations in a 10-min period) and a 30-min output interval. All sensors were connected to a Campbell 21X data logger.

It is thus evident that all instrumentation, with the exception of the net radiometer and the psychrometer installed at 0,50 m, were placed at heights above the equilibrium boundary layer i.e. at heights exceeding 0,60 m.

Analysis of micro-meteorological observations

Each of the micro-meteorological methods (Eqs. 6, 9, 11, 12 and 13) for determining LEo was compared against the lysimeter values of LEo. Conventional statistical analyses and the simulation index, SI, of Willmott (1982) were used. Advection was ignored when LEo was calculated.

Eo, in $mm \cdot 2h^{-1}$, was obtained by dividing LEo by 7 200/L.

Estimation of advection

Hourly mean advection was calculated by rearranging Eq. 6, thus:

$$A = -LEo\,(\beta + 1) - Rn - G \tag{14}$$

In Eq. 14 LEo was measured lysimetrically while the Bowen ratio, β was calculated from measurements of ΔTa and Δe at 1,00 and 2,00 m height.

It was assumed that ambient temperature, wet bulb temperature, net radiation and soil heat flux density were measured with an accuracy of ± 0,1°C, ± 0,3°C, ± 10% of Rn and ± 10% of G respectively. It has been shown that the

TABLE 2
RESULTS OF STATISTICAL TESTS CARRIED OUT BETWEEN MEASURED Eo AND Eo CALCULATED FROM EQS. 6, 9, 11, 12 AND 13 RESPECTIVELY, USING HOURLY MICRO-METEROLOGICAL DATA. RESULTS WERE OBTAINED FROM DAYLIGHT EVAPORATING RATES

Statistical parameter	**Parameter values**				
	Eq. 6 (Bowen ratio)	**Eq.9 (IRT)**	**Eq. 11 (PME)**	**Eq. 12 (C)**	**Eq. 13 (EC)**
n	21	21	21	15	15
Slope through origin	0,75	1,24	0,96	0,92	0,51
r	0,88	0,92	0,94	0,52	0,75
SI	0,77	0,88	0,95	0,70	0,49
MAD	1,42 mm·dl^{-1}	1,61 mm·dl^{-1}	0,80 mm·dl^{-1}	1,16 mm·dl^{-1}	2,65 mm·dl^{-1}
Mean difference	1,02 mm·dl^{-1}	1,32 mm·dl^{-1}	0,01 mm·dl^{-1}	0,14 mm·dl^{-1}	2,65 mm·dl^{-1}
RMSE	1,74 mm·dl^{-1}	1,95 mm·dl^{-1}	0,95 mm·dl^{-1}	1,49 mm·dl^{-1}	2, 95 mm·dl^{-1}
S. RMSE	1,65 mm·dl^{-1}	1,47 mm·dl^{-1}	0,75 mm·dl^{-1}	1,09 mm·dl^{-1}	2,92 mm·dl^{-1}
U. RMSE	0,09 mm·dl^{-1}	0,44 mm·dl^{-1}	0,20 mm·dl^{-1}	0,40 mm·dl^{-1}	0,03 mm·dl^{-1}

n : number of observations
r : correlation coefficient
SI : simulation index
MAD: mean absolute difference
RMSE : root mean square error
S. RMSE : systematic root mean square error
U. RMSE : unsystematic root mean square error
dl : daylight period

TABLE 3
COMPARISON BETWEEN MEASURED Eo AND ESTIMATED Eo AT TWO DIFFERENT HEIGHTS USING EDDY CORRELATION METHODS

DOY	**Hour**	**Eo measured lysimetrically (mm·h^{-1})**	**Estimated Eo (mm·h^{-1})**	
			EC.No 1 H=1,50 m	**EC.No 2 H=0,25 m**
107	9:00 - 10:00	0,36	0,14	0,17
	10:00 - 11:00	0,48	0,22	0,24
	11:00 - 12:00	0,32	0,24	0,28
	12:00 - 13:00	0,52	0,26	0,27

accuracy of the grass lysimeter is ± 0,02 mm, which is equivalent to ± 14 W·m^{-2} (Van Zyl and De Jager, 1992). Such values produced large measurement errors in A. These were accounted for by rejecting values of A comparable in magnitude to the magnitude of measurement error.

The maximum possible measurement error in A, denoted ϵ_A, was obtained from the following expression, viz.:

$$\epsilon_A = LEo\left[\xi 1 + \frac{\beta(\xi 2 + \xi 3)}{\beta + 1}\right] + (Rn \times \xi 4) + (G \times \xi 5) \qquad (15)$$

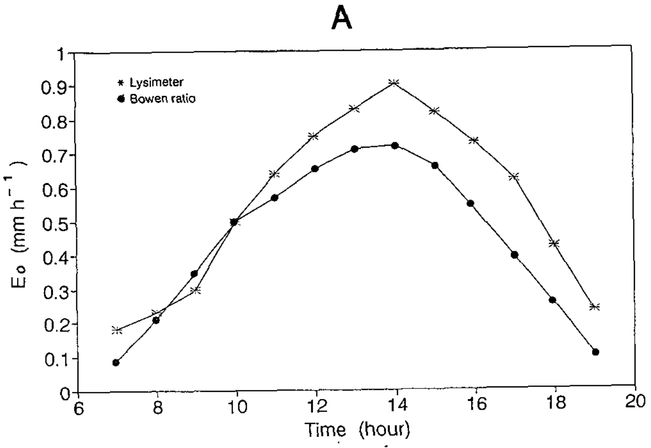
where:
$\xi 1$, $\xi 2$, $\xi 3$, $\xi 4$ and $\xi 5$ are the relative errors in LEo, ambient temperature, wet bulb temperature, net radiation, Rn, and soil heat flux density, G.

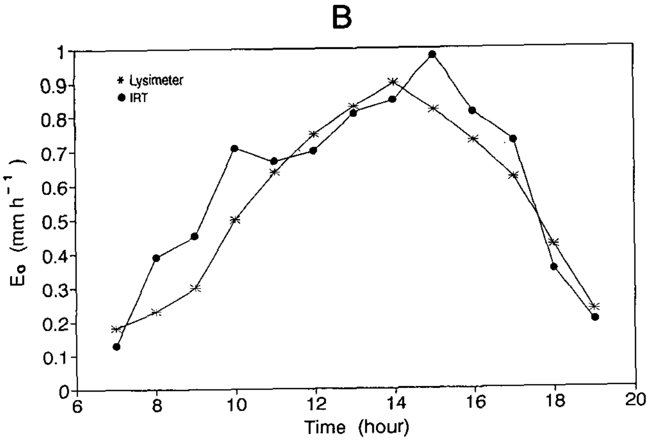
Hourly values of these are given by:

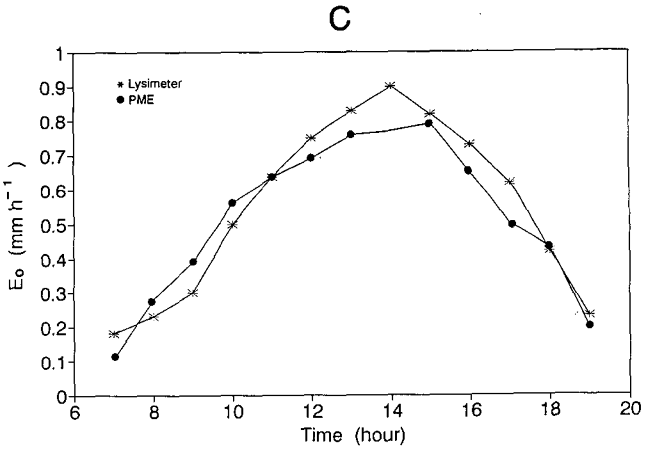
$$\xi 1 = \frac{28}{LEo}\ ;\ \xi 2 = \frac{0{,}2}{|\Delta T|}\ ;\ \xi 3 = \frac{0{,}6}{|\Delta Tw|}\ ;\ \xi 4 = \frac{0{,}2}{|Rn|}$$

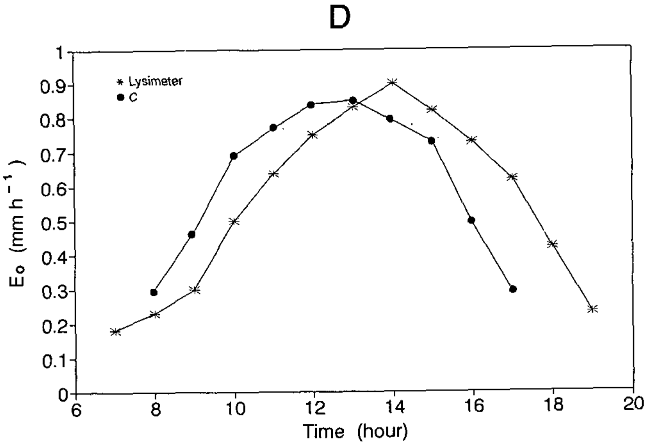
and

$$\xi 5 = \frac{0{,}2}{|G|}$$









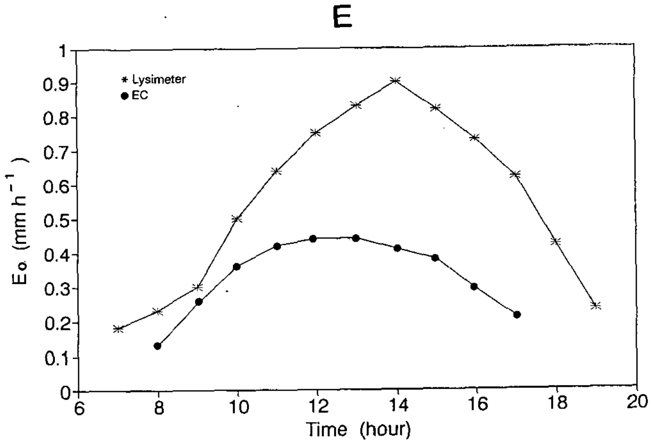


Figure 2
Hourly variation of Eo over the daylight period.
A) Lysimeter and Bowen ratio
B) Lysimeter and IRT
C) Lysimeter and PME
D) Lysimeter and C
E) Lysimeter and EC

ΔTw is the difference in the wet bulb temperatures, measured at 1,00 and 2,00 m.

The following rejection criteria were used to estimate true minimum advection, viz.:

- when A calculated from Eq. 14 was less than ϵ_A; and
- when $\Delta e < 20$ Pa

Results and discussion

Micro-meteorological observations

Table 1 presents the results of the statistical tests comparing two-hourly (2h) Eo measured with Eo calculated using Eqs. 6, 9, 11, 12 and 13 respectively. Figures 2A to 2E represent the variation in hourly mean Eo either calculated or measured by lysimeter. Table 2 is a summary of the results of the statistical tests comparing daylight Eo measured with calculated values of Eo during daylight hours. Daylight Eo was obtained by adding all hourly values between sunrise and sunset for the specific day. Figures 3A through 3E graphically compare Eo calculated by Eqs. 6, 9, 11, 12 and 13 with Eo measured for the daylight period.

The underestimation of Eo, using the Bowen ratio, is evident from Figs. 2A and 3A and Tables 1 and 2. This is particularly the case at relatively high rates of evaporation. There is nonetheless a consistency in the differences and a significant correlation coefficient of 0,88 was obtained. Because of this it was decided to evaluate advection using the Bowen ratio method.

The IRT method utilised to estimate Eo compared favourably with lysimeter values of Eo. The latter technique generally overestimated Eo (see Figs. 2B and 3B). The slope through the origin was 1,13 and 1,24 for the two-hourly and daylight comparisons respectively (Tables 1 and 2). The good comparison of Eo is attributable to the fact that measurements of canopy surface temperature account for advection.

An excellent comparison was obtained between Eo calculated from the Penman-Monteith equation, and Eo measured. This is reflected by the relatively high SI value (Willmott, 1982) of 0,95 and low mean absolute difference of 0,80 $mm{\cdot}dl^{-1}$ (see Tables 1 and 2), where dl denotes daylight period. A slight underestimation of Eo, at relatively high evaporation rates, usually between 11:00 and 17:00, is evident from Fig. 2C. The good comparison in this case suggests that, as in the case of the IRT technique, boundary layer phenomena such as canopy surface and bulk air conductance compensate for advection.

Eo obtained from eddy correlation measurements (Eq. 13) compared poorly with Eo measured (Tables 1 and 2). Underestimation of Eo, over the full range of evaporation rates, is clearly illustrated in both Figs. 2E and 3E. The fact that virtually all the points lie below the 1:1 line suggests the presence of a systematic error (see Tables 1 and 2). The magnitude of this error of approximately 200% is too large to attribute to advection. Hence this method was not pursued any further. Eddy correlation measurements of Eo, using two identical systems, carried out simultaneously at heights of 0,25m and 1,50 m above the grass surface on DOY 107 are given in Table 3. While good agreement between these two was found, underestimation of Eo by almost a factor two is evident. Savage et al. (1991) and Dugas et al. (1991), also reported significant underestimation of eddy correlation measurements when compared to other methods.

From the slope through the origin, SI and MAD in Tables 1 and 2 it appears that utilisation of the sensible heat technique (Eq. 12), to determine Eo, resulted in a better result than those obtained using the EC technique (Eq. 13). The better performance of Eq. 12 could be due to the dominant role played by net radiation in Eq. 12, whereas net radiation does not feature in eddy correlation calculations. Furthermore, results obtained with Eq. 12 exhibited an one-hour lag, behind lysimeter Eo values (see Fig. 2D).

Determination of advection

Variation in hourly mean advected heat flux density, A, calculated from Eq. 14, is illustrated in Fig. 4. After the computer rejection procedure only 75 of the original 250 measured values remained. The average advection of the 75 unrejected observations was 301 $W{\cdot}m^{-2}$, with a standard deviation of 146 $W{\cdot}m^{-2}$. This means that advection occurred on at least 30% (75/250) of the measurement instances.

That advection was to be expected, is supported by low mean relative humidities prevailing at a height of 2,00 m above ground level. On days when measurements were made, these averaged 24% with a minimum of 12% on one occasion. Furthermore, the grassland surrounding the experimental site was dormant for the whole of the experimental period resulting in no transpiration from this region.

The mean wind speed, measured at a height of 2,00 m, on the grass site, for days when measurements were made, was 5,04 $m{\cdot}s^{-1}$ and never dropped below 3,60 $m{\cdot}s^{-1}$. Measurements of wind direction indicated that, except for three out of the 21 measuring days, the wind never blew from the direction of the potato crop which might slightly have alleviated advection. This also eliminates differences in roughness conditions between the potato crop and reference crop (grass) as a cause for error in the study.

Conclusions

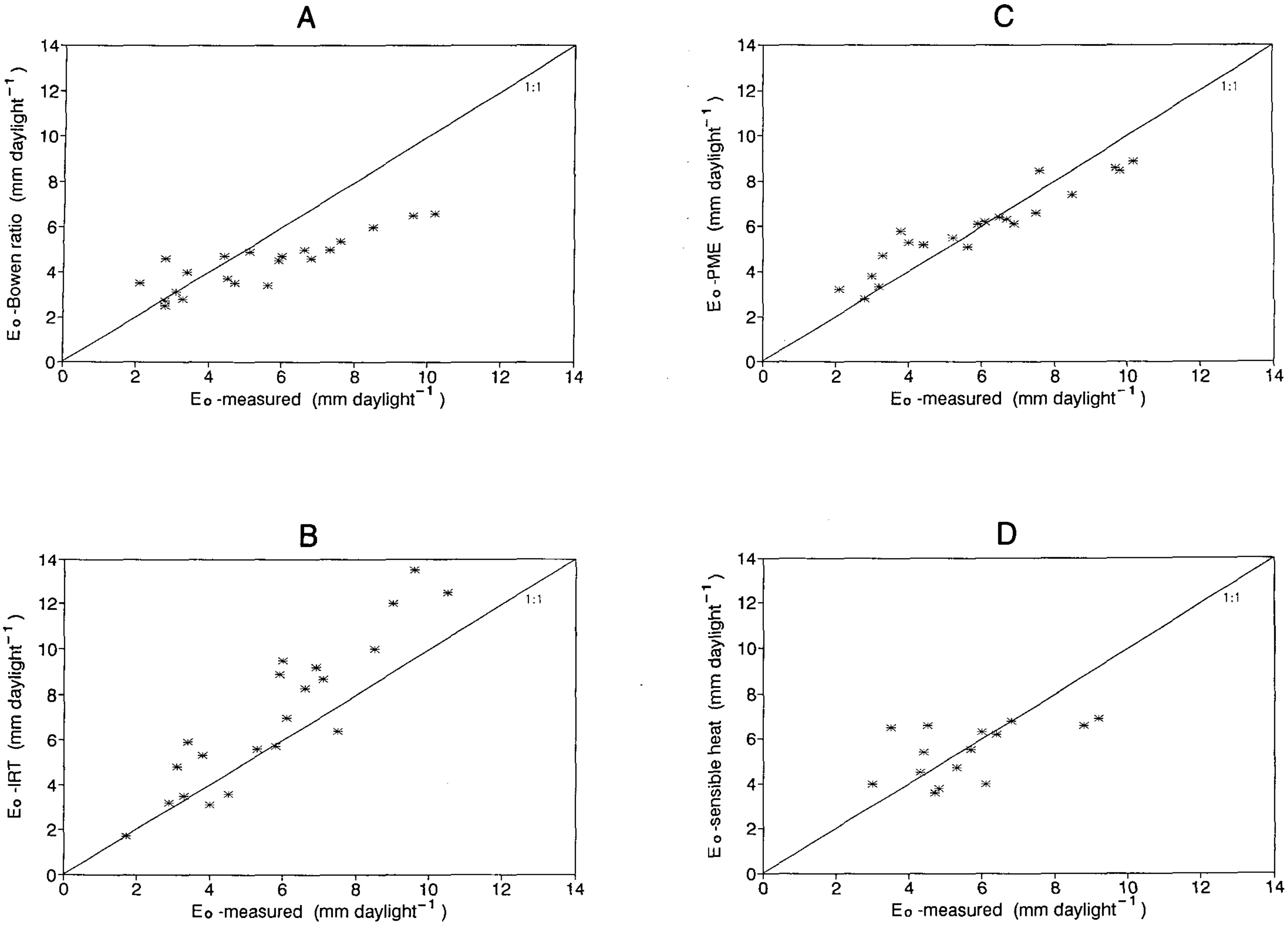
Measurements of net radiation, soil heat flux density, Bowen ratio and Eo measured in a lysimeter were used to estimate advection on a small grass-covered area. The 0,64 ha experimental grass site was found to be subject to advective fluxes. The average advection over 75 one-hour observation periods was 301 $W.m^{-2}$. Advection occurred on at least 30% of the observation periods.

The technique, employing the surface energy balance equation and the infrared thermometer, can be used to estimate Eo reliably. Omission of an advection term did not influence the result, because direct measurement of canopy surface temperature seemed to account for advection.

Except for a slight underestimation at high evaporation rates, the Penman-Monteith equation once again proved to be the most accurate method of estimating reference crop evaporation under the present experimental conditions of limited fetch. This result strongly supports the findings of Allen (1986) and Van Zyl and De Jager (1987).

The method using the energy balance equation and sensible heat flux density as measured with vertical wind and temperature turbulent fluctuations, showed promise. The existence of a one-hour time lag behind lysimeter values of Eo was demonstrated and requires yet to be explained.

The eddy correlation approach (Eq. 13) proved unreliable for estimating Eo, under the present experimental conditions.



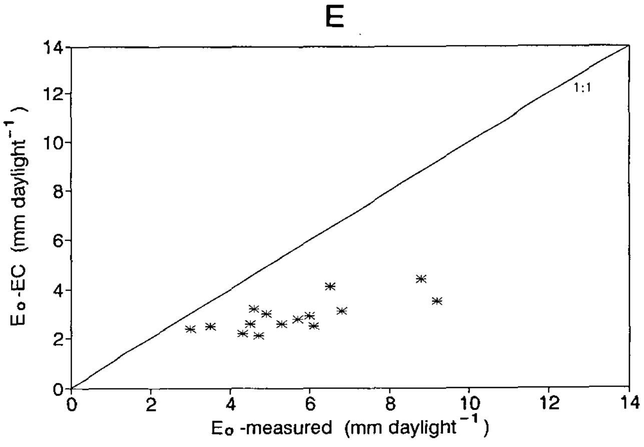


Figure 3

Comparison between daylight Eo measured lysimetrically and Eo estimated from

A) Bowen ratio
B) IRT
C) PME
D) C
E) EC

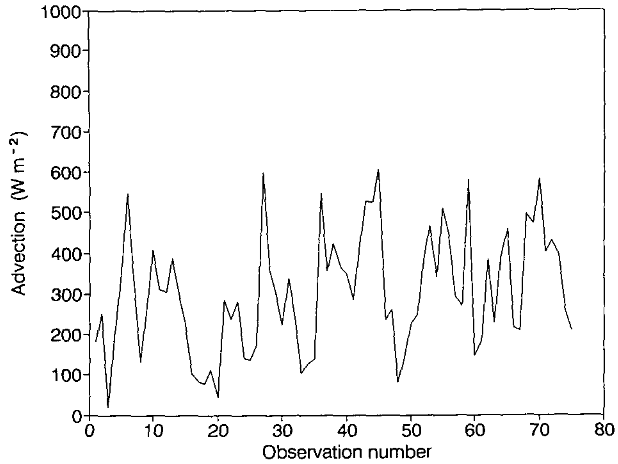


Figure 4
Hourly variation of minimum advection over the experimental period when ambient temperature and vapour pressure were measured at 1,00 m and 2,00 m

Under-estimation of Eo occurred in this study when instruments were exposed at a height of 2,0 m. Underestimation is possibly due to the fact that the eddies measured were representative, to a large extent, of the dry environment surrounding the experimental site rather than the exposure of the site itself. It seems that the theoretical fetch suggested by Tanner (1990), of at least 500 m for the present set-up should be adhered to.

For routine measurement of Eo, micro-meteorological techniques, such as the Bowen ratio, infrared thermometer and eddy correlation methods are problematical, because of the continuous attention required. Furthermore, eddy correlation instrumentation cannot be exposed to rain or dew.

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