RESEARCH ON THE CLIMATIC DEPENDENCE OF EVAPORATION COEFFICIENTS

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Report to the Water Research Commission on the Project

"Research on the climatic dependence of evaporation coefficients"

Head of Department	:	Professor J.M. de Jager
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EXECUTIVE SUMMARY

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RATIONALE FOR THE STUDY

Atmospheric evaporative demand ,AED, is defined as the upper limit of evaporation from a natural vegetative surface of which the water content of the soil surface layer is at its current value. AED represents the sum of evaporation from vegetative and soil surfaces of a natural terrestrial surface. It is calculated as the product of evaporation coefficient ,k_c, and reference crop evaporation, E_o, and is invaluable for estimating the upper limit of crop water requirements. From this the daily soil water content in cropped lands may be computed. Such information is used extensively in practical problem solving, for example by applying the PUTU-system of crop growth models.

The accuracy of AED estimated in the aforementioned manner however, depends entirely upon the reliability of k_c and the accuracy with which E_o is calculated or measured. Inaccuracies in k_c-values cause insufficient or over-irrigation with detrimental financial implications, not only to individual farmers, but for the country in general.

Furthermore, while E_o may accurately be estimated from the Penman-Monteith equation (PME), uncertainty as to the extent of the climatic dependence of k_c exists. Study of these matters forms the major thrust of this report.

OBJECTIVES

The overall objective of the study was to determine:

1. in what manner the crop coefficients of onion, potato and wheat are influenced by climate,

2. theoretical and experimental values of crop coefficients for the mentioned crops for relevant regions in the RSA having analogues climate, and

3. the degree of agreement between experimental and theoretical evaluations of crop coefficients.

As the project progressed, the need to include a summer crop became evident and the project evaluation committee recommended that wheat be replaced by maize. Wheat crop evaporation has already been the subject of extensive research. The inclusion of maize, however, eliminated the study on onion as the latter part of the growth season of this crop coincides with that of maize.

Specific objectives of the study were to

- evaluate hourly mean and daylight mean evaporation coefficients;
- investigate their behaviour throughout the crop growing season;
- relate the hourly mean and daylight mean evaporation coefficients to the weather elements, solar radiation, ambient air temperature, wind speed and water vapour pressure, and

- determine monthly mean evaporation coefficients for different localities throughout the RSA for potato and maize crops.

THEORY

The crop evaporation coefficient, k_c, may be calculated from the ratio of the energy equivalents of upper limit crop evaporation and reference crop evaporation. Hence, mathematically

$$k_c = \frac{LE_c}{LE_o} \tag{1}$$

or

$$k_c = \frac{R_{nc} + G_c + C_c}{R_{no} + G_o + C_o} \tag{2}$$

where R_n = net radiation ($W\ m^{-2}$)

G = soil heat flux density ($W\ m^{-2}$)

C = sensible heat flux density ($W\ m^{-2}$)

LE = latent heat flux density ($W\ m^{-2}$)

E = evaporation rate (mm)

and L = coefficient of vaporization of water at constant temperature ($J\ kg^{-1}$)

The subscripts c and o refer to the crop being investigated and the reference crop respectively.

Thus k_c may firstly be determined directly using lysimeters and Eq. 1. Alternatively, evaluation of k_c from Eq. 2 requires the simultaneous measurement of all the energy terms above both surfaces. In Eq. 2, R_n and G may be measured using net radiometer and soil heat flux sensors, while methods such as infrared thermometry (IRT) and eddy correlation technique (measurement of high frequency vertical wind speed and temperature fluctuations) can be used to determine sensible heat flux C. The Penman-Monteith equation (PME), Bowen ratio and measurement of water vapour flux density by eddy correlation techniques, can also be used to evaluate LE_o.

It needs to be emphasized that the IRT-technique and PME can only be used in the case of water non-stressed complete vegetative cover. Fortunately, these conditions often apply to irrigated crops and then k_c equals the upper limit vegetation evaporation coefficient which is denoted k_{vo}.

Thus for this special case of complete vegetative cover

$$k_c = k_{vo} \qquad (3)$$

and the problem reduces to determining k_{vo} and its climatic dependence.

It was further shown theoretically that the climatic dependence of k_c is determined by k_{vo}. An equation for calculating k_{vo} in terms of soil and vegetation parameters was derived from Eq. 1. For water non-stressed conditions, it reads

$$k_{vo} = \{\frac{E_o}{AED} - k_{so} F_g (1 - F_v)\}/F_v \qquad (4)$$

where

k_{so} = upper limit soil surface evaporation coefficient

F_g = factor accounting for soil surface wetness

and F_v = fractional interception of solar radiation.

Eq. 4 was much used in this study.

PROCEDURE

Eqs. 1, 2 and especially 4 were used to determine k_{vo} for relating to climate. When applying Eq. 4, it was assumed that k_{so} = 1 and theoretical expressions were introduced for F_g and F_v. Accurate estimates of k_{vo} thus depended entirely upon the accuracy with which E_o, AED, F_g and F_v were determined.

In order to obtain a large number of widely varying sets of conditions, hourly mean observations of the various weather variables were collected at hourly intervals. Good results were further obtained using daytime averages of these values .

Both E_o and AED (i.e. LE_o and LE_c) were measured lysimetrically. The short grass lysimeter for measuring E_o was 0,7 m deep with an exposed evaporating surface of 5 m^2. It was able to measure E_o accurate to within ± 0,05 mm. A 2 m deep weighing lysimeter with 10 m^2 evaporating surface was used to measure AED in both potato and maize. It provided an accuracy of ± 0,07 mm of evaporation. Alternative methods included the essentially meteorological techniques such as the Bowen ratio method, the energy budget method with sensible heat being determined by eddy correlation and the direct eddy correlation method. The Penman-Monteith equation and energy budget/infra-red thermometer techniques were also used to determine E_o. All meteorological methods were calibrated against short grass, or cropped precision lysimeters.

Experimentation proceeded on maize and potatoes from 1990 through 1992. Calibration took place during 1990 and 1991. During 1990 k_{vo}, for potatoes, was computed from Eq. 4 and the Penman-

Monteith determination of E_o, with AED for the crop being measured lysimetrically. During 1992 for maize, E_o was once again calculated from the Penman-Monteith equation. During this period however, AED for maize was not only measured lysimetrically, but in addition, determinations thereof were obtained from eddy correlation measurements suplemented by net radiation and soil heat flux density values.

In all cases, the relationship between k_{vo} and the weather elements was determined using multiple regression analysis. The independent variables were solar radiation, air temperature, wind speed and water vapour pressure.

From the resultant regression equations climate corrected monthly mean evaporation coefficients for potato and maize crops for eighteen localities in the RSA were computed and tabulated.

RESULTS

Measurement of reference crop evaporation (Eo)

The reliability of five micro-meteorological techniques for measuring E_o were examined. Values of E_o obtained using the different techniques were compared against E_o measured lysimetrically.

- The Bowen ratio underestimated, daylight E_o, by 25%. The discrepancies occurred especially at relatively high evaporation rates. The slope through the origin and the correlation coefficient, were 0,75 and 0,88 respectively.

- The energy budget/infra-red thermometer technique overestimated daylight E_o by approximately 24%. The slope through origin and correlation coefficient were 1,24 and 0,92 respectively.

- The Penman-Monteith estimates compared excellently with measured E_o. Comparisons yielded a slope through the origin of 0,96 and a correlation coefficient of 0,94.

- The energy budget equation/eddy correlation sensible heat method overestimated daylight E_o by 8%. The slope through the origin and correlation coefficient was 0,92 and 0,52 respectively. Eddy correlation measurements were made at a height of 2 m above grass level. Corresponding values for hourly measurements made at 0,25 m above grass level were 0,84 and 0,87 respectively.

- Direct eddy correlation determinations of E_o made at 2 m height yielded a slope through the origin and correlation coefficient of 0,51 and 0,75 respectively for the daylight period. Hourly comparisons at a height of 0,25 m above grass level yielded values of 1,08 and 0,79 respectively for these same statistical parameters.

Measurement of atmospheric evaporative demand (AED)

AED for the maize crop, was determined using the energy budget/eddy correlation sensible heat technique. When compared to lysimeter measurements this technique yielded a slope through the origin and correlation coefficient of 0,76 and 0,83 respectively on 317 hourly values. Corresponding values obtained using the direct eddy correlation method were 1,10 and 0,75 respectively.

Based upon these results, it was decided to rely upon weather data and the Penman-Monteith equation and both the 10 m^2 lysimeter and the energy budget/eddy correlation sensible heat methods when determining crop evaporation coefficients for maize. The Penman-Monteith equation and the 10 m^2 lysimeter planted to potatoes were used when determining crop evaporation coefficients in the case of potatoes. For both crops, the mentioned methods had proved to be acceptably accurate.

Micro-meteorological determination of the climatic dependence of upper limit vegetation evaporation coefficients.

The theory developed stipulates that the climatic dependence of crop evaporation coefficients manifests itself in the variation in the upper limit vegetation evaporation coefficient, k_{vo}. For this reason, multiple regression analysis was used to develop relationships between hourly or daytime means of k_{vo}, and hourly or daylight means of the weather elements. The regressions yielded high coefficients of determination of 0,87 for both mature potato and maize crops. During early growth stages, for canopies with incomplete vegetative cover, the coefficients of determination were 0,99 and 0,74 for potato and maize respectively. These high r^2-values however, are to a large extent due to the rapid increase with time in F_v, the fractional radiation interception. The resultant regression expression for k_{vo} in terms of climate for incomplete vegetation cover, must thus at this stage be deemed to be preliminary.

For the hourly multiple regression analysis the corresponding r^2-values were 0,39 and 0,21 for potato for early and late season respectively. Values for maize were 0,29 and 0,46 respectively.

Macro-meteorological determination (automatic weather station) of the influence of climate on upper limit vegetation evaporation coefficients.

Macro-scale weather was measured using an automatic weather station. The elements measured included solar radiation flux density, air temperature, wind speed and water vapour. Multiple regression analysis of k_{vo} on values of macro-daytime mean values of the weather elements yielded coefficients of determination of 0,73 and 0,70 for mature potato and maize respectively. Coefficients of determination, when k_{vo} for early growth stages was related to mean daylight weather elements were 0,94 and 0,82 for potatoes and maize respectively.

The resulting two equations, which should be used for computing k_{vo} for late season (i.e. mature crops) are:

For potato

$$k_{vo} = 1,0598 - 0,0007\ S_t + 0,0156\ T_a - 0,0054\ u_z + 0,1714\ e \tag{5}$$

and for maize

$$k_{vo} = 0,4767 + 0,0001\ S_t + 0,0134\ T_a - 0,0427\ u_z + 0,3831\ e \tag{6}$$

In Eqs. 5 and 6 S_t, T_a, u_z and e denote daytime mean radiation flux density, air temperature, wind speed and water vapour pressure respectively.

The k_{vo}-functions developed for both potato and maize during early growth stages differ from these and are artefacts of the expressions used to account for fractional radiation interception, F_v. It is nevertheless suggested that Eqs. 5 and 6 should also be used to calculate k_{vo} during the crop establishment stage.

Values of evaporation coefficients for potato and maize crops for different localities in the RSA.

Monthly mean k_{vo}-values for an established potato crop were computed for different localities (i.e. climates) in the RSA. They vary between 1,51 and 1,01 and are presented in tabular form. The corresponding range for a maize crop was found to be 1,56 and 0,89.

The simple set of tables included in the final report make possible easy application of the results in practice.

CONCLUSIONS

The three major conclusions addressing the stated objectives of the work are:

- The climatic dependence of evaporation coefficients was demonstrated. It manifested itself primarily in the upper limit vegetation evaporation coefficient, k_{vo}.

- This climatic dependence was formulated using a multiple regression equation from which values for different climatic regions have been tabulated.

- While limited available time and equipment prevented a rigid practical verification of the results, the goodness of fit of the regression equations developed, emphasizes the accuracy of the technique.

Additional results obtained from the work worthy of note include:

- The Penman-Monteith equation proved reliable for estimating E_o. It can be used with confidence to calculate upper limit vegetation evaporation coefficients on hourly or daytime basis.

- The energy budget/eddy correlation sensible heat method, is reasonably reliable for determining atmospheric evaporative demand and upper limit vegetation evaporation coefficients in maize.

- The k_{vo}-values developed for both potato and maize during crop establishment stages here, are artefacts of the expressions used to account for the fractional interception of radiation by the vegetation cover. As such, they may only be applied provided the same F_v expressions, as here developed, are used. In the interim, k_{vo} for the mature period, calculated from Eqs. 5 and 6 should be used for the entire growing season, including the early development stage.

RECOMMENDATIONS FOR FUTURE RESEARCH

The climatic dependence of vegetation evaporation coefficients has been demonstrated in this study particularly for maize and potato crops offering complete vegetation cover. The major wastage of water in crop production, however, occurs as a result of the evaporation of water through the soil surface from sparse vegetation canopies. There thus remains an urgent need to produce accurate sub-models for vegetation and soil evaporation from sparse canopies and determine their climatic dependence.

Uncertainties in the values of vegetation evaporation coefficients developed for both potato and maize during the developing stages of these crops became apparent from this study. These uncertainties are artefacts of the expressions used to account for the fractional radiation interception of the vegetation cover ,F_v. Validation of the mathematical expression for F_v for row crops is required.

The measurement of sensible heat obtained from sonic anemometer and fine-wire-thermocouple and observations of turbulent fluctuations in atmospheric water vapour content are indispensable in this type of work. Possibly the most important factor affecting the accuracy of these measurements is the height of exposure of these instruments. This aspect deserves to be finalised.

A useful future study would be comparison of the values of evaporation coefficients derived using the methods here proposed against actual measured values in different climates. This represents extensive experimention spread over the entire country. The results however would be most beneficial. It is suggested that the necessary field measurements be accumulated from other on-going projects.

The degree of architectural similarity of different plant types needs to be determined. This will greatly extend the potential for the practical application of the theory and results here obtained. The climatic dependence factor, ν will have to be evaluated for each group of architecturally similar plants. The methods here developed may be used for this.

Technological transfer of results

All persons, or instances, interested in managing agricultural water use need to be encouraged to use climate corrected evaporation coefficients. Evaporation coefficients relevent to the full cover stages of potato and maize can now be computed using the mathematical relationships, here derived, or extracted from the tables produced. From these, crop water requirements may rapidly be calculated from automatic weather station data. For other crops, architecturally similar to potato or maize, the same relationships here developed could be used as a first approximation.

Furthermore, the equations here developed can easily be incorporated into crop growth models used for irrigation scheduling.

Monthly mean upper limit vegetation evaporation coefficients have been developed for potato and maize for eighteen localities throughout South Africa. These can now be applied when estimating atmospheric evaporative demand, given estimates of reference crop evaporation. This new development needs to be brought to the attention of all irrigators.

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LIST OF SYMBOLS

A	Advected heat flux density (W m^{-2})
AED	Atmospheric evaporative demand (mm)
C	Sensible heat flux density (W m^{-2})
C_p	Specific heat of air (J kg^{-1} $°C^{-1}$)
D	Number of days elapsed since the last immediate wetting event in excess of 10 mm
d	Zero displacement level (m)
dl	Daylight
E	Total crop evaporation (mm)
$\overline{e}$	Long term monthly mean daylight water vapour pressure (kPa)
e'	Water vapour density fluctuation (kg m^{-3})
e	Water vapour pressure (Pa)
e°	Monthly mean saturated water vapour pressure (kPa)
e_8	Monthly mean water vapour pressure at 08:00 (kPa)
e°_8	Monthly mean saturated water vapour pressure at 08:00 (kPa)
e_{14}	Monthly mean water vapour pressure at 14:00 (kPa)
e°_{14}	Monthly mean saturated water vapour pressure at 14:00 (kPa)
EB_B	Energy budget and Bowen ratio technique
EB_C	Energy budget and eddy correlation technique
EC	Eddy correlation
EB_{IRT}	Energy budget and infra-red thermometer technique
e_o	Water vapour pressure determined above grass (W m^{-2})
E_o	Reference crop evaporation (mm)
E_s	Soil surface evaporation (mm)
E_{so}	Upper limit soil evaporation (mm)

E_v	Vegetation evaporation (mm)
E_{vo}	Upper limit vegetation evaporation (mm)
F	Width of inter-row sunlit ground surface measured at noon (m)
F_g	Normalized factor reflecting the degree of soil surface wetness
F_h	Normalized factor reflecting physiological limitation due to plant water stress
F_v	The fractional interception defined as the fraction of incoming solar radiant flux density intercepted by the vegetated cover
G	Soil heat flux density (W m^{-2})
h	Height of reference crop (m)
H	Energy available to evaporate water (W m^{-2})
k	Von Karman's constant (= 0,41)
k_c	Evaporative coefficient
k_{so}	Upper limit soil evaporation coefficient
k_v	Vegetation evaporation coefficient (mm)
k_{vo}	Upper limit vegetation evaporation coefficient
k_{voh}	Hourly upper limit vegetation evaporation coefficient
k_{vod}	Daylight upper limit vegetation evaporation coefficient
L	Latent heat of evaporation (J kg^{-1})
LAI	Leaf area index
p	Atmoshperic pressure (Pa)
R_a	Monthly mean extraterrestrial solar radiation (W m^{-2})
r_a	Bulk aerodynamic resistance (s m^{-1})
r_c	Canopy surface resistance (s m^{-1})
r_c	Resistance to heat transfer (s m^{-1})
r_e	Resistance to water vapour transfer (s m^{-1})
RMSE	Root mean square error

R_n	Net radiation (W m^{-2})
R_{no}	Net radiation measured above grass (W m^{-2})
R_s	Monthly mean hourly total radiation (W m^{-2})
r_{ST}	Stomatal resistance (s m^{-1})
RW	Row width (m)
s	Slope of the saturated water vapour pressure temperature curve (Pa $°C^{-1}$)
T'	Vertical temperature fluctuation (°C)
$\overline{T}_a$	Monthly mean daylight temperature (°C)
T_a	Ambient air temperature (°C)
$\overline{T}_{max}$	Monthly mean daily maximum temperature (°C)
$\overline{T}_{min}$	Monthly mean daily minimum temperature (°C)
T_o	Ambient temperature measured above grass (W m^{-2})
T_s	Grass canopy surface temperature (°C)
$\overline{u2}$	Monthly mean bi-hourly wind speed (m s^{-1})
$\overline{u}_z$	Monthly mean daylight wind speed (m s^{-1})
u_z	Wind speed measured at height z (m s^{-1})
u_{zo}	Wind speed measured above grass (W m^{-2})
W'	Vertical wind speed fluctuation (m s^{-1})
x	Distance of the measuring point downwind from the edge of the area, covered by a uniform reference crop
z	Height of anemometer above ground surface in the short grass covered area (m)
z_o	Roughness parameter (m)
z_{om}	Roughness parameter for momentum exchange (m)
z_{ov}	Roughness parameter for water vapour pressure exchange (m)
z_p	Height at which water vapour pressure was measured (m)
z_w	Height at which wind speed was measured (m)
β	Bowen ratio

ρ	Density of moist air (kg m^{-3})
ϕa	Aerodynamic conductance (m s^{-1})
γ^*	γ (1 + $\phi a/\phi c$)
γ	Psychrometric constant (= 0,066 kPa $°C^{-1}$)
ϕc	Canopy surface conductance (m s^{-1})
δe	Water vapour pressure deficit (kPa)
$\delta(x)$	Thickness of the equilibrium boundary layer
ν	Climatic adjustment factor
ϕST	Stomatal conductance (m s^{-1})
μ	Monthly mean proportion of hourly possible sunshine

CHAPTER 1

1. INTRODUCTION

1.1 RATIONALE FOR THE STUDY

Atmospheric evaporative demand ,AED, is defined as the upper limit of evaporation from a natural vegetative surface of which the water content of the soil surface layer is at its current value. It is evaluated as the product of evaporation coefficient ,k_c, and reference crop evaporation, E_o, and is invaluable for estimating upper limit total crop evaporation from which the daily soil water content from cropped lands may be computed. This approach is used extensively in models in the PUTU-system of crop growth models. The accuracy of estimated AED in this manner however, depends entirely upon the reliability of the evaporation coefficient k_c and the accuracy with which reference crop evaporation E_o is calculated or measured.

While E_o may be accurately estimated from the Penman-Monteith equation (PME), some uncertainty in the magnitude and climatic dependence of the evaporation coefficients exists. Study of these matters will form the major thrust of this report.

Inaccuracies in evaporation coefficient values, their climatic dependence and seasonal variation could, for example, cause insufficient, or over-irrigation with detrimental financial implications, not only to individual farmers, but for the country in general.

1.2 OBJECTIVES

The objectives of this study were to

- evaluate hourly evaporation coefficients for the daylight period;
- investigate their behaviour throughout the growing season;
- relate the evaporation coefficients to the weather elements, solar radiation, ambient temperature, wind speed and water vapour pressure, and
- determine evaporation coefficients for different localities throughout the RSA for potato and maize crops.

1.3 ATMOSPHERIC EVAPORATIVE DEMAND AND EVAPORATION COEFFICIENT CONCEPTS

1.3.1 General

The work of this project primarily involves investigation of atmospheric evaporative demand and evaporation coefficients. The definitions of these concepts are appropriate at this stage.

Accurate prediction of crop-water utilization is of utmost importance during irrigation scheduling. One way of achieving this, is to calculate actual atmospheric evaporative demand, AED, using reliable evaporation coefficients and evaporation from a reference crop. AED is defined (De Jager and Van Zyl, 1989) 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 evaporation from the vegetation and the water status of the top 150 mm of soil equals its current value.

The evaporation coefficient concept defines total crop evaporation as follows *viz.*

$$E = k_c E_o \qquad 1.1$$

where

k_c = crop evaporation coefficient, and

E_o is evaporation from a reference crop, defined as the rate of total evaporation from an extended surface of 80 mm to 150 mm tall vegetative cover of uniform height, actively growing, completely shading the ground and not deficient in water or nutrients (Doorenbos and Pruitt, 1977).

The relevant equation for calculating AED, for the special case of no water stress,

$$AED = k_c E_o \qquad 1.2$$

Now (see De Jager and Van Zyl, 1989)

$$E = E_v + E_s \qquad 1.3$$

with $E_v = k_v E_o$ 1.4

and $E_s = k_s E_o$ 1.5

From Eq. 1.1, the crop evaporation coefficient ,k_c, may be expressed mathematically as

$$k_c = k_v + k_s \qquad 1.6$$

or,

$$k_c = k_{vo} F_v F_h + k_{so} F_g (1 - F_v) \qquad 1.7$$

where, for the special case of no water stress (F_h = 1)

$$k_c = k_{vo} F_v + k_{so} F_g (1 - F_v) \qquad 1.8$$

(De Jager and Van Zyl, 1989)

In Eqs. 1.6 and 1.8 the vegetation, soil, upper limit vegetation and upper limit soil, evaporation coefficients, k_v, k_s, k_{vo}, and k_{so} respectively, are defined by

$$k_v = E_v/E_o \qquad 1.9$$

$$k_s = E_s/E_o \qquad 1.10$$

$$k_{vo} = E_{vo}/E_o \qquad 1.11$$

$$k_{so} = E_{so}/E_o \qquad 1.12$$

Here

E_{vo}, E_{so}, E_v and E_s represent upper limit vegetation, upper limit soil, total crop and total soil evaporation rate respectively. F_v is a normalized factor reflecting the degree of foliage cover of the ground surface. F_g is a normalized factor reflecting the degree of soil surface wetness. F_h is a normalized factor reflecting physiological limitation on plant evaporation due to plant water stress. For consistency, the symbol ,F_v, here replaces the original 'F_1' suggested by De Jager and Van Zyl (1989).

Several expressions for F_v and F_g appear in the literature (Ritchie, 1972; Hanks and Hill, 1980; De Jager, et al, 1982; Monteith, 1981 and Wright, 1981). One such expression for F_g (De Jager et al., 1982) is:

$$F_g = e^{-0,4D} \qquad 1.13$$

where,

D is the number of days elapsed since the immediate previous wetting event in excess of 10 mm.

A major objective of the work was the evaluation of k_{vo} and its dependence upon climate. The expression for k_{vo} with which this was accomplished follows from Eq. 1.8 which may be rewritten as

$$k_{vo} = \{ k_c - k_{so} F_g (1 - F_v) \} / F_v \qquad 1.14$$

or,

$$k_{vo} = \{ \frac{AED}{E_o} - k_{so} F_g (1 - F_v) \} / F_v \qquad 1.15$$

since from Eq. 1.2 k_c would be given by

$$k_c = AED/E_o \qquad 1.16$$

Following De Jager (1993), the fractional interception, F_v, may be defined as the fraction of incoming solar radiant flux density intercepted by the vegetative cover.

Thus, Eq. 1.15 may be used to determine k_{vo} for an incomplete vegetative cover with a partially wet soil surface by making certain assumptions regarding F_g and F_v and measuring, or calculating AED and E_o. The latter could be measured in lysimeters. Alternatively AED and E_o can be estimated from reliable micro-meteorological measurements.

Pruitt and Doorenbos (1977), Doorenbos and Kassam (1979), Jagtap and Jones (1989) and Stanghellini, et al. (1990) showed that evaporation coefficients are affected by climate. For example, Jagtap and Jones (1989) found that errors in estimated AED could be as high as a total of 190 mm over the entire growing season when evaporation coefficients developed under one set of conditions were used under different climatic conditions.

1.3.2 Factors influencing the measurement of E_o

Great care needs to be taken when measuring E_o. Factors influencing E_o have been documented from various sources (Jensen, et al. 1990). Amongst others, these are:

1. E_o from grassed surfaces differ to that from lucerne for example.
2. The consequences of cutting are a difficulty in all crops, but are most pronounced in grasses (use two or more lysimeters and stagger cutting).
3. Water consumption of all reference crops changes with plant height.
4. Varietal differences (in lucerne in particular) in water consumption have not been fully documented.
5. Large differences of peak period E_o may exist between warm- and cool-season grass types. Cool-season grasses have a lower degree of stomatal control with corresponding high E_o than do warm-season grasses.
6. Grass height must be between 8 cm - 15 cm and at least 8 cm tall.
7. Beard (1985) ranked grass types relative to potential E_o.
8. Beard (1985) analysed the effects of leaf/shoot ratios, greater horizontal leaf orientation, short clipping height, more uniform and dense stands. These effects are associated with reduced leaf area (increased canopy resistance) and lower surface roughness (increased aerodynamic resistance).
9. Average lucerne E_o to grass ratios varying between 1,28 and 1,15 have been reported. In dry areas, values of 1,37 have been reported and 1,63 for calm, humid conditions.

Advantages include the facts that E_o:

(a) offers workers with a mental representation of the evaporation process,

(b) expedites selection of consistent crop coefficients in new areas,

(c) simplifies calibration of reference equations in new areas,

(d) removes confusion regarding the base of crop coefficients reported in the literature when the reference crop is specified,

(e) makes relevant the use of wide range of measured grass to E_o ratios reported in work from around the world (Marsh et al. 1980; Hargreaves and Samani, 1982; Beard, 1985; Snyder and Pruitt, 1985; Snyder et al. 1987a; Snyder et al. 1987b).

1.4 OBJECTIVE OF THE STUDY

The overall objective of this study was to verify the findings of Pruitt and Doorenbos (1977), Doorenbos and Kassam (1979), Jagtap and Jones (1989) and Stanghellini, et al. (1990) that evaporation coefficients are affected by climate, and to describe mathematically the influence of different weather variables such as radiation, ambient air temperature, wind speed and water vapour pressure on the evaporation coefficients for the potato and maize crop.

1.5 OUTLINE OF THE STUDY PROGRAMME

The different phases of the work endeavoured to:

- Explain the concepts of upper limit vegetation evaporation and vegetation evaporation coefficient (see chapter 2).

- Evaluate the accuracy of five micro-meteorological techniques for estimating E_o.
  These include the energy budget equation and Bowen ratio (EB_B); Penman-Monteith equation (PME); the energy budget equation and infrared thermometry (EB_{IRT}); the energy budget equation and sensible heat obtained from eddy correlation measurements (EB_C) and direct eddy correlation measurements of water vapour (EC) (see Chapter 3).

- Measure AED for the maize crop using EB_C and EC (see Chapter 4).

- Develop mathematical relationships describing the influence of the weather variables, net radiation, ambient temperature, wind speed and water vapour pressure on upper limit vegetation evaporation coeficients for the potato and maize crops respectively using micro-meteorological measurements (see chapters 5 and 6).

- Develop mathematical relationships between vegetation evaporation coefficients and mean daylight climate, measured by an automatic weather station (AWS), for the potato and maize crop (see Chapters 7 and 8).

- Develop values of evaporation coefficients for the potato and maize crops for use in different localities in the RSA (see Chapter 9).

- Summarize most siginficant findings of the investigation (see Chapter 10).

CHAPTER 2

2. THE NATURE OF THE VEGETATION EVAPORATION COEFFICIENTS k_{vo} AND k_v

2.1 INTRODUCTION

A detailed definition and discussion of the upper limit vegetation evaporation coefficient, k_{vo}, and the vegetation evaporation coefficient, k_v, and their interdependence are presented in De Jager and Van Zyl (1989) and De Jager (1993). Because of their immediate importance in the present study a brief analysis of these concepts, their interrelation and variation with plant growth stage will now be given.

According to Eq. 1.7 and the definitions of the terms F_v, F_h and F_g it is evident that the only aspects of the crop evaporation coefficient which can be influenced by climate are the upper limit vegetation (k_{vo}) and soil evaporation (k_{so}) coefficients. The latter plays a minor role and will be assumed to be equal to unity. Hence this entire study considers the determination of k_{vo} and how it is affected by climate.

2.2 DEFINITIONS

De Jager and Van Zyl (1989) defined the vegetation evaporation coefficient, k_v, as

$$k_v = E_v/E_o \qquad 2.1$$

where

E_v = vegetation evaporation rate

E_o = reference crop evaporation rate

The upper limit vegetation and soil evaporation coefficients are given in Eq. 1.11 and 1.12 respectively.

Now, since

$$E = E_v + E_s \qquad 2.2$$

$$E_v = E - E_s \qquad 2.3$$

where

E = total crop evaporation rate, and

E_s = soil surface evaporation rate.

For zero vegetation water stress $F_h = 1$, which means that AED = E and hence from Eq. 2.3

$$E_v = AED - E_s \qquad 2.4$$

$$k_v = (AED - E_s)/E_o \qquad 2.5$$

and from Eq. 1.4

$$k_{vo} = (AED - E_s)/E_o\ F_v \qquad 2.6$$

Now given E_o and AED, application of Eq. 2.5 or 2.6 requires evaluation of Es and Fv

Evaluation of E_s

Substitution of the second term in Eq. 1.7,in Eq. 1.5 yields

$$E_s = k_{so}\ F_g\ (1 - F_v)\ E_o \qquad 2.7$$

which is equivalent to

$$E_s = k_s\ E_o \qquad 2.8$$

which yields the expression

$$k_s = k_{so}\ F_g\ (1 - F_v) \qquad 2.9$$

which may be evaluated assuming k_{so} = 1 and using an empirical expression for F_g, *viz.*

$$F_g = e^{-0,4D} \qquad 2.10$$

(De Jager, et al. 1982)

Evaluation of F_v

A necessary concept for determining the effect of crop radiation upon k_v is F_v, defined as the fraction of incoming solar radiant flux density intercepted by the vegetative cover (De Jager, 1993). It is termed the fractional interception.

From Ritchie (1983) and Campbell (1977), fractional interception may be approximated by

$$F_v = 1 - e^{-0,7LAI} \qquad 2.11$$

Empirical values adopted

The nature of k_{vo} and k_v depend greatly upon the values of the exponents in Eqs. 2.10 and 2.11 and some assumption regarding k_{so} (e.g. $k_{so} = 1$). In a preliminary experiment De Jager et al. (1982) showed that the exponent in Eq. 2.10 equals 0,4 d^{-1}. Should F_v be considered to be proportional to relative vegetation evaporation rate (E_v/E_o) then the work of Ritchie (1983) would suggest exponents in Eq. 2.11 of 0,9 for a dry soil surface and 0,4 for a wet soil surface. In this study an intermediate value 0,7 was chosen in Eq. 2.11.

2.3 PRACTICAL PROCEDURES FOR EVALUATING k_{vo} AND k_v

Uncertainties in the assumptions regarding $k_{so} = 1$ and the nature of F_g could however be eliminated when evaluating k_v by considering two special cases, *viz.* either a mature crop or a dry soil surface. In both cases E_s would equal zero in Eqs. 2.5 and 2.6, thereby simplifying procedures considerably.

Assuming k_{so} = 1 and substituting k_c E_o for AED in Eq. 1.15 and also Eqs. 2.7, 2.10 and 2.11 for E_s, F_g and F_v respectively in Eq. 2.6, yield

$$k_{vo} = (k_c E_o - e^{-0,4D} e^{-0,7LAI} E_o)/(1 - e^{-0,7LAI}) E_o$$
$$= (k_c - e^{-(0,4D + 0,7LAI)})/(1 - e^{-0,7LAI}) \qquad 2.12$$

Similar substitutions yield

$$k_v = (k_c - e^{-0,4D + 0,7LAI}) \qquad 2.13$$

Special cases of Eq. 2.12 and 2.13 include, firstly a newly wetted surface (i.e. D = 0) for which

$$k_{vo} = (k_c - e^{-0,7LAI})/(1 - e^{-0,7LAI}) \qquad 2.14$$

and $$k_v = (k_c - e^{-0,7LAI}) \qquad 2.15$$

Eqs. 2.14 and 2.15 are only valid for the definitions of F_g and F_v given in Eqs. 2.10 and 2.11, respectively.

Secondly, for a mature crop, completely covering the soil surface (usually LAI > 3), the following is true, *viz.*

F_v > 0,94 and

$$k_{vo} \approx k_v \approx k_c \qquad 2.16$$

Thirdly, for a dry soil surface, D = ∞ and $E_s = k_s = F_g = 0$

Now from Eq. 2.5 and 2.6

$$k_v = AED/E_o \qquad 2.17$$

and $$k_{vo} = AED/F_v E_o \qquad 2.18$$

from which k_v, or k_{vo}, could be estimated given some information regarding F_v.

Any of Eqs. 2.6 and the special cases 2.12 and 2.14 and 2.16 can be used to calculate k_{vo}. Similarly k_v can be calculated from either Eqs. 2.5, or 2.13, or 2.15.

2.4 NATURE OF k_{vo}

Discussion of the factors influencing kvo are illuminating. De Jager (1993) suggests that k_{vo} may be considered for growing conditions reflecting either no water stress, or for conditions exhibiting water stress.

Assuming non-water stressed conditions, potential vegetation evaporation, E_{vo}, may be assumed to

(i) be directly proportional to the fraction of incoming solar radiant-flux density intercepted by the crop, F_v, and also

(ii) bear a strict relationship to E_o, the reference evaporation. Said relationship is quantified by k_{vo}, the upper limit vegetation evaporation coefficient.

These assumptions may be defined mathematically by $E_{vo} = F_v\ k_{vo}\ E_o$ where, k_{vo} is defined as the ratio of potential vegetation evaporation rate to the reference crop evaporation rate under identical atmospheric conditions. It is an empirical coefficient reflecting the interaction between climate and crop morphology and physiology at the given crop growth stage.
Radiation fractional interception may be obtained in one of three ways, viz.

- simulation using $F_v = 1 - e^{-0.7LAI}$

- measuring the sun fleck area per unit ground surface
- setting F_v equal to the visually estimated vertical projection of vegetation cover per unit of ground surface area.

The third of these approximation methods represents an approach similar to the methods of estimating the crop evaporative coefficient adopted by Abbaspour, Hall, and Moon, (1992) and Smith (1970) for example. Abbaspour *et al.*,(1992) used this method in a modelling exercise and the Smith (1989) work is aimed at practical irrigation scheduling. In South Africa, irrigation managers (see Mottram and de Jager, 1993) follow the third of the mentioned techniques with success.

An interesting experiment endeavouring to examine the seasonal variation in k_{vo} and k_v, but with the influence of climate having been removed from k_{vo} was conducted. This entailed assuming that for given E_o the influence of climate upon k_c is the same for all growth stages. Values of k_{vo} and k_v corresponding to the given climate (E_o), were then computed for different growth stages from reported data.

From a previous study on wheat (Van Zyl, De Jager and Maree, 1989) thirteen data sets corresponding to nearly constant values of E_o were selected. The latter was calculated from the PME. Concomitant values of AED measured lysimetrically, measured values of LAI and recorded dates of wetting events were then used to calculate k_v and k_{vo}. To obtain these hypothetical results some assumption regarding the nature of F_v was required. Two case studies were undertaken, viz.

$$F_v = (1 - e^{-0.7LAI}) \qquad 2.19$$

and

$$F_v = 1/[1 + e^{2(1,8 - LAI)}] \qquad 2.20$$

The exponential function ,Eq. 2.19, follows the suggestion of De Jager et al. (1989). The logistic function Eq. 2.20 is one reported in Chapter 5 where it was determined from examining particular sets of conditions meeting the caveats expressed by Eq. 2.18 (dry soil surface). Values of F_v so estimated were then compared with LAI to obtain Eq. 2.20.

The seasonal variation in k_{vo} and k_v so obtained are illustrated in Fig. 2.1 and Fig. 2.2 which show the variation of k_{vo} and k_v for presumable constant weather conditions (here constant E_o) throughout the wheat growing season as calculated from the thirteen data sets.

The values of k_{vo} during the early growth stages, i.e. at low LAI, are markedly higher than unity and k_v, than is the case later in the season. This is possibly attributable to the fact that the radiative energy and aerodynamic water vapour exchange due to wind speed and water vapour pressure are significantly higher for sparse compared to dense (i.e. when $F_v > 0,94$) vegetation.

Figs. 2.1 and 2.2 illustrate that k_{vo} calculated from Eq. 2.6 is an artefact of the expression used for F_v. This has four important consequences:

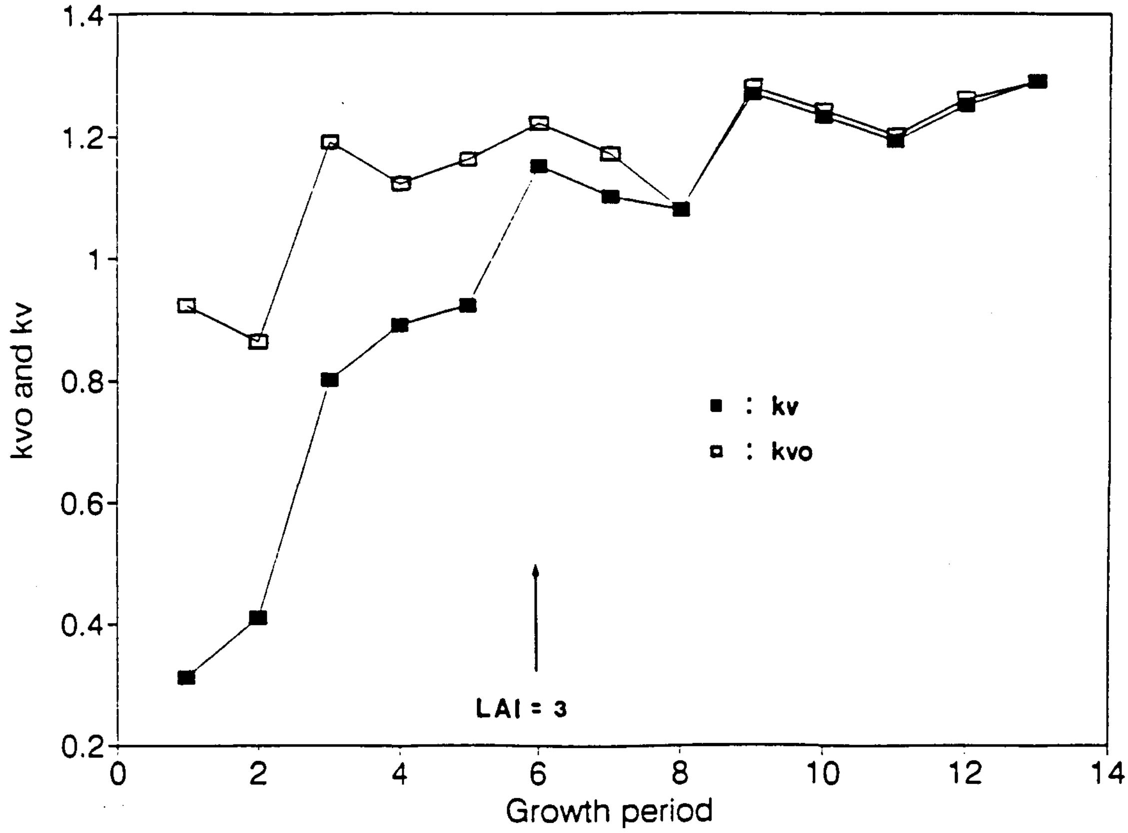


FIG. 2.1 Variation of k_{vo} and k_v with growth stage of wheat under virtually constant climatic conditions. Eqs. 2.17, 2.18 and 2.19 were used to calculate k_{vo} and k_v.

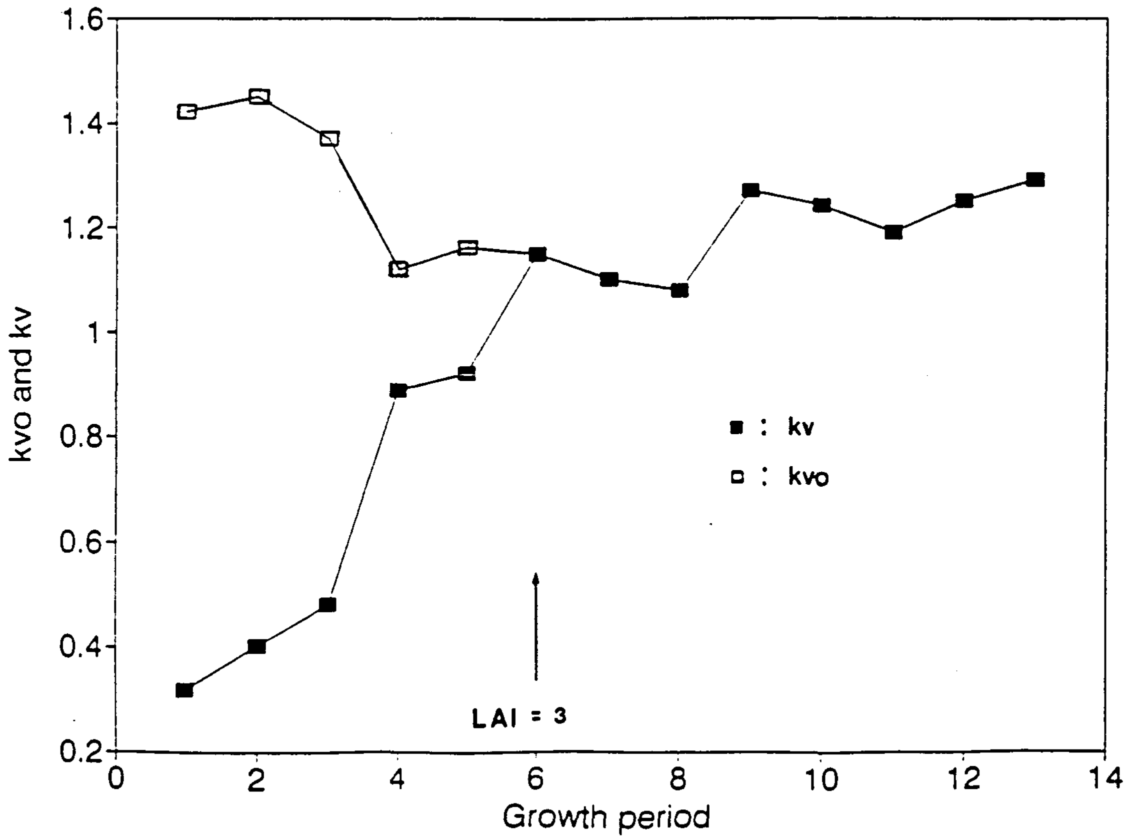


FIG. 2.2 Variation of k_{vo} and k_v with growth stage of wheat under virtually constant climatic conditions. Eqs. 2.17, 2.18 and 2.20 were used to calculate k_{vo} and k_v.

(i) The accuracy of the k_{vo} so determined depends acutely upon the reliability of the expression used for F_v.

(ii) Values of k_{vo} applied in practice must have been obtained using the same expression for F_v as for which they were originally determined.

(iii) Application of this theory to quantifying the influence of climate upon crop evaporation coefficients is based upon the assumption that, although the absolute value of k_{vo}, which is a function of F_v, may be incorrect, any variation in its value due to changing climate will produce a proportional change in any vegetation evaporation coefficient, irrespective of the definition of F_v.

(iv) The reservations expressed in (i), (ii) and (iii) only apply in the early growth stages, or when incomplete vegetative cover prevails.

Study of the influence of sparse canopies upon evaporation coefficients is planned for a follow-up project.

CHAPTER 3

3. ACCURACY OF MICRO-METEOROLOGICAL TECHNIQUES FOR ESTIMATING REFERENCE CROP EVAPORATION

3.1 INTRODUCTION

As was already mentioned in Chapter 1, accurate estimates of E_o are a prerequisite for calculating k_{vo}. In this chapter, five micro-meteorological techniques will be investigated to estimate E_o.

Numerous climatological methods of estimating E_o 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 and 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 E_o are those derived directly from the surface energy budget equation ,EB, and the eddy correlation technique, EC.

Methods derived from the EB used in this study are:

- EB and Bowen ratio (Bowen, 1926) - EB_B
- EB and infrared thermometry, (Choudhury, et al., 1986) - EB_{IRT}
- Penman-Monteith equation, (Thom, 1975) - PME
- EB and sensible heat flux density, (Thom, 1975) - EB_C

Sensible heat exchange at the surface ,C, can be obtained from eddy correlation measurements.

In most applications E_o is measured in a lysimeter. Unfortunately, this usually takes place within relatively small grass covered areas. The problem therefore arises, especially in arid and semi-arid regions, how does advected energy influence the micro-meterological methods in such situations of limited fetch. This is investigated in this chapter.

With a view of establishing the reliability of the evaporation coefficients determined later in the study, the specific objectives of Chapter 3 were to:

(i) determine the accuracy of E_o estimates by comparing values obtained using the EB_B, EB_{IRT}, EB_C, PME, and EC methods against lysimeter observations, and

(ii) determine the magnitude of advected heat flux density during 1990 using EB_B and lysimeter observations.

3.2 GENERAL

3.2.1 Method

The purpose of the work was to investigate the influence of advection upon micro-meteorological estimates of E_o obtained under limited fetch conditions. The latter were realised by making all measurements in the centre of an area covered by short-grass, which was approximately 80 m x 80 m in size (see Fig. 3.1). Four of the micro-meteorological techniques examined involved modifications of the energy balance equation.

These modifications involved introduction into the energy balance equation of:

(i) the Bowen ratio,

(ii) an estimate of sensible heat, utilizing the infrared thermometer, IRT,

(iii) energy and aerodynamic terms (a combination method) to produce what is known as the Penman-Monteith equation (PME),

(iv) an estimate of sensible heat flux, C, obtained from a sonic anemometer and fine-wire-thermocouple.

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. Direct measurements of E_o were made in a short-grass lysimeter.

The EB_{IRT} and PME methods exhibited little advective response, but all the eddy correlation techniques correlated poorly with measured E_o during 1990. Correlation coefficients of 0,62 and 0,51 (see Table 3.1) for EC and EB_C were obtained. Hence, these four techniques were not used to estimate advection. The EB_B method correlated well and responded to advection. Hence, this technique in the theory proposed by Lang (1973) was used to investigate advection.

3.3 THEORY

3.3.1 The energy budget equation

Following the derivation of Lang (1973) the energy budget for a grass surface is described by

$$H + C + A + LE_o = 0 \qquad 3.1$$

where $H = R_n + G$ 3.2

where R_n = net radiation ($W\ m^{-2}$)

G = soil heat flux density ($W\ m^{-2}$)

C = sensible heat flux density ($W\ m^{-2}$)

A = advected heat flux density ($W\ m^{-2}$).

L = latent heat of evaporation ($2,45 \times 10^{-6}\ J\ kg^{-1}$)

E_o = reference crop evaporation ($kg\ m^{-2}\ s^{-1}$)

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

The sign convention of Houghton (1985) was used in Eq. 3.1 viz. all incoming energy (including advection) was denoted positive and all outgoing energy negative.

Eq. 3.1 was modified in several ways enabling determination of LE_o using the different micro-meteorological techniques (see Eqs. 3.5, 3.8, 3.10, 3.11 and 3.12).

3.3.2 Determination of LEo using EBB

Eq. 3.1 can be rewritten (see also Lang, 1973) as

$$R_n + G + A = - C - LE_o \qquad 3.3$$

Dividing both sides of Eq. 3.3 by LE_o, resulted in

$$\frac{R_n + G + A}{LE_o} = - \left[\frac{C}{LE_o} + 1 \right] \qquad 3.4$$

Rearanging Eq. 3.4 gives

$$LE_o = -(Rn + G + A)/(\beta + 1) \qquad 3.5$$

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

Application of aerodynamic theory then yields

$$\beta = \frac{\rho C_p\ (Ta_1 - Ta_2)\ r_e}{L\ (e_1 - e_2)\ r_c} \quad \text{(Campbell, 1977)} \qquad 3.6$$

In Eq. 3.6

ρ = density of moist air (= 1,204 kg m^{-3} at 20°C and air pressure of 100 kPa)

C_p = specific heat of air (= 1010 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 subscribts 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. 3.6 may be rewritten as

$$\beta = \gamma \frac{\blacktriangle T}{\blacktriangle e} \text{ (dimensionless)} \qquad 3.7$$

where

γ = psychrometric constant (= $\frac{\rho C_p}{L}$ = 66 Pa $°C^{-1}$)

$\blacktriangle T_a = Ta_1 - Ta_2$ (°C)

and $\blacktriangle e = e_1 - e_2$ (Pa)

Thus, in this application, LE_o may be determined by substituting into Eq. 3.5 measurements of R_n, G, LE_o, together with T_a and e measured at two different heights.

3.3.3 Determination of LE_o using EB_{IRT}

LE_o may be obtained by substituting C, calculated from Eq. 3.8 into Eq. 3.1, where

$$C = \rho \, C_p \, \phi_a \, (T_s - T_a) \qquad 3.8$$

In Eq 3.8

ρ = density for moist air (kg m^{-3})

T_s = grass canopy surface temperature (°C), measured with the infrared thermometer

ϕ_a = aerodynamic conductance (m s^{-1})

$$= k^2 \, u_z/\{\ln(z - d)/z_o\}^2 \qquad 3.9$$

k = Von Karman's constant (0 = 0,41)

u_z = wind speed at measuring height z (m s^{-1})

d = 0,63 h, the zero displacement level (m)

z_o = 0,13 h, the roughness parameter (m)

z = height of anemometer above ground surface in the short grass covered area (= 1,00 m)

and h = height of reference crop (m)

3.3.4 Determination of LEo using PME

Utilization of Eq. 3.1 and 3.8 to estimate LE_o require measurement of canopy surface temperature, T_s. The latter is difficult to measure (Berliner, et al., 1984). Penman (1948) however, solved the problem by eliminating T_s. This, together with the introduction of crop canopy conductance (Monteith, 1964) and aerodynamic conductance terms (Thom, 1975) and assuming A = O, resulted in the Penman-Monteith equation, which expresses LE_o as

$$LE_o = \frac{sH}{s+\gamma^*} + \frac{\rho\, C_p\, \delta e\, \phi_a}{s + \gamma^*} \qquad 3.10$$

where,

H = available energy to evaporate water (W m^{-2})

s = slope of the saturated water vapour pressure temperature curve (Pa °C^{-1})

γ^* = $\gamma\ (1 + \phi_a/\phi_c)$

ϕ_a = aerodynamic conductance $(={}^1/r_a)$(m s^{-1})

r_a = bulk aerodynamic resistance (s m^{-1})

ϕ_c = canopy surface conductance $(={}^1/r_c)$(m s^{-1})

ϕ_c = 0,03 m s^{-1} (from Russel, 1980)

r_c = canopy surface resistance (s m^{-1})

δe = water vapour pressure deficit (Pa)

The aerodynamic resistance was determined in this chapter using the logarithmic wind profile without correction for atmospheric stability as described by Thom (1975)(see Eq. 3.9).

3.3.5 Determination of LE_o using EBC

The sensible heat term in Eq. 3.1 can also be obtained from sonic anemometer and fine wire thermocouple observations, using

$$C = \rho\, C_p\, \overline{W'T'} \qquad 3.11$$

where

W' = vertical wind speed fluctuation (m s^{-1})

and T' = vertical temperature fluctuation (°C)

3.3.6 Determination of LE_o using EC

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

$$LE_o = L\ \overline{W'e'} \qquad 3.12$$

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

3.4 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

$$\delta(\chi) = 0,1\ x^{0,8}\ z_o^{0,2} \qquad 3.13$$

In Eq. 3.13

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. 3.1).

The thickness of the equilibrium boundary layer for the minimum short-grass fetch for the present experiment of x = 40 m (see Fig.3.1), was, according to Eq. 3.13, equal to 0,60 m. It is therefore evident that measurements made above 0,60 m, were outside the regime wherein the logarithmic wind profile prevailed and atmospheric conditions are determined by the surface conditions.

When micro-meteorological measurements are made at the surface (grass covered lysimeter in this case), or within the equilibrium boundary layer A in Eq. 3.1 equals zero. Lysimeter observations are thus unaffected by advection. When micro-meteorological measurements are made outside this boundary layer, A in Eq. 3.1 cannot be ignored.

3.5 EXPERIMENTAL SITE

The study was carried out on a 0,64 ha square grass site (see Fig. 3.1) during the spring (beginning September till end of November 1990) and summer (beginning January till end of March 1992) on the West Campus of the University of the Orange Free State situated at latitude 26°15' S and longitude 29°6' W.

Reference evaporation, E_o, was measured on the grass site, labelled GS in Fig. 3.1, utilizing a weighing lysimeter. This has 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. 3.1). The entire grass site (GS) was irrigated frequently throughout the growing season so as to prevent moisture stress. This ensured that evaporation proceeded at its upper limit for whatever atmospheric conditions existed throughout the experiment.

The area surrounding the site consisted of dry grassland (DG) extending infinitely as indicated in Fig.3.1, and a section planted

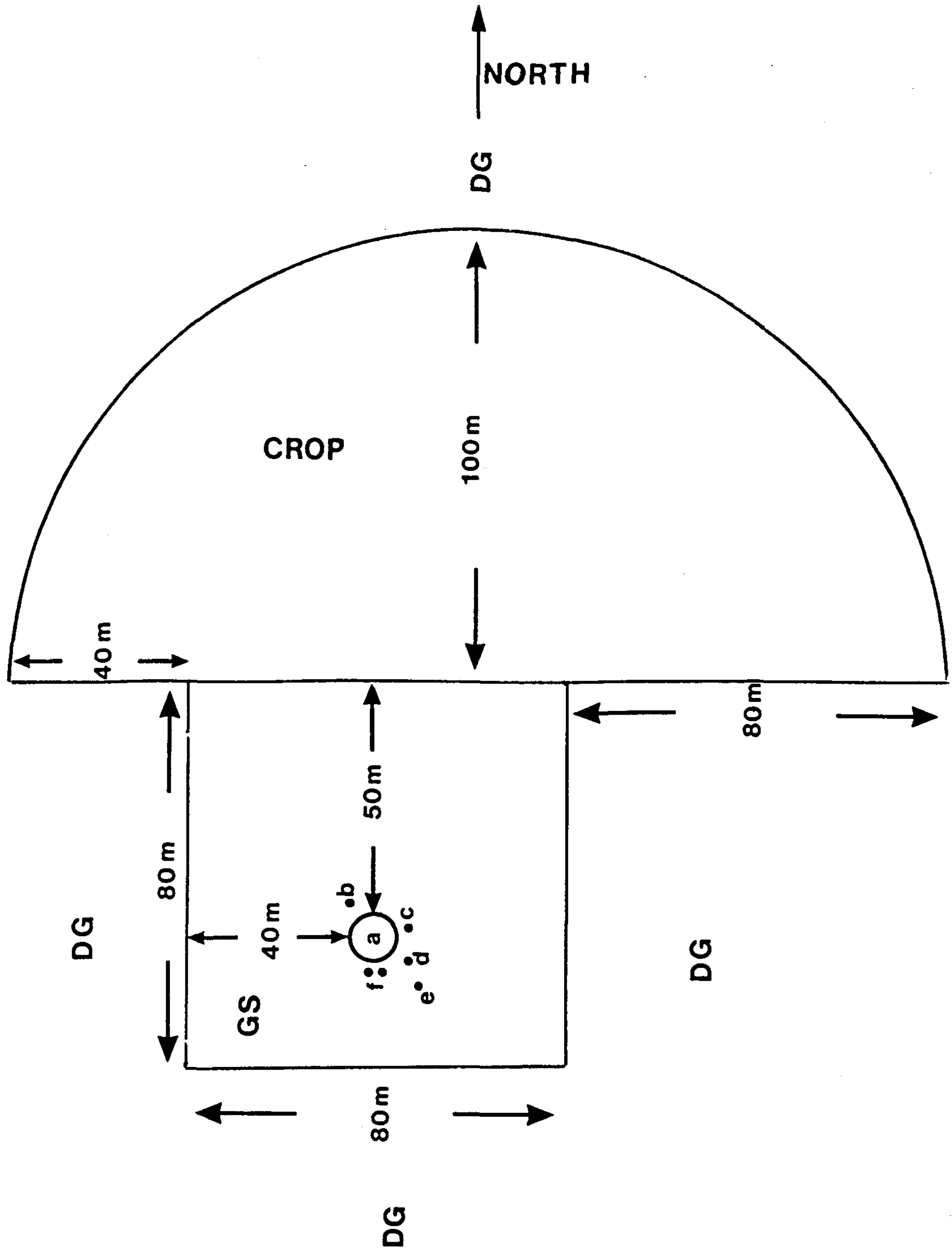


FIG 3.1 Experimental site indicating the instrumentation layout and the fetch in different directions.

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 hygrometer
GS: Grass site
DG: Dry grassland
CROP: Crop field

to potatoes during 1990 and maize during 1992. This site, labelled CROP (Fig 3.1) was kept well watered throughout the study.

The minimum and maximum distances from the centre of the lysimeter to the edge of the grass site were 40 m and 50 m respectively (see Fig. 3.1).

3.6 CALIBRATION OF INSTRUMENTS

The Funk type net radiometers used were calibrated frequently against a standard Middleton net radiometer above a green grass surface. Virtually no deviation of the former were observed when compared to its standard counterpart. The slope through the origin and correlation coefficient were of the order of 1,00 and 0,98 respectively during each calibration event.

A conversion factor, supplied by the manufacturers, were used to convert the analog signal from the soil heat flux sensors to W m^{-2}.

The aspirated psychrometers were calibrated once a week against the sling psychrometer, while the wind speed sensors were calibrated against a portable WILHELM LAMPBRECHT wind run meter.

The infrared thermometer was calibrated according to the method prescribed by the manufacturers. It entails measuring the temperature of a surface black body radiator, of which the temperature was known. The reading on the infrared thermometer was adjusted using the emissivity control unit, to ensure coinsidence between the temperature of the black body radiator and the observed reading.

The lysimeters were calibrated frequently using standard weights.

Although the newly bought Krypton hygrometers, sonic anemometers and fine-wire-thermocouples were never calibrated, these instruments were compared against each other under similar conditions. The two systems compared excellently.

3.7 MICRO-METEOROLOGICAL OBSERVATIONS

The following data set of approximately 200 hourly means were measured from October through November during 1990.

- Net radiation (calculated from 3000 instantaneous observations per hour) using a Funk type net radiometer installed 1,00m above ground level.

- Soil heat flux density (calculated from 3 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) utilizing self-designed (see Van Zyl and De Jager, 1985) and constructed aspirated psychrometers. Water vapour pressure and ambient temperature were measured at 0,50 m 1,00 m and 2,00 m above ground level. The psychrometers were calibrated on the day prior to use, using a sling psychrometer.

- Wind speed (calculated from 3000 observations per hour) using a generator type three-cup anemometer installed at a height of 1,00 m and 2,00 m above ground level.

- Reference crop surface temperature (calculated from 3 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 above ground level of the following were made:

- Vertical fluctuations in wind speed W' using a Campbell Scientific sonic anemometer.

- Vertical fluctuations in ambient temperature T' using a Campbell Scientific fine-wire-thermocouple.

- Fluctuations in water vapour pressure, e' using a Campbell Scientific Krypton hygrometer.

During 1990 the latter three measurements were made at 2,00 m above grass level (Kaimal, 1975). The latter three measurements were also carried out during 1992, but at a height of 0,25 m. A total of 317 hourly mean data sets were collected. It was decided to lower eddy correlation instrumentation during 1992 because of the following reasons, viz:
During 1990 these instruments were installed at a height of 2m above grass level (Kaimal, 1975; Tanner, 1990). In the flux

equations, Eqs. 3.11 and 3.12, the transport of sensible heat and water vapour is driven by the vertical wind component. The ability of the atmosphere to transport sensible heat and water vapour depends directly on the magnitude of the fluctuations in vertical wind, W'. Near the surface the magnitude of W' is limited. Further away from the surface transport is more efficient because the eddies are larger, (W' is longer) and easily detected. This implies that the accuracy of measurements made at 2,00 m should exceed that of measurements made near the surface. However, because of limited fetch available it was decided to lower the measuring height of W', T' and q' to 0,25 m above the surface of the grass.

The sampling rate of eddy correlation measurements was 5 Hz, with a 10 min sub-interval averaging period (i.e. 3000 observations in 10 min period) and a 30 min output interval. All sensors were connected to a Campbell 21X data logger.

It is evident that during 1990 all instrumentation, with the exception of the net radiometer and the psychrometer were placed at heights above the equilibrium boundary layer i.e. at heights exceeding 0,60 m.

3.8 ANALYSIS OF MICRO-METEOROLOGICAL OBSERVATIONS

Each of the micro-meteorological methods (Eqs. 3.5, 3.8, 3.10, 3.11, and 3.12) for determining LE_o was compared against the lysimeter values of LE_o. Conventional statistical analyses and the simulation index ,SI, of Willmott (1982) were used. Advection was ignored when LE_o was calculated.

E_o, in mm $(2h)^{-1}$, was obtained by dividing LE_o by 7200/L.

3.9 ESTIMATION OF ADVECTION

Hourly mean advection was calculated by rearranging Eq. 3.5, thus

$$A = -LE_o\,(\beta + 1) - R_n - G \qquad 3.14$$

In Eq. 3.14 LE_o was measured lysimetrically while the Bowen ration, ß was calculated from Eq. 3.7 and measurements of ΔT_a and Δe at 1,00 m 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 R_n and ± 10% of G respectively. It has been shown that the accuracy of the grass lysimeter is ± 0,02 mm, which is equivalent to ± 14 W m^{-2} (Van Zyl and De Jager, 1992). Such inaccuracies could produce large measurement error in A. In practice values of A comparable in magnitude to the magnitude of measurement error (as calculated from Eq. 3.15 below) were rejected.

The maximum possible measurement error in A, denoted ε_A, may be expressed.

$$\varepsilon_A = (LE_o \;\; \xi 1) \left[\frac{\beta\,(\xi 2 + \xi 3)}{\beta + 1} \right] + (R_n \times \xi 4) + (G \times \xi 5) \qquad 3.15$$

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

Hourly values of these are given by

$$\xi 1 = \frac{28}{LE_o} ; \xi 2 = \frac{0,2}{|\Delta T|} ; \xi 3 = \frac{0,6}{|\Delta T_w|} ; \xi 4 = \frac{0,2}{|R_n|}$$

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

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

The following rejection criteria were used to eliminate doubtful estimates of true minimum advection viz.

- when A calculated from Eq. 3.14 was less than ε_A, and
- when $\Delta e < 20$ Pa

3.10 ACCURACY OF MEASUREMENT OF E_o

3.10.1 Comparison of different methods

The 1990 results are presented in Tables 3.1, 3.2 and Figs. 3.2 through 3.11. Table 3.1 summarizes the results of the statistical tests comparing two-hourly (2h) E_o measured with E_o calculated using Eqs. 3.5, 3.8, 3.10, 3.11 and 3.12 respectively. Figs. 3.2 to 3.6 are the variation in hourly mean E_o either calculated or measured by lysimeter. Table 3.2 is a summary of the results of the statistical tests comparing daylight E_o measured with calculated values of E_o during daylight hours. Daylight E_o was obtained by adding all hourly values between sunrise and sunset for the specific day. Figs. 3.7 through 3.11 graphically compare E_o calculated by Eqs. 3.5, 3,8, 3.10, 3.11, and 3.12 with E_o measured for the daylight period.

TABLE 3.1. Results of statistical tests carried out between E_o measured lysimetrically and E_o calculated from Eqs. 3.5, 3.8, 3.10, 3.12, and 3.13 respectively, using hourly micro-meteorological data. Results were obtained for two-hourly (2h) evaporating rates.

Statistical parameter	Parameter values				
	Eq.3.5 (EB_B)	Eq.3.8 (EB_{IRT})	Eq.3.10 (PME)	Eq.3.12 (EB_C)	Eq.3.13 (EC) 1990
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 " "	0,48 " "	0,34 " "	0,54 " "	0,77 " "
S. RMSE	0,36 " "	0,24 " "	0,21 " "	0,39 " "	0,75 " "
U. RMSE	0,09 " "	0,24 " "	0,13 " "	0,15 " "	0,02 " "

n : number of observations
r : correlation coefficient
SI : simulation index
MAD : mean absolute difference

RMSE : root mean square error
S. RMSE: systematic root mean quare error
U. RMSE: unsystematic root mean square error

TABLE 3.2. Results of statistical tests carried out between measured E_o and E_o calculated from Eqs. 3.5, 3.8, 3.10, 3.12 and 3.13 respectively, using hourly micro-meteorological data. Results were obtained for daylight evaporating rates.

Statistical parameter	Parameter values				
	Eq.3.5 (EB_B)	Eq.3.8 (EB_{IRI})	Eq.3.10 (PME)	Eq.3.12 (EB_C)	Eq.3.13 (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	1,42mm $(dl)^{-1}$	1,61mm $(dl)^{-1}$	0,80mm $(dl)^{-1}$	1,16mm $(dl)^{-1}$	2,65mm$(dl)^{-1}$
Mean difference	1,02 " "	1,32 " "	0,01 " "	0,14 " "	2,65 " "
RMSE	1,74 " "	1,95 " "	0,95 " "	1,49 " "	2,95 " "
S. RMSE	1,65 " "	1,47 " "	0,75 " "	1,09 " "	2,92 " "
U. RMSE	0,09 " "	0,44 " "	0,20 " "	0,40 " "	0,03 " "

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

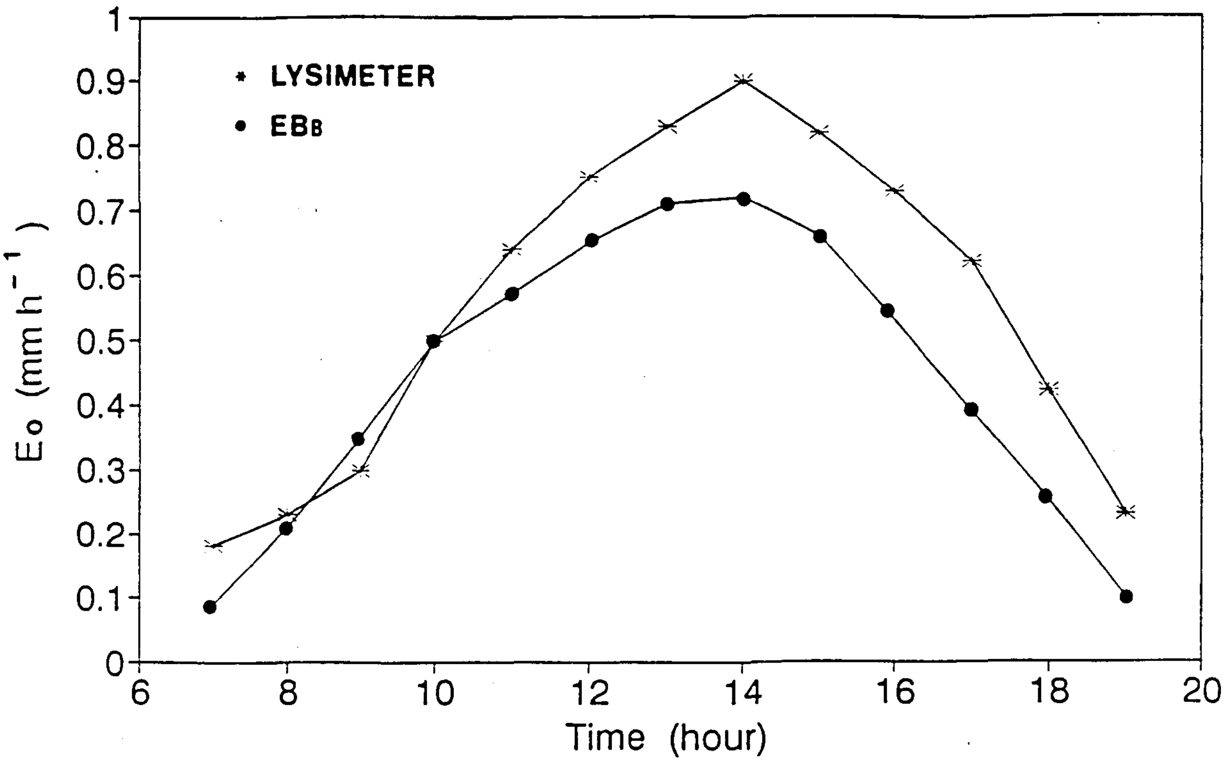


FIG. 3.2 Hourly variation of Eo measured lysimetrically and estimated from EBB over the daylight period during 1990.

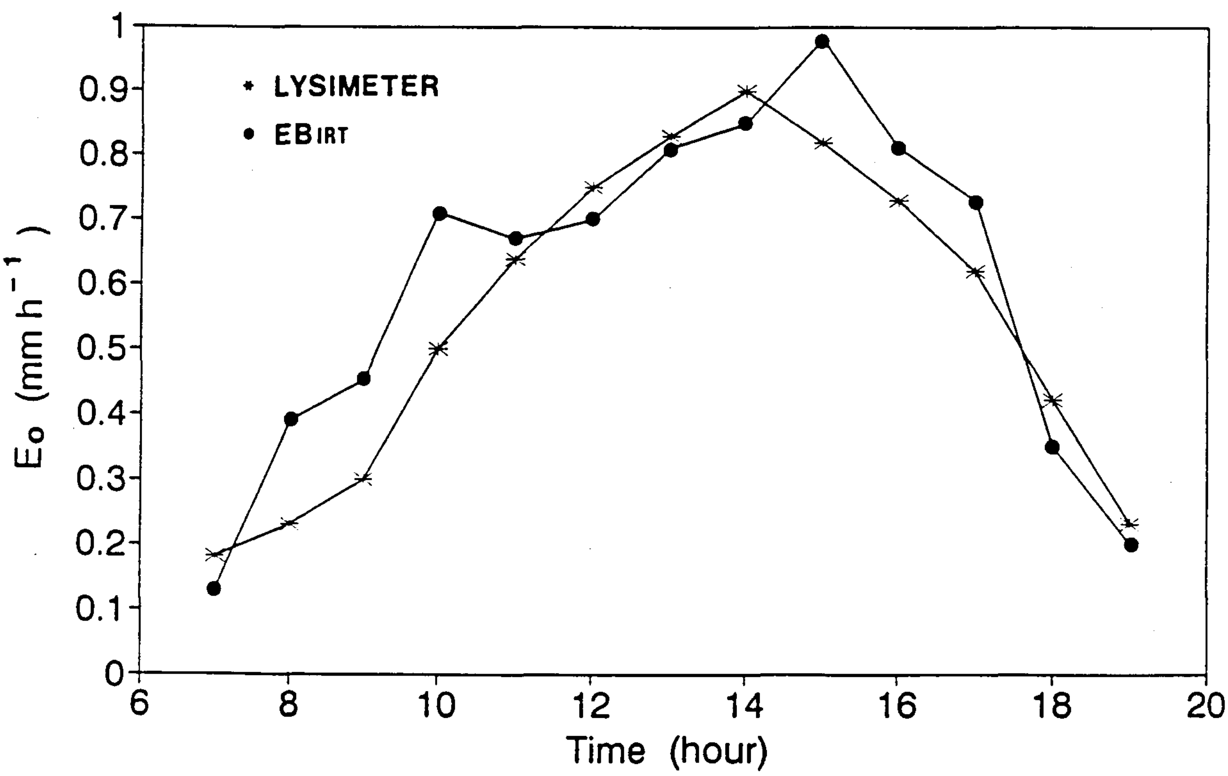


FIG. 3.3 Hourly variation of Eo measured lysimetrically and estimated from EBIRT over the daylight period during 1990.

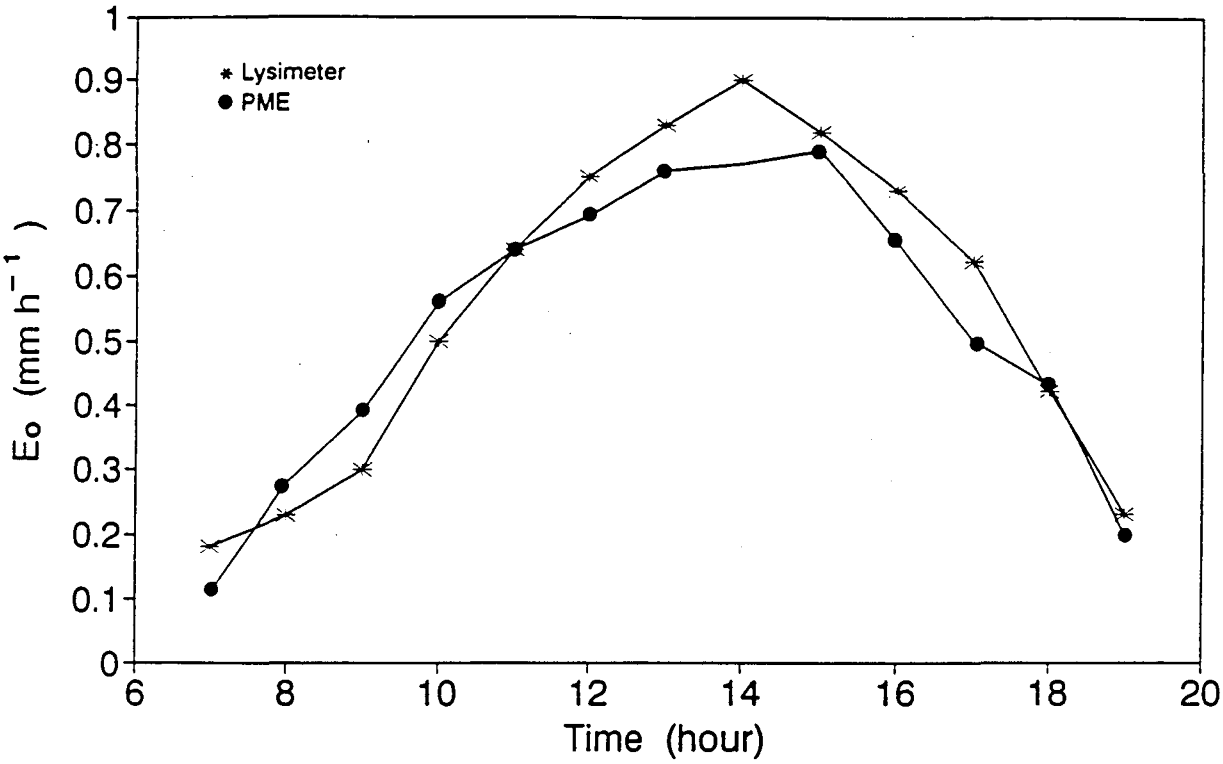


FIG. 3.4 Hourly variation of E_o measured lysimeterically and estimated from the PME over the daylight period during 1990.

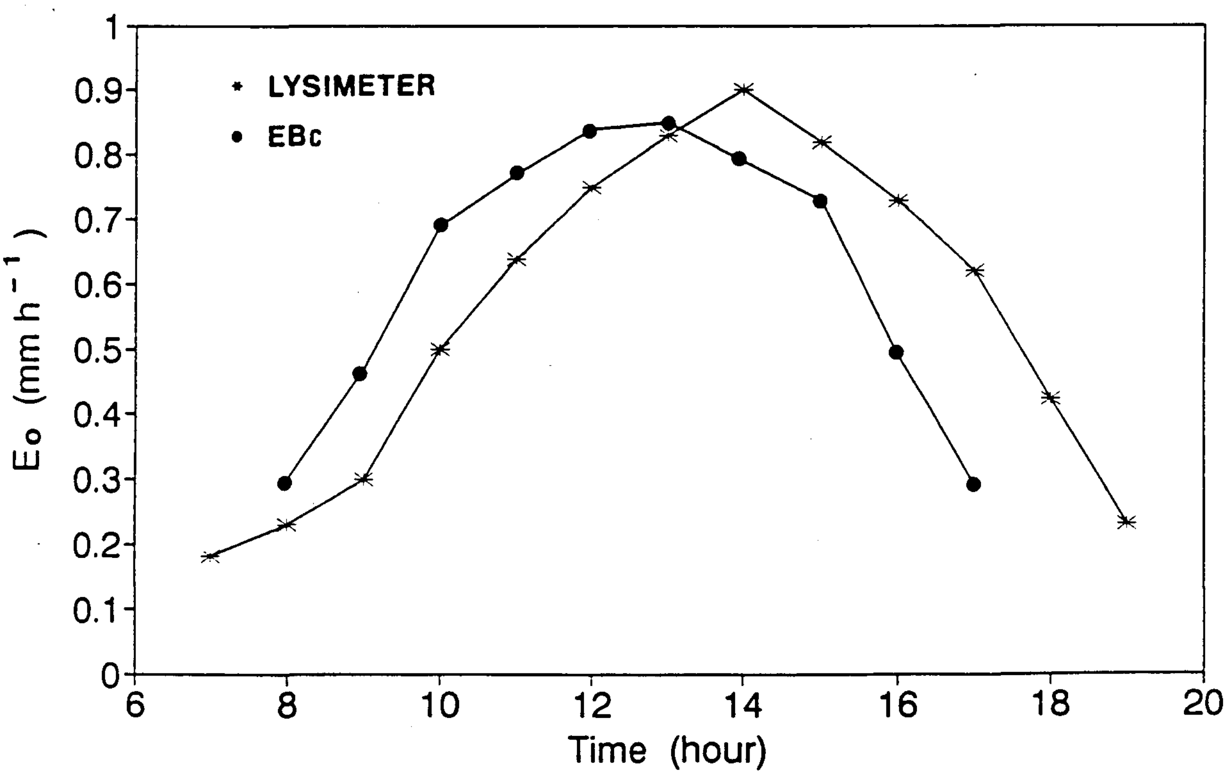


FIG. 3.5 Hourly variation of E_o measured lysimetrically and E_o estimated from EBc over the daylight period during 1990.

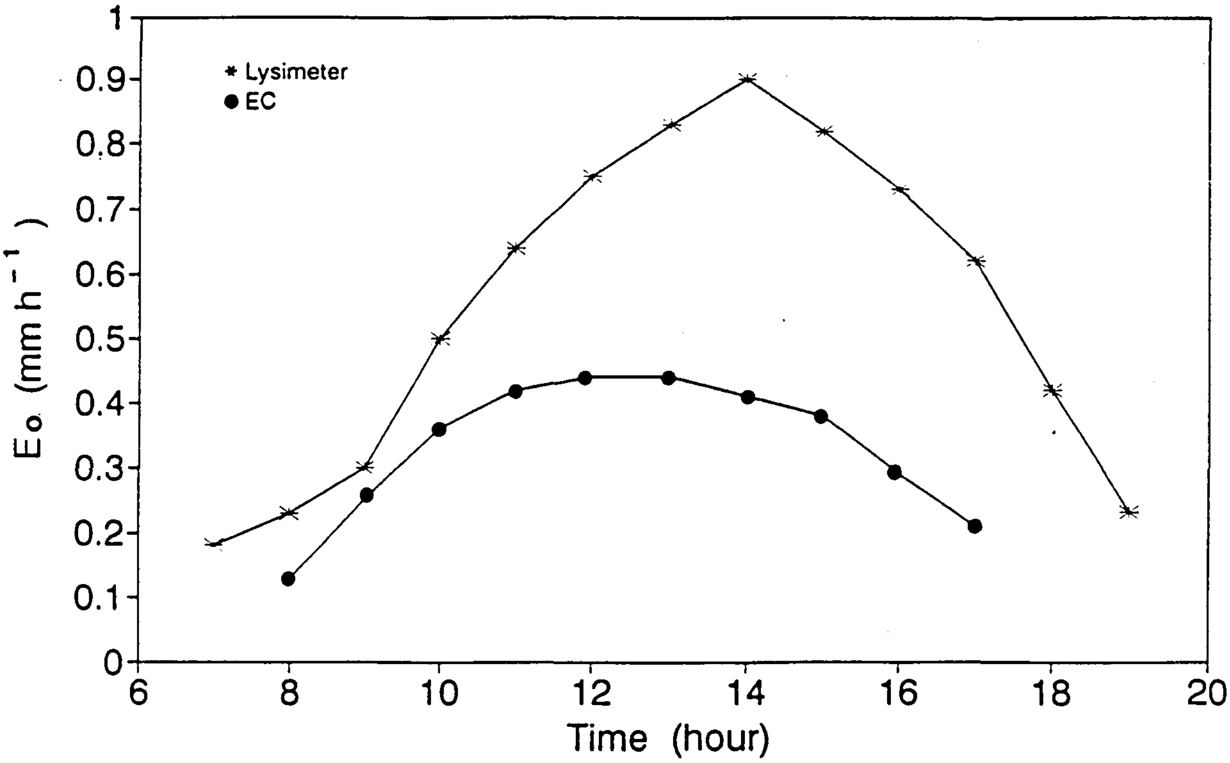


FIG. 3.6 Hourly variation of E_o measured lysimetrically and E_o estimated from EC over the daylight period during 1990.

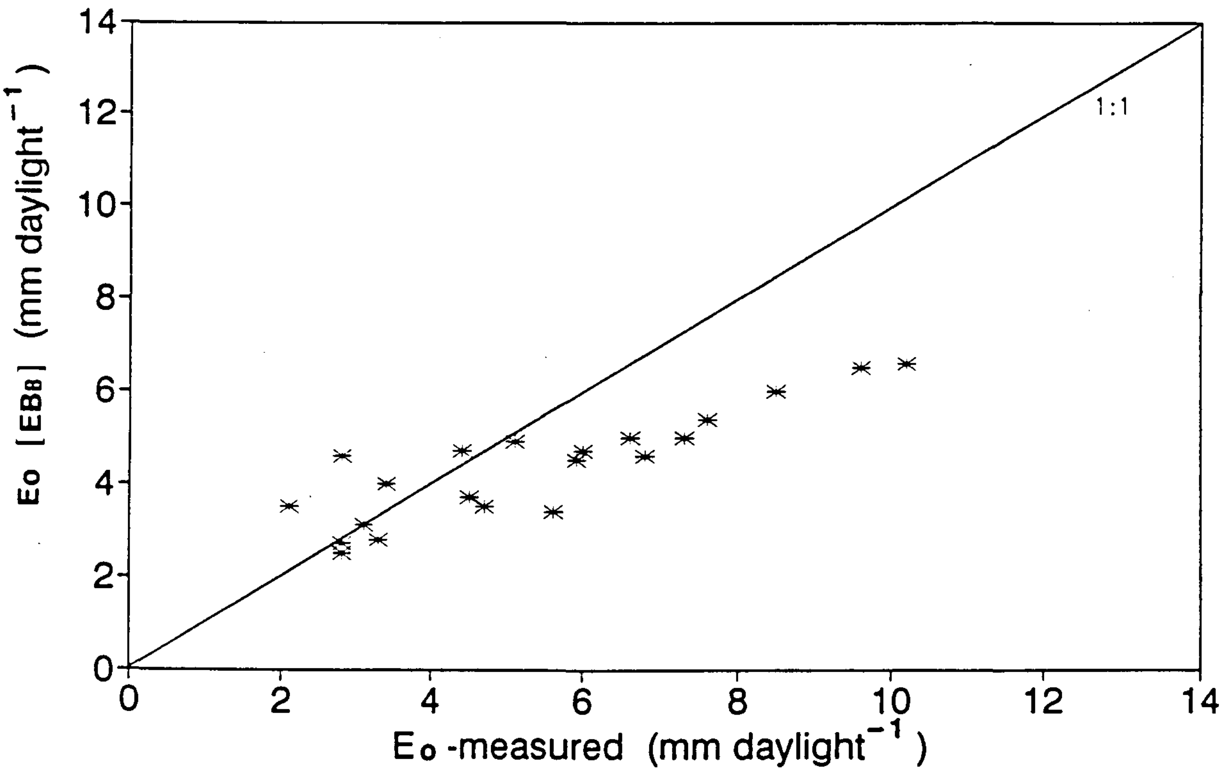


FIG. 3.7 Comparison between daylight E_o measured lysimetrically and E_o estimated from EB_B during 1990.

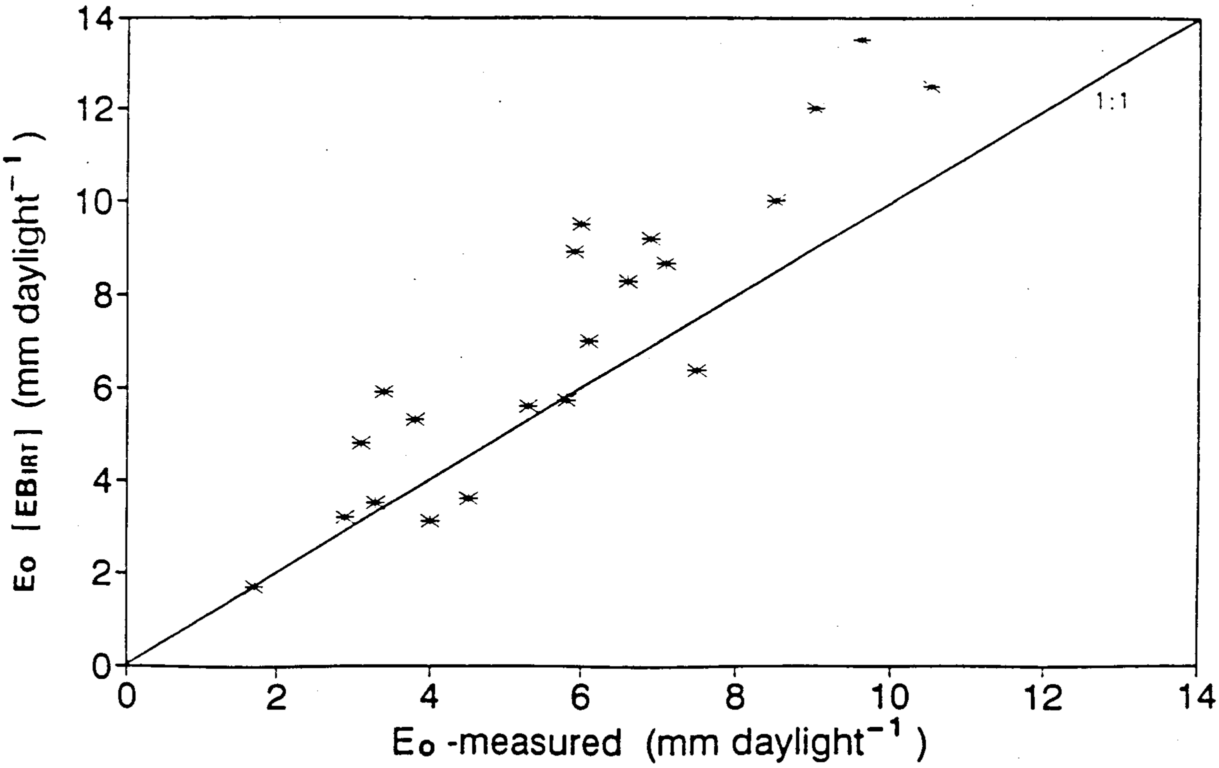


FIG. 3.8 Comparison between daylight E_o measured lysimetrically and E_o estimated from EB_{IRT} during 1990.

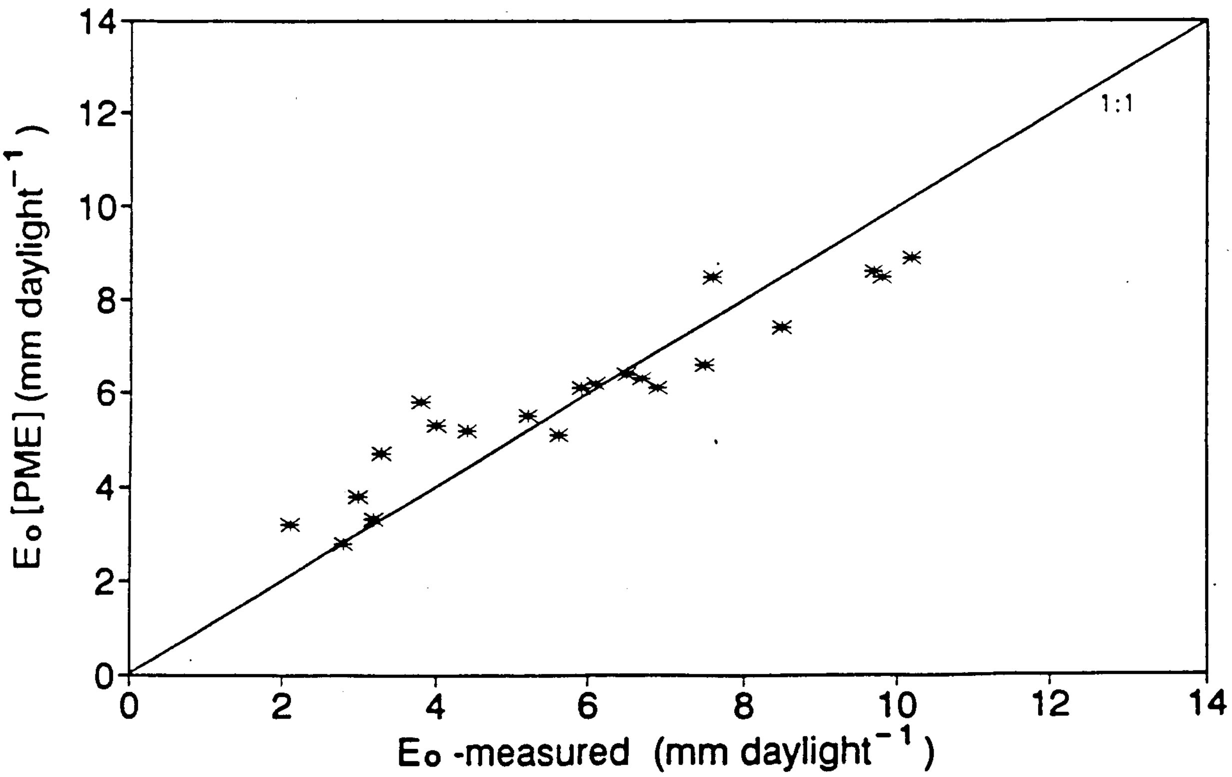


FIG. 3.9 Comparison between daylight E_o measured lysimetrically and E_o estimated from PME during 1990.

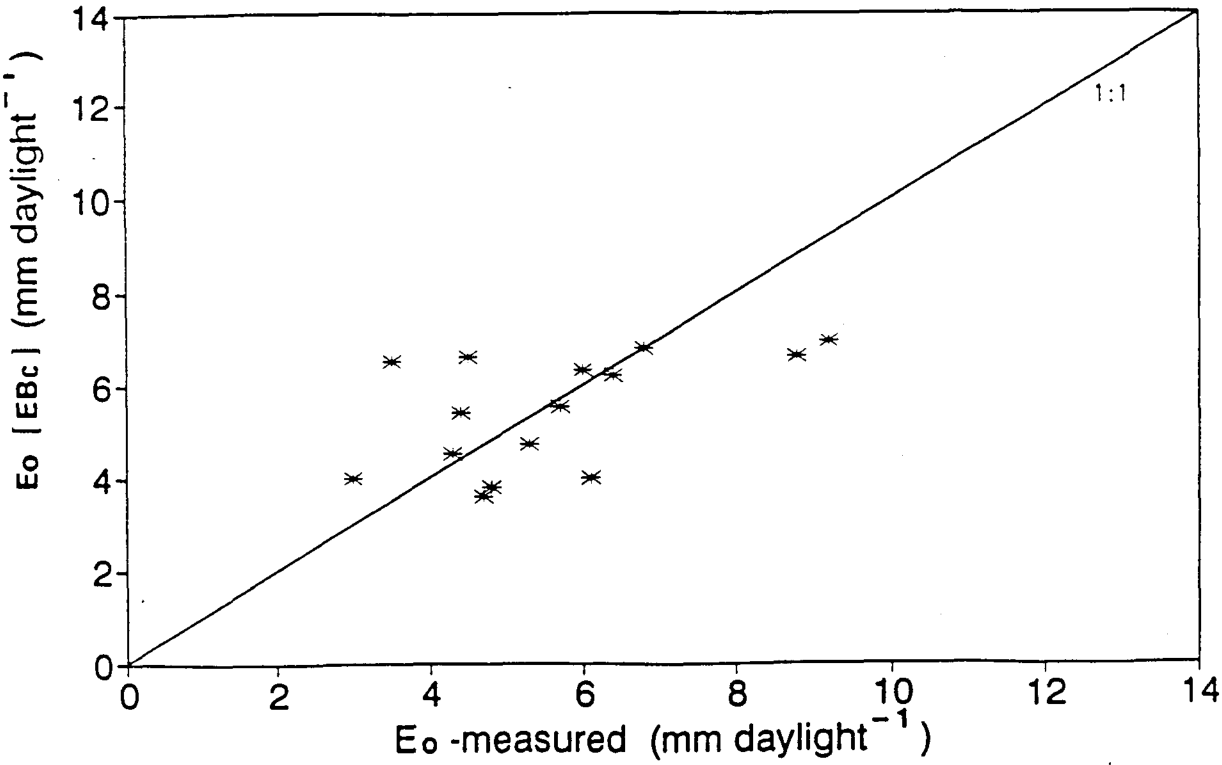


FIG. 3.10 Comparison between daylight E_o measured lysimetrically and E_o estimated from EBc during 1990.

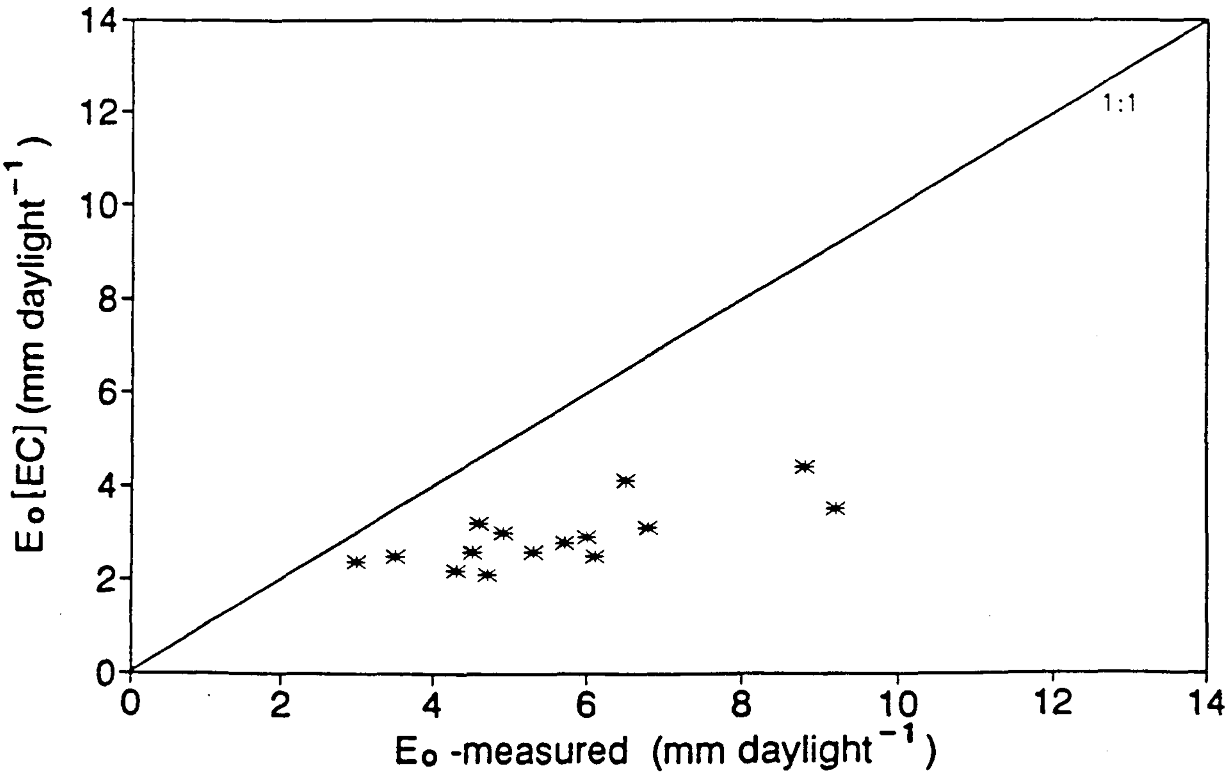


FIG. 3.11 Comparison between daylight E_o measured lysimetrically and E_o measured EC during 1990.

The underestimation of E_o, using the Bowen ratio, is evident from Figs. 3.2 and 3.7 and Tables 3.1 and 3.2. 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 EB_B, the energy budget/Bowen ratio method.

The EB_{IRT} method utilized to estimate E_o compared favourably with lysimeter values of E_o. This technique generally overestimated E_o (see Figs. 3.3 and 3.8). The slope through the origin was 1,13 and 1,24 for the two-hourly and daylight comparisons respectively (Tables 3.1 and 3.2). The favourable comparison with E_o is attributable to the fact that measurements of canopy surface temperature account for advection.

An excellent comparison was obtained between E_o calculated from the PME, and E_o measured. This is reflected by the relatively high SI-value (Willmott, 1982) of 0,95 and low mean absolute difference of 0,80 mm dl^{-1} (see Table 3.1), where dl denotes daylight period. A slight underestimation of E_o, at relatively high evaporation rates, usually between 11:00 and 17:00, is evident from Fig. 3.4. The good comparison in this case suggests that, as in the case of the EB_{IRT} technique, boundary layer phenomena such as canopy surface and bulk air conductance compensate for advection.

E_o obtained from eddy correlation measurements ,EC, (Eq. 3.12) during 1990 when measurements were made at 2,00 m height compared poorly with E_o measured (Tables 3.1 and 3.2). Underestimation of E_o, over the full range of evaporation rates, is clearly illustrated in both Figs. 3.6 and 3.11. The fact that virtually all the points lie below the 1:1 line suggest the presence of a systematic error (see Tables 3.1 and 3.2). The magnitude of this error of approximately 200% is too large to attribute to advection. Hence this method was not pursued any further. Savage, et al. (1991) and Dugas, et al. (1991), also reported significant underestimation of eddy correlation measurements when compared to other methods.

Results of comparison between E_o measured and eddy correlation (EC) measurements made at 0,25 m during 1992 improve markedly (Fig. 3.12). The slope through the origin, r^2 and standard error of estimate was 1,08, 0,63 and 0,22 mm h^{-1}. A total of 317 data sets were used in the analysis. This improvement can be explained as follows, viz. During both the 1990 and 1992 experimental periods abnormally dry weather conditions were experienced. As a result of these dry environmental conditions and the fact that EC was measured at 2m above grass level, which is outside the boundary layer of the grass site, the EC technique during 1990 particularly measured much water vapour from the dry surrounds, rather than water vapour originated from the grass site itself. Measurements made at 0,25 m i.e. within the equilibrium boundary layer above the grass during 1992 indicated that the eddies measured were representative of the grass site itself. The scatter in Fig. 3.11 results, because eddy sizes decrease as the measuring level approaches the surface. This might result in erroneous measurements of water vapour using EC.

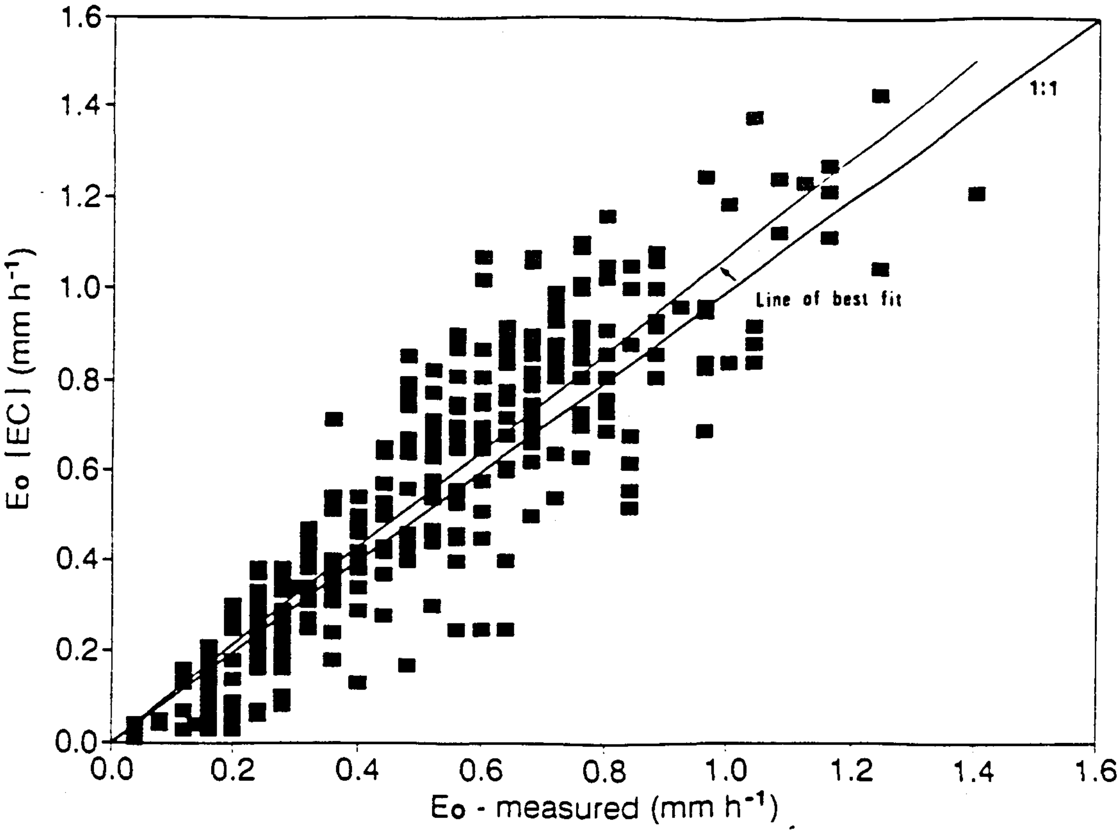


FIG. 3.12 Comparison between hourly E_o measured lysimetrically and E_o estimated from EC during 1992.

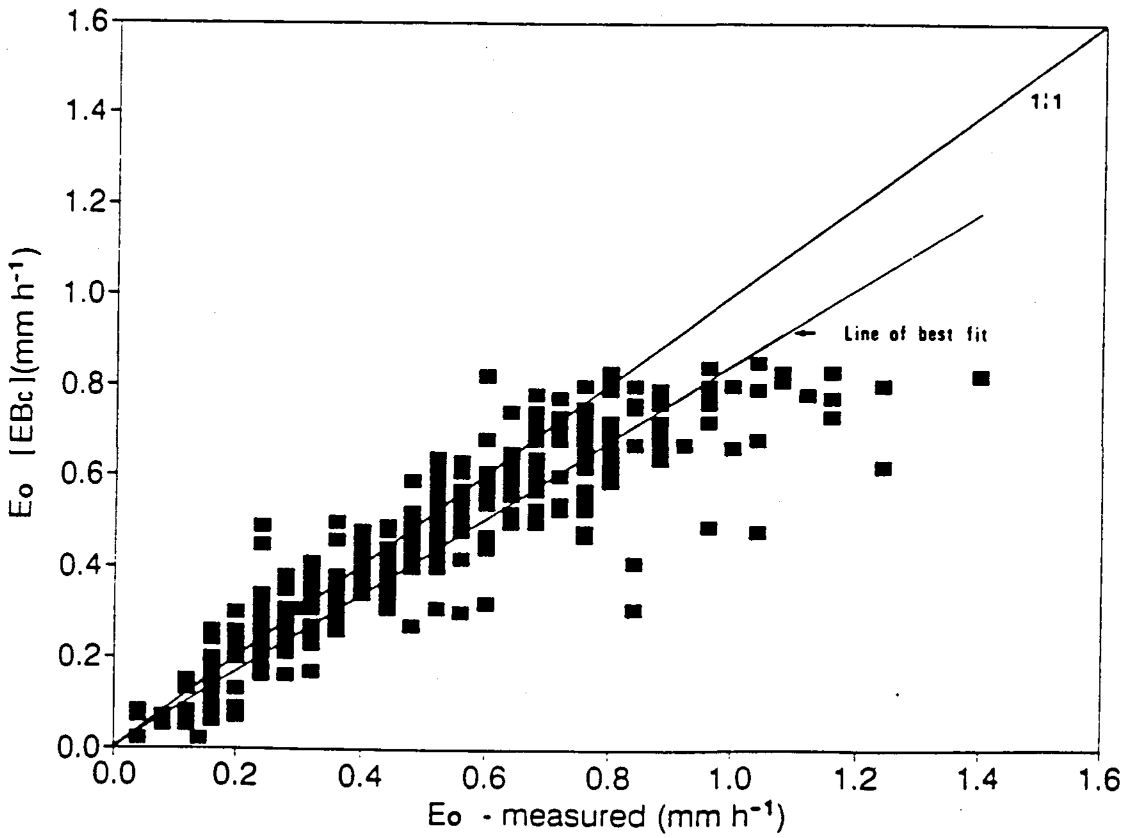


FIG. 3.13 Comparison between hourly E_o measured lysimetrically and E_o estimated from EBc during 1992.

From the slope through the origin, SI and MAD in Tables 3.1 and 3.2 it appears that utilization of the EBc (Eq. 3.11), to determine Eo during 1990, resulted in a better result than those obtained using the EC technique (Eq. 3.12). The better performance of Eq. 3.11 could be attributable to the dominant role played by net radiation in Eq. 3.11, whereas net radiation does not feature in direct eddy correlation calculations. Furthermore, results obtained with Eq. 3.11 exhibited an one hour lag, behind lysimeter Eo values (see Fig. 3.5).

Comparison between Eo measured and Eo estimated from EBc during 1992 yielded a slope through the origin of 0,84, r^2 of 0,76 and standard error of estimate of 0,11 mm h^{-1}. The relatively small underestimation of Eo using EBc was observed (Fig. 3.13). A possible explanation is, that the grass surrounding the grass lysimeter, although green and unstressed, was shorter than the grass inside the lysimeter which could have resulted in a slight overestimation of lysimeter Eo values. No lag behind lysimeter Eo values was observed during 1992.

3.10.2 The influence of advection

Variation in hourly mean advected heat flux density, A, calculated from Eq. 3.14, is illustrated in Fig. 3.14. 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 m^{-2}, with a standard deviation of 146 W m^{-2}. This means that advection did occur on at least 30% (75/250) of the measurement instances.

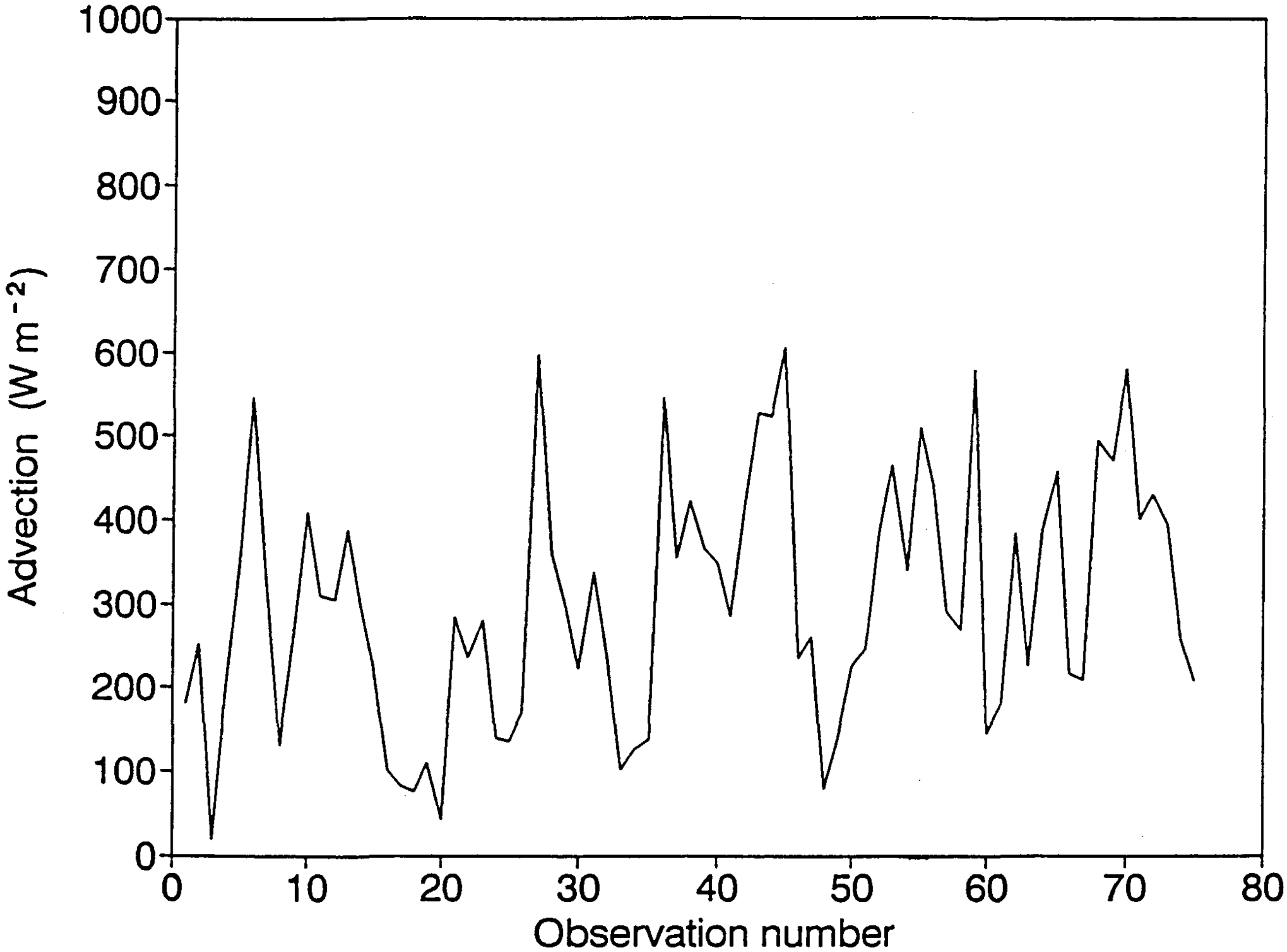


FIG. 3.14 Hourly variation of minimum advection over the experimental period when ambient temperature and vapour pressure were measured at 1,00m and 2,00m.

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, above the grass site, for days when measurements were made, was 5,04 m s^{-1} and never dropped below 3,60 m 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 of error.

3.11 CONCLUSIONS.

Measurements of net radiation, soil heat flux density, Bowen ratio and E_o measured in a lysimeter were used to estimate advection on a small grass covered area. The 0,64ha experimental grass site was found to be subject to advective fluxes when measurements were made at height exceeding 0,60 m. The average advection over 75 one hour observation periods was 301 W m^{-2}. Advection occurred on at least 30% of the observation periods.

For small grass sites of this size, it seems that the technique, employing the surface energy budget equation and the infrared thermometer, can be used to estimate E_o 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 bi-hourly 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 budget equation and sensible heat flux density as measured with vertical wind and temperature turbulant fluctuations, showed promise. The existence of a one hour time lag behind lysimeter values of E_o, observed during 1990, and the absence thereof during 1992 requires yet to be explained.

The eddy correlation approach (Eq. 3.12) proved unreliable for estimating E_o, during the 1990 experimental conditions. Underestimation of E_o occurred in this study when instruments were exposed at a height of 2,00 m. Underestimation during this period 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 500m for measurements of this type should be adhered to when measurements are made at height 2,00 m above grass level. A vast improvement in E_o was observed when eddy correlation (EC) measurements were made at a height of 0,25 m above grass level, which is within the boundary layer.

CHAPTER 4

4. DETERMINATION OF ATMOSPHERIC EVAPORATIVE DEMAND FOR THE MAIZE CROP FROM EDDY CORRELATION TECHNIQUES DURING 1992

4.1 INTRODUCTION

During 1990 eddy correlation measurements were made above only grass and not above potatoes. The reason why no measurements were made above potatoes was two-fold. Firstly it had been necessary to solve problems originally experienced with the sonic anemometer, fine-wire-thermocouple and Krypton hygrometer and secondly to familiarize the operating priciples of these instruments.

The objective of the work reported in this chapter was to determine AED for the maize crop using eddy correlation measurements.

4.2 MATERIALS AND METHOD

AED for maize was determined from Eqs. 3.1 (with A = 0), 3.11 and 3.12 using hourly measurements of $\overline{W'T'}$ and $\overline{W'e'}$. When L.AED (expressed in W m^{-2}) was determined from Eqs. 3.1 and 3.12 LE_o was replaced by L.AED. Net radiation in Eq. 3.1 was measured 1,0 m above a well-watered maize crop surface. Soil heat flux measurements were made within and between the maize crop rows at a depth of 0,5 mm below ground surface. The mean of the latter two measurements were used to calculate G in Eq. 3.1. $\overline{W'T'}$ and $\overline{W'e'}$ were measured 0,25 m above the maize crop canopy.

L.AED calculated in W m^{-2} was converted to mm h^{-1} by multiplying by 3600/L. AED for maize was also measured hourly using the maize lysimeter. Hourly AED for maize, calculated from Eqs. 3.1, 3.11 and 3.12, was then compared statistically with AED measured lysimetrically. A total of 317 hourly data sets between DOY 7 and DOY 100 were used in the comparison during 1992.

4.3 RESULTS AND DISCUSSION

Figs. 4.1 and 4.2 compared AED measured in the lysimeter with AED calculated from Eqs. 3.1 and 3.11 and AED measured using the EC technique (see Eq. 3.12). Results of statistical tests carried out are summarized in Table 4.1.

Large scale scatter observed in the case of EC measurements (see Fig. 4.2 and r^2 = 0,55 in Table 4.1) could be ascribed to the small eddies present at low levels above the maize crop canopy.

TABLE 4.1. Results of statistical tests carried out between lysimetrically measured AED for maize and AED calculated from Eqs. 3.1 (with A = 0) 3.11 and 3.12 using techniques EBc and EC .

Statistical parameter	Parameter value	
	EBc	EC
n	317	317
Slope through origin	0,76	1,10
r^2	0,69	0,55
Standard error or estimation (SEE)	0,12 mm h^{-1}	0,26 mm h^{-1}

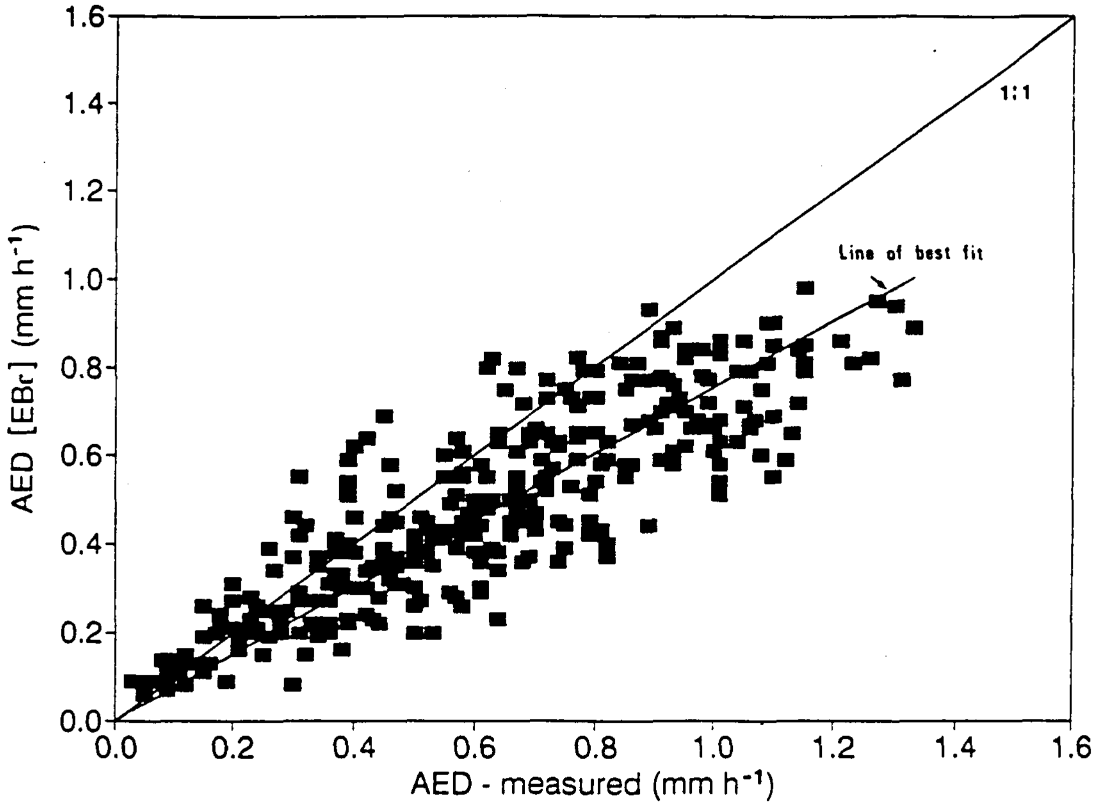


FIG. 4.1 Comparison between hourly AED measured lysimetrically and AED estimated from EBc

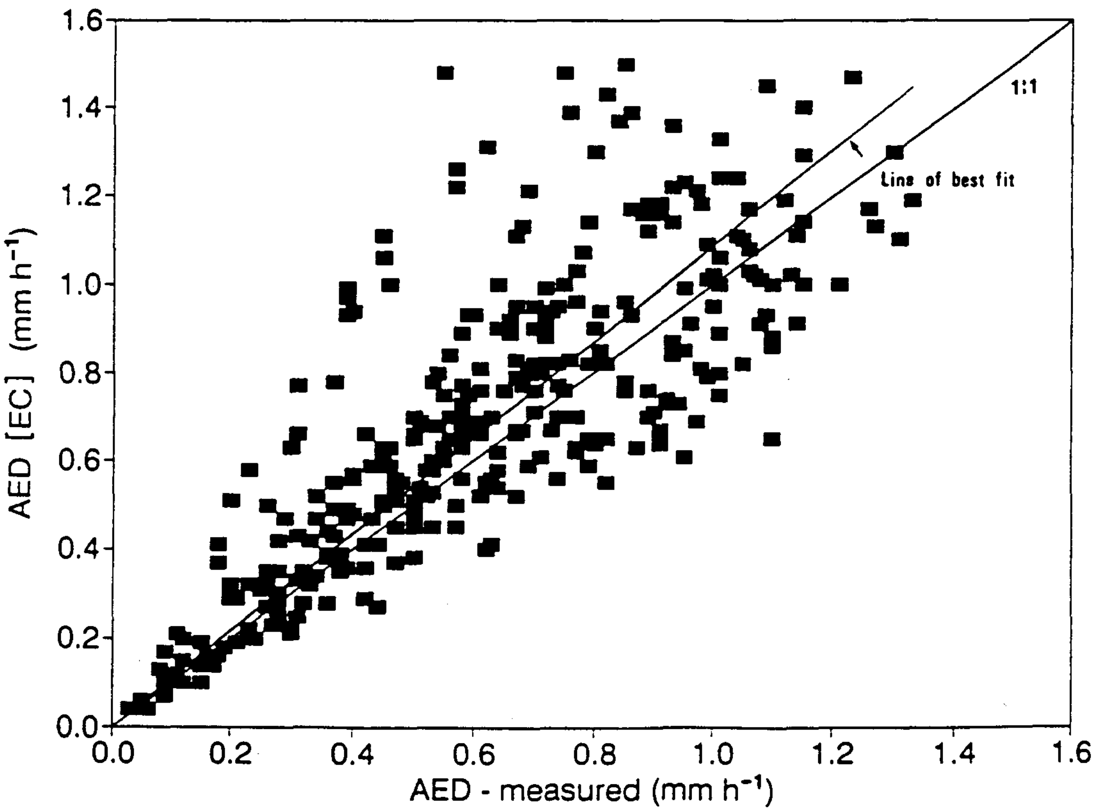


FIG. 4.2 Comparison between hourly AED measured lysimetrically and AED measured using EC technique.

AED measured lysimeterically exceeds AED estimated from EB_C by 24% (see Table 4.1). The observed underestimation can be explained as follows viz:

On DOY 25 the maize crop was 1 m high. This value increased from 1 m to 2,3 m on DOY 52 and then remains constant at 2,3 m until DOY 100. The distance from the edge of the maize crop site to the maize lysimeter in the direction of the prevailing wind direction was approximately 100 m. This means that the maize plants in the lysimeter were subjected to limited fetch. The minimum fetch required for a 2 m high plant is 200 mm (Campbell, 1977). The dry environmental conditions which existed for the duration of this investigation during 1992, together with the limited fetch from DOY 25 till DOY 100 implies that the maize plants in the lysimeter were subject to advection, which would cause high evaporation rates and which did not reflect the true vertical exchange of latent heat flux density.

Based on the evidences in the above paragraph, it is now assumed that the EB_C technique reflects true vertical exchange of latent heat flux density above the maize.

This assumption was examined by calculating the mean evaporation coefficient for the case F_v = 1. Hence

$$\overline{k_c} = \sum_{h=1}^{236} AED \Big/ \sum_{h=1}^{236} E_o \qquad 4.1$$

where h denotes hourly value

In Eq. 4.1

$$\sum_{h=1}^{236} AED \ (= 141,73 \text{ mm})$$ is the sum of 236 hourly values of AED measured lysimetrically and

$$\sum_{h=1}^{236} E_o \ (= 102 \text{ mm})$$ is the sum of the corresponding lysimetrically measured hourly values of E_o (from chapter 3).

Hence, the value calculated for $\overline{k_c}$ in Eq. 4.1 for maize was 1,39. Doorenbos & Kassam (1979) and Jensen, et al., (1982) reported values of 1,05 to 1,20 (mean of 1,13) and 1,13 for k_c for maize respectively during mid-season. The figure 1,39 is 23% higher than that published by the latter, suggesting that the lysimeter was influenced by advection. This, together with the fact that

$$\sum_{h=1}^{236} E_o \ (EB_C) = 96,35 \text{ mm}$$ approximated

$$\sum_{h=1}^{236} E_o \ (= 102 \text{ mm})$$ measured lysimetrically during 1992 and the areas under the two curves (see Fig. 3.5 in Chapter 3) are nearly equal, support the assumption that AED determined from EB_C using $\overline{W'T'}$ are not really being affected by advection present above the maize crop. During 1990 (see Chapter 3) $\overline{W'T'}$, was measured 2 m above grass level, which is outside the equilibrium boundary layer of the grass site.

4.4 CONCLUSIONS

AED for maize measured by the eddy correlation technique ,EC, overestimated AED measured in the lysimeter. Relatively large scatter suggested inaccuracies occurred when measurements were made at 0,25 m, because at low levels the eddies are small.

AED determined from the energy budget equation and measurements of net radiation soil heat flux density, vertical wind speed and vertical temperature fluctuations underestimated AED measured lysimetrically. Significant reduction in scatter, compared to eddy correlation measurements, were observed. This was attributable to the significant role of net radiation in the energy budget equation. The fact that mean hourly net radiation was obtained from 3000 instantaneous observations per hour, ensures acceptable accuracy in net radiation measurements (see Chapter 3).

The maize lysimeter was subject to high advection because of limited fetch. It is therefore suggested that measurements did not reflect the true exchange of vertical latent heat flux density, a matter which should be investigated in a follow-up study.

The energy budget equation and measurements of net radiation, soil heat flux density, vertical fluctuations in wind speed and ambient temperature can therefore be used to estimate hourly AED in maize using the EBC technique. The latter method is possibly not seriously affected by advection. The influence of advection on eddy correlation measurements needs to be addressed in a separate study.

CHAPTER 5

5. INFLUENCE OF WEATHER ELEMENTS ON THE UPPER LIMIT VEGETATION EVAPORATION COEFFICIENT FOR THE POTATO CROP USING MICRO-METEOROLOGICAL MEASUREMENTS DURING 1990.

5.1 INTRODUCTION

In Chapter 2 and particularly Eqs. 2.4 and 2.7 it was shown that by definition the evaporation coefficients k_v and k_s are functions of climate, F_v and F_g. The latter two are purely functions of vegetative cover and soil surface wetness and hence independent of climate. The climatic dependence of the evaporation coefficient must thus be accounted for in the upper limit evaporation coefficients k_{vo} and k_{so}.

The influence of k_s, on seasonal crop evaporation is intermittent (depending upon wetting frequency), or negligible once complete vegetation cover is attained. So, given this and the state of the art of present knowledge, it was decided to assume $k_{so} = 1$ throughout the study and link the entire influence of climate upon the evaporation coefficients to k_{vo} alone.

5.2 OBJECTIVE

The objective of the work discussed in Chapter 5 was to examine the influence of climate on the upper limit vegetation evaporation coefficient ,k_{vo}, for the potato crop using micro-meteorological measurements and to develop a relationship between k_{vo} and the weather elements net radiation, ambient temperature, water vapour pressure and wind speed.

5.3 MATERIALS AND METHOD

5.3.1 Determination of reference evaporation

Because of the inability of the EB_B to estimate E_o reliably, this method was not considered suitable for calculating k_{vo} (see Eqs. 3.1 and 3.6).

During 1990 no eddy correlation measurements were made above the potato crop. This period had been used to familiarize the operating principles of the instruments and solve initial problems.

It was decided to use the PME measurements to obtain E_o (See Chapter 3). Certain relationships were substituted for air density (ρ), specific heat capacity (C_p), latent heat of evaporation (L), the psychrometric constant (γ) and ϕ_a = $^1/r_a$ in Eq. 3.10. These are as follows:

$$\rho = p \times 29/(8.310001 \times (T_a + 273.16)) \qquad 5.1$$

$$C_p = 1005 \text{ J kg}^{-1} \text{ °C}^{-1} \text{ (Rosenberg, } \underline{\text{et al}}\text{., 1983)} \qquad 5.2$$

$$L = -2359.02 \times T_a + 2500470 \text{ (Campbell, 1977)} \qquad 5.3$$

$$\gamma = 1005 \times 10 \times p/(L \times 0,625) \text{ (Monteith, 1975)} \qquad 5.4$$

and

$$r_a = \{ \ln ((z_w - d)/z_{om}) \ln ((z_p - d)/z_{ov})/(k^2 \ u_z)) \text{ (Jensen, } \underline{\text{et al}}\text{., 1982)} \qquad 5.5$$

respectively

In Eqs. 5.1 through 5.5

p = atmospheric pressure (kPa)

z_w = height at which wind speed was measured (m)

z_{om} = roughness parameter for momentum exchange (= 0,123 h), where h is the height of the vegetation (m)

z_p = height at which water vapour pressure was measured (m)

z_{ov} = roughness parameter for water vapour pressure exchange (= 0,1 z_{om}) (m)

The PME using Eqs. 5.1 through 5.5 to estimate hourly E_o values had been shown to compare well with lysimeter measurements. The coefficient of determination of the regression line, slope through the origin and standard error of estimate of the regression were 0,89; 0,96 and 0,08 mm h^{-1} from 368 observed values respectively.

5.3.2 Measurement of AED and k_{vo}

The Penman-Monteith equation (Eq.3.10) cannot be used to estimate AED and therefore k_{vo} for the potato crop, because throughout the course of the study the latter never attained complete cover of the soil surface. To a certain extent, this argument also holds true for the EB_{IRT} technique (Eqs. 3.1 and 3.8).

AED for potatoes was thus measured using the 10 m^2 lysimeter. F_v was calculated from Eqs. 2.16 and 2 17 and F_g from Eq. 2.8. The upper limit vegetation evaporation coefficient was calculated using Eq. 1.15. The potatoes were planted on DOY 223. The row width of the potatoes was 0,9 m and plant density 3 plants per square meter. From DOY 289 onward the fractional ground cover was 0,9 which corresponded to a LAI of 2,5 and F_v of 0,83 (see Figs. 5.1 and 5.2).

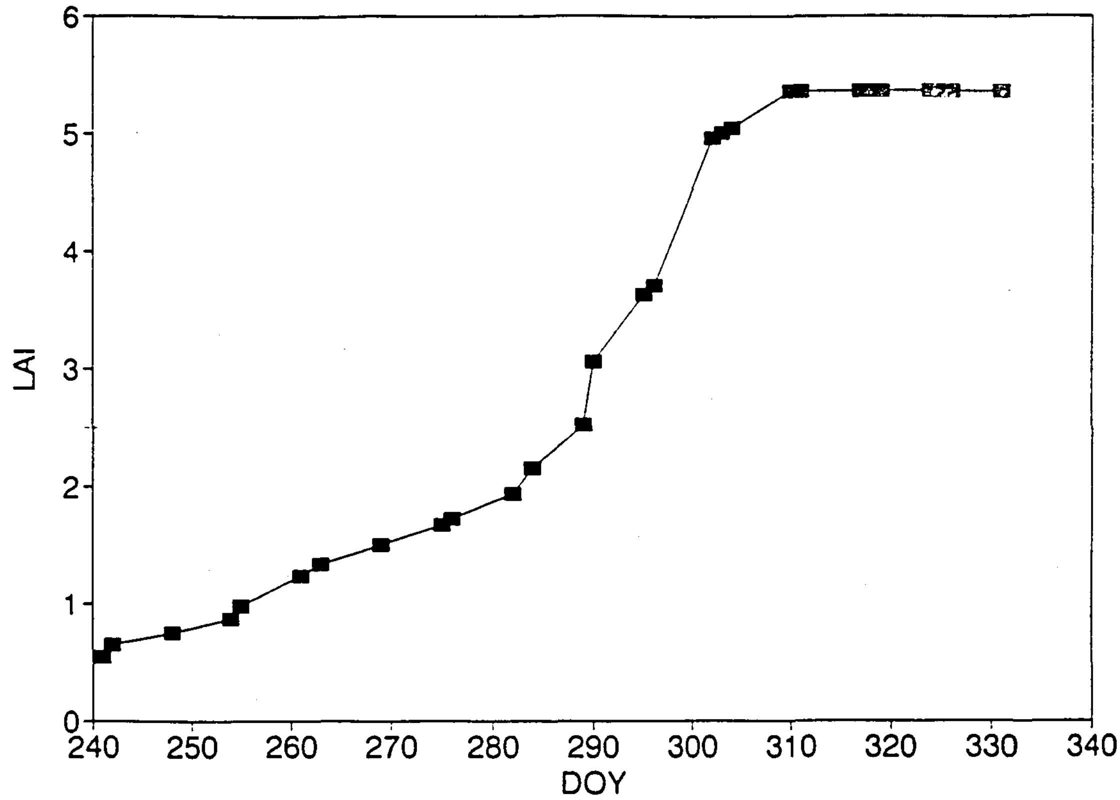


FIG. 5.1 Variation of LAI for potatoes from DOY 241 till 331. The planting date was DOY 223.

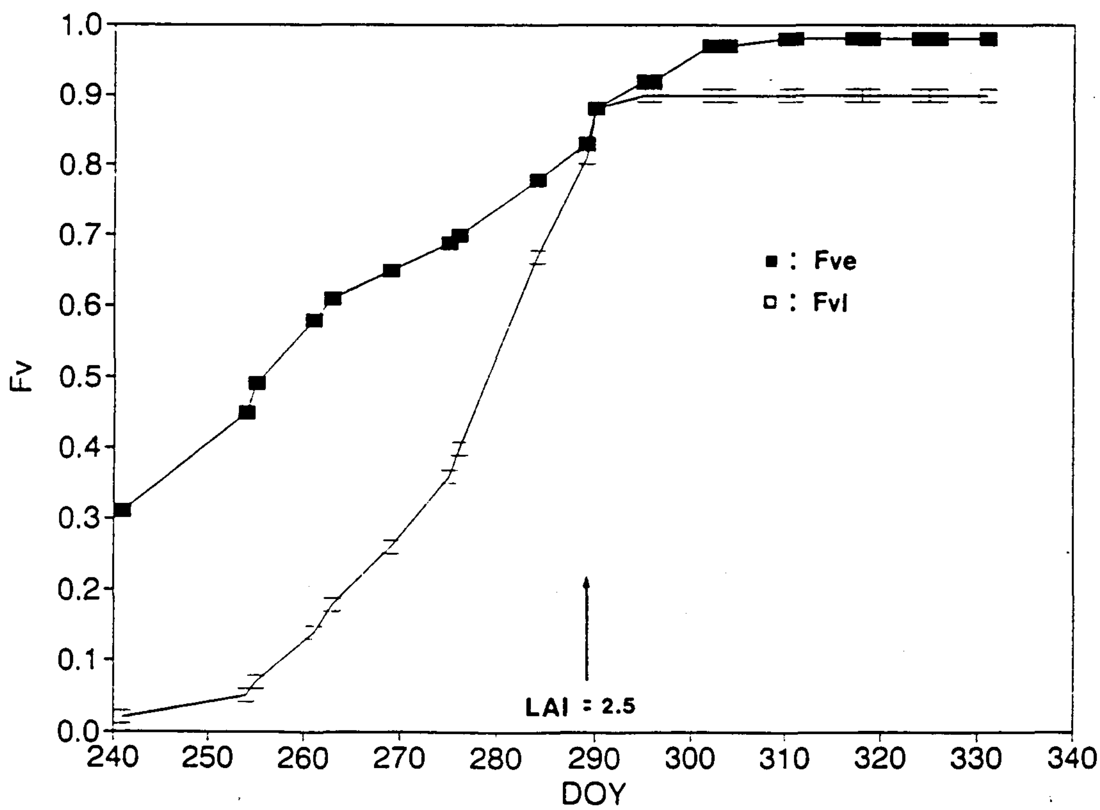


FIG. 5.2 Variation of F_v for potatoes from DOY 241 till 331. The planting date was DOY 223.

5.3.3 Experimental procedure

It was decided to collect hourly values in order to develop a relationship between k_{vo} and the weather elements, because the inherent diurnal variations make possible collecting numerous hourly data sets in a single season. Nine to ten different data sets each corresponding to widely differing climatic conditions were collected in the course of one day. Furthermore, this meant that the experiment could be carried out on a single site instead of at various localities.

The study was undertaken during the spring (September through November) of 1990 on the agrometeorological experimental site (see Fig. 3.1) on the West Campus of the University of the Orange Free State, South Africa.

The grass lysimeter was also used to measure E_o hourly. A lysimeter planted to potatoes was installed in the centre of a potato field, 2 ha in size. The exposed area, resolution, depth and accuracy at moderate wind speeds of this lysimeter were 10 m^2, 0,07 mm, 2,5 m and 0,02 mm respectively. Meteorological instrumentation (net radiometer, aspirated psychrometer and wind speed sensor) used during the study were installed on the grass site.

The degree of wetness of the soil surface ,F_g, varied from wet to dry during the investigation (Fig. 5.3). The degree of wetness was accounted for by calculating F_g using Eq. 1.7. The entire experimental plot was irrigated frequently to prevent moisture stress. This ensured that vegetation evaporation proceeded at

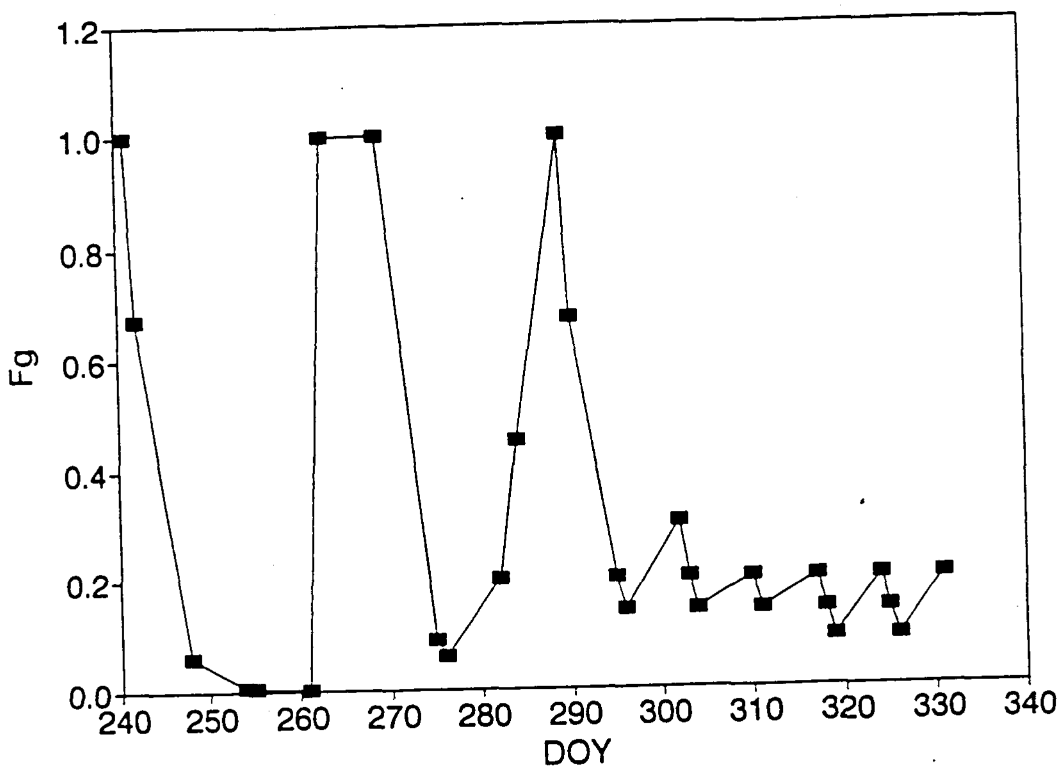
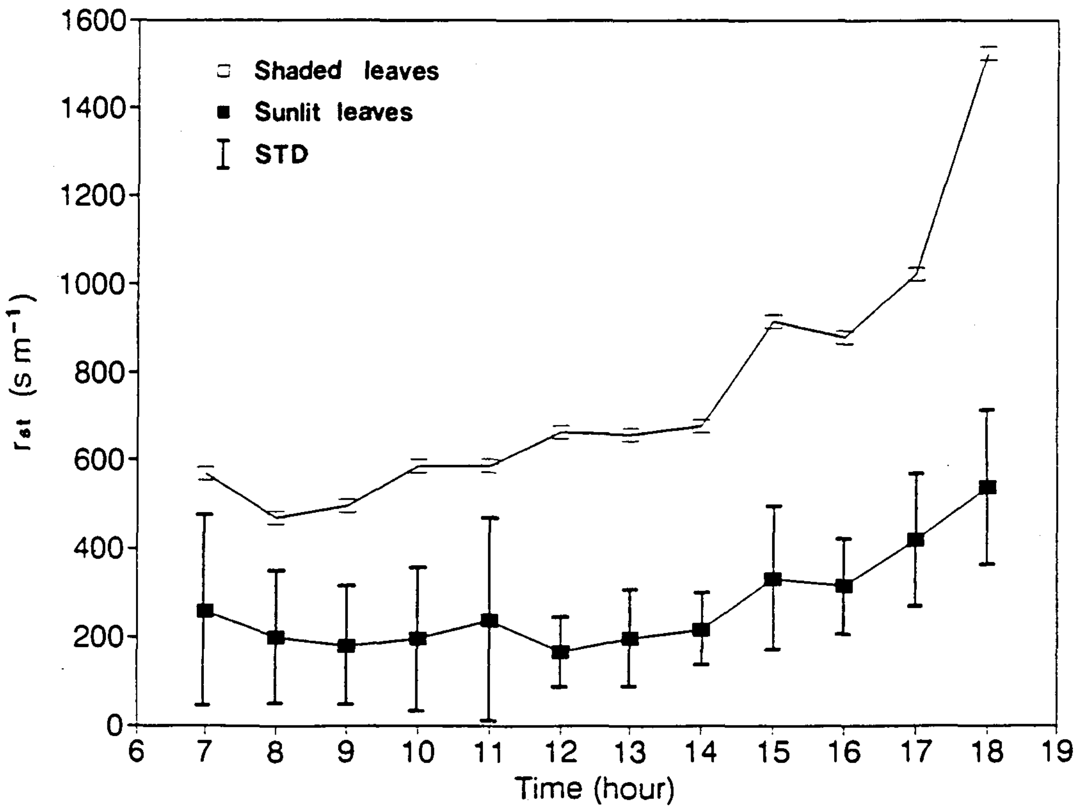


FIG 5.3 Variation of F_g for potatoes from DOY 241 till 331.



FIG, 5.4 Mean hourly stomatal resistance of sunlit and shaded potato leaves for the 1990 season.

the maximum rate at all times in both crops (potatoes and grass) during the experiment. The root zone was maintained close to field capacity by frequent irrigation so that Fh = 1 at all times in both lysimeters. Measured mean hourly stomatal resistances approximated 200 s m^{-1} for sunlit leaves and 600 s m^{-1} for shaded leaves (see Bristow, 1982) supporting the contention that little stress could have been present on the days of observation (Fig. 5.4). Stomatal resistance was measured on the half hour using a LICOR-1600 steady state autoporometer. A total of approximately 2600 measurements were made during the study.

Hourly mean measurements of the following meteorological variables were made on the grass viz.

- net radiation, R_{no}, at 1 m height.
- ambient temperature, T_o, and wet bulb temperature at 1,5 m above grass level.
- wind speed u_{zo} at height 1,5 m above grass level.

Water vapour pressure e_o, was calculated from ambient and wet bulb temperatures.

Self constructed ventilated fine wire copper-constantan thermocouples (see Van Zyl and De Jager, 1986), were used to measure ambient and wet bulb temperatures.

Hourly observations were obtained between 7:00 till 18:00 on certain days of the year (DOY) viz., 241, 248, 254, 255, 261, 263, 269, 275, 276, 284, 289, 290, 295, 296, 302, 303, 304, 310, 311, 317, 318, 319, 324, 325, 326 and 331. A total of 257 data sets were collected.

The influence of weather elements on k_{vo} was investigated by simple linear and multiple linear regression analysis, firstly on the entire 257 hourly data sets and secondly on hourly data values collected on DOY 241 through 284 and on DOY 289 through 331 separately.

Between DOY 289 and 331 the measured fractional vegetation ground cover, named F_{vf}, was constant at 0,9. F_{vf} is given by

$$F_{vf} = (RW - F)/RW \qquad 5.6$$

where
RW = row width (m)
and F = width of sunlit inter-row ground surface measured at noon (m)

Between DOY 241 and 331 hourly k_{vo} was calculated from Eqs. 1.7, 1.9, 2.16 of 2.17, E_o (PME) or E_o measured lysimetrically (LYS) and AED measured lysimetrically. Values of k_{vo} calculated hourly were denoted by k_{voh} (F_{ve}, PME) when F_v was calculated using Eq. 2.16 and k_{voh} (F_{vl}, PME) when F_v was calculated from the logistic function Eq. 2.17. The subscript $_h$ here refers to hourly values. Later subscript $_d$ will be used to denote daylight values. From DOY 289 through 331 k_{voh} was also calculated for F_{vf} measured, and was denoted by k_{voh} (F_{vf}, PME). A transient coefficient = 3,0 was used in Eq. 2.17 to calculate k_{voh} (F_{vf}, PME).

5.4 RESULTS AND DISCUSSION

5.4.1 Analysis of data

During experimentation, measured leaf area index of the potatoes varied between 0,5 and 5,4 (see Fig. 5.1). The vertically projected area of leaf cover of the ground, F_{vf} (Eq. 5.6) at a LAI =

2.5 approximated 0,90. This constituted almost complete vegetative cover. Theoretical F_{ve} = 0,83 (see Fig. 5.2).

Fig. 5.5 clearly illustrates the hourly variation in k_{voh} (F_{ve}, PME) from DOY 241 till 331. The theoretical relative error in k_{voh} (F_{ve}, LYS) was ± 0,40 at dawn (8:00) for moderate wind speeds of 2 to 3 m s^{-1}. This relative error at noon (12:00) was only ± 0,04. The differences in relative error are attributable to low evaporation rates experienced at early morning by comparison to those to those experienced at noon. The lower the evaporation rate the larger the relative error in E_o and AED, and hence k_{voh} (F_{ve}, LYS). Hourly variations in k_{voh} (F_{ve}, LYS) ranged between approximately 0,1 and 2,5 which mostly far exceeded the highest recorded relative error of ± 0,40. It is therefore evident that the variations in k_{voh} (F_{ve}, LYS) were real and not due to errors in measurement of E_o and/or AED.

The relative error in k_{voh} (F_{ve}, LYS) was obtained as follows:
For wind speeds ranging from 2,5 to 3,0 m s^{-1} the accuracy of the two lysimeters was 0,02 mm. The relative error in measured AED and E_o for evaporating rates of 0,1 mm h^{-1} (early morning) and 1,0 mm h^{-1} (mid-day) was 0,20 (= 0,02/0,1) and 0,02 (0,02/1,0) respectively. The relative error in k_{voh} (F_{ve}, LYS) is therefore the summation of the relative error in AED and E_o, which in this case was 0,40 and 0,04 for the two times of day respectively.

It was postulated that the hourly weather changes illustrated in Figs. 5.6, 5.7, 5.8 and 5.9 were responsible for the significant changes in k_{voh} (F_{ve}, PME).

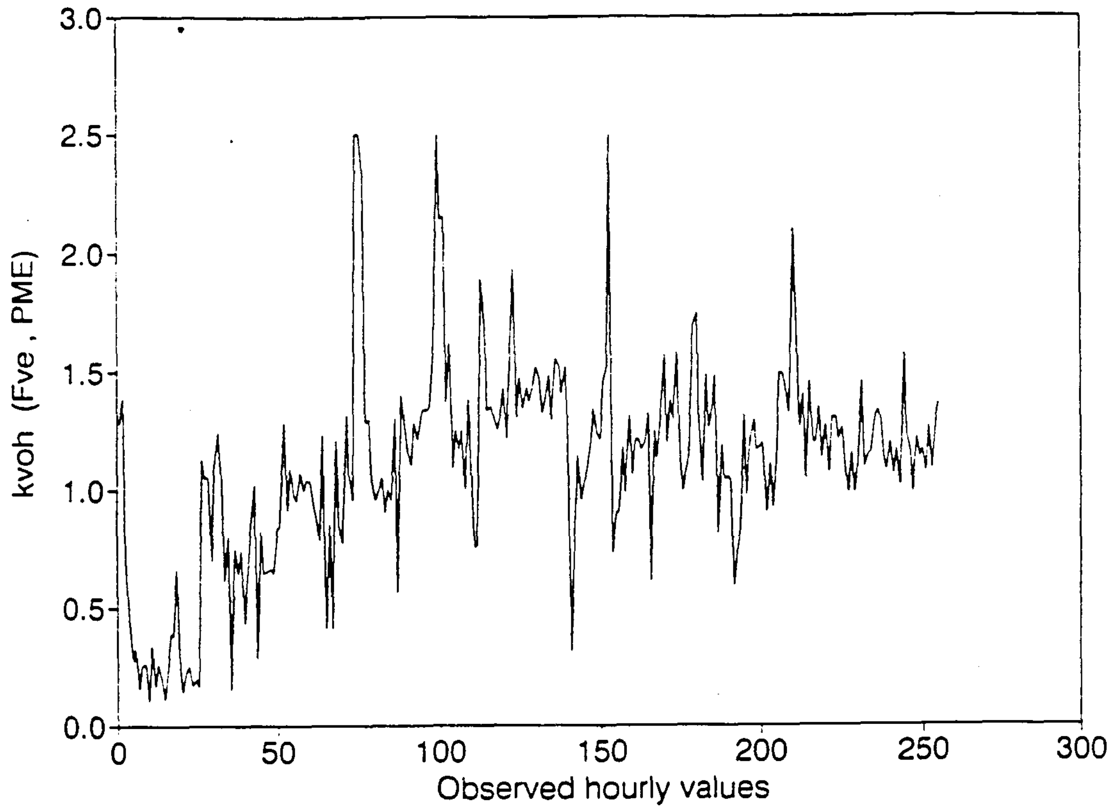


FIG. 5.5 Variation in hourly values of k_{voh} (F_{ve}, PME) for potatoes from DOY 241 till 331.

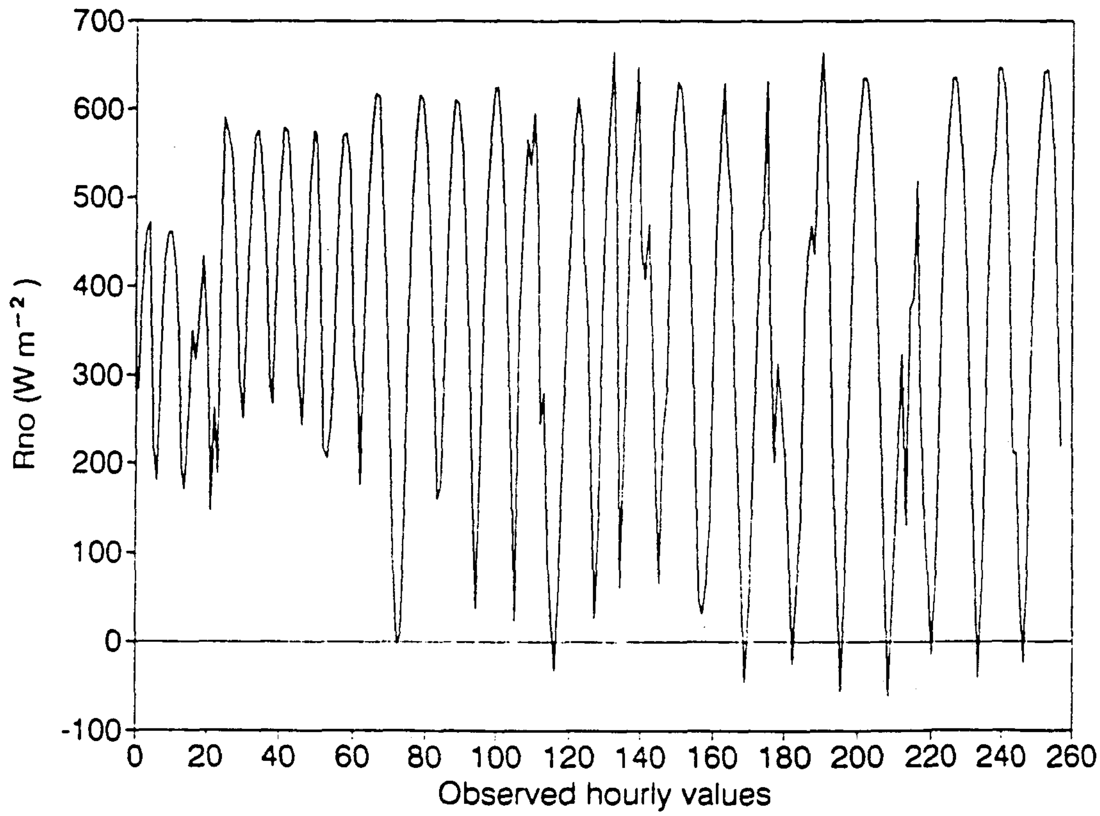


FIG. 5.6 Variations in hourly values of net radiation (R_{no}) from DOY 241 till 331.

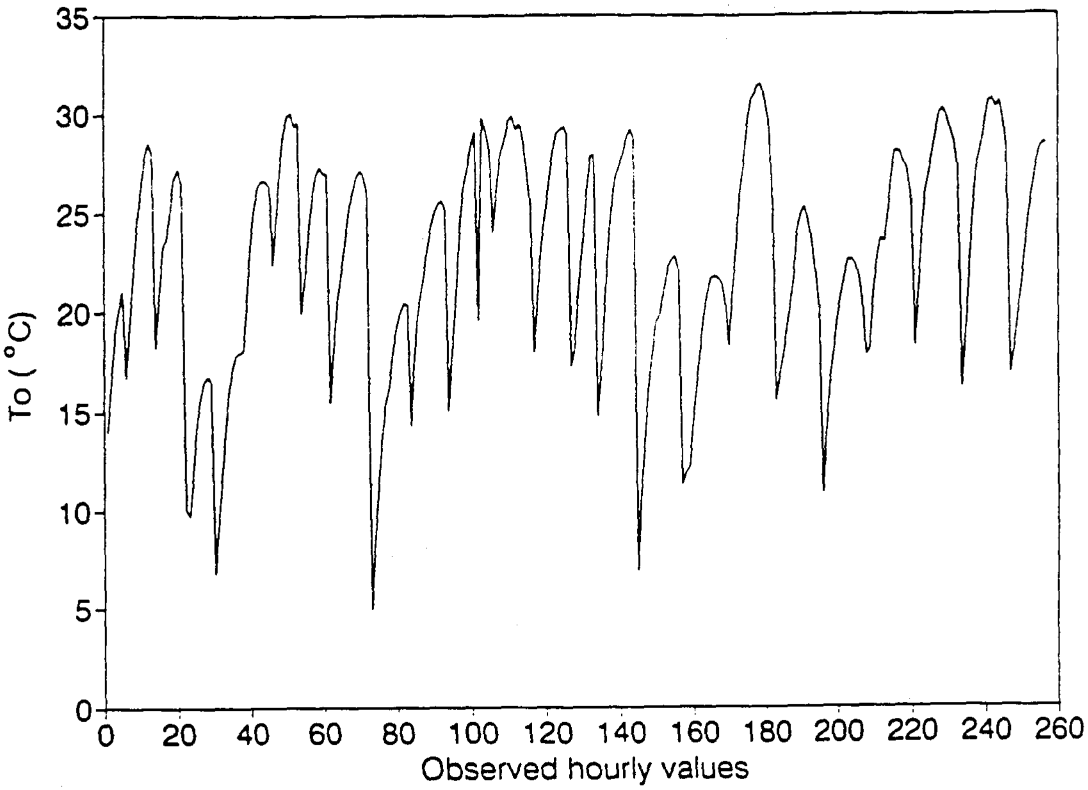


FIG. 5.7 Variation in hourly values of ambient temperature (T_o) from DOY 241 TO 331.

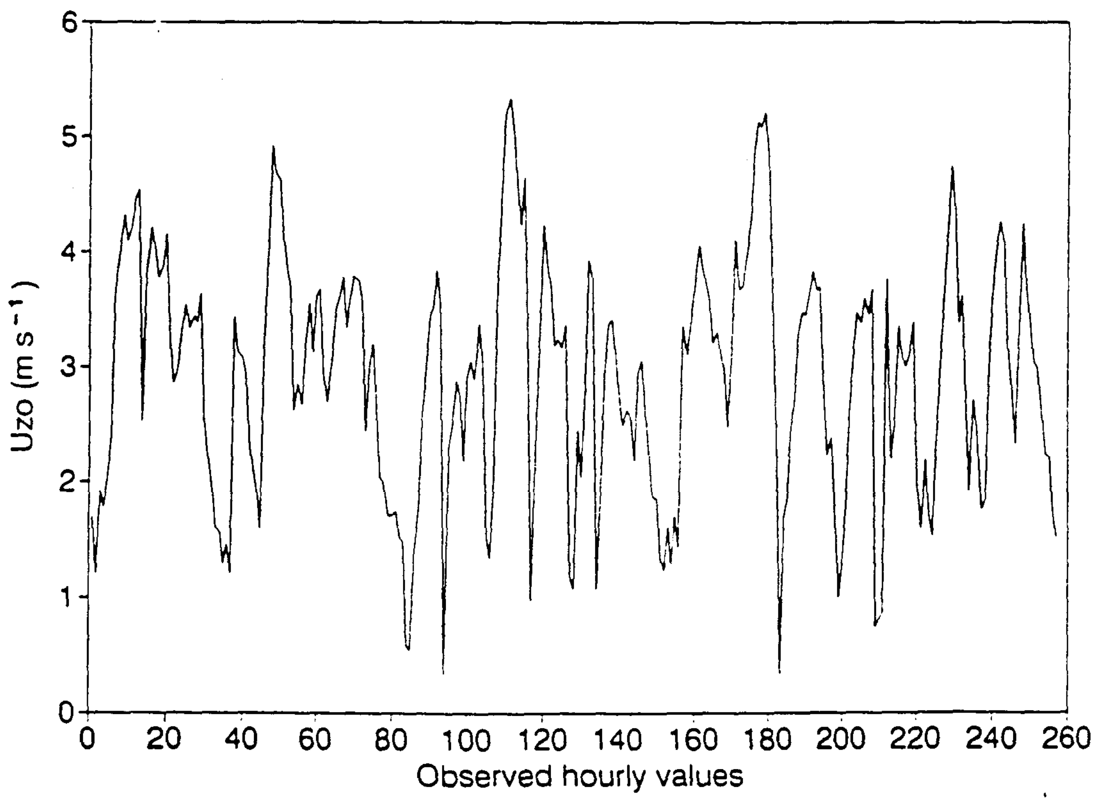


FIG. 5.8 Variation in hourly values of wind speed (u_{zo}) from DOY 241 till 331.

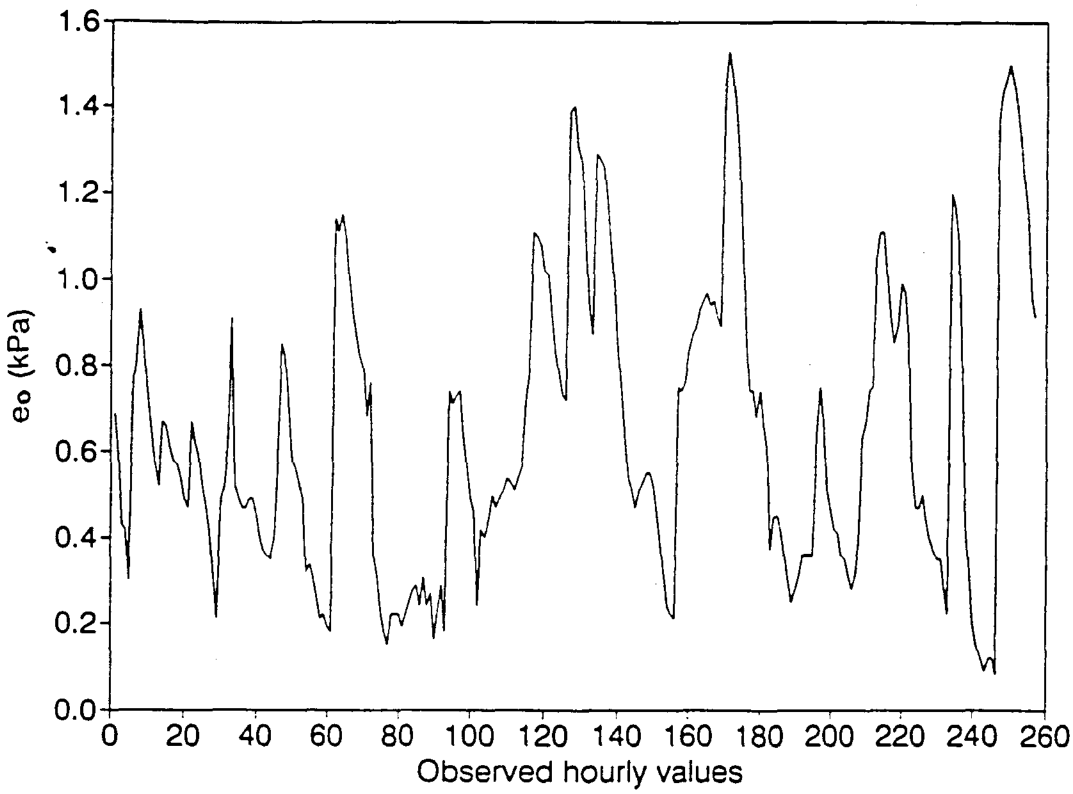


FIG. 5.9 Variation in hourly values of water vapour pressure (e_o) from DOY 241 till 331.

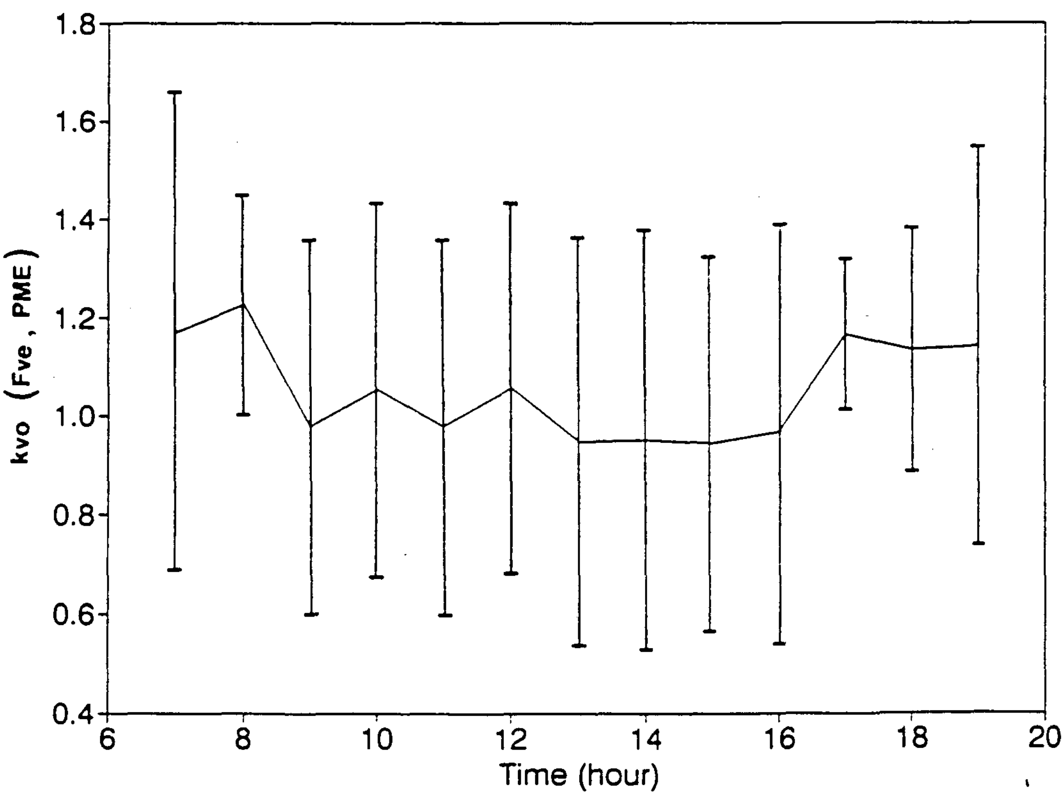


FIG. 5.10 Mean hourly variation in k_{vo} (F_{ve}, PME) for the period DOY 241 till 331. The bar indicates 1 standard deviation.

Hourly relationships between k_{voh} (F_{ve}, PME), k_{voh} (F_{vl}, PME) and k_{voh} (F_{vf}, PME) and weather elements, using multiple linear regression analyses, were computed to quantify the climate's control of k_{vo}. The results are presented in Table 5.1.

Table 5.1 is a list of the regression coefficients, coefficient of determination ,r^2 and significance level of the multiple regression equation k_{voh} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_{zo} + a_4 e_o$.

Multiple regression analyses were carried out firstly for the entire period i.e. from DOY 241 till 331 and thereafter for the periods DOY 241 till 284 and DOY 289 till 331.

Because of the low r^2 obtained from hourly values, improved relationships were sought by examining the same regressions but firstly using three-hourly means and secondly daylight values for the same time intervals, i.e. DOY 241 through 331, DOY 241 through 284 and DOY 289 through 331.

The three-hourly results were little better than the hourly results. The highest r^2 obtained with the use of three-hourly data was 0,53 at a 1% significant level.

Table 5.2 summarizes the regression coefficients, coefficient of determination, r^2 and significance level of the equation k_{vod} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_{zo} + a_4 e_o$. The subscript $_d$ denotes mean daylight values, i.e. the mean of the daylight hourly values collected each DOY.

TABLE 5.1 Summary of the regression coefficients, coefficient of determination, r^2 and significance level of the multiple regression equation k_{voh} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_{zo} + a_4 e_o$, obtained from micro-meteorological hourly observations for the potato crop.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{voh} (F_{ve}; PME)	241-331	255	0,27	1%	0,2605	-0,0006	0,0361	-0,2883	0,1581
k_{voh} (F_{vl}; PME)	241-331	255	0,08	1%	1,7022	-0,0007	0,0191	-0,1890	0,0924
k_{voh} (F_{ve}; PME)	241-284	62	0,39	1%	0,7519	0,0001	0,0285	-0,3350	0,5526
k_{voh} (F_{vl}; PME)	241-284	62	0,09	1%	2,9218	-0,0015	0,0088	-0,3956	0,5889
k_{voh} (F_{ve}; PME)	289-331	193	0,21	1%	1,3488	-0,0007	0,0319	-0,2135	0,0415
k_{voh} (F_{vl}; PME)	289-331	193	0,20	1%	1,3799	-0,0007	0,0345	-0,2230	0,0769
k_{voh} (F_{vf}; PME)	289-331	193	0,21	1%	1,3538	-0,0007	0,0341	-0,2178	0,0867

TABLE 5.2 Summary of the regression coefficients, coefficient of determination, r^2 and significance level of the multiple regression equation k_{vod} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_{zo} + a_4 e_o$, obtained from micro-meteorological daylight observations for the potato crop.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	254-326	22	0,62	1%	0,9802	-0,0005	0,0438	-0,3973	0,6488
k_{vod} (F_{vl}; PME)	254-326	22	0,43	1%	0,7659	-0,0010	0,0381	-0,0706	0,2790
k_{vod} (F_{ve}; PME)	254-284	7	0,99	1%	0,1202	0,0021	0,0556	-0,5814	0,6577
k_{vod} (F_{vl}; PME)	254-284	7	0,75	5%	-2,8041	-0,0608	0,0195	0,8991	0,2918
k_{vod} (F_{ve}; PME)	289-326	15	0,86	1%	1,0757	-0,0005	0,0158	-0,0179	0,4190
k_{vod} (F_{vl}; PME)	289-326	15	0,87	1%	1,0874	-0,0005	0,0153	-0,1023	0,4811
k_{voh} (F_{vf}; PME)	289-326	15	0,85	1%	1,0654	-0,0004	0,0151	-0,0985	0,4824

The best relationship for the first period i.e. DOY 254 till 284 which emerged was

$$k_{vod}\ (F_{ve},\ PME) = 0,1202 + 0,0021\ R_{no} + 0,0556\ T_o - 0,5814\ U_{zo} + 0,6577\ e_o \qquad 5.7$$

with a r^2 of 0,99 at 1% significance level.

For the second period i.e. from DOY 289 till 326

$$k_{vod}\ (F_{vl},\ PME) = 1,0874 - 0,0005\ R_{no} + 0,0153\ T_o - 0,1023\ u_{zo} + 0,4811\ e_o \qquad 5.8$$

was best with a r^2 of 0,87 and a significance level of 1%.

Eqs. 5.7 and 5.8 explained as much as 99% and 87% of the variation in k_{vo}, both at a significance level of 1,0%. The daylight multiple linear regressions do indeed reflect considerable improved agreement over the hourly analyses.

The r^2 in the early season were greater than in the late season. This was probably due to F_{ve} and F_{vl} not adequately removing the influence of increasing LAI.

The evaporation coefficients thus determined will be valid only in climates where the range of values of individual elements lie within the experimental range (see Tables 5.3 and 5.4).

It was furthermore shown that T_o, u_{zo} and e_o, individually, had little influence on variations in k_{vod} (F_{ve}, PME) for the first period (DOY 254 till 284). The coefficients of determination (r^2) were 0,04; 0,03 and 0,10 for the different weather elements respectively. However R_{no} was shown to have a pronounced effect on k_{vod} for the same period. A coefficient of determination (r^2)

of 0,58 was obtained for daylight values. The relationship found was

Table 5.3 Mean, standard deviation and range of seven daylight evaporation coefficients k_{vmd} (F_{ve} or F_{vl}, PME) and weather elements from DOY 254 till 284.

Variable	Mean	Standard deviation (1 SD)	Range
k_{vod} (F_{ve},PME)	0,60	± 0,24	0,20 - 0,82
k_{vod} (F_{vl},PME)	1,09	± 0,43	0,13 - 1,45
R_{no}	397 W m^{-2}	± 44 W m^{-2}	306 - 457 W m^{-2}
T_o	21,72 °C	± 3,98 °C	15,33 - 25,97 °C
u_{zo}	3,33 m s^{-1}	± 0,36 m s^{-1}	2,61 - 3,89m s^{-1}
e_o	0,58 kPa	± 0,12 kPa	0,37 - 0,76 kPa

Table 5.4 Mean, standard deviation and range of fifteen daylight evaporation coefficients k_{vmd} (F_{ve} or F_{vl} or F_{vf}; PME), and weather elements from DOY 289 till 326.

Variable	Mean	Standard deviation (1 SD)	Range
k_{vod} (F_{ve},PME)	1,21	± 0,13	0,87 - 1,41
k_{vod} (F_{vl},PME)	1,28	± 0,15	0,87 - 1,51
k_{vod} (F_{vf},PME)	1,28	± 0,1	0,88 - 1,51
R_{no}	344 W m^{-2}	± 75 W m^{-2}	206 - 494 W m^{-2}
T_o	22,78 °C	± 3,92 °C	16,65 - 28,78 °C
u_{zo}	2,70 m s^{-1}	± 0,73 m s^{-1}	0,94 - 4,26m s^{-1}
e_o	0,59 kPa	± 0,26 kPa	0,20 - 1,03 kPa

$$k_{vod}\ (F_{ve},\ PME) = -0{,}9996 + 0{,}0021\ R_{no} \qquad 5.9$$

Eq. 5.9 suggests that k_{vod} (F_{ve}, PME) increases with an increase in net radiation during early growth stages.

For the period DOY 289 till 326 simple regression analysis yielded r^2-values of 0,01; 0,36; 0,00 and 0,23 for R_{no}, T_o, u_{zo} and e_o respectively when related to k_{vod} (F_{ve}, PME) individually.

The best r^2 for daylight comparisons resulted when the combined effect of all four weather elements R_{no}, T_o, u_{zo} and eo was considered. This finding further supports the conclusion that the variations observed in calculated k_{vod} (F_{ve}, PME) were due to changing weather conditions.

The mean k_{vod} (F_{ve}, PME) observed from DOY 289 till 326 was 1,21 ± 0,13 (Table 5.4) when F_{ve} > 0,83 (see Fig. 5.2). This is in close agreement with the value of 1,05 - 1,20 for evaporation coefficients ,k_c, of potatoes reported by Doorenbos & Kassam (1979). At nearly complete cover, k_{vo} approaches k_c (see Eq. 2.14).

Considering that positive values of regression coefficients in Eqs. 5.7 and 5.8 imply that AED increases with respect to E_o, while negative values indicate that AED decreases with respect to E_o, the mean daylight variations in k_{vod} (F_{ve}, PME) due to the four weather elements can be explained as follows:

Virtually no differences in temperature and water vapour pressure were observed in the ambient air above the grass and the potatoes. However surface temperatures, as measured with the infrared thermometer, were generally lower over the grass compared to potatoes. Between 7:00 and 9:00 small differences were observed, but differences ranging from 1°C to 5°C occurred between 9:00 and 19:00. The lower grass temperatures compared to potato temperatures mean that the assumed saturated water vapour pressure in stomatal cavities of potatoes was higher than was the case for grass. This results in a higher vapour pressure gradient between stomatal cavity and ambient air above potatoes. This means that the evaporation rate from potatoes exceeded the evaporation rate from grass, causing an increase in k_{vod} (F_{ve}, PME) and explaining the positive regression coefficient for air temperature in Eqs. 5.7 and 5.8.

Mean hourly water vapour pressure measured over grass declined (see Fig. 5.14) from 0,9 kPa at 7:00 to about 0,5 kPa at 16:00 in similar fashion to the trend depicted for k_{vod} (F_{ve}, PME) in Fig. 5.10. It is apparent from Figs. 5.10 and 5.11 that k_{vod} (F_{ve}, PME) increased with increasing water vapour pressure.

During early season, the net radiation measured over the potatoes was slightly lower than over short grass between 9:00 and 15:00. This means that relatively more energy was available for evaporation from grass than from potatoes. During this period the potatoes were only wetted on three occasions (see Fig. 5.3), which means that over these days (from DOY 241 till 289) the mean calculated F_g of 0,38 constituted a semi-dry exposed soil surface. Evaporation from the soil surface therefore decreased and the temperature of the soil surface consequently increased. This in turn increased upward radiation, which is responsible for the reduction in net radiation compared to that of grass. As F_{ve} increased over the early growing season AED increased with respect to E_o. During this phase an increase in net radiation was observed. This phenomenon explained the positive regression coefficient for R_{no} in Eqs. 5.7 and 5.9. At a stage when F_{ve} reaches a maximum value, the regression coefficient of net radiation is negative. The latter cannot be physically interpreted at this stage. No correlation was found between k_{vo} (F_{ve}, PME) and R_{no}. The r^2 was 0,01.

Mean hourly wind speeds over the entire experimental period showed a gradual increase from about 1,8 m s^{-1} at 7:00 to 3,3 m s^{-1} at 15:00 and eventually dropped to 2,8 m s^{-1} at 19:00. It is difficult to relate this scenario to the variations in k_{vod} (F_{ve}, PME) (Fig. 5.12). Higher wind speeds were however recorded over grass suggesting a slightly lower bulk aerodynamic resistance and hence increased E_o. This would tend to reduce k_{vod} (F_{ve}, PME) with increasing wind speed and explain the negative sign of the fourth term in Eqs. 5.7 and 5.8.

To summarize then, the diurnal variation between k_{vo} and e_o is quite similar (Figs. 5.10 and 5.11). This is not the case between kvo and the other three remaining weather elements, viz u_{zo}, R_{no} and T_o (see Figs. 5.10, 5.12, 5.13 and 5.14).

5.4.2 Computation of k_{vo} for different climates

The statistical significance found for Eqs. 5.7 and 5.8 makes acceptable their use for creating climatic correction factors for evaporation coefficients. For the sake of simplicity in the ensuing discussion k_{vod} (F_{ve}, PME) will be understood for k_{vo}

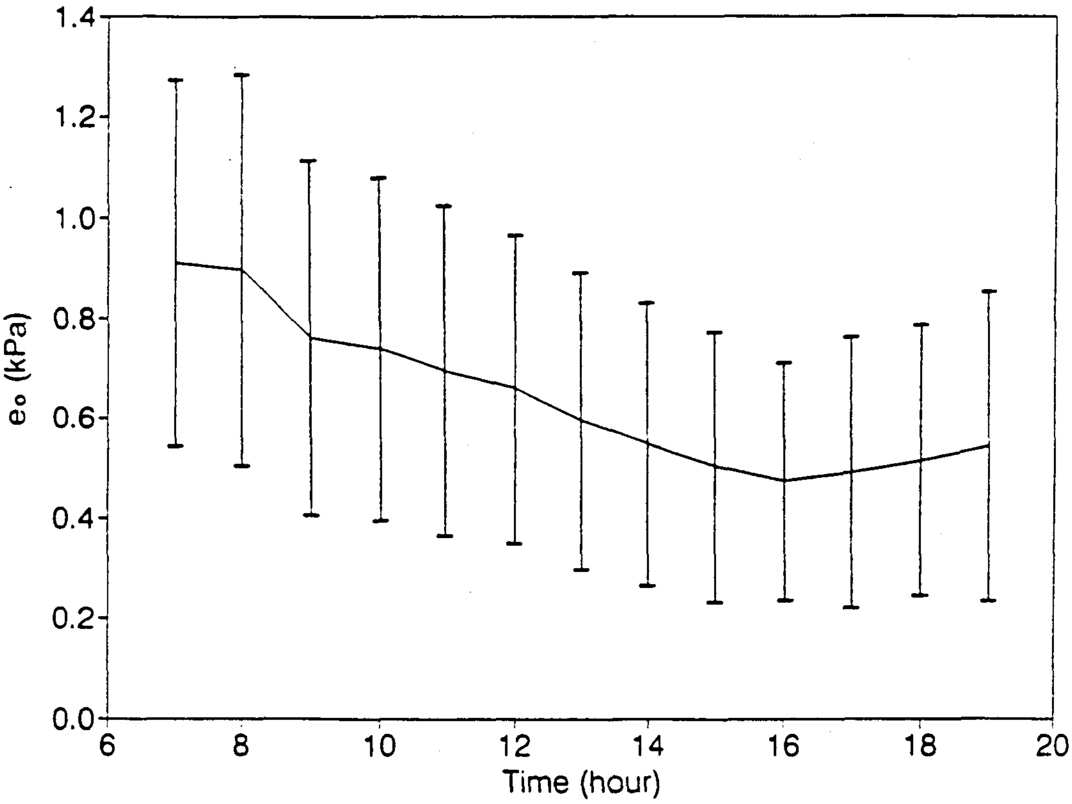


FIG. 5.11 Mean hourly variation in e_o for the period DOY 241 till 331. The bar indicates 1 standard deviation.

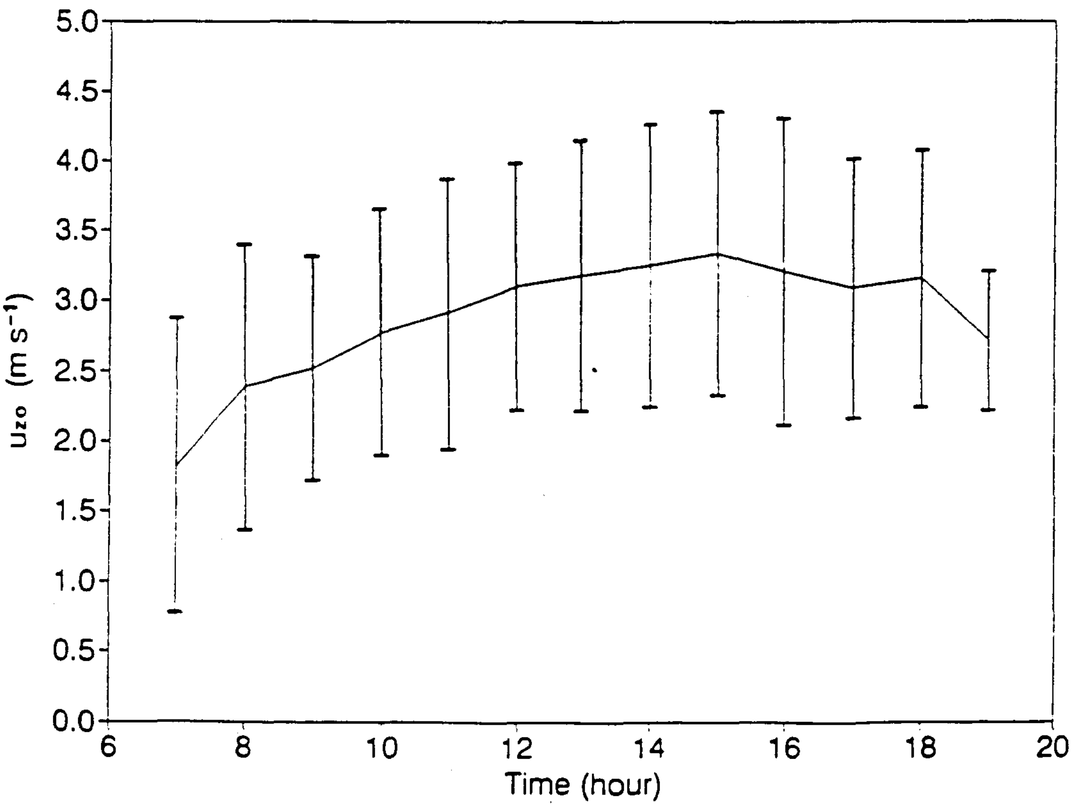


FIG. 5.12 Mean hourly variation in U_{zo} for the period DOY 241 till 331. The bar indicates 1 standard deviation.

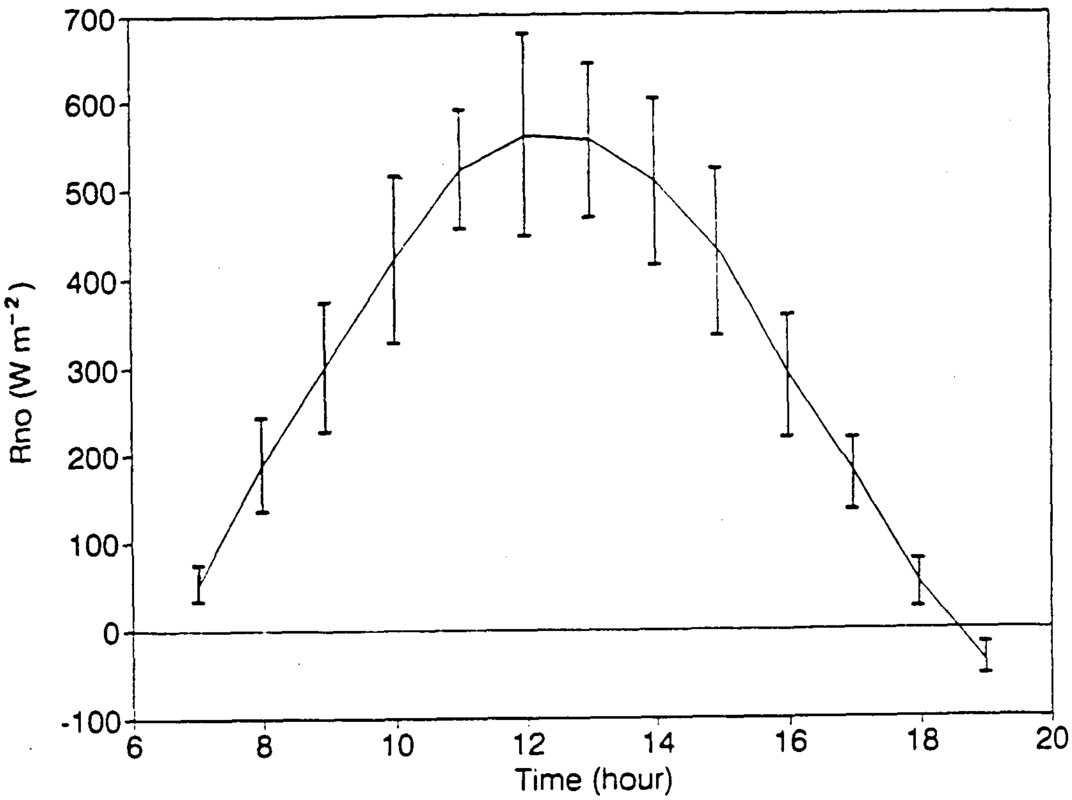


FIG. 5.13 Mean hourly variation in R_{no} for the period DOY 241 till 331. The bar indicates 1 standard deviation.

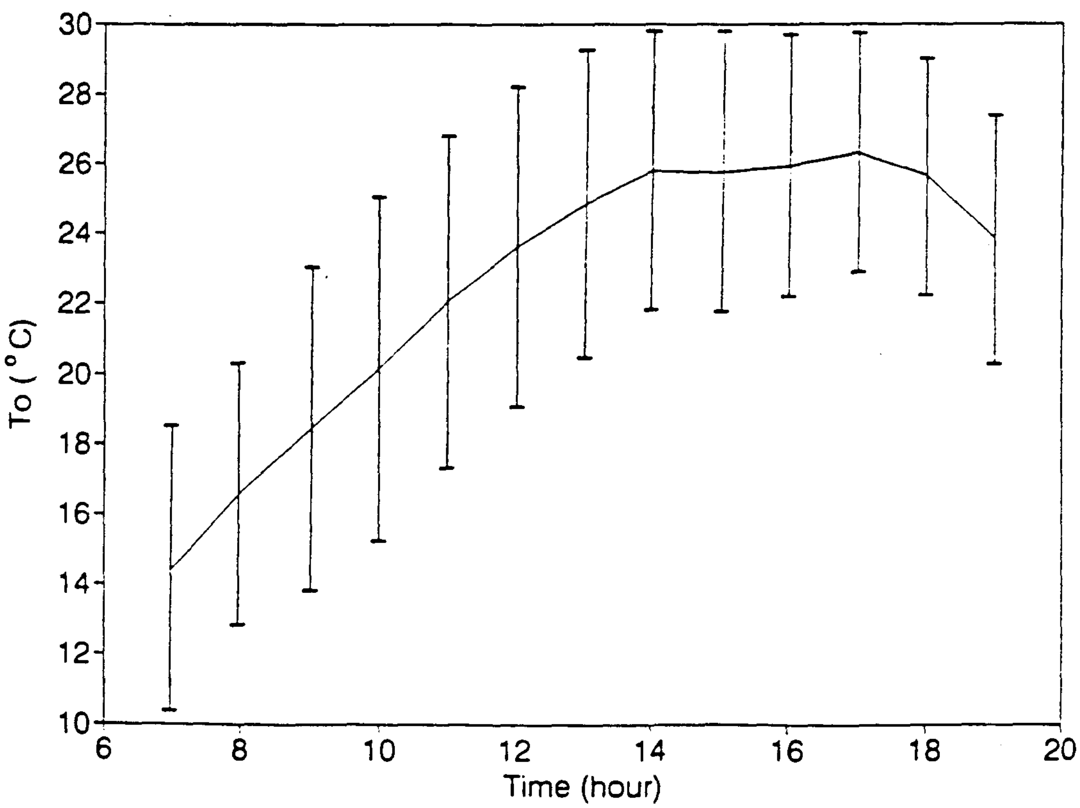


FIG. 5.14 Mean hourly variation in T_o for the period DOY 241 till 331. The bar indicates 1 standard deviation.

henceforward. Suppose an evaporation coefficient was determined for a given crop under given average climatic conditions. Define this as the normal evaporation coefficient and denote it as k_{vo}^*. Such coefficient would have been measured under a specified set of conditions, named normal, and described by say R_{no} = 344 W m^{-2}, T_o = 22,78°C, u_{zo} = 2,70 m s^{-1} and e_o = 0,59 kPa (see Table 5.4).

The question now arises: What will be the true k_{vo} for the given crop, under a different set of conditions, described say by R_{no} = 494 W m^{-2}, T_o = 28,78°C, u_{zo} = 4,26 m s^{-1} and e_o = 1,03 kPa (see Table 5.4).

The conversion of k_{vo}^* to k_{vo} for the new set of conditions is achieved by multiplying by an evaporation coefficient climate adjustment factor denoted by say ν. This climatic adjustment factor is defined as the ratio of the evaporation coefficient pertaining to a given set of climatic conditions, to that found for normal conditions, viz.

$$\nu = \frac{k_{vo}}{k_{vo}^*} \qquad 5.10$$

In Eq. 5.10 k_{vo} may be calculated from Eq. 5.8 for any set of conditions and a table for ν. In practice then, the true evaporation coefficient could be obtained from the value of ν extracted from such table and substituted in

$$k_{vo} = \nu\ k_{vo}^* \qquad 5.11$$

Ideally, it would be necessary to repeat the present experiment for all crops. However, as a first approximation it may be assumed that Eq. 5.8 is valid for field crops with similar architecture to that of potatoes. This assumption makes possible extrapolation of the theory to other crops for which the normal evaporation coefficient and weather conditions under which it was determined are known.

By architectural similarity is meant that either

- k_{vo} for the crop under consideration equals k_{vo} for potatoes under the same average climatic conditions, or

- although k_{vo} for the crop might not be equal to k_{vo} for potatoes under the same average climatic conditions, the deviation in k_{vo} from k_{vo}^* is similar to the corresponding deviation for potatoes.

If the first assumption is valid, k_{vo} for the new crop can simply be determined from Eq. 5.8.

In the case of the second assumption, ν may be obtained for a different crop, given $k_{vo}*$ for that crop and the climatic conditions under which it was obtained. This is achieved by writing Eq. 5.10 as follows:

$$\nu = \frac{k_{vo}* + \blacktriangle k_{vo}}{k_{vo}*} \qquad 5.12$$

where $\blacktriangle k_{vo}$ is the change in $k_{vo}*$ brought about by different climatic conditions. This may be computed from Eq. 5.8. Thus,

$$\blacktriangle k_{vo} = \frac{\delta k_{vo} \blacktriangle R_{no}}{\delta R_{no}} + \frac{\delta k_{vo} \blacktriangle T_o}{\delta T_o} + \frac{\delta k_{vo} \blacktriangle u_{zo}}{\delta u_{zo}} + \frac{\delta k_{vo} \blacktriangle e_o}{\delta e_o} \qquad 5.13$$

(Note correcting u_{zo} for standard height of exposure of anemometers is necessary (see Allen, et al., 1979)).

Numerically then, the present example becomes

$$\Delta k_{vo} = - 0,0005 (494-344) + 0,0153 (28,78-22,78) - 0,1023 (4,26-2,70) + 0,4811 (1,03-0,59)$$
$$= 0,0690$$

and hence from Eq. 5.12

$$\nu = 1,0 + 0,0690/1,2724 = 0,84$$

The relative importance and contribution of each weather element are aptly illustrated by this example. The validity of the architectural similarity assumption awaits verification.

These procedures to determine k_{vo} have the advantage of eliminating the need to repeat the numerous and time consuming experiments here undertaken for potatoes on other crops.

The term F_h in Eq. 1.7 simulates the influence of water stress upon the evaporation coefficient. A multiplicative law for estimating the limitation due to a number of processes in combination is here assumed. The exact nature of the interaction between F_h and k_{vo} requires further investigation.

The reliability of this model requires further testing on independent data.

5.5 CONCLUSION

Hourly values for k_{vo} for potato varied between approximately 0,1 and 2,5. This generally exceeded the experimental relative error of 0,40, and could not be ascribed to errors in the measurement of E_o and AED. It was thus concluded that the large variations in k_{vo} were due to the combined and varying influence of radiation, ambient temperature, water vapour pressure and wind speed.

The relationship between evaporation coefficients and weather elements was sought using single and multiple linear regression procedures. A multiple linear regression model for predicting k_{vo} from values of net radiation, ambient temperature, water vapour pressure and wind speed was developed. The reliability of this model for daylight values is reflected by a coefficient of determination of r^2 of 0,99 and 0,87 for early and mid-season stages respectively, significant at the 1% confidence level. The mean k_{vo} (F_{ve}, PME) for the early season was 0,60 ± 0,24 and 1,21 ± 0,13 for mid-season.

Furthermore, the concept of a normalized evaporation coefficient measured under specified conditions and the adjustment thereof for climatic variation was developed. The resultant climatic adjustment factor is defined as the ratio of actual (k_{vo}) to normal (k_{vo}^*) evaporation coefficient, i.e.

$$\nu = \frac{k_{vo}}{k_{vo}^*}$$

As interim measure and a first approximation it is suggested that use of this equation might be extended to other field crops, with architecture similar to that of potatoes. Corresponding relationships need to be developed for all crops. The validity of this approximation also needs verification.

The sensitivity of all calculations of k_{vo} as here defined to vertically projected leaf area cover of the ground surface was demonstrated. Use of a logistic model with transient coefficient equal to 3,0 for F_v (i.e. F_{v1}) is also appropriate for potatoes.

It may further be concluded that it has been difficult to measure hourly evaporation coefficients to serve as analogues for longer time intervals. This approach offers so great a potential for rapidly producing results that the perfection of the micro-meteorological techniques has become a priority.

CHAPTER 6

6. INFLUENCE OF WEATHER ELEMENTS ON UPPER LIMIT VEGETATIVE EVAPORATION COEFFICIENTS FOR THE MAIZE CROP USING MICRO-METEOROLOGICAL MEASUREMENTS DURING 1992.

6.1 INTRODUCTION

The objective of the work discussed in this chapter was, for maize, to develop a relationship between k_{vo} and the weather elements net radiation ,R_{no}, air temperature ,T_o, wind speed ,u_{zo}, and water vapour pressure ,e_o and to investigate the influence of stomatal behaviour of grass and maize on k_{vo}. The subscript $_o$ signifies measurements carried out over the short grass surface.

6.2 MATERIALS AND METHOD

A similar approach to that described for potatoes in Chapter 5 was followed, but for maize in this chapter. A mathematical relationship between k_{vo} and the micro-meteorological weather elements was sought.

The study was carried out on the same experimental plot, but planted to maize however. Both the grass site and maize plot were kept well watered, to prevent any water stress. As was the case with potatoes, low values of stomatal resistance were measured, indicating that no stress persisted during the study. Mean hourly stomatal resistance for grass and maize of the order of 300 s m^{-1} and 150 s m^{-1} respectively were observed (see Fig. 6.6).

The maize was planted on the 1991-12-10 (DOY 345) at a row width of 0,9 m. The date of emergence was 1991-12-22 (DOY 357). The plant density was 4,5 plants per square meter.

The following mean hourly measurements were made on the grass site:

- AED for the maize was measured with the large 10 m^2 lysimeter planted to maize.
- Net radiation 1 m above grass level using a net radiometer.
- Wet and dry bulb temperatures 1,3 m above grass level using aspirated thermistors.
- Wind speed 1 m above grass level using a three cup electric generator anemometer.
- Soil heat flux density 5 mm below ground level on the grass surface using soil heat flux sensors.
- Vertical wind fluctuations using the sonic anemometer installed 0,25 m above the grass surface.
- Temperature fluctuations using a fine-wire copper-constantan thermocouple 0,25 m above the grass surface.
- Water vapour density using a krypton hygrometer, also installed at a height of 0,25 m above the grass surface.

The latter three measurements were duplicated at a height of 0,25 m above the maize crop surface. The instrument levels were adjusted as the maize crop developed so as to ensure a constant measuring height of 0,25 m above the maize crop surface throughout the growing season.

Net radiation was measured 1 m above the maize crop surface and soil heat flux density between and within the maize crop rows. The soil heat flux sensors were embedded 5 mm below the ground surface.

Leaf stomatal resistance of both the grass and maize were measured on the half hour using the LICOR steady state autoporometer. Measurements were made on leaves exposed to sunlight. Five measurements were made on the grass leaves and five on the maize leaves, on each occassion. The mean of the five leaves was used to calculate stomatal mean hourly resistance and stomatal conductance. A total of about 3000 measurements were made during the study.

Leaf area indices (LAI) were measured weekly on five maize plants outside the lysimeter. The same plants were used each week. The leaf area of each leaf was determined from the product of leaf length x leaf width x 0,75. LAI was then calculated from the sum of the leaf areas of the five individual plants and the plant density. The LAI was used to calculate F_{ve} or F_{vl} from Eqs. 2.18 and 2.19.

The area of the ground covered by the maize leaves at noon was determined by measuring the sunlit ground surface with a meter rule. These measurements offerred an alternative estimate of F_v termed F_{vf} and was calculated using Eq. 5.6.

Wetting events were carefully recorded in order to calculate F_g from Eq. 1.13.

Hourly measurements were carried out on DOY 7, 9, 13, 14, 17, 20, 21, 27, 28, 29, 34, 35, 37, 41, 42, 44, 48, 49, 51, 55, 56, 62, 63, 65, 69, 70, 71, 76, 77, 79, 84, 86, 91, 93 and 100 of 1992.

k_{vo} was determined from Eq. 1.9 using lysimeter values of AED, E_o calculated from the PME, F_v calculated from Eqs. 2.16 or 2.17 or 5.6 while F_g was obtained from Eq. 1.7.

The relationship between k_{vo} and the weather elements R_{no}, T_o, u_{zo}, and e_o was obtained from a multiple regression analysis.

The following combinations were used to relate k_{vo} to the weather elements i.e. k_{voh} (F_{ve}, PME), k_{voh} (F_{vl}, PME) and k_{vod} (F_{vf}, PME).

The subscripts $_h$ and $_d$ refer to hourly and daylight values respectively. PME refers to E_o calculated from the PME.

6.3 RESULTS AND DISCUSSION

6.3.1 Analysis of data

Figs. 6.1; 6.2; 6.3 and 6.4 show the variation in LAI, F_v (estimated from Eqs. 5.6; 2.18; 2.19), F_g and height of maize crop with DOY respectively. At a LAI of 4,21 on DOY 41, F_v approaches unity from Eqs. 5.6, 2.18 and 2.19.

Fig. 6.5 shows the hourly variation of k_{voh} (F_{ve}, PME) obtained with Eq. 1.9, the PME and micro-meteorological weather data from DOY 7 till 100.

Associated hourly variations of R_{no}, T_o, u_{zo} and e_o (see Figs. 5.6 through 5.9) and mean hourly variation in k_{voh} (F_{ve}, PME) and the weather elements (see Figs. 5.10 through 5.14) exhibited a similar trend as in Chapter 5.

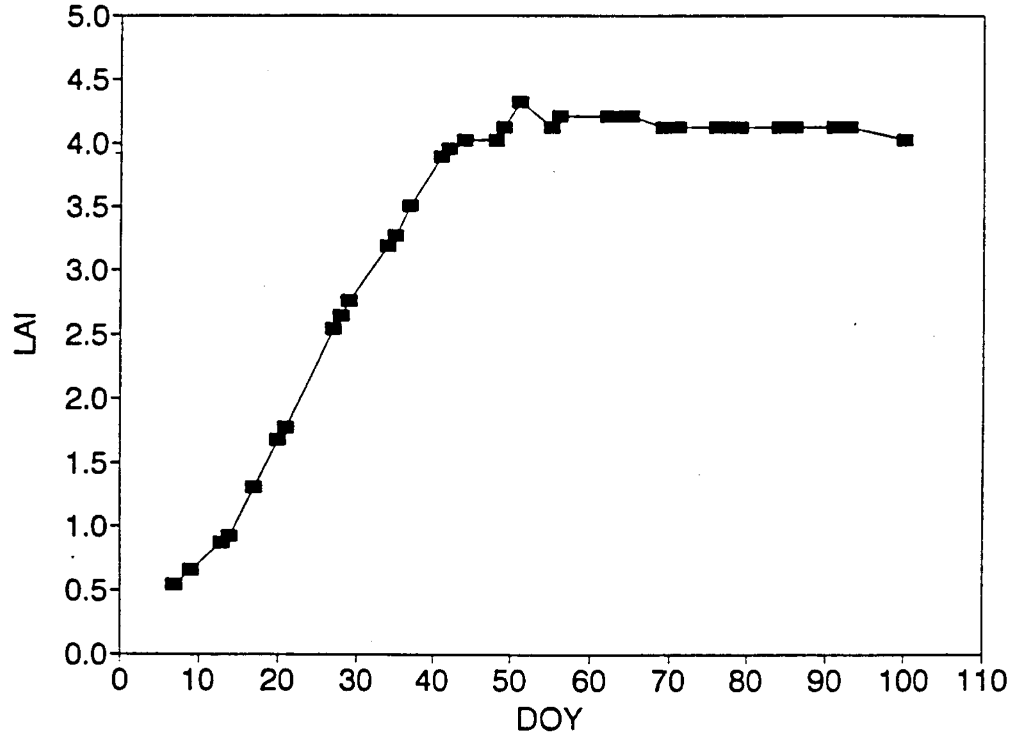


FIG. 6.1 Daily variation in measured LAI for maize.

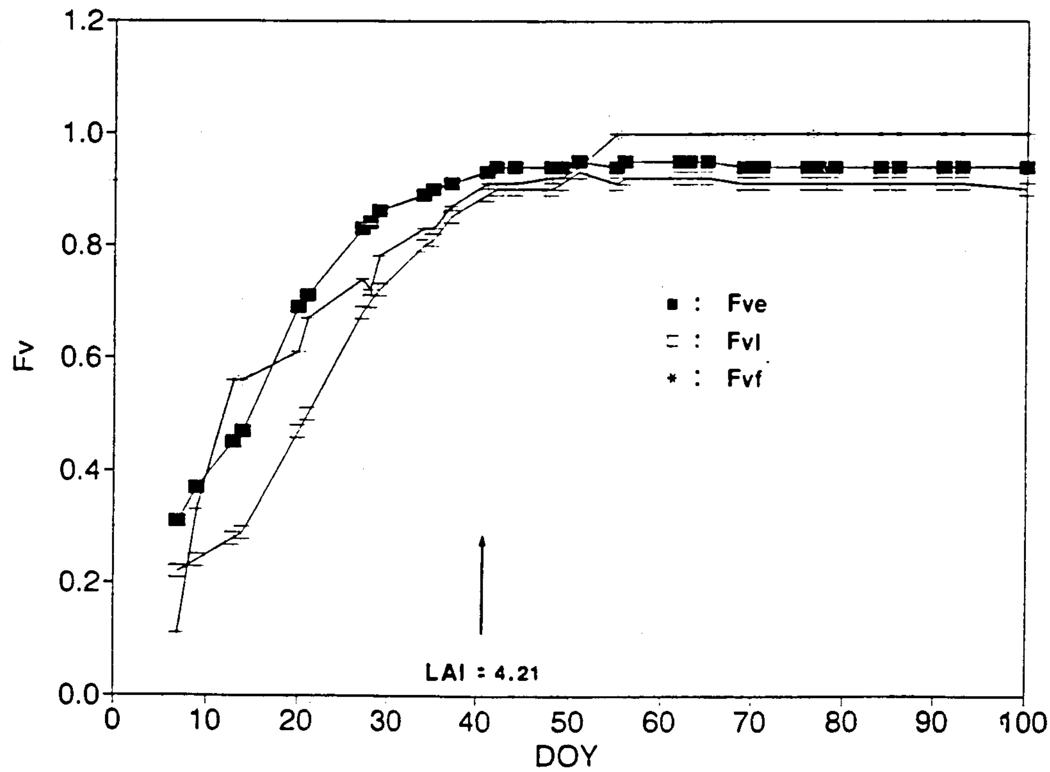


FIG. 6.2 Daily variation in F_v calculated for maize using Eqs. 2.16, 2.17 and 5.6.

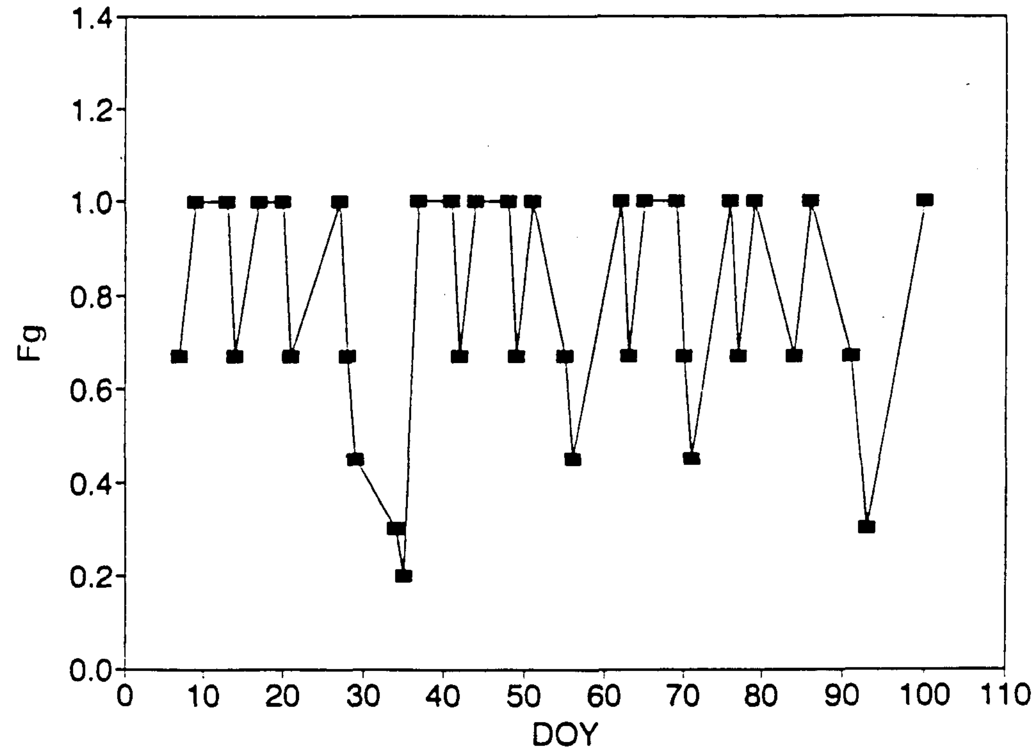


FIG. 6.3 Daily variation in F_g calculation for maize using Eq. 1.7.

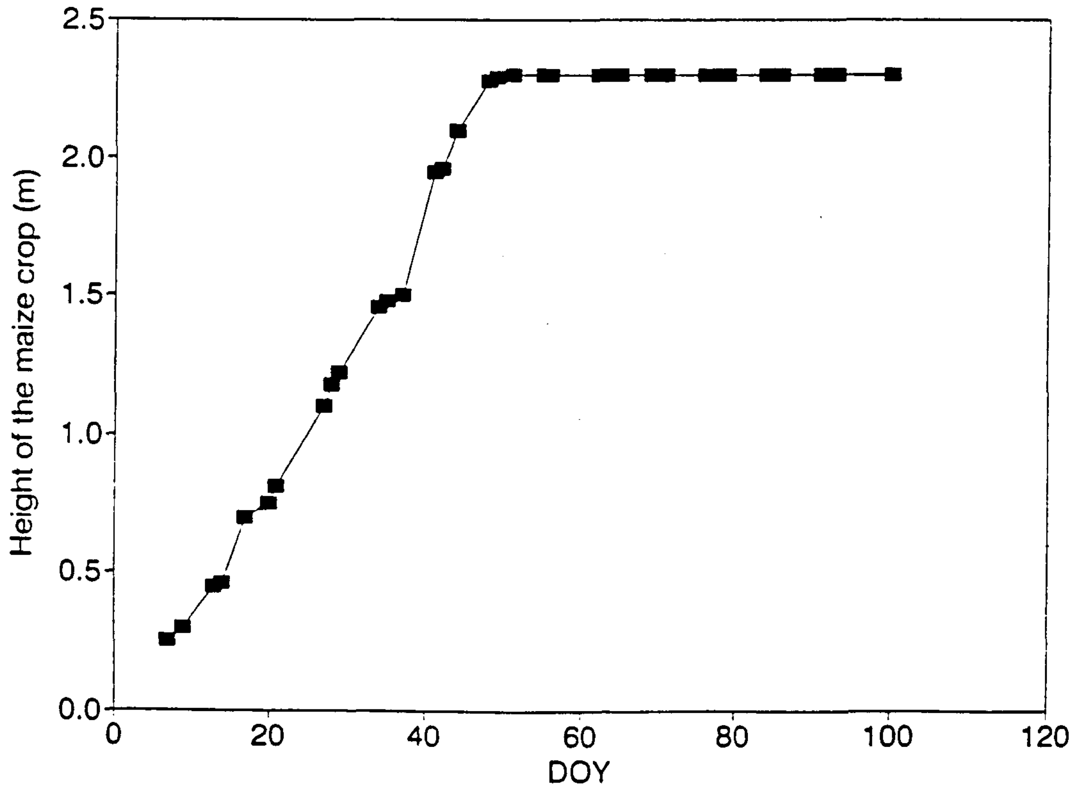


FIG. 6.4 Daily variation in measured crop height for the maize crop.

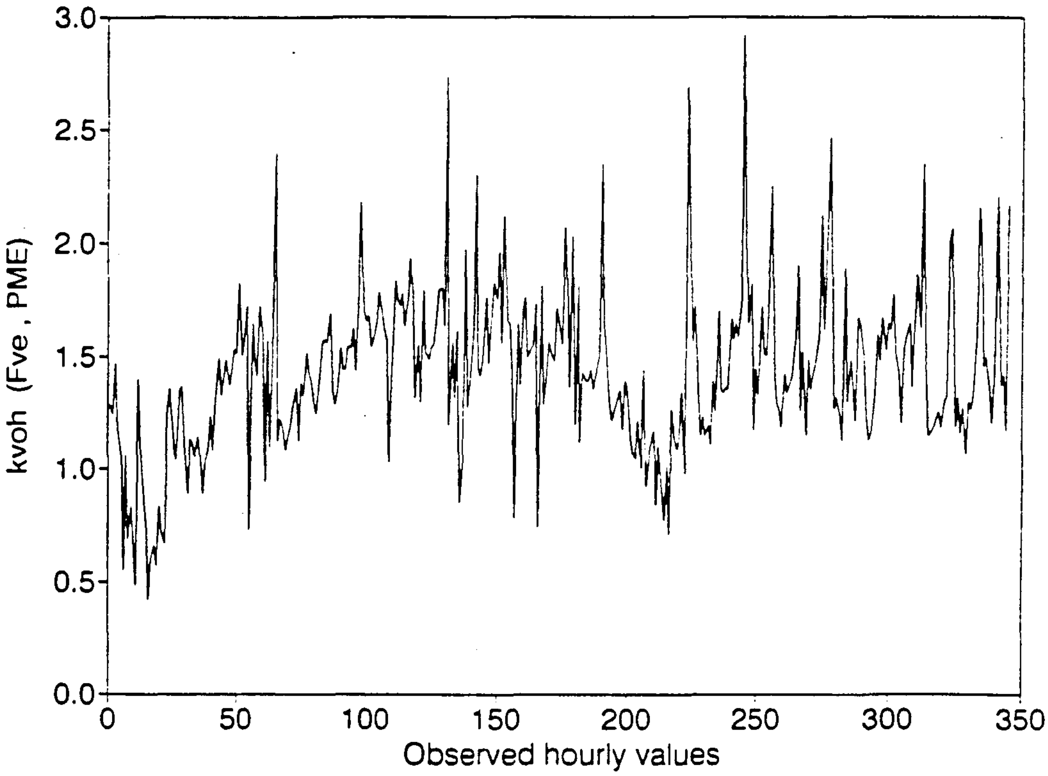


FIG. 6.5 Hourly variation in k_{vor} (F_{ve}, PME) from DOY 7 to 100.

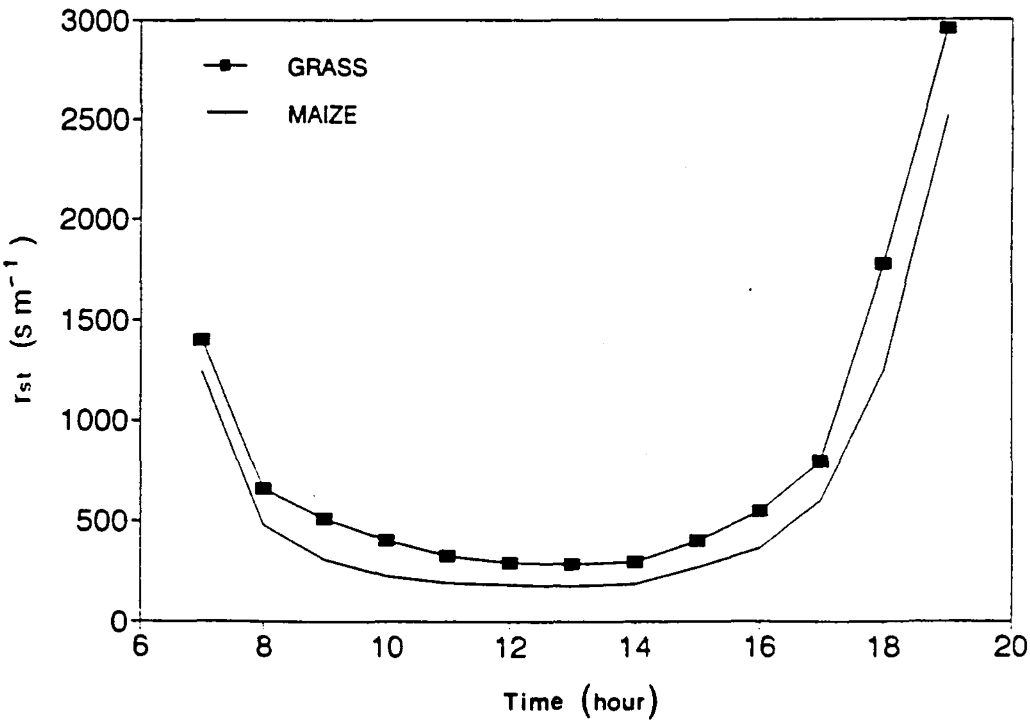


FIG. 6.6 Mean hourly variation in maize and grass stomatal resistance, r_{st}, for the period DOY 7 till 100. The standard deviation at 12:00 was ± 146 and ± 189 s m^{-1} for maize and grass respectively.

Tables 6.1 and 6.2 summarize the regression coefficients, coefficient of determination, r^2 and significance level of k_{vo} of the multiple regression of k_{vo} and the micro-meteorological weather elements R_{no}, T_o, u_{zo} and e_o for the maize crop, carried out on hourly and daylight basis respectively.

The low r^2-values indicated that, as with potatoes, k_{voh} correlated poorly with the relevant hourly weather elements (Table 6.1).

Good correlations were obtained between all the cases of k_{vod} and the four weather elements, when the season was split into a developing stage, stretching from DOY 13 till 37 and mature stage covering DOY 41 till 100. This is reflected by the relatively high r^2, ranging from 0,87 to 0,74 (Table 6.2). The regression relationships reflecting best fit for the periods DOY 9 till 37 and DOY 41 till 100 respectively were

$$k_{vod}\ (F_{ve},\ PME) = 1{,}3240 - 0{,}0053\ R_{no} + 0{,}0719\ T_o - 0{,}1146\ u_{zo} + 0{,}3609\ e_o \qquad 6.1$$

and

$$k_{vod}\ (F_{ve},\ PME) = 0{,}9825 - 0{,}0001\ R_{no} + 0{,}0280\ T_o - 0{,}1171\ u_{zo} + 0{,}1536\ e_o \qquad 6.2$$

The coefficients of determination ,r^2, were 0,87 and 0,74, both with a significance level 1%. Eqs. 6.1 and 6.2 are only valid within the range of weather elements indicated in Tables 6.3 and 6.4.

Linear relationships between any of the k_{vod}-values (see Tables 6.1 and 6.2 column one) and the individual weather elements

TABLE 6.1 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation k_{voh} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_z + a_4 e_o$, obtained from hourly micro-meteorological data for the maize crop.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{voh} (F_{ve}; PME)	9-100	345	0,37	1%	1,4813	-0,0006	0,0164	-0,1508	0,0926
k_{voh} (F_{vl}; PME)	9-100	345	0,36	1%	0,4720	-0,0007	0,0195	-0,1582	0,1062
k_{voh} (F_{vf}; PME)	9-100	345	0,36	1%	1,3285	-0,0006	0,0199	-0,1423	0,1405
k_{voh} (F_{ve}; PME)	9-37	109	0,29	1%	0,4064	-0,0006	0,0367	-0,1238	0,4094
k_{voh} (F_{vl}; PME)	9-37	109	0,25	1%	0,7724	-0,0007	0,0312	-0,1499	0,3777
k_{voh} (F_{vf}; PME)	9-37	109	0,28	1%	0,3027	-0,0007	0,0418	-0,1236	0,4485
k_{voh} (F_{ve}; PME)	41-100	236	0,47	1%	1,4322	-0,0007	0,0239	-0,1570	0,0537
k_{voh} (F_{vl}; PME)	41-100	236	0,47	1%	1,4479	-0,0008	0,0251	-0,1612	0,0547
k_{voh} (F_{vf}; PME)	41-100	236	0,46	1%	1,3500	-0,0007	0,0237	-0,1515	0,0951

TABLE 6.2 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation k_{vod} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 R_{no} + a_2 T_o + a_3 u_z + a_4 e_o$, obtained from daylight micro-meteorological data for the maize crop.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	9-100	33	0,50	1%	1,6263	-0,0010	0,0152	-0,1635	0,1351
k_{vod} (F_{vl}; PME)	9-100	33	0,49	1%	0,5905	-0,0010	0,0192	-0,1700	0,1277
k_{vod} (F_{vf}; PME)	9-100	33	0,48	1%	1,3959	-0,0007	0,0170	-0,1551	0,2072
k_{vod} (F_{ve}; PME)	9-37	11	0,74	1%	1,3240	-0,0053	0,0719	-0,1146	0,3609
k_{vod} (F_{vl}; PME)	9-37	11	0,67	5%	2,1738	-0,0061	0,0640	-0,1502	0,2738
k_{vod} (F_{vf}; PME)	9-37	11	0,70	1%	1,1311	-0,0056	0,0835	-0,1100	0,3796
k_{vod} (F_{ve}; PME)	41-100	22	0,87	1%	0,9904	-0,0001	0,0264	-0,1164	0,1517
k_{vod} (F_{vl}; PME)	41-100	22	0,87	1%	0,9825	-0,0001	0,0280	-0,1171	0,1536
k_{vod} (F_{vf}; PME)	41-100	22	0,84	1%	0,9040	0,0001	0,0233	-0,1161	0,2234

TABLE 6.3 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e_a and various methods to calculate k_{vod} for the period DOY 9 through 37.

	S_t W m^{-2}	T_a ^oC	u_z m s^{-1}	e_a kPa	k_{vod} (F_{vo}, PME)	k_{vod} (F_{vl}, LYS)	k_{vod} (F_{vf}, PME)
MEAN	418	28,86	2,69	0,97	1,24	1,33	1,30
STD	41	2,17	0,93	0,17	0,28	0,34	0,30
MIN	364	25,13	1,38	0,67	0,74	0,59	0,75
MAX	503	31,75	3,95	1,21	1,64	1,69	1,68

TABLE 6.4 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e_o and various methods to calculate k_{vod} for the period DOY 41 through 100.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e_o kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, LYS)	k_{vod} (F_{vf}, PME)
MEAN	337	24,47	2,08	0,92	1,49	1,52	1,47
STD	76	3,69	0,65	0,29	0,17	0,17	0,18
MIN	157	15,89	1,05	0,34	1,04	1,05	1,02
MAX	469	30,05	3,60	1,38	1,73	1,76	1,74

yielded a highest r^2 of 0,48 (significant at 1%). The latter figure was obtained between k_{vod} (F_{ve}, PME) and water vapour pressure between DOY 41 and 100. The second best performance was obtained between k_{vod} (F_{ve}, PME) and ambient temperature between DOY 41 and 100. The r^2 was 0,37 at a 1% significance level. Relationships with net radiation and wind speed were significantly lower than this. Evidently water vapour pressure and ambient temperatures are the major climatic factors contributing to variation in k_{vo} in maize.

6.3.2 Upper limit evaporation coefficient, k_{vo}

High k_{vod}-values of approximately 1,50 (see table 6.4) were attained for $F_v \approx 1$. At values of $F_v = 1$, k_{vo} equals the crop evaporation coefficient, k_c (Eq. 2.14). Doorenbos and Kassam (1979), reported values of k_c ranging from 1,05 to 1,20 and Jensen et al. (1982) values of 1,05 and 1,20, yielding a mean of 1,13 for maize. Stanghelini et al. (1990); Gianquinto, et al (1990) reported k_c-values exceeding 1,6 for tomatoes.

The value of approximately 1,5 for k_{vo} for maize is about 33% higher than those reported by Jensen et al. (1982). Such result warrants comment.

An explanation for the high k_{vod} was sought by investigating the relative values of stomatal conductance of the two vetetative types. It is evident from Fig. 6.6 that the measured stomatal resistance of grass constantly exceeds that of maize. Furthermore, when the stomatal conductance, ϕ_{ST} (= $1/r_{ST}$), of maize was regressed against grass, it was found that ϕ_{ST} of maize was about

33% higher than that of grass. The r^2 applicable to this regression was 0,99 for 13 data sets (see Fig. 6.7).

Because the maize plant and grass are of the same family, it might be expected that ϕ_{ST} for maize should approximate ϕ_{ST} for grass. This however was not the case, and the fact that the transpiration capability from maize leaves was 33% higher than that of grass might contribute to the high k_{vo} of 1,5. The conductance of individual leaves for gaseous exchange of course, says nothing about what happens in a closed canopy of the crop where radiation distribution plays an important role.

Mean hourly values of the ratio (ϕ_{ST} maize)/(ϕ_{ST} grass) and k_{vo} (F_{ve}, PME) are plotted against time of day in Figs. 6.8 and 6.9. Both k_{vo} (F_{ve}, PME) and (ϕ_{ST} maize)/(ϕ_{ST} grass) declined gradually from early morning towards noon and then increased again towards evening. A linear regression yielded the following relationship viz.

$$k_{vo} = 0,9225 \{(\phi_{ST} \text{ maize})/(\phi_{ST} \text{ grass})\} + 0,7905 \qquad (6.3)$$

The r^2 was 0,52 at a significance level of 1%.

Most significantly of course, is the effect of F_v which may have been underestimated by Eq. 2.16 and 2.17. This would cause serious overestimation of k_{vo}.

Another cause for concern is the fact that the maize in the lysimeter could have been subject to advection, at a stage when

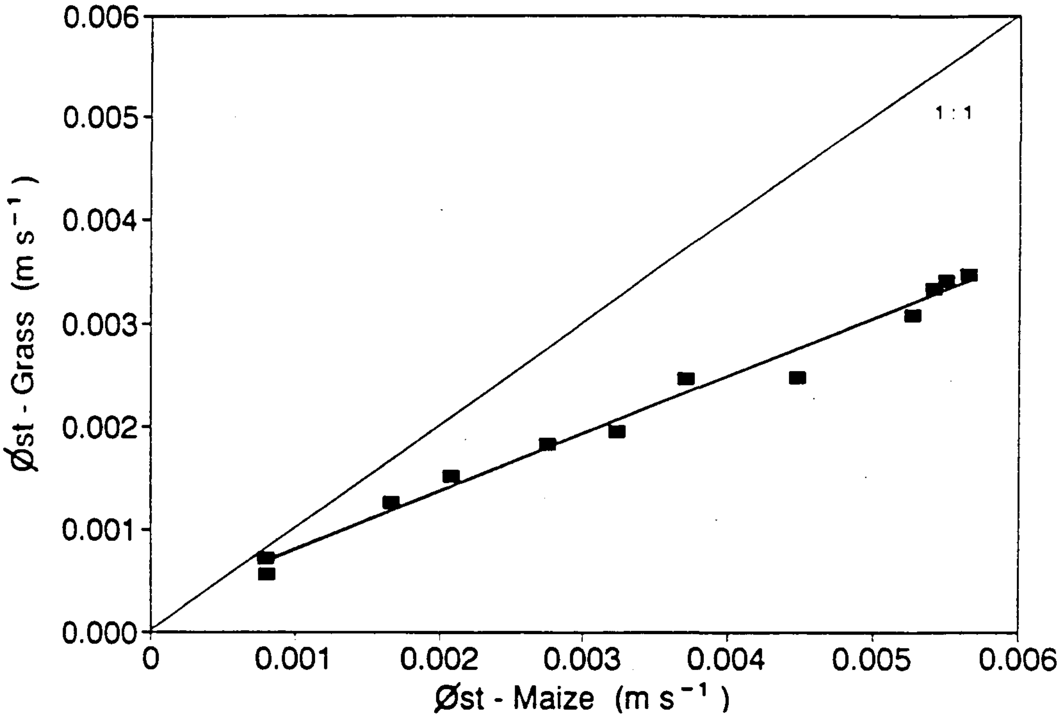


FIG. 6.7 Comparison between stomatal conductance , ϕ_{ST}, for grass and maize crops.

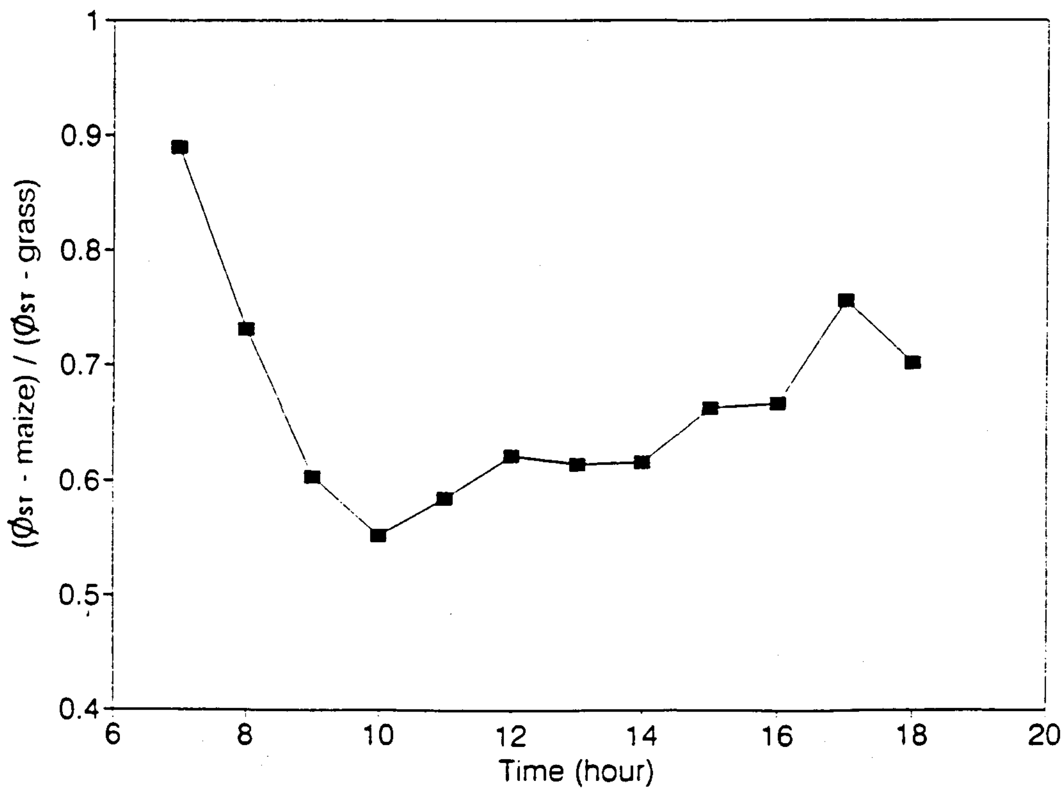


FIG. 6.8 Diurnal variation in the mean hourly ratio (ϕ_{ST} - maize)/(ϕ_{ST} - grass).

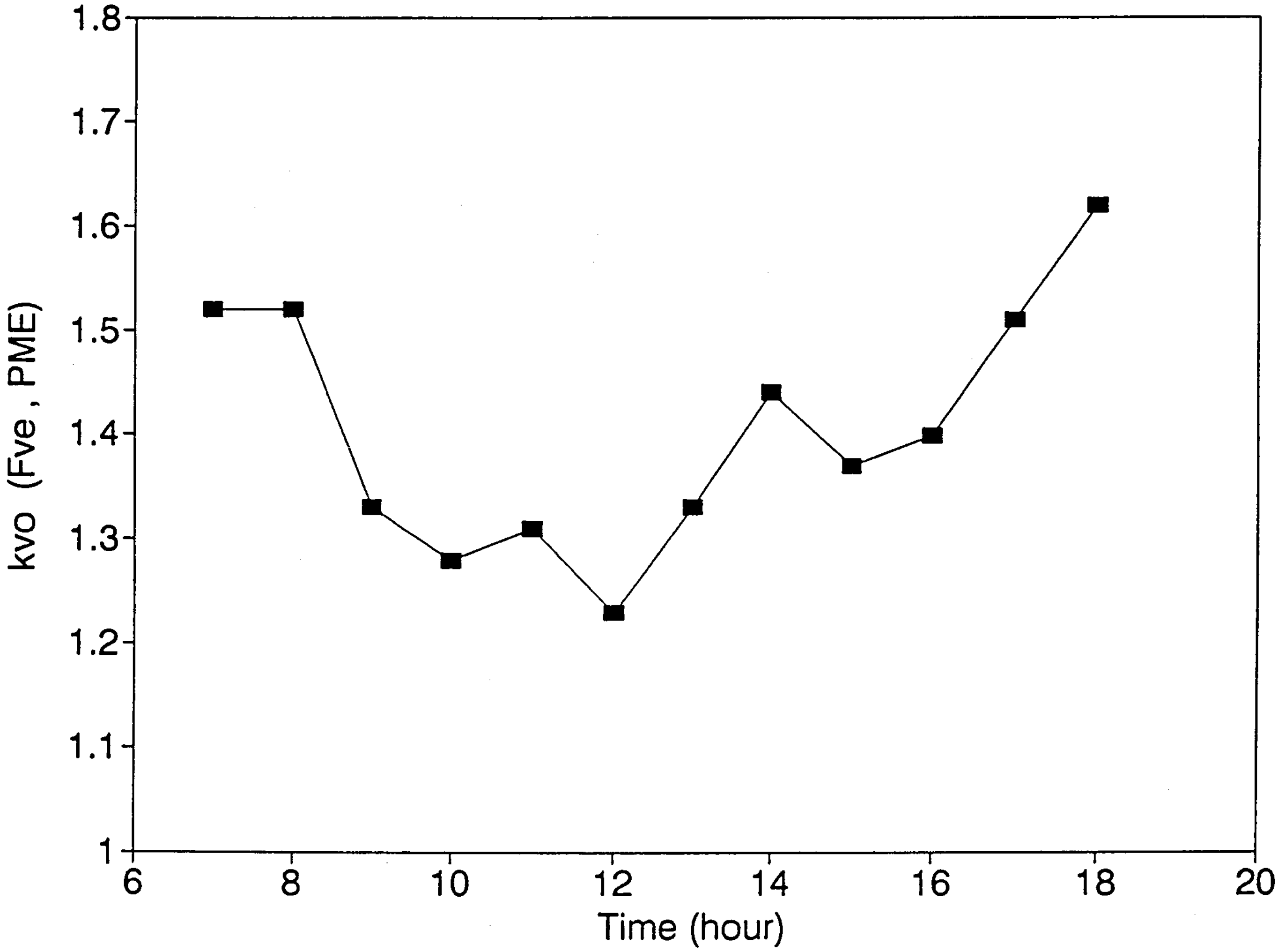


FIG. 6.9 Diurnal variation in mean hourly k_{vo} (F_{ve}, PME).

the height of the maize crop reached 1 m and higher i.e. on DOY 22 onwards (see Fig. 6.4 and Chapter 4). In Chapter 4 the EBc technique using measurements of net radiation, soil heat flux density and $\overline{W'T'}$, probably was not subject to advection as witnessed by an average of 24% underestimation of lysimeter AED, for the maize crop. Discrepancies thus varied between 24% and 33%.

6.4 CONCLUSIONS

Weather elements such as net radiation, ambient temperature, wind speed and water vapour pressure were found to affect upper limit vegetation evaporation coefficients for the maize crop. Relatively high coefficients of determinations (r^2) were obtained for k_{vo} in terms of these weather elements. For the growth period during which F_v, the normalized factor reflecting the degree of foliage cover, was less than 0,95 r^2 = 0,74 at a 1% confidence level. For the period when F_v equaled 0,95, r^2 = 0,87 also at a 1% confidence level. The upper limit evaporation koefficient k_{vo} was shown to increase with increasing water vapour pressure ,e_o, and ambient temperature ,T_o.

Upper limit vegetation evaporation coefficients of approximately 1,50 at a F_v-value of 0,95 are 24 to 33% greater than values previously reported for maize. This could be due to the AED used in Eq. 1.9 to calculate k_{vo} being unrealistically high as a result of the presence of advection.

Variation in climate influenced the ratio of stomatal conductance of maize to that of grass, which could contribute to explaining the variation of k_{vo} with climate.

CHAPTER 7

7. DEVELOPMENT OF UPPER LIMIT VEGETATION EVAPORATION COEFFICIENTS FOR POTATOES UTILIZING MACRO-WEATHER STATION DATA

7.1 INTRODUCTION

Micro-meteorological weather data are seldom used for scheduling irrigation on farm level. Here automatic (AWS), or manual, weather data are preferable. It was therefore necessary to quantify the influence of climate on vegetation evaporation coefficients calculated using weather data from an automatic or manually recorded weather station and the PME.

In Chapter 5 it was shown, using hourly micro-meteorological observations, that poor multiple correlations between k_{vo} and the weather elements were obtained. Good agreement however, was attained when daylight values were used. Preliminary tests on hourly and daylight data from the AWS yielded similar results. It was therefore decided to confine analyses to daylight periods.

7.1.1 Objectives

The objectives of the work in this chapter were, for potatoes, to:

- develop, for the potato crop, a relationship between daylight upper limit k_{vod} and the weather elements total radiation (S_t), ambient temperature (T_a), wind speed (u_z) and water vapour pressure (e).

7.2 MATERIALS AND METHOD

7.2.1 Observations

During 1990 exactly the same procedures, as described in Chapter 5, were followed to determine the influence of weather elements on k_{vod} in potatoes. The only exceptions were:

- Weather elements were measured using an AWS or manual station instead of micro-meteorological data.
- E_o was calculated from the PME as formulated in the PUTU system (De Jager, 1992).
- Only daylight values of the weather variables were considered.
- Relevant days were 254, 255, 261, 263, 269, 284, 289, 290, 295, 296, 302, 303, 304, 310, 311, 317, 319, 324, 326 and 331.

7.2.2 Vegetative cover aspects

Computed values of k_{vo} depend markedly of the equation used to calculate F_v. Should inconsistencies in k_{vo} due to incorrect estimations of F_v occur then the equation describing k_{vo} for partial cover will differ from that for full cover. Also for row crops and sparse cover this approach need special attention. Hence the investigation was carried out by splitting the season. The influence of F_v in the full cover portion of the season is negligible.

It is important to note that whereas F_{ve} and F_{vl} in Chapter 5 was obtained from measured values of either LAI or the width of the ground surface exposed to direct sunlight at noon (F_{vf}), crop growth models in fact simulate LAI from which F_v is then calculated using Eqs. 2.16 and 2.17. The exponential approach will be labelled F_{ve}. An alternative logistic equation labelled F_{vl} was also investigated. How the latter (Eq. 2.17) was developed is explained in Chapter 2.2.

The two formulae were:

$$F_{ve} = 1 - EXP^{(-0,7LAI)} \qquad 2.18$$

and $$F_{ve} = 1/[1 + EXP(3^{(1,8-LAI)})] \qquad 2.19$$

7.2.3 Analysis of observations

A multiple regression analysis was carried out to develop a relationship between k_{vo} in terms of the macro weather elements. Values of reference crop evaporation were calculated using the PME and hourly values from the AWS. Multiple regression were carried out against daylight values of the macro weather elements derived from AWS.

7.3 RESULTS AND DISCUSSION

Figs. 7.1 and 7.2 show the variation in k_{vod} (F_{ve}, PME) and k_{vod} (F_{vl}, PME) for the period DOY 254 through 331. The marked effect of mode of calculating F_v upon k_{vod} is well illustrated.

Table 7.1 summarizes the regression constants, coefficient of determination ,r^2, of k_{vod} obtained from the multiple regression of k_{vod} against the weather variables as measured by the AWS for the daylight (totals of hourly) period.

The best multiple regression fit for the periods DOY 254 to 284 and DOY 289 to 331 was obtained using F_{ve}. The two equations which should be used for computing k_{vo} are thus:

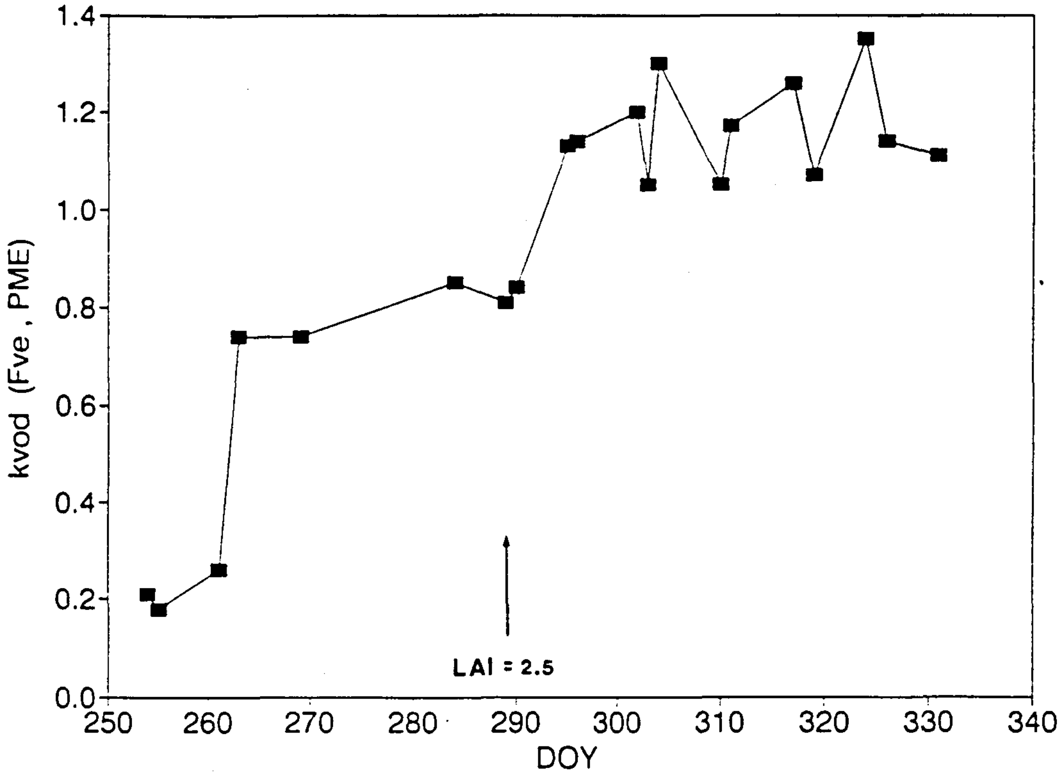


FIG. 7.1 Variation of k_{voc} (F_{ve}, PME) for potatoes with DOY. The planting date was DOY 222 during 1990.

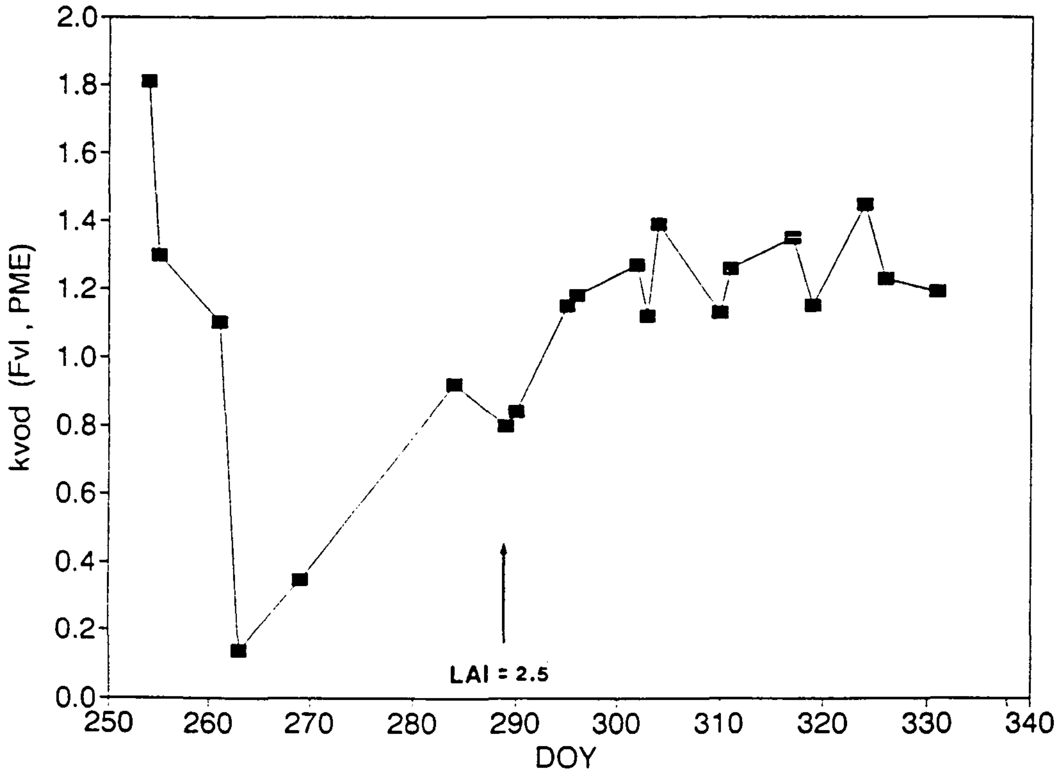


FIG. 7.2 Variation of k_{voc} (F_{vl}, PME) for potatoes with DOY. The planting date was DOY 222 during 1990.

$$k_{vod}\ (F_{ve},\ PME) = -1,0983 + 0,0023\ S_t + 0,0309\ T_a - 0,1448\ u_z + 0,6884\ e \qquad 7.1$$

for early season (i.e. from DOY 254 till DOY 284), and

$$k_{vod}\ (F_{ve},\ PME) = 1,0598 - 0,0007\ S_t + 0,0156\ T_a - 0,0054\ u_z + 0,1714\ e \qquad 7.2$$

for the last period i.e. from DOY 289 till 331.

Eq. 7.1 explains as much as 94% of the variation in daily k_{vo} at a significance level of 1%, while Eq. 7.2 explains 72% at a significance level of 1%. Because the latter equation is insensitive to error in F_v this form will be applied later in the work when values of k_{vod} are computed for use elsewhere in the RSA.

The fact that these two equations are not identical, implies that the early season function describing F_v probably requires some modification. This problem will be addressed in a future project. The full canopy equation here derived is correct and applies for most of the growing season.

Eqs. 7.1 and 7.2 are only valid between the ranges (maximum and minimum values) of weather elements given in tables 7.2 and 7.3.

To assess the correctness of Eqs. 7.1 and 7.2 theoretical values of AED were calculated from

$$AED = \{k_{vo}\ F_v + F_g\ (1 - F_v)\}\ E_o \qquad 7.3$$

and compared against corresponding values of AED measured in the lysimeter.

TABLE 7.1 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation for k_{vod} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_o + a_1 S_t + a_2 T_a + a_3 u_z + a_4 e$, obtained from mean hourly daylight AWS data for the potato crop.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	254-331	20	0,64	1%	2,1272	-0,0015	0,0235	-0,2353	0,4598
k_{vod} (F_{vl}; PME)	254-331	20	0,47	1%	0,9378	-0,0014	0,0158	0,0842	0,2071
k_{vod} (F_{ve}; PME)	254-284	6	0,94	10%	-1,0983	0,0023	0,0309	-0,1448	0,6884
k_{vod} (F_{vl}; PME)	254-284	6	0,94	10%	0,0522	-0,0019	-0,0312	0,3742	0,5978
k_{vod} (F_{ve}; PME)	289-331	14	0,72	1%	1,0598	-0,0007	0,0156	-0,0054	0,1714
k_{vod} (F_{vl}; PME)	289-331	14	0,70	1%	1,1178	-0,0008	0,0154	-0,0022	0,2308
k_{vod} (F_{vf}; PME)	289-331	14	0,70	1%	1,1458	-0,0008	0,0146	-0,0038	0,2326

TABLE 7.2 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e_o and various methods to calculate k_{vod} for the period DOY 254 through 284.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e_o kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)
MEAN	586	20,64	5,90	0,67	0,50	0,94
STD	73	4,75	1,29	0,17	0,28	0,56
MIN	467	13,92	3,53	0,51	0,18	0,14
MAX	678	24,39	7,39	0,99	0,85	1,81

TABLE 7.3 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 289 through 331.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e_o kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)
MEAN	555	22,63	4,86	0,78	1,12	1,18	1,18
STD	88	3,70	0,93	0,34	0,15	0,18	0,17
MIN	340	15,63	3,67	0,24	0,81	0,80	0,82
MAX	668	27,28	7,00	1,32	1,35	1,45	1,45

TABLE 7.4 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation for k_{vod} (F_{ve} or F_{vl} or F_{vf}; PME) = $a_0 + a_1 S_t + a_2 T_a + a_3 u_2 + a_4 e$, obtained from mean hourly daylight S_t and u_2, and daylight maximum and minimum ambient temperatures and relative humidities.

	DOY	n	r^2	Significance level	a_0	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	254-331	20	0,57	1%	1,8057	-0,0009	0,0333	-0,2395	0,2838
k_{vod} (F_{vl}; PME)	254-331	20	0,44	1%	0,5562	-0,0008	0,0185	0,0918	0,2134
k_{vod} (F_{ve}; PME)	254-284	6	0,96	10%	-1,5779	0,0029	0,0409	-0,1501	0,6843
k_{vod} (F_{vl}; PME)	254-284	6	0,93	10%	-0,1879	-0,0015	-0,0219	0,3744	0,3827
k_{vod} (F_{ve}; PME)	289-331	14	0,73	1%	1,1951	-0,0007	0,0142	-0,0190	0,1436
k_{vod} (F_{vl}; PME)	289-331	14	0,73	1%	1,3461	-0,0009	0,0142	-0,0247	0,1941
k_{vod} (F_{vf}; PME)	289-331	14	0,73	1%	1,3688	-0,0009	0,0134	-0,0258	0,1941

TABLE 7.5 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e_o and various methods to calculate k_{vcd} for the period DOY 254 through 284.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e_o kPa	k_{vcd} (F_{ve}, PME)	k_{vcd} (F_{vl}, PME)	k_{vcd} (F_{vf}, PME)
MEAN	586	20,92	5,90	0,62	0,50	0,94	0,47
STD	72	4,50	1,29	0,19	0,28	0,56	0,34
MIN	468	14,57	3,53	0,40	0,18	0,14	0,10
MAX	678	24,93	7,39	0,98	0,85	1,81	0,83

TABLE 7.6 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 289 through 331.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e_o kPa	k_{vod} (F_{vc}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)
MEAN	585	22,93	4,99	0,69	1,12	1,18	1,18
STD	111	3,89	0,89	0,32	0,15	0,18	0,17
MIN	331	15,30	3,78	0,20	0,81	0,80	0,82
MAX	728	27,53	7,00	1,28	1,35	1,45	1,45

In Eq. 7.3 k_{vo} was calculated from Eqs. 7.1 and 7.2, F_{ve} from Eq. 2.16 and F_g from Eq. 1.7. Statistical tests on AED calculated compared to AED measured were carried out. The slope through the origin, r^2 and standard error of AED calculated were 0,99; 0,95 and 0,64 mm dl^{-1} respectively where dl^{-1} denotes per daylight period. It should be emphazised that this cannot be deemed to be a validation of AED estimated, but merely an indication of the goodness of fit of Eq. 7.3, using Eq. 7.1 and 7.2, because the tests were conducted using the same data with which Eqs. 7.1 and 7.2 were developed. A strict test of accuracy requires independant weather data.

The discussion here has concerned itself with data collected from an AWS. In practice this should be the major weather data source. Certain cases exist where data is obtained from manual stations. The corresponding regression equation are given in Table 7.4 and ranges in Tables 7.5 and 7.6. Exactly the same arguments offered for the AWS apply to the manual case.

7.4 CONCLUSION

The high standard deviation of ± 0,14 in k_{vo} observed from DOY 289 till 331 in potatoes was once again ascribed to the influence of climate on upper limit vegetation evaporation coefficients.

The function, Eq. 2.16 seems to provide reliable estimates of F_v for substitution in Eq. 7.3. This means that measurements of F_v are not needed in order to calculate k_{vod}. This method may thus be used to adjust k_{vod} for climatic variations.

Inconsistencies, due to the method of estimating F_v, in k_{vod} computed during the crop development stage (Eq. 7.1) require refinement, but the high r^2 obtained when fitting Eqs. 7.1 and 7.2 suggest that they can be used to obtain reliable estimates of k_{vo}.

The full canopied crop is dealt with by Eq. 7.2.

CHAPTER 8

8. DEVELOPMENT OF UPPER LIMIT VEGETATION EVAPORATION COEFFICIENTS FOR THE MAIZE CROP UTILIZING MACRO-WEATHER DATA.

8.1 OBJECTIVES

In similar fashion to and for the same reasons the work of Chapter 7 was repeated but for maize. The objectives of the work in chapter 8 were to:

- investigate the effect of climate on k_{vo} for maize using daylight values of weather elements S_t, T_a, u_z and e recorded by the AWS, or manual station.

8.2 METHODS AND MATERIALS

8.2.1 Procedure

Precisely the same procedures were adopted in developing a relationship between k_{vo} and the macro-weather elements for maize as was done for potatoes in Chapter 7. The results will be presented in the same format as for potatoes.

Measurements were carried out on the following days of 1992, viz: DOY 13, 14, 21, 27, 28, 29, 34, 35, 37, 41, 42, 44, 48, 49, 51, 55, 56, 62, 63, 65, 70, 71, 76, 79, 84, 86, 91, 93 and 100.

8.2.2 Advection

Care was exercised to make measurements within the equilibrium boundary layer as prescribed by Eq. 3.13. The results from Chapter 4 however suggests that the maize lysimeter was subject to advection, on average, amounting to as much as ± 24% of the value AED recorded in the lysimeter. While advection is a natural phenomenon, it was decided to adjust AED measurements to apply to infinitely large maize lands. This problem did not arise in the potato study. In this way the climate dependence of the

k_{vo} values determined could be established. A warning is recorded that, should these k_{vo} be applied to small fields, e.g. 5 ha small adjustments for advection should be considered.

From the work in Chapter 4, two adjustments for advection presented themselves, viz:

(i) AED measured lysimetrically could be multiplied by 0,76 to compensate advective influences experienced by the maize planted in the lysimeter. This approach assumes that daily advection equalled the average advection as measured by the EB_C method (See Chapter 4), and

(ii) advection did not affect the EB_C method, which could then be applied directly to determining AED.

Both methods were investigated.

8.3 RESULTS AND DISCUSSION

8.3.1 Regression model for k_{vod}

Tables 8.1, 8.4 and 8.7 present summaries of the statistical parameters describing the best fit of a multiple regression equation of k_{vod} calculated with different expressions for F_v on S_t, T_a, u_z and e. The analyses were conducted for AWS as well as manual station data.

In Tables. 8.4 and 8.7 all possible combinations of k_{vod}, exept those including the terms EB_C and EC, were obtained by multiplying AED by 0.76. In Table. 8.1 AED was not multiplied by 0.76.

Considering the high estimates of k_{vo}, probably stemming from advection, it was difficult deciding which equations to select for calculating k_{vo}. Although the (F_{vf} [EB_C], PME) version did not yield the best r^2 values, it was decided that since this equation provided values within the range reported by Jensen et al (1982) (see Chapter 6) it would be appropriate to use this approach for both AWS and manual data. The k_{vod} (F_{ve} [EB_C], PME) versions from tables 8.4 and 8.7 were therefore used to calculate the evaporation coefficients for maize reported in Chapter 9.

It is important to note that regression analysis basically explains variance about a mean value. As such, approximately the same regression coefficients, i.e. relative contribution of the different independent variables to explaining such variance would be attained were the dependent variable (k_{vo} in this case) decreased by a consistent amount. This means that the coefficients here derived could apply in circumstances where k_{vo} operates at a different general level to that measured in this experiment.

Indeed, this is the justification for the architectural similarity assumption made in Chapter 5. This assumption will be applied in Chapter 9 and extends the range of crops for which the regression coefficients here derived apply. They are therefore more general in nature when used to estimate climatic adjustment factors, ν, for evaporation coefficients.

This argument was further extended to investigate the advection problems experienced with maize. The assumption was made that a general level of advection of ± 24% operated upon all lysimeter measurements (see Chapter 6). Advection in the maize lysimeter could then be adjusted for by a blanket multiplication factor of 0,76 on measured AED. Applying this in the calculation of k_{vod} (F_{ve} [EB_C], PME) produced equally good coefficients of determination, r^2 (see Tables, 8.1, 8.4 and 8.7) for the multiple regressions. Values of k_{vod} (F_{ve} [0,76], PME) also lay within the observed range reported by Jensen et al (1982).

The two equations therefore selected from Table 8.4 were as follows:

$$k_{vod}\ (F_{vf}\ [EBC],\ PME) = 4{,}4164 - 0{,}0008\ S_t - 0{,}0892\ T_a - 0{,}1204\ u_z - 0{,}0979\ e \qquad (8.1)$$

for the early season, i.e. from DOY 13 till 37 and

$$k_{vod}\ (F_{vf}\ [EBC],\ PME) = 0{,}4767 + 0{,}0001\ S_t + 0{,}0134\ T_a - 0{,}0427\ u_z + 0{,}3831\ e \qquad (8.2)$$

for the mature period i.e. from DOY 41 till 100.

Eqs. 8.1 and 8.2 are only strictly valid within the ranges (maximum - minimum) in the weather elements for which they were derived. These are specified in Tables 8.5 and 8.6.

Figs. 8.1 through 8.5 show the temporal variation in calculated k_{vod} (F_{ve}, PME); k_{vod} (F_{vl}, PME); k_{vod} (F_{vf}, PME); k_{vod} (F_{vf} [EBC], PME) and k_{vod} (F_{vf} [EC], PME) respectively. The mean k_{vod} (F_{vf} [EBC], PME) between DOY 13 and 37 was 0,89 ± 0,42 and 1,09 ± 0,27 from DOY 41 till 100. Short term fluctuations in k_{vod} may be ascribed to climatic controls.

The high values of k_{vod} (F_{vf} [EC], PME) of 1,5 and 1,56 observed for the period DOY 41 till 100 are to be expected, because EC

TABLE 8.1 Summary of the regression coefficients, coefficient of determination r^2 and significance levels of the multiple regression equation for k_{vod} (F_v, PME) = a_o + a_1 S_t + a_2 T_a + a_3 u_z + a_4 e, obtained from daylight AWS data for the maize crop. In this expression F_v is replaced by any one of F_{ve} or F_{vl} or F_{vf}. Here AED for maize, measured lysimetrically, was not multiplied by 0.76.

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	13-100	30	0,57	1%	1,6887	-0,0009	0,0192	-0,1408	0,2122
k_{vod} (F_{vl}; PME)	13-100	30	0,41	1%	2,2726	-0,0011	-0,0055	-0,1058	0,2448
k_{vod} (F_{vf}; PME)	13-100	30	0,58	1%	1,3869	-0,0006	0,0206	-0,1316	0,3179
k_{vod} (F_{ve}; PME)	13-37	9	0,94	1%	3,1842	-0,0042	0,0156	-0,1356	0,7352
k_{vod} (F_{vl}; PME)	13-37	9	0,86	1%	4,7435	-0,0047	-0,0563	-0,1403	1,4061
k_{vod} (F_{vf}; PME)	13-37	9	0,90	1%	2,6670	-0,0039	0,0266	-0,1335	0,8268
k_{vod} (F_{ve}; PME)	41-100	21	0,69	1%	0,6356	-0,0001	0,0360	-0,0987	0,3425
k_{vod} (F_{vl}; PME)	41-100	21	0,63	1%	0,9271	-0,0004	0,0258	-0,0242	0,2924
k_{vod} (F_{vf}; PME)	41-100	21	0,70	1%	0,5231	-0,0001	0,0329	-0,0971	0,4200

TABLE 8.2 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 13 through 37.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)
MEAN	641	28,06	3,43	1,09	1,30	1,19	1,35
STD	51	1,94	1,42	0,21	0,35	0,46	0,36
MIN	590	24,06	1,88	0,74	0,53	0,04	0,62
MAX	734	30,84	5,84	1,47	1,79	1,75	1,83

TABLE 8.3 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 41 through 100.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)
MEAN	560	24,46	2,76	0,95	1,55	1,55	1,53
STD	99	3,43	1,23	0,30	0,31	0,22	0,31
MIN	295	15,46	0,80	0,37	1,02	1,17	1,02
MAX	702	29,62	5,36	1,42	2,40	2,14	2,32

TABLE 8.4 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation for k_{vod} (F_v, PME) = $a_o + a_1 S_t + a_2 T_a + a_3 u_r + a_4 e$, obtained from mean hourly daylight AWS data for the maize crop. In this expression F_v is replaced by any one of F_{ve} or F_{vl} or F_{vf} or F_{vf} [EBc] or F_{vf} [EC]. AED for maize, measured lysimetrically, was here multiplied by 0.76 (see Eq. 1.9).

	DOY	n	r^2	Significance level	a_o	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	13-100	30	0,52	1%	1,4540	-0,0007	0,0094	-0,1205	0,1746
k_{vod} (F_{vl}; PME)	13-100	30	0,46	1%	1,6957	-0,0008	0,0040	-0,1491	0,1908
k_{vod} (F_{vf}; PME)	13-100	30	0,53	1%	1,2280	-0,0006	0,0116	-0,1078	0,2282
k_{vod} (F_{vf}[EBc];PME)	13-100	30	0,29	1%	1,6450	-0,0002	-0,0118	-0,1230	0,1522
k_{vod} (F_{vf}[EC];PME)	13-100	30	0,34	1%	1,2966	-0,0010	0,0465	-0,1234	-0,0198
k_{vod} (F_{ve}; PME)	13-37	9	0,90	1%	2,9226	-0,0038	-0,0029	-0,1301	0,8398
k_{vod} (F_{vl}; PME)	13-37	9	0,87	1%	5,3046	-0,0057	-0,0519	-0,1723	1,2097
k_{vod} (F_{vf}; PME)	13-37	9	0,86	1%	2,1754	-0,0033	0,0149	-0,1183	0,7882
k_{vod} (F_{vf}[EBc];PME)	13-37	9	0,51	10%	4,4164	-0,0008	-0,0892	-0,1204	-0,0979
k_{vod} (F_{vf}[EC];PME)	13-37	9	0,45	10%	3,6846	-0,0029	0,0447	0,0040	-1,4407
k_{vod} (F_{ve}; PME)	41-100	21	0,69	1%	0,4723	-0,0001	0,0276	-0,0735	0,2584
k_{vod} (F_{vl}; PME)	41-100	21	0,69	1%	0,4558	-0,0001	0,0294	-0,0741	0,2548
k_{vod} (F_{vf}; PME)	41-100	21	0,69	1%	0,4205	-0,0001	0,0251	-0,0717	0,3034
k_{vod} (F_{vf}[EBc];PME)	41-100	21	0,36	1%	0,4767	+0,0001	0,0134	-0,0427	0,3831
k_{vod} (F_{vf}[EC];PME)	41-100	21	0,55	1%	0,7384	-0,0002	0,0393	-0,1430	0,3529

TABLE 8.5 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 13 through 37.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)	k_{vod} (F_{vf}[EBC];PME)	k_{vod} (F_{vf}[EC];PME)
MEAN	641	28,06	3,43	1,09	0,91	0,90	0,96	0,89	1,53
STD	51	1,94	1,42	0,21	0,35	0,51	0,32	0,42	0,48
MIN	590	24,06	1,88	0,74	0,11	-0,43	0,28	0,34	0,61
MAX	734	30,84	5,84	1,47	1,34	1,36	1,35	1,59	2,19

TABLE 8.6 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 41 through 100.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)	k_{vod} (F_{vf}[EBC];PME)	k_{vod} (F_{vf}[EC];PME)
MEAN	560	24,46	2,76	0,95	1,16	1,18	1,15	1,09	1,54
STD	99	3,43	1,23	0,30	0,24	0,24	0,23	0,27	0,43
MIN	295	15,46	0,80	0,37	0,76	0,76	0,78	0,63	0,76
MAX	702	29,62	5,36	1,42	1,81	1,84	1,77	1,73	2,65

TABLE 8.7 Summary of the regression coefficients, coefficient of determination, r^2 and significance levels of the multiple regression equation for k_{vod} (F_v, PME) = $a_0 + a_1 S_t + a_2 T_a + a_3 u_z + a_4 e$, obtained from mean measured daylight S_t and u_z, and daylight maximum and minimum ambient temperatures and relative humidities. In this expression Fv is replaced by any one of F_{ve} or F_{vl} or F_{vf} or F_{vf} [EBC] or F_{vf} [EC]. AED for maize, measured lysimetrically, was here multiplied by 0,76 (see Eq. 1.9).

	DOY	n	r^2	Significance level	a_0	a_1	a_2	a_3	a_4
k_{vod} (F_{ve}; PME)	13-100	30	0,50	1%	1,5686	-0,0008	0,0094	-0,1192	0,1030
k_{vod} (F_{vl}; PME)	13-100	30	0,45	1%	1,7674	-0,0009	0,0063	-0,1468	0,1143
k_{vod} (F_{vf}; PME)	13-100	30	0,49	1%	1,3451	-0,0007	0,0117	-0,1058	0,1544
k_{vod} (F_{vf}[EBc];PME)	13-100	30	0,30	1%	1,3568	-0,0002	-0,0029	-0,1165	0,2180
k_{vod} (F_{vf}[EC];PME)	13-100	30	0,37	1%	1,4132	-0,0012	0,0483	-0,1208	-0,0908
k_{vod} (F_{ve}; PME)	13-37	9	0,82	5%	1,9086	-0,0040	0,0374	-0,1115	0,8248
k_{vod} (F_{vl}; PME)	13-37	9	0,79	5%	3,9848	-0,0053	-0,0115	-0,1649	1,2226
k_{vod} (F_{vf}; PME)	13-37	9	0,77	5%	1,0458	-0,0038	0,0658	-0,0937	0,7308
k_{vod} (F_{vf}[EBc];PME)	13-37	9	0,39	10%	2,5803	0,0003	-0,0593	-0,1737	0,4370
k_{vod} (F_{vf}[EC];PME)	13-37	9	0,37	10%	4,2498	-0,0035	0,0395	-0,0138	-1,5801
k_{vod} (F_{ve}; PME)	41-100	21	0,69	1%	0,5810	-0,0002	0,0313	-0,0767	0,1441
k_{vod} (F_{vl}; PME)	41-100	21	0,70	1%	0,5681	-0,0002	0,0330	-0,0775	0,1394
k_{vod} (F_{vf}; PME)	41-100	21	0,68	1%	0,5149	-0,0001	0,0289	-0,0744	0,1972
k_{vod} (F_{vf}[EBc];PME)	41-100	21	0,34	5%	0,5141	-0,0001	0,0188	-0,0427	0,2932
k_{vod} (F_{vf}[EC];PME)	41-100	21	0,57	1%	0,8641	-0,0004	0,0473	-0,1452	0,1761

TABLE 8.8 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 13 through 37.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)	k_{vod} (F_{vf}[EBC];PME)	k_{vod} (F_{vf}[EC];PME)
MEAN	641	29,01	3,43	0,99	0,91	0,90	0,96	0,89	1,53
STD	51	1,17	1,42	0,16	0,35	0,51	0,32	0,42	0,48
MIN	590	27,07	1,88	0,71	0,11	-0,43	0,28	0,34	0,61
MAX	734	30,77	5,84	1,18	1,34	1,36	1,35	1,59	2,19

TABLE 8.9 Mean, standard deviation (STD), minimum (min) and maximum (max) values of S_t, T_a, u_z, e and various methods to calculate k_{vod} for the period DOY 41 through 100.

	S_t W m^{-2}	T_a °C	u_z m s^{-1}	e kPa	k_{vod} (F_{ve}, PME)	k_{vod} (F_{vl}, PME)	k_{vod} (F_{vf}, PME)	k_{vod} (F_{vf}[EBC];PME)	k_{vod} (F_{vf}[EC];PME)
MEAN	561	24,40	2,73	0,91	1,17	1,19	1,16	1,10	1,56
STD	97	3,71	1,21	0,29	0,23	0,24	0,23	0,27	0,44
MIN	295	15,77	0,80	0,33	0,76	0,76	0,78	0,63	0,76
MAX	702	29,87	5,36	1,43	1,81	1,84	1,77	1,73	2,65

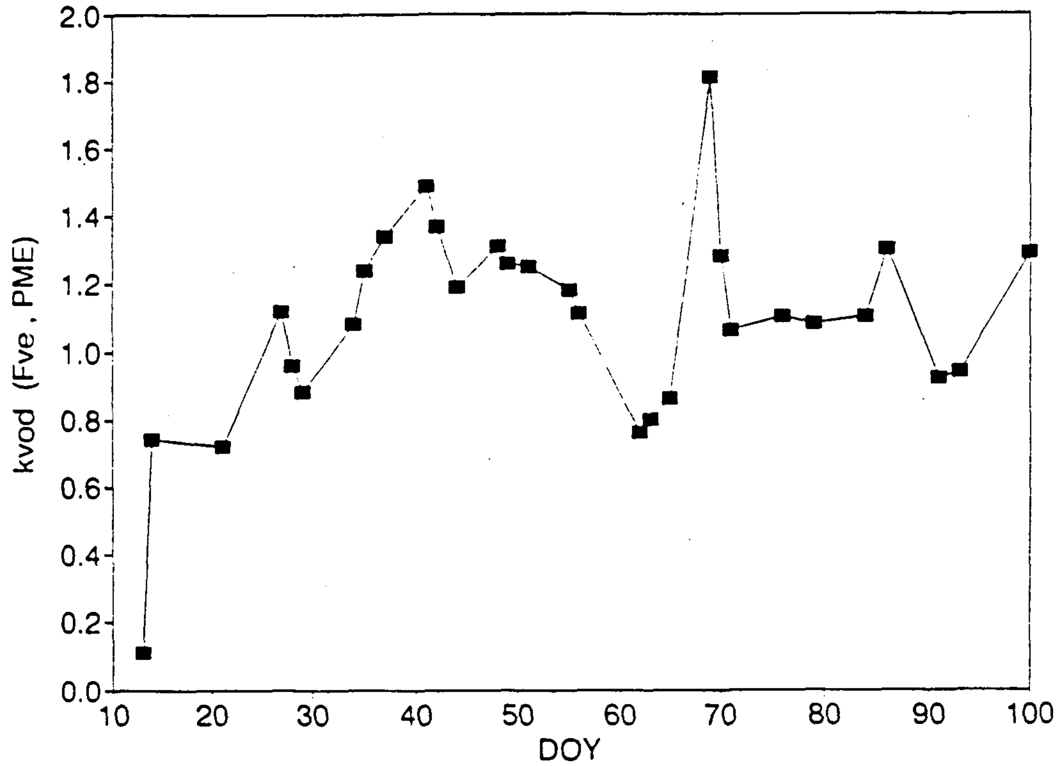


FIG. 8.1 Variation of $k_{v\infty}$ (F_{ve}, PME) with DOY during 1992. Planting date was DOY 347 during 1991.

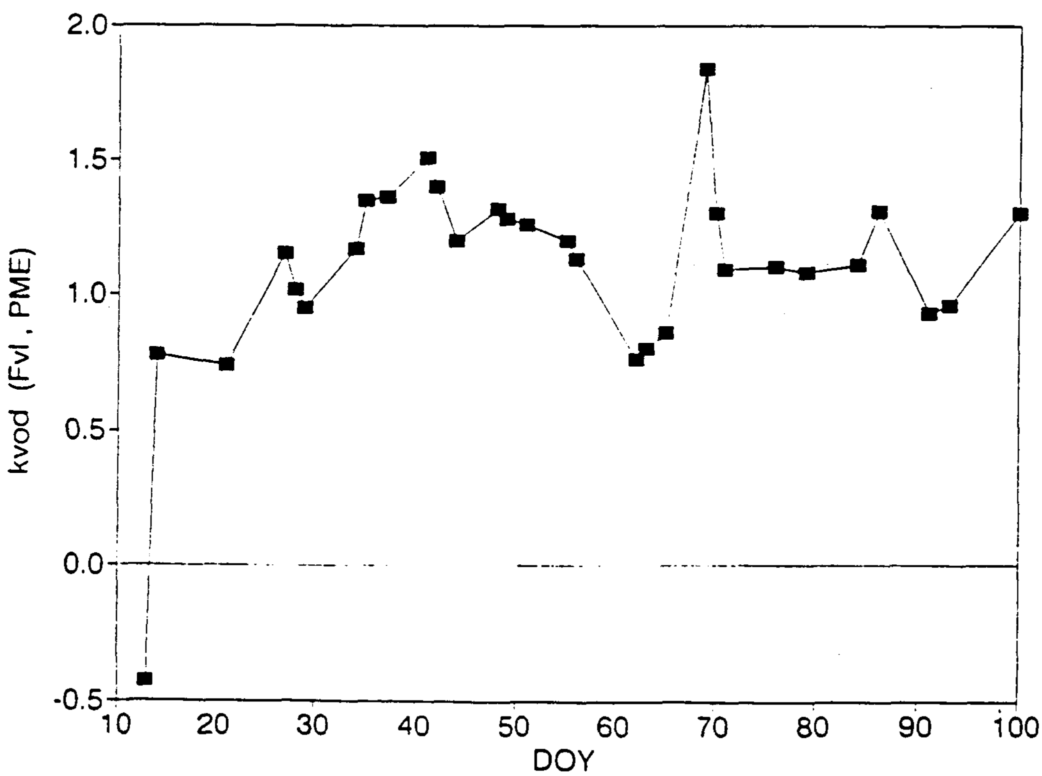


FIG. 8.2 Variation of $k_{v\infty}$ (F_{v}, PME) with DOY during 1992. Planting date was DOY 347 during 1991.

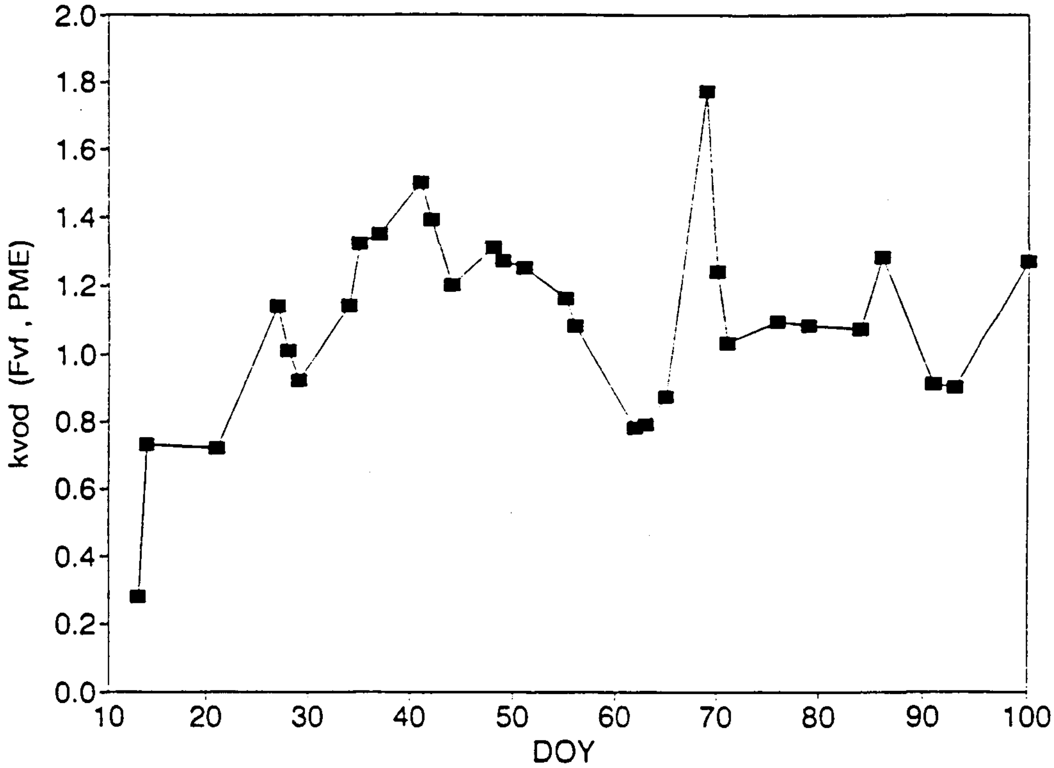


FIG. 8.3 Variation of k_{vod} (F_{vf}, PME) with DOY during 1992. Planting date was DOY 347 during 1991.

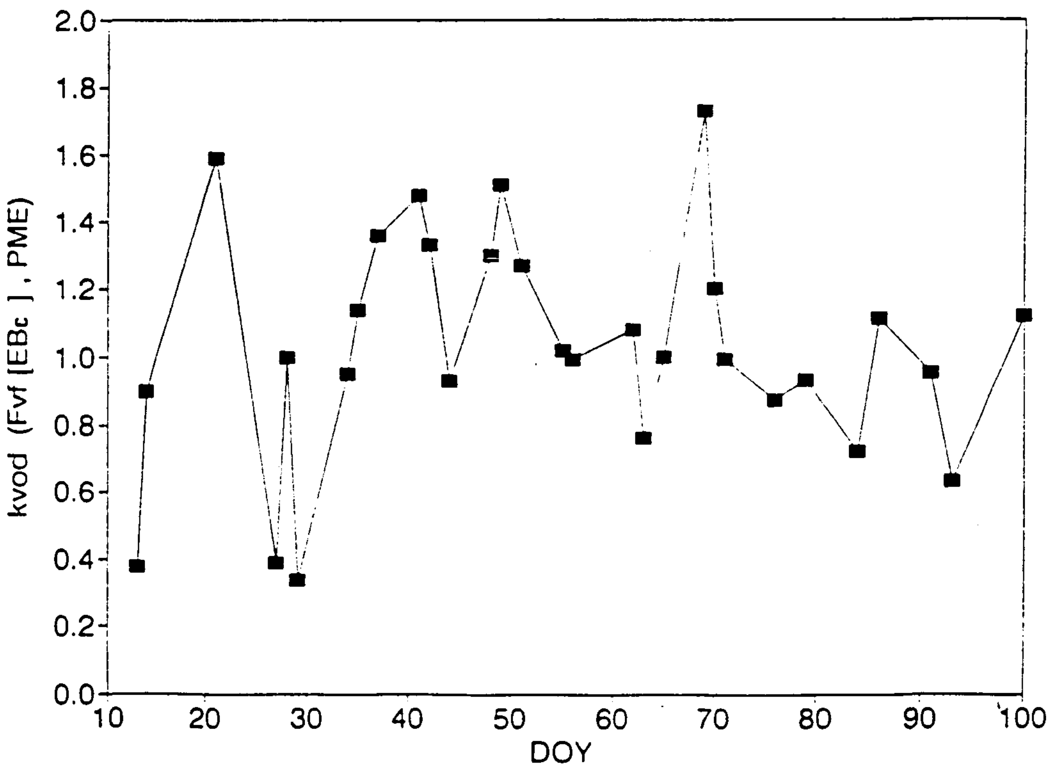


FIG. 8.4 Variation of k_{vod} (F_{vf} [EBc], PME) with DOY during 1992. Planting date was DOY 347 during 1991.

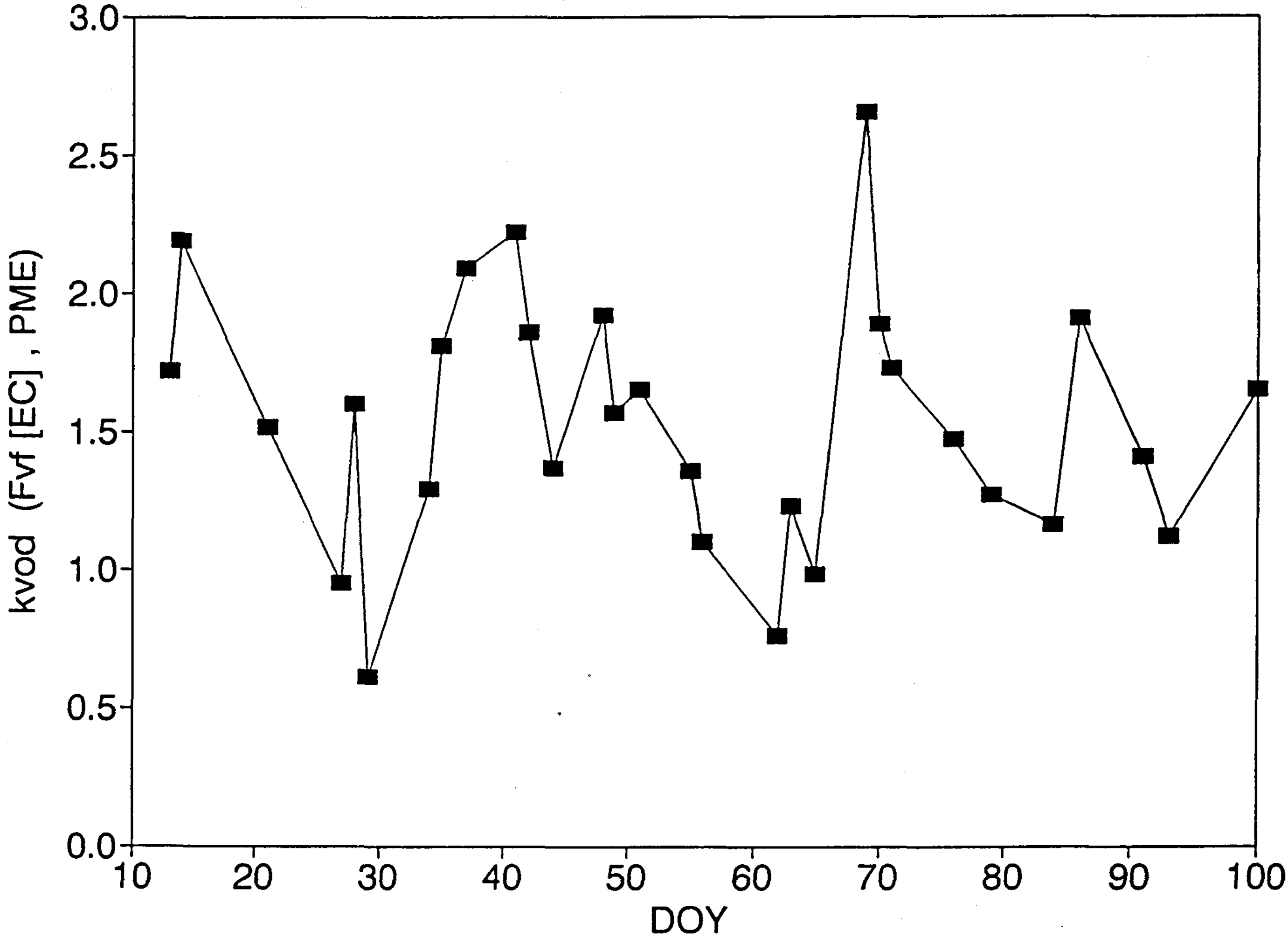


FIG. 8.5 Variation of k_{vod} (F_{vf} [EC], PME) with DOY during 1992. Planting date was DOY 347 during 1991.

measurements overestimated AED measured in the lysimeter (see Chapter 4).

Once again, the goodness of fit of Eqs. 8.1 and 8.2 was confirmed by comparing lysimeter measured AED to AED calculated using these equations and Eqs. 2.16 and 1.7. Good agreement was reflected by r^2 of 0,91 and a slope through the origin of 0,75. Reassuring is the slope of 0,75 which is comparable with the 0,76 adjustment for possible advection in lysimter measurements.

8.4 CONCLUSIONS

It was concluded that the two equations (Eqs. 8.1 and 8.2) can be used to estimate k_{vo}, provided F_g and F_v are given, and reference evaporation is calculated from the PME as used in the PUTU system (De Jager, 1992) with weather data from the automatic or manual weather station.

CHAPTER 9

9. DEVELOPMENT AND IMPLEMENTATION OF UPPER LIMIT VEGETATION EVAPORATION COEFFICIENTS FOR POTATOES AND MAIZE FOR DIFFERENT LOCALITIES IN THE R.S.A.

9.1 INTRODUCTION

9.1.1 General

The climatic dependence of k_{vo} has been demonstrated in Chapters 5, 6, 7 and 8. In Chapters 7 and 8 relationships were developed between k_{vo} and mean daylight total radiation, ambient temperature, wind speed and water vapour pressure.

9.1.2 Objectives

The objective of this part of the study was to compute k_{vo} and the climatic adjustment factor, ν, for potatoes and maize for different climates in the RSA for each month of the year.

9.2 PROCEDURE

9.2.1 Localities

The following localities for which k_{vo} and ν were to be calculated for potatoes and maize were selected: Aliwal North, Bloemfontein, Cape Town, Cedara, Ceres, Durban, Estcourt, Kimberley, Ladysmith, Pietersburg, Piet Retief, Port Elizabeth, Potchefstroom, Pretoria, Prieska, Riversdale, Rustenburg and Upington. These localities represent regions where potatoes and maize are grown (see Fig. 9.1). Furthermore long term data (see Section 9.2.2) on sunshine duration, wind speed, maximum and minimum daily temperatures and maximum and minimum daily relative humidities were readily available for these localities.

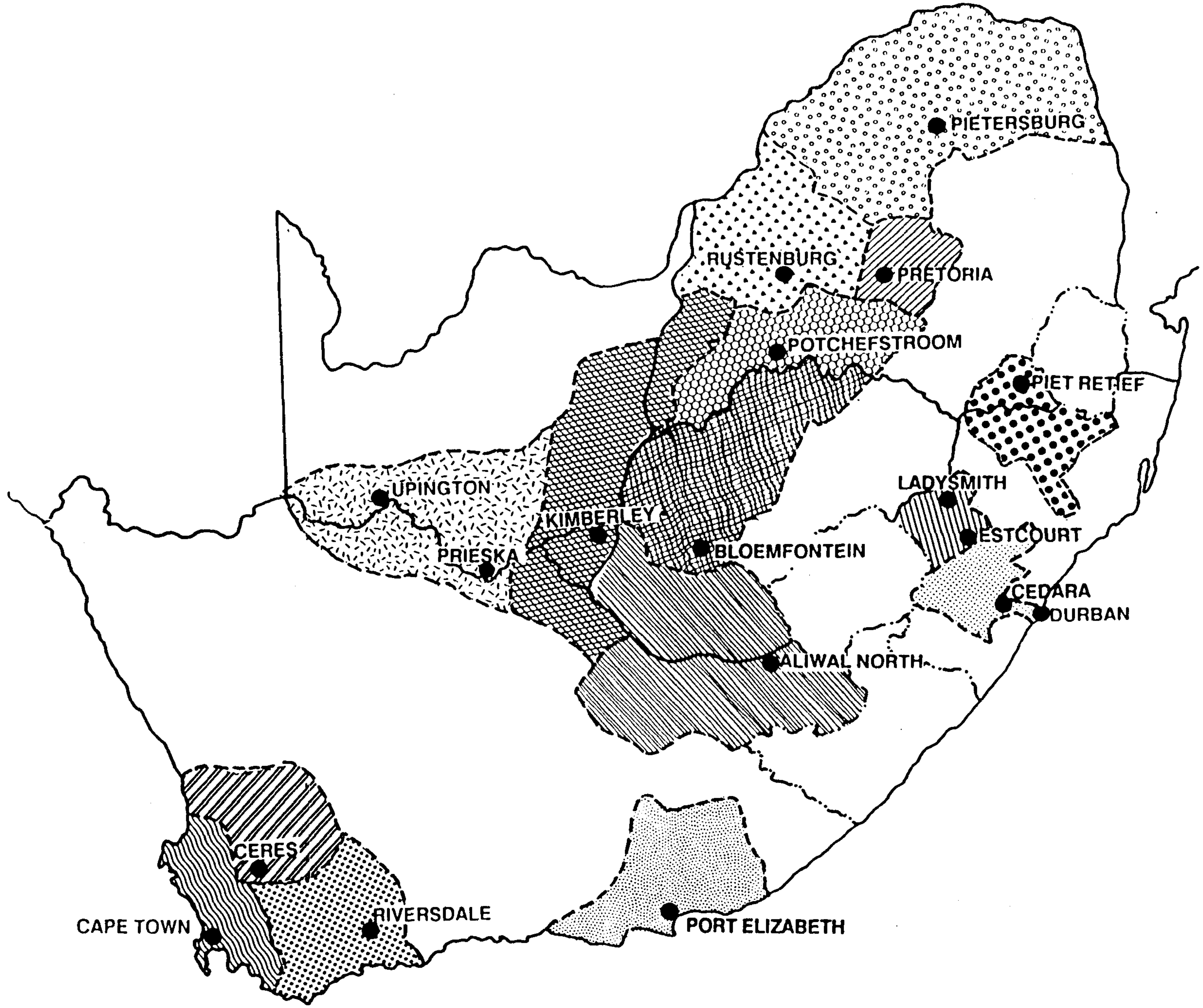


FIG. 9.1 Map of the RSA indicating the major potato and maize producing areas for which upper limit vegetation evaporation coefficients and climatic adjustment factors were computed.

9.2.2 Weather data

Theoretical values of k_{vo} and ν were computed for each month of the year at each of the localities selected. To achieve this, estimates of the long term monthly mean daily value of each of the required weather elements on the right hand side of Eqs. 7.1, 7.2, 8.1 and 8.2 were needed. How such values were obtained will now be described.

Long term monthly mean daily weather data for undertaking the objectives of this project are available in WB 28 (1974), WB 38 (1975) and WB 40 (1986).

The forms in which these data are provided are:-

Sunshine duration	-	monthly mean proportion of hourly possible sunshine, η
Temperature	-	monthly means of daily maximum and daily minimum temperature (°C).
Vapour pressure	-	monthly mean relative humidities at 08:00 and 14:00 (%).
Wind -	-	monthly mean bi-hourly wind speed ($m\ s^{-1}$).

The formulae applied to these data in order to estimate the required values of the weather elements are:

<u>Radiation (R_s)</u> (Angstrom's formula)

Here the assumption was made that monthly empirical constants in Angstrom's formula could be used on an hourly basis. Hence

$$R_s = (0,25 + 0,5\ \eta)\ R_a \qquad 9.1$$

where

R_s = Monthly mean hourly total radiation ($W\ m^{-2}$)

R_a = Monthly mean extraterrestrial solar radiation ($W\ m^{-2}$)

The constants 0,5 and 0,25 are the empirical values of Angstrom's formula for general use. The value of R_a was computed from DOY and latitude by the procedures in the PUTU-system as described by Jensen and Haise (1963).

Temperature (T_a)

The assumption was made that daylight temperature could be calculated using

$$\overline{T}_a = (2\overline{T}_{max} + \overline{T}_{min})/3 \qquad 9.2$$

$\overline{T}_a$ = monthly mean daylight temperature (°C)

$\overline{T}_{max}$ = monthly mean daily maximum temperature (°C)

$\overline{T}_{min}$ = monthly mean daily minimum temperature (°C)

Vapour pressure (e)

The Clausius-Clapeyron equation was used to compute monthly mean saturated vapour pressure at 08:00 and 14:00 ($e°_8$ and $e°_{14}$) from monthly mean relative humidities at 08:00 and 14:00 (RH_8 and RH_{14}) and monthly mean daily maximum and daily minimum temperatures.

Thus, using $e° = 0{,}611\ EXP\ [5347.16 - [/(273.16 -]/(273.16 + T_a)]]$ 9.3

it is possible to compute monthly mean vapour pressures at 08:00 and 14:00 and long term monthly mean daylight vapour pressure $\overline{e}$, as follows:

$$e_8 = e°_8\ RH_8/100 \qquad 9.4$$

$$e_{14} = e°_{14}\ RH_{14}/100 \qquad 9.5$$

$$\bar{e} = (e_8 + 2e_{14})/3 \qquad 9.6$$

where

$\bar{e}$ = long term monthly mean daylight vapour pressure (kPa)

Wind ($\bar{u}_z$)

Monthly mean daylight wind speed ,u_z, was calculated from monthly mean bi-hourly wind speed ($\overline{u2}$) (m s^{-1}) using

$$\bar{u}_z = \left(\sum_{n=7}^{n=18} \overline{u2} \right)/6 \qquad 9.7$$

9.2.3 Computation of k_{vo}

The long term monthly mean daylight values of incoming solar ra diation ($\bar{S}_t$) temperature ($\bar{T}_a$), vapour pressure ($\bar{e}$) and wind speed ($\bar{u}_z$) for each month of the year, for each of the selected localities were determined from the necessary data extracted from RSA Weather Bureau tables using Eqs. 9.1 through 9.7. These values were then substituted in Eqs. 7.1, 7.2, 8.1 and 8.2 to calculate the monthly mean daylight kvo values given in Table 9.1 and 9.2.

9.2.4 Computation of ν

The climatic adjustment factor ,ν, was calculated from Eqs. 5.12, 5.13, 7.1, 7.2, 8.1 and 8.2.

9.3 RESULTS AND DISCUSSION

9.3.1 Computed values of k_{vo} and ν

Tables 9.1 and 9.2 list the long term monthly mean daylight values of the weather elements and corresponding theoretical values of k_{vo} and ν for potatoes and maize. Values are given for each month of the year for each of the selected localities for both potatoes (Table 9.1) and maize (Table 9.2). Upper limit evapoartion coefficients for early growing season and late growing season (when F_v approximates unity) are denoted by k_{voe} and k_{vom} respectively. These represent the values which may be used to calculate atmospheric evaporative demand, from which irrigation may then be scheduled.

Values for the late growing season are directly comparable to existing values of the crop evaporation coefficient k_c. During this growth phase F_v approximates unity and k_{vo} equals k_c. It is reassuring to note that the k_{vo} values here listed are within reasonable agreement to those reported in the literature. For example for potato $k_{vo} = k_c = 1,1$. (Jensen, et al., 1982). It must be emphasized that strictly the values quoted in these tables are valid only within the range of values for which the regressions were carried out. Boundary values for these ranges for S_t, T_a, u_z and e are listed in Tables 7.5, 7.6, 8.8, and 8.9.

9.3.2 Application of the results

The localities where these coefficients apply are illustrated in Fig. 9.1 and the values quoted should be of value to irrigation managers and farmers. The given values of k_{vo} may be used to calculate atmospheric evaporative demand using a personal computer. Firstly, reference evaporation needs to be calculated, using the Penman-Monteith equation given relevant reliable estimates of weather elements. Thereafter k_c may be calculated once F_g and F_v have been estimated from Eq. 2.8 and Eq. 2.16 respectively. Substitution of these values into Eq. 1.1 then yields atmospheric evaporative demand, AED. Vegetation and soil surface evaporation may be calculated from

$$E_v = F_v k_{vo} E_o \qquad 9.8$$

and

$$E_s = F_g k_{so} E_o \qquad 9.9$$

Such values may then be used in a simple procedure whereby the soil water balance may be computed and the irrigation of potato or maize crops may be scheduled.

The small values of k_{vo} obtained for the early season resulted because mean values of the variables were taken over the entire early season period. They are actually meaningless. Early season situations were included here purely as a research exercise. This problem will be investigated in the follow-up project. Furthermore these low values of k_{vo} are most probably induced by inaccuracies and underestimation of F_v in early season. The recommendation is that ν the adjustment factor for the mature period, be applied for the early season.

9.4 CONCLUSIONS

In this chapter methods were outlined whereby daylight values of the weather elements may be computed given values reported in RSA Weather Bureau Bulletins. These values were then substituted into appropriate equations from which upper limit vegetation evaporation coefficients for potato and maize were computed. The regions for which the computations of k_{vo} were carried out are illustrated in Fig. 9.1. The values for each month of the year for the two crops and the selected areas are furthermore tabulated in Tables 9.1 and 9.2 for each month of the year.

TABLE 9.1 Summary of the mean monthly weather elements, k_{vo}, climatic adjustment factors ,v, and normal evaporation coefficients for the potatoes during early (e) and mature (m) periods. The * refers to k_{vo} values corresponding to the locality and its mean weather variables.

Locality	Month	Mean monthly weather elements				Mean monthly Evaporation coefficients		Climatic adjustment factors		Normal evaporation coefficients	
		R_s W m^{-2}	T_a °C	e kPa	u_z m s^{-1}	k_{voe}	k_{vom}	v_e	v_m	k^*_{voe}	k^*_{vom}
ALIWAL NORTH	1	578	24.77	1.26	3.7	1.33	1.24	2.69	1.09	0.49	1.13
	2	541	23.53	1.36	3.4	1.32	1.26	2.66	1.12	0.49	1.13
	3	507	20.90	1.20	3.3	1.07	1.22	2.16	1.08	0.49	1.13
	4	446	16.97	0.96	3.3	0.64	1.16	1.29	1.02	0.49	1.13
	5	357	12.60	0.72	3.4	0.12	1.11	0.23	0.98	0.49	1.13
	6	323	9.87	0.61	3.8	****	1.07	****	0.95	0.49	1.13
	7	331	10.20	0.57	3.9	****	1.06	****	0.94	0.49	1.13
	8	427	11.47	0.53	4.5	****	1.01	****	0.89	0.49	1.13
	9	500	15.87	0.63	4.2	0.37	1.04	0.75	0.92	0.49	1.13
	10	533	18.60	0.80	4.3	0.63	1.09	1.27	0.96	0.49	1.13
	11	535	21.50	1.00	4.0	0.90	1.17	1.83	1.03	0.49	1.13
	12	595	23.70	1.11	3.9	1.20	1.18	2.43	1.04	0.49	1.13
BLOEMFONTEIN	1	590	25.43	1.50	4.2	1.47	1.28	2.97	1.13	0.49	1.13
	2	536	23.97	1.55	3.4	1.45	1.31	2.93	1.15	0.49	1.13
	3	493	21.93	1.39	3.1	1.22	1.28	2.47	1.13	0.49	1.13
	4	459	17.67	1.07	2.9	0.82	1.18	1.66	1.04	0.49	1.13
	5	374	13.97	0.78	2.8	0.32	1.13	0.66	1.00	0.49	1.13
	6	335	10.63	0.47	2.6	****	1.06	****	0.93	0.49	1.13
	7	360	10.90	0.57	2.8	0.05	1.06	0.11	0.94	0.49	1.13
	8	445	13.30	0.61	3.7	0.22	1.04	0.44	0.92	0.49	1.13
	9	510	17.80	0.73	4.4	0.49	1.08	0.99	0.96	0.49	1.13
	10	531	20.33	0.91	4.7	0.70	1.14	1.42	1.00	0.49	1.13
	11	576	22.57	1.12	4.8	1.00	1.18	2.02	1.04	0.49	1.13
	12	602	24.57	1.23	4.6	1.23	1.21	2.48	1.07	0.49	1.13
CEDARA	1	452	21.57	1.84	5.0	1.15	1.37	2.32	1.21	0.49	1.13
	2	439	21.57	1.81	4.9	1.12	1.37	2.26	1.21	0.49	1.13
	3	428	20.77	1.67	4.9	0.97	1.34	1.96	1.19	0.49	1.13
	4	417	18.60	1.32	4.2	0.74	1.26	1.49	1.12	0.49	1.13
	5	349	16.13	0.98	3.2	0.42	1.22	0.84	1.08	0.49	1.13
	6	314	13.80	0.74	3.1	0.11	1.17	0.22	1.03	0.49	1.13
	7	324	13.93	0.71	3.4	0.07	1.15	0.14	1.02	0.49	1.13
	8	395	15.83	0.84	4.8	0.18	1.15	0.37	1.02	0.49	1.13
	9	441	17.73	1.07	5.5	0.41	1.18	0.82	1.04	0.49	1.13
	10	411	18.67	1.32	5.6	0.52	1.26	1.05	1.11	0.49	1.13
	11	421	19.60	1.58	5.2	0.81	1.31	1.63	1.16	0.49	1.13
	12	440	20.97	1.72	5.3	0.98	1.34	1.98	1.19	0.49	1.13

CERES	1	583	24.37	1.20	5.4	1.04	1.21	2.10	1.07	0.49	1.13
	2	572	23.90	1.39	5.0	1.19	1.24	2.41	1.10	0.49	1.13
	3	497	22.07	1.28	4.4	0.97	1.25	1.96	1.11	0.49	1.13
	4	420	17.73	1.18	3.6	0.71	1.23	1.43	1.08	0.49	1.13
	5	312	14.07	1.00	3.4	0.25	1.21	0.51	1.07	0.49	1.13
	6	321	12.63	0.97	3.4	0.20	1.18	0.41	1.04	0.49	1.13
	7	311	11.90	0.88	3.7	0.05	1.16	0.11	1.02	0.49	1.13
	8	367	12.60	0.93	4.2	0.16	1.14	0.33	1.00	0.49	1.13
	9	454	14.97	0.89	4.7	0.34	1.10	0.68	0.97	0.49	1.13
	10	517	16.83	0.90	5.1	0.50	1.09	1.00	0.96	0.49	1.13
	11	557	20.47	1.10	6.1	0.69	1.15	1.40	1.01	0.49	1.13
	12	593	22.90	1.15	6.2	0.87	1.17	1.76	1.03	0.49	1.13
ESTCOURT	1	583	23.17	1.68	2.0	1.83	1.29	3.70	1.14	0.49	1.13
	2	572	22.90	1.70	1.7	1.85	1.30	3.74	1.15	0.49	1.13
	3	497	21.77	1.57	1.5	1.58	1.31	3.20	1.16	0.49	1.13
	4	420	19.27	1.25	1.3	1.14	1.27	2.30	1.13	0.49	1.13
	5	312	16.13	0.89	1.2	0.56	1.24	1.12	1.09	0.49	1.13
	6	321	13.40	0.67	1.2	0.34	1.15	0.69	1.02	0.49	1.13
	7	311	13.50	0.64	1.5	0.26	1.15	0.52	1.02	0.49	1.13
	8	367	15.87	0.72	2.0	0.44	1.16	0.89	1.03	0.49	1.13
	9	454	18.77	0.92	2.3	0.83	1.18	1.67	1.04	0.49	1.13
	10	517	20.53	1.19	2.6	1.16	1.21	2.36	1.07	0.49	1.13
	11	557	21.43	1.42	2.3	1.49	1.24	3.02	1.09	0.49	1.13
	12	593	22.73	1.58	2.2	1.74	1.26	3.52	1.11	0.49	1.13
KIMBERLEY	1	583	27.57	1.36	4.2	1.42	1.29	2.88	1.14	0.49	1.13
	2	548	26.37	1.47	3.7	1.45	1.32	2.93	1.17	0.49	1.13
	3	504	24.13	1.36	3.6	1.22	1.30	2.48	1.15	0.49	1.13
	4	467	20.27	1.11	3.5	0.86	1.22	1.74	1.08	0.49	1.13
	5	374	16.23	0.80	3.5	0.31	1.17	0.62	1.03	0.49	1.13
	6	339	13.23	0.66	3.7	0.01	1.12	0.01	0.99	0.49	1.13
	7	363	13.40	0.61	4.1	****	1.10	****	0.97	0.49	1.13
	8	449	15.87	0.62	4.6	0.19	1.08	0.38	0.95	0.49	1.13
	9	519	19.63	0.67	4.7	0.48	1.09	0.97	0.97	0.49	1.13
	10	536	22.67	0.87	5.0	0.71	1.16	1.43	1.02	0.49	1.13
	11	569	24.90	1.02	4.9	0.97	1.20	1.97	1.06	0.49	1.13
	12	602	26.70	1.17	4.6	1.25	1.23	2.53	1.09	0.49	1.13
LADYSMITH	1	514	24.63	1.74	2.0	1.76	1.37	3.55	1.21	0.49	1.13
	2	484	24.23	1.72	1.7	1.70	1.38	3.44	1.22	0.49	1.13
	3	466	23.10	1.50	1.5	1.50	1.34	3.03	1.19	0.49	1.13
	4	435	20.70	1.16	1.3	1.16	1.27	2.34	1.12	0.49	1.13
	5	365	17.40	0.86	1.2	0.70	1.22	1.42	1.08	0.49	1.13
	6	339	14.03	0.65	1.2	0.39	1.15	0.79	1.01	0.49	1.13
	7	362	14.23	0.64	1.5	0.40	1.13	0.81	1.00	0.49	1.13
	8	410	16.63	0.76	2.0	0.59	1.15	1.20	1.02	0.49	1.13
	9	482	19.63	0.91	2.3	0.91	1.17	1.85	1.04	0.49	1.13
	10	465	21.93	1.22	2.6	1.11	1.27	2.25	1.12	0.49	1.13
	11	481	22.90	1.43	2.3	1.36	1.31	2.76	1.16	0.49	1.13
	12	490	24.57	1.55	2.2	1.53	1.35	3.10	1.20	0.49	1.13

PIET RETIEF	1	495	22.70	1.80	2.0	1.69	1.37	3.43	1.21	0.49	1.13
	2	483	22.50	1.76	1.7	1.67	1.37	3.38	1.21	0.49	1.13
	3	437	21.67	1.59	1.5	1.46	1.36	2.95	1.20	0.49	1.13
	4	457	19.57	1.29	1.3	1.26	1.26	2.55	1.11	0.49	1.13
	5	389	16.63	1.00	1.2	0.83	1.21	1.67	1.07	0.49	1.13
	6	344	13.70	0.78	1.2	0.48	1.16	0.96	1.02	0.49	1.13
	7	363	13.77	0.82	1.5	0.51	1.15	1.03	1.02	0.49	1.13
	8	433	15.87	0.98	2.0	0.78	1.16	1.57	1.03	0.49	1.13
	9	476	17.23	1.15	2.3	0.99	1.18	1.99	1.04	0.49	1.13
	10	442	19.20	1.40	2.6	1.10	1.28	2.23	1.13	0.49	1.13
	11	462	20.70	1.60	2.3	1.38	1.32	2.79	1.17	0.49	1.13
	12	499	22.23	1.67	2.2	1.56	1.33	3.17	1.18	0.49	1.13
PIETERSBURG	1	530	24.17	1.73	3.1	1.61	1.35	3.25	1.19	0.49	1.13
	2	490	23.80	1.71	2.9	1.52	1.36	3.08	1.21	0.49	1.13
	3	488	22.57	1.55	2.7	1.40	1.32	2.83	1.17	0.49	1.13
	4	479	20.37	1.31	2.6	1.15	1.25	2.34	1.11	0.49	1.13
	5	419	17.50	0.96	2.6	0.69	1.19	1.39	1.05	0.49	1.13
	6	385	14.57	0.76	2.6	0.39	1.13	0.79	1.00	0.49	1.13
	7	398	14.63	0.76	2.6	0.42	1.13	0.84	1.00	0.49	1.13
	8	472	16.93	0.81	2.9	0.65	1.12	1.32	0.99	0.49	1.13
	9	518	20.17	0.98	3.6	0.87	1.16	1.76	1.02	0.49	1.13
	10	528	22.07	1.26	4.2	1.06	1.23	2.13	1.08	0.49	1.13
	11	528	22.80	1.49	3.8	1.30	1.28	2.63	1.13	0.49	1.13
	12	539	23.57	1.62	3.2	1.52	1.31	3.08	1.16	0.49	1.13
PORT ELIZABETH	1	503	22.57	1.85	6.1	1.14	1.34	2.31	1.19	0.49	1.13
	2	495	22.67	1.95	5.7	1.25	1.37	2.54	1.21	0.49	1.13
	3	437	21.77	1.87	5.1	1.13	1.39	2.28	1.22	0.49	1.13
	4	394	19.77	1.60	4.6	0.86	1.34	1.73	1.19	0.49	1.13
	5	307	17.93	1.36	3.9	0.53	1.34	1.08	1.18	0.49	1.13
	6	311	16.27	1.14	3.7	0.37	1.27	0.75	1.12	0.49	1.13
	7	311	15.77	1.12	3.9	0.31	1.26	0.63	1.11	0.49	1.13
	8	358	16.00	1.20	4.8	0.35	1.24	0.71	1.09	0.49	1.13
	9	427	16.83	1.31	5.7	0.48	1.22	0.98	1.08	0.49	1.13
	10	458	18.07	1.43	6.3	0.59	1.23	1.19	1.09	0.49	1.13
	11	502	19.60	1.57	6.4	0.81	1.25	1.65	1.10	0.49	1.13
	12	522	21.33	1.69	6.3	1.02	1.28	2.06	1.13	0.49	1.13
POTCHEFSTROOM	1	555	24.63	1.57	2.4	1.67	1.31	3.38	1.16	0.49	1.13
	2	512	23.87	1.57	2.2	1.58	1.33	3.20	1.18	0.49	1.13
	3	495	22.47	1.43	1.9	1.45	1.30	2.93	1.15	0.49	1.13
	4	474	19.17	1.12	1.9	1.08	1.21	2.19	1.07	0.49	1.13
	5	403	15.67	0.79	1.6	0.62	1.15	1.26	1.02	0.49	1.13
	6	361	12.50	0.62	1.6	0.31	1.10	0.64	0.97	0.49	1.13
	7	382	12.80	0.58	2.0	0.29	1.08	0.58	0.95	0.49	1.13
	8	475	15.83	0.61	2.4	0.55	1.07	1.12	0.94	0.49	1.13
	9	531	19.77	0.78	2.8	0.86	1.11	1.75	0.99	0.49	1.13
	10	523	22.27	1.03	3.1	1.05	1.20	2.13	1.06	0.49	1.13
	11	549	23.33	1.30	2.8	1.37	1.25	2.78	1.10	0.49	1.13
	12	555	24.23	1.44	2.5	1.55	1.28	3.14	1.13	0.49	1.13

PRETORIA	1	546	24.00	1.60	2.4	1.65	1.31	3.34	1.16	0.49	1.13
	2	510	23.73	1.69	2.2	1.65	1.35	3.34	1.19	0.49	1.13
	3	480	22.50	1.56	1.9	1.50	1.33	3.03	1.18	0.49	1.13
	4	481	19.90	1.25	1.9	1.21	1.24	2.44	1.09	0.49	1.13
	5	418	16.80	0.94	1.6	0.80	1.18	1.62	1.04	0.49	1.13
	6	376	13.87	0.74	1.6	0.47	1.13	0.95	1.00	0.49	1.13
	7	396	14.17	0.72	2.0	0.45	1.12	0.92	0.99	0.49	1.13
	8	479	16.83	0.81	2.4	0.74	1.11	1.49	0.98	0.49	1.13
	9	522	20.50	0.95	2.8	0.98	1.16	1.99	1.03	0.49	1.13
	10	521	22.37	1.25	3.1	1.20	1.24	2.43	1.10	0.49	1.13
	11	553	22.73	1.44	2.8	1.46	1.26	2.95	1.11	0.49	1.13
	12	570	23.47	1.54	2.5	1.63	1.28	3.31	1.13	0.49	1.13
PRIESKA	1	621	29.60	1.16	3.5	1.53	1.27	3.11	1.12	0.49	1.13
	2	569	28.73	1.35	3.1	1.58	1.32	3.19	1.17	0.49	1.13
	3	521	26.07	1.34	3.3	1.35	1.31	2.73	1.16	0.49	1.13
	4	476	21.47	1.07	3.1	0.95	1.23	1.92	1.09	0.49	1.13
	5	375	16.77	0.85	3.2	0.41	1.19	0.82	1.05	0.49	1.13
	6	334	13.30	0.72	3.2	0.11	1.14	0.22	1.01	0.49	1.13
	7	357	13.23	0.66	3.6	0.06	1.11	0.13	0.98	0.49	1.13
	8	447	15.63	0.66	3.7	0.33	1.08	0.67	0.96	0.49	1.13
	9	537	19.77	0.68	3.6	0.69	1.09	1.40	0.96	0.49	1.13
	10	561	23.20	0.78	3.7	0.91	1.14	1.84	1.01	0.49	1.13
	11	602	26.20	0.90	3.7	1.18	1.18	2.39	1.04	0.49	1.13
	12	626	28.70	1.03	3.4	1.45	1.23	2.93	1.08	0.49	1.13
RIVERSDALE	1	474	24.23	1.62	3.7	1.32	1.36	2.67	1.21	0.49	1.13
	2	449	24.17	1.74	3.2	1.41	1.40	2.86	1.24	0.49	1.13
	3	405	22.90	1.68	3.0	1.26	1.41	2.55	1.24	0.49	1.13
	4	367	20.43	1.45	2.7	0.99	1.36	2.00	1.20	0.49	1.13
	5	294	17.50	1.20	2.6	0.57	1.32	1.15	1.17	0.49	1.13
	6	313	15.63	1.06	2.9	0.41	1.25	0.84	1.11	0.49	1.13
	7	305	14.73	1.02	3.0	0.32	1.23	0.66	1.09	0.49	1.13
	8	333	15.50	1.06	3.6	0.35	1.23	0.72	1.09	0.49	1.13
	9	405	16.80	1.15	3.4	0.65	1.22	1.32	1.07	0.49	1.13
	10	436	18.87	1.25	3.7	0.81	1.24	1.64	1.10	0.49	1.13
	11	464	21.07	1.41	3.8	1.04	1.29	2.11	1.14	0.49	1.13
	12	471	22.93	1.49	3.9	1.15	1.32	2.33	1.17	0.49	1.13
RUSTENBURG	1	546	25.60	1.83	2.4	1.86	1.38	3.76	1.22	0.49	1.13
	2	510	24.90	1.77	2.2	1.74	1.38	3.52	1.22	0.49	1.13
	3	481	23.60	1.60	1.9	1.57	1.36	3.17	1.20	0.49	1.13
	4	481	20.73	1.31	1.9	1.28	1.26	2.59	1.11	0.49	1.13
	5	418	17.43	0.95	1.6	0.82	1.19	1.66	1.05	0.49	1.13
	6	376	14.50	0.76	1.6	0.50	1.14	1.02	1.01	0.49	1.13
	7	396	14.60	0.74	2.0	0.48	1.13	0.98	1.00	0.49	1.13
	8	479	17.17	0.77	2.4	0.72	1.11	1.45	0.98	0.49	1.13
	9	522	21.10	0.96	2.8	1.01	1.17	2.04	1.04	0.49	1.13
	10	521	23.47	1.21	3.1	1.21	1.25	2.45	1.11	0.49	1.13
	11	552	24.33	1.52	2.8	1.56	1.30	3.16	1.15	0.49	1.13
	12	570	25.10	1.65	2.5	1.77	1.32	3.57	1.17	0.49	1.13

UPINGTON	1	637	30.13	1.15	3.5	1.58	1.26	3.20	1.12	0.49	1.13
	2	571	29.17	1.32	3.1	1.58	1.33	3.19	1.17	0.49	1.13
	3	528	27.07	1.32	3.3	1.38	1.32	2.79	1.17	0.49	1.13
	4	486	22.67	1.03	3.1	0.98	1.23	1.99	1.09	0.49	1.13
	5	387	18.23	0.80	3.2	0.44	1.19	0.89	1.05	0.49	1.13
	6	347	15.17	0.68	3.2	0.17	1.15	0.34	1.02	0.49	1.13
	7	369	15.13	0.62	3.6	0.12	1.12	0.24	0.99	0.49	1.13
	8	458	16.67	0.60	3.7	0.35	1.08	0.71	0.96	0.49	1.13
	9	543	20.87	0.65	3.6	0.72	1.10	1.47	0.97	0.49	1.13
	10	566	23.80	0.77	3.7	0.93	1.15	1.89	1.01	0.49	1.13
	11	609	27.13	0.92	3.7	1.24	1.19	2.50	1.06	0.49	1.13
	12	636	29.20	0.99	3.4	1.46	1.22	2.95	1.08	0.49	1.13
DURBAN	1	467	25.47	2.37	5.0	1.66	1.51	3.36	1.33	0.49	1.13
	2	471	25.63	2.40	4.9	1.71	1.51	3.47	1.34	0.49	1.13
	3	425	25.17	2.29	4.9	1.53	1.52	3.11	1.34	0.49	1.13
	4	407	23.07	1.96	4.2	1.30	1.45	2.62	1.28	0.49	1.13
	5	343	20.73	1.64	3.2	1.00	1.41	2.02	1.24	0.49	1.13
	6	302	18.67	1.32	3.1	0.64	1.35	1.29	1.19	0.49	1.13
	7	316	18.50	1.35	3.4	0.64	1.34	1.29	1.18	0.49	1.13
	8	378	19.23	1.46	4.8	0.69	1.32	1.39	1.17	0.49	1.13
	9	405	20.53	1.68	5.5	0.83	1.36	1.68	1.20	0.49	1.13
	10	402	21.63	1.84	5.6	0.95	1.40	1.91	1.24	0.49	1.13
	11	437	22.97	2.04	5.2	1.26	1.43	2.55	1.27	0.49	1.13
	12	458	24.53	2.20	5.3	1.46	1.47	2.95	1.30	0.49	1.13
CAPE TOWN	1	574	22.37	1.56	5.4	1.20	1.24	2.43	1.10	0.49	1.13
	2	567	22.60	1.67	5.0	1.33	1.27	2.68	1.13	0.49	1.13
	3	491	21.43	1.53	4.4	1.10	1.29	2.24	1.14	0.49	1.13
	4	379	18.70	1.46	3.6	0.83	1.32	1.69	1.16	0.49	1.13
	5	284	16.30	1.34	2.9	0.56	1.33	1.13	1.17	0.49	1.13
	6	293	14.80	1.15	3.4	0.33	1.26	0.68	1.12	0.49	1.13
	7	279	13.70	1.13	3.7	0.21	1.25	0.43	1.11	0.49	1.13
	8	329	14.43	1.12	4.2	0.27	1.22	0.54	1.08	0.49	1.13
	9	419	15.40	1.11	4.7	0.42	1.17	0.85	1.03	0.49	1.13
	10	497	17.57	1.29	5.1	0.74	1.18	1.49	1.04	0.49	1.13
	11	599	19.63	1.39	6.1	0.96	1.15	1.94	1.02	0.49	1.13
	12	585	21.03	1.43	6.2	0.98	1.19	1.98	1.05	0.49	1.13

TABLE 9.2 Summary of the mean monthly weather elements, k_{vo}, climatic adjustment factors ,v, and normal evaporation coefficients for the maize during early (e) and mature (m) periods. The * refers to k_{vo} values corresponding to the locality and its mean weather variables.

Locality	Month	Mean monthly weather elements				Mean monthly Evaporation coefficients		Climatic adjustment factors		Normal evaporation coefficients	
		R_s W m^{-2}	T_a °C	e kPa	u_z m s^{-1}	k_{voe}	k_{vom}	v_e	v_m	k^*_{voe}	k^*_{vom}
ALIWAL NORTH	1	578	24.77	1.26	3.7	1.18	1.18	1.33	1.08	0.88	1.09
	2	541	23.53	1.36	3.4	1.34	1.21	1.52	1.11	0.88	1.09
	3	507	20.90	1.20	3.3	1.63	1.12	1.85	1.02	0.88	1.09
	4	446	16.97	0.96	3.3	2.05	0.97	2.33	0.88	0.88	1.09
	10	533	18.60	0.80	4.3	1.73	0.89	1.97	0.81	0.88	1.09
	11	535	21.50	1.00	4.0	1.49	1.02	1.69	0.93	0.88	1.09
	12	595	23.70	1.11	3.9	1.25	1.10	1.42	1.00	0.88	1.09
BLOEMFONTEIN	1	590	25.43	1.50	4.2	1.02	1.26	1.16	1.15	0.88	1.09
	2	536	23.97	1.55	3.4	1.29	1.29	1.46	1.18	0.88	1.09
	3	493	21.93	1.39	3.1	1.56	1.21	1.77	1.10	0.88	1.09
	4	459	17.67	1.07	2.9	2.02	1.03	2.29	0.95	0.88	1.09
	10	531	20.33	0.91	4.7	1.52	0.94	1.73	0.86	0.88	1.09
	11	576	22.57	1.12	4.8	1.26	1.05	1.42	0.96	0.88	1.09
	12	602	24.57	1.23	4.6	1.07	1.13	1.21	1.03	0.88	1.09
CEDARA	1	452	21.57	1.84	5.0	1.35	1.29	1.53	1.18	0.88	1.09
	2	439	21.57	1.81	4.9	1.37	1.28	1.56	1.17	0.88	1.09
	3	428	20.77	1.67	4.9	1.47	1.22	1.67	1.11	0.88	1.09
	4	417	18.60	1.32	4.2	1.79	1.08	2.03	0.99	0.88	1.09
	10	411	18.67	1.32	5.6	1.62	1.02	1.84	0.94	0.88	1.09
	11	421	19.60	1.58	5.2	1.55	1.15	1.76	1.05	0.88	1.09
	12	440	20.97	1.72	5.3	1.39	1.22	1.58	1.12	0.88	1.09
CERES	1	583	24.37	1.20	5.4	1.01	1.08	1.15	0.98	0.88	1.09
	2	572	23.90	1.39	5.0	1.09	1.16	1.24	1.06	0.88	1.09
	3	497	22.07	1.28	4.4	1.40	1.11	1.58	1.02	0.88	1.09
	4	420	17.73	1.18	3.6	1.95	1.05	2.21	0.96	0.88	1.09
	10	517	16.83	0.90	5.1	1.80	0.87	2.04	0.80	0.88	1.09
	11	557	20.47	1.10	6.1	1.30	0.96	1.48	0.87	0.88	1.09
	12	593	22.90	1.15	6.2	1.04	1.01	1.18	0.92	0.88	1.09
ESTCOURT	1	583	23.17	1.68	2.0	1.48	1.39	1.68	1.27	0.88	1.09
	2	572	22.90	1.70	1.7	1.55	1.41	1.75	1.28	0.88	1.09
	3	497	21.77	1.57	1.5	1.74	1.34	1.98	1.23	0.88	1.09
	4	420	19.27	1.25	1.3	2.08	1.19	2.36	1.09	0.88	1.09
	10	517	20.53	1.19	2.6	1.74	1.13	1.98	1.04	0.88	1.09
	11	557	21.43	1.42	2.3	1.64	1.25	1.87	1.15	0.88	1.09
	12	593	22.73	1.58	2.2	1.49	1.34	1.70	1.23	0.88	1.09

KIMBERLEY	1	583	27.57	1.36	4.2	0.85	1.23	0.97	1.13	0.88	1.09
	2	548	26.37	1.47	3.7	1.04	1.28	1.18	1.17	0.88	1.09
	3	504	24.13	1.36	3.6	1.29	1.21	1.47	1.10	0.88	1.09
	4	467	20.27	1.11	3.5	1.70	1.06	1.93	0.97	0.88	1.09
	10	536	22.67	0.87	5.0	1.28	0.94	1.45	0.86	0.88	1.09
	11	569	24.90	1.02	4.9	1.05	1.04	1.19	0.95	0.88	1.09
	12	602	26.70	1.17	4.6	0.88	1.13	1.00	1.04	0.88	1.09
LADYSMITH	1	514	24.63	1.74	2.0	1.40	1.43	1.59	1.31	0.88	1.09
	2	484	24.23	1.72	1.7	1.49	1.42	1.70	1.30	0.88	1.09
	3	466	23.10	1.50	1.5	1.66	1.33	1.88	1.22	0.88	1.09
	4	435	20.70	1.16	1.3	1.95	1.18	2.21	1.08	0.88	1.09
	10	465	21.93	1.22	2.6	1.66	1.16	1.88	1.06	0.88	1.09
	11	481	22.90	1.43	2.3	1.57	1.27	1.78	1.16	0.88	1.09
	12	490	24.57	1.55	2.2	1.42	1.34	1.61	1.23	0.88	1.09
PIET RETIEF	1	495	22.70	1.80	2.0	1.58	1.42	1.79	1.30	0.88	1.09
	2	483	22.50	1.76	1.7	1.65	1.42	1.87	1.30	0.88	1.09
	3	437	21.67	1.59	1.5	1.80	1.35	2.04	1.23	0.88	1.09
	4	457	19.57	1.29	1.3	2.02	1.21	2.30	1.11	0.88	1.09
	10	442	19.20	1.40	2.6	1.90	1.19	2.16	1.09	0.88	1.09
	11	462	20.70	1.60	2.3	1.77	1.31	2.00	1.19	0.88	1.09
	12	499	22.23	1.67	2.2	1.61	1.36	1.82	1.24	0.88	1.09
PIETERSBURG	1	530	24.17	1.73	3.1	1.29	1.37	1.47	1.25	0.88	1.09
	2	490	23.80	1.71	2.9	1.38	1.36	1.57	1.25	0.88	1.09
	3	488	22.57	1.55	2.7	1.54	1.30	1.74	1.18	0.88	1.09
	4	479	20.37	1.31	2.6	1.78	1.18	2.02	1.08	0.88	1.09
	10	528	22.07	1.26	4.2	1.40	1.11	1.59	1.02	0.88	1.09
	11	528	22.80	1.49	3.8	1.36	1.23	1.54	1.13	0.88	1.09
	12	539	23.57	1.62	3.2	1.34	1.32	1.52	1.21	0.88	1.09
PORT ELIZABETH	1	503	22.57	1.85	6.1	1.09	1.26	1.23	1.16	0.88	1.09
	2	495	22.67	1.95	5.7	1.12	1.32	1.27	1.21	0.88	1.09
	3	437	21.77	1.87	5.1	1.33	1.30	1.51	1.19	0.88	1.09
	4	394	19.77	1.60	4.6	1.63	1.19	1.85	1.09	0.88	1.09
	10	458	18.07	1.43	6.3	1.54	1.03	1.75	0.95	0.88	1.09
	11	502	19.60	1.57	6.4	1.34	1.11	1.52	1.01	0.88	1.09
	12	522	21.33	1.69	6.3	1.17	1.18	1.33	1.08	0.88	1.09
POTCHEFSTROOM	1	555	24.63	1.57	2.4	1.33	1.35	1.51	1.23	0.88	1.09
	2	512	23.87	1.57	2.2	1.46	1.34	1.66	1.23	0.88	1.09
	3	495	22.47	1.43	1.9	1.65	1.28	1.87	1.17	0.88	1.09
	4	474	19.17	1.12	1.9	1.99	1.12	2.26	1.02	0.88	1.09
	10	523	22.27	1.03	3.1	1.54	1.08	1.75	0.98	0.88	1.09
	11	549	23.33	1.30	2.8	1.43	1.21	1.63	1.11	0.88	1.09
	12	555	24.23	1.44	2.5	1.37	1.29	1.55	1.18	0.88	1.09
PRETORIA	1	546	24.00	1.60	2.4	1.39	1.35	1.58	1.23	0.88	1.09
	2	510	23.73	1.69	2.2	1.46	1.39	1.66	1.27	0.88	1.09
	3	480	22.50	1.56	1.9	1.64	1.33	1.87	1.22	0.88	1.09
	4	481	19.90	1.25	1.9	1.91	1.18	2.16	1.08	0.88	1.09
	10	521	22.37	1.25	3.1	1.51	1.16	1.71	1.06	0.88	1.09
	11	553	22.73	1.44	2.8	1.47	1.26	1.67	1.15	0.88	1.09
	12	570	23.47	1.54	2.5	1.42	1.32	1.61	1.20	0.88	1.09

PRIESKA	1	621	29.60	1.16	3.5	0.74	1.21	0.85	1.11	0.88	1.09
	2	569	28.73	1.35	3.1	0.89	1.29	1.01	1.18	0.88	1.09
	3	521	26.07	1.34	3.3	1.15	1.24	1.30	1.13	0.88	1.09
	4	476	21.47	1.07	3.1	1.64	1.08	1.86	0.99	0.88	1.09
	10	561	23.20	0.78	3.7	1.38	0.97	1.56	0.89	0.88	1.09
	11	602	26.20	0.90	3.7	1.06	1.06	1.21	0.97	0.88	1.09
	12	626	28.70	1.03	3.4	0.84	1.16	0.96	1.06	0.88	1.09
RIVERSDALE	1	474	24.23	1.62	3.7	1.27	1.30	1.44	1.19	0.88	1.09
	2	449	24.17	1.74	3.2	1.35	1.36	1.53	1.25	0.88	1.09
	3	405	22.90	1.68	3.0	1.52	1.33	1.73	1.22	0.88	1.09
	4	367	20.43	1.45	2.7	1.83	1.22	2.08	1.12	0.88	1.09
	10	436	18.87	1.25	3.7	1.82	1.08	2.06	0.99	0.88	1.09
	11	464	21.07	1.41	3.8	1.57	1.17	1.78	1.07	0.88	1.09
	12	471	22.93	1.49	3.9	1.38	1.22	1.57	1.12	0.88	1.09
RUSTENBURG	1	546	25.60	1.83	2.4	1.23	1.46	1.39	1.33	0.88	1.09
	2	510	24.90	1.77	2.2	1.35	1.43	1.53	1.31	0.88	1.09
	3	481	23.60	1.60	1.9	1.54	1.36	1.75	1.25	0.88	1.09
	4	481	20.73	1.31	1.9	1.82	1.21	2.07	1.11	0.88	1.09
	10	521	23.47	1.21	3.1	1.41	1.16	1.61	1.06	0.88	1.09
	11	552	24.33	1.52	2.8	1.32	1.31	1.50	1.19	0.88	1.09
	12	570	25.10	1.65	2.5	1.26	1.38	1.43	1.27	0.88	1.09
UPINGTON	1	637	30.13	1.15	3.5	0.69	1.22	0.78	1.12	0.88	1.09
	2	571	29.17	1.32	3.1	0.86	1.29	0.97	1.18	0.88	1.09
	3	528	27.07	1.32	3.3	1.05	1.24	1.20	1.14	0.88	1.09
	4	486	22.67	1.03	3.1	1.53	1.08	1.74	0.99	0.88	1.09
	10	566	23.80	0.77	3.7	1.32	0.98	1.50	0.89	0.88	1.09
	11	609	27.13	0.92	3.7	0.97	1.08	1.11	0.99	0.88	1.09
	12	636	29.20	0.99	3.4	0.80	1.15	0.90	1.05	0.88	1.09
DURBAN	1	467	25.47	2.37	5.0	0.93	1.55	1.06	1.41	0.88	1.09
	2	471	25.63	2.40	4.9	0.92	1.56	1.05	1.43	0.88	1.09
	3	425	25.17	2.29	4.9	1.02	1.52	1.16	1.39	0.88	1.09
	4	407	23.07	1.96	4.2	1.33	1.39	1.52	1.27	0.88	1.09
	10	402	21.63	1.84	5.6	1.31	1.26	1.48	1.15	0.88	1.09
	11	437	22.97	2.04	5.2	1.19	1.37	1.35	1.26	0.88	1.09
	12	458	24.53	2.20	5.3	1.01	1.46	1.14	1.33	0.88	1.09
CAPE TOWN	1	574	22.37	1.56	5.4	1.16	1.19	1.31	1.08	0.88	1.09
	2	567	22.60	1.67	5.0	1.18	1.25	1.34	1.14	0.88	1.09
	3	491	21.43	1.53	4.4	1.43	1.20	1.62	1.10	0.88	1.09
	4	379	18.70	1.46	3.6	1.87	1.16	2.12	1.06	0.88	1.09
	10	497	17.57	1.29	5.1	1.71	1.03	1.95	0.94	0.88	1.09
	11	599	19.63	1.39	6.1	1.31	1.06	1.49	0.97	0.88	1.09
	12	585	21.03	1.43	6.2	1.18	1.08	1.34	0.99	0.88	1.09

A simple outline of how the results may be applied, e.g. in practic irrigation scheduling are given.

The results find application not alone in irrigation scheduling, but cou also be of great use modelling water consumption in crops.

CHAPTER 10

10. SUMMARY AND CONCLUSIONS

10.1 GENERAL

In the past, many problems have been experienced with the use of crop evaporation coefficients. Basically these problems arise from the inability of most techniques to separate vegetation evaporation from soil evaporation. This study is based upon a new definition of atmospheric evaporative demand (De Jager, et al. 1989) which accommodates both vegetation evaporation and soil surface evaporation. The theory furthermore recognises a vegetation evaporation coefficient and a soil evaporation coefficient. All four these concepts were considered in this study. The necessary equations for computing vegetation and soil evaporation from vegetation and soil evaporation coefficients were formulated, applied and analysed.

The other major cause for concern regarding the traditional crop evaporation coefficients stems from the climatic dependence of evaporation coefficients. The objective of this study was therefore to identify the major weather elements influencing the crop evaporation coefficient and produce a theory whereby a crop evaporation coefficient corrected for climate may be calculated.

The techniques developed have noteworthy implications for the accurate calculation of reference crop evaporation, atmospheric evaporative demand, evaporation coefficients and effective crop water consumption. Their application will increase water use efficiency and hence bring about considerable savings in the RSA's most scarce commodity, water.

10.2 METHOD

The study was restricted to the potato and maize crops. The theory of vegetation evaporation coefficients was analysed and it was found that the only component of the evaporation coefficient which could be influenced by climate was the so called upper limit vegetation evaporation coefficient ,k_{vo},.

The study undertook to:-

(i) Analyse and explain in detail the concept evaporation coefficient.

(ii) Evaluate the accuracy of, and influence of advection on five micro-meteorological techniques for measuring natural surface evaporation. The techniques involved were the energy budget/Bowen ratio, the energy budget/infrared thermometer, the energy budget/eddy correlation sensible heat, the direct eddy correlation, and the Penman-Monteith techniques. Other instrumentation included a short grass covered lysimeter and a large 10 m^2 lysimeter in which the agronomic crops under investigation were established.

(iii) Develop mathematical expressions for the upper limit evaporation coefficient ,k_{vo}, in terms of both micro- and macro-meteorological measurements of the weather elements.

(iv) Use the macro-meteorological equations developed under (iii) to compute a mean monthly, or standard, k_{vo}* for the major potato and maize producing areas in the RSA.

The necessary measurements in lysimeter and atmosphere for the relevant crops were made. From these k_{vo} was estimated and multiple regression equations for k_{vo} derived. These equations were based upon hourly and daylight values of the weather elements. The method accommodated estimations of the soil surface evaporation coefficient which accounted for soil surface evaporation.

Initially it was planned to make observations on an hourly basis using the micro-meteorological techniques. Hourly values would, in short time, provide many sets of data upon which to carry out the multiple regressions. Unfortunately, the high degree of variance obtained with the different systems made it impossible to utilize hourly values in the study. Instead the analysis had to resort to the use of daylight values which exhibited less sampling variation.

A further complication was experienced due to the degree of advection to which the lysimeters were subjected on the present site. Care was taken to meet all the necessary precautions for adequate fetch, as prescribed by present day theory. It appears however, that the unusual, extreme conditions experienced during the seasons under investigation, produced considerable advection which complicated matters. Where possible readings were adjusted for advection. Essentially, only measurements free of advection, or which had been ajusted for advection, were used in the analyses.

10.3 RESULTS

10.3.1 Technique Accuracies for measuring Reference Evaporation

It was shown that the Penman-Monteith equation (PME), as previously standardized form, provided adequate measurements of reference crop evaporation on which the theory could be based.

Comparison of reference crop evaporation, E_o, using PME, and lysimeter E_o yielded a slope through the origin and coefficient of determination, (r^2), of 0,97 and 0,89 respectively.

The energy budget/Bowen ratio (EB_B) technique for estimating E_o, although well correlated with measured E_o, responded to advection. This technique was used to investigate the extent of advection experienced during 1990.

The energy budget/infrared thermometer (EB_{IRT}) technique compared favourable with measured E_o. Although this technique over-estimated daylight Eo by 24%; the coefficient of determination, r^2, was 0,85.

The energy budget/eddy correlation sensible heat (EB_C) technique and direct eddy correlation measurements (EC) proved unreliable for estimation of E_o during the experimental conditions prevailing during 1990. Comparisons between the two techniques and measured E_o yielded a slope through the origin of 0,92 and 0,51 repectively and r^2 of 0.27 and 0,56 respectively. Considerable inprovement emerged from the 1992 studies. Corresponding stastical parameters were 0,76 and 0,84, respectively for EB_C and 1,08 and 0,63 respectively for EC. This improvement was made possible by adjusting the heights of the sensors. During 1990 eddy correlation measurements were made 2,00 m above the grass site. This is outside the equilibrium boundary layer of the grass site. During 1992 measurements were made at 0,25 m above grass level, which is inside the equilibrium boundary layer of the grass. It is therefore concluded that the abnormally dry weather conditions, which persisted during both seasons, detrimentally influenced measurements made at the higher level.

10.3.2 AED for maize

During 1992, hourly AED, Atmospheric evaporative demand, from maize was determined from EB_B and EC. All relevant measurements were made within the equilibrium boundary layer of the maize crop. EB_B compared to AED measured by the lysimeter yielded a slope through the origin and r^2 of 0,76 and 0,69 respectively. EB_C therefore underestimated measured AED by approximately 24%. The EC technnique however, overestimated measured AED in the lysimeter by 10%. The r^2 was 0,55 suggesting the presence of large scale scatter.

10.3.3 k_{vo} for Potato

During 1990, climatic dependence of the upper limit vegetation evaporation coefficients, k_{vo}, for potatoes was demonstrated. The goodness of fit of k_{vo} in relation to both daylight micro- and macro-weather elements was determined by multiple regression analysis. Coefficients of determination ranged between 0,99 and 0,94 for the developing stage and 0,87 to 0,72 during the mature stage. It should be emphazised that the high r^2 values obtained during the early stages could be spurious due to the seasonal development of vegetation cover of the ground. During the mature stage vegetation cover factor, F_v, approximates unity an hence k_{vo} $\approx$ k_c. During this stage k_{vo} varied between 1,12 and 1,18 depending upon the method used to calculate F_v. It was furthermore shown that, of the four weather elements solar radiation, windspeed, air temperature and water vapour pressure, the latter two made the major contribution to explaining the variations in k_{vo}. Increased k_{vo} was assosiated with increasing air temperature and water vapour pressure.

10.3.4 k_{vo} for Maize

In this study the EBc and lysimeter techniques were applied. The latter were adjusted for 24% advection. During 1992, climatic dependence, k_{vo}, for maize was also demonstrated. Multiple regression analysis of k_{vo} on daylight values of both micro- and macro-weather elements yielded r^2 values of the same order of magnitude as those attained for potatoes. During the mature stage ($F_v \approx 1$) the overall mean k_{vo} computed from daylight weather variables. Futhermore a diurnal variation of conductances of individual leaves of maize to grass was found. This could contribute to explaining the variation of k_{vo} with climate.

10.3.5 The standard upper limit evaporation coefficient k_{vo}*

A theory for developing a standard upper limit evaporation coefficient k_{vo}* was established. This k_{vo}* applies to a given set of climatic conditions. It is transformed to different climatic conditions by a multiplication factor, ν. The latter is derived from the multiple regression coefficients of the appropiate empirical equation.

Assuming a principle of architectural simularity of crops, i.e. explicity roughly similar corp morphology, makes possible application of the determined $k_{vo}*$ and ν to any climate. Standard upper limit vegetation evaporation coefficients for maize and potatoes developed for appropriate mean daylight weather elements were 1,13 and 1,09 respectively.

10.3.6 Geographic distribution of $k_{vo}*$ and ν for maize and potatoes

Eighteen localities in the RSA where maize and potatoes are cultivated were selected. The derived multiple regression equations were used to compute relevant monthly values of $k_{vo}*$ and ν for the two crops. These were tabulated and will be invaluable in modeling studies and irrigation scheduling especially during mature crop growth stages.

10.4 CONCLUSIONS

- Climatic dependence of evaporation coefficients was demonstrated. It manifests itself in the upper limit vegetation evaporation coefficient, k_{vo}.
- Preliminary investigations have shown that upper limit vegetation evaporation coefficients, k_{vo}, declined with increasing vegetative cover during the development stage of the crop i.e. when $F_v < 1$.
- The Penman-Monteith equation proved to be a reliable estimator of E_o, and can be used with confidence to calculate upper limit vegetation evaporation coefficients on hourly and daylight basis.
- The energy budget/eddy correlation sensible heat measurements compared favourably with lysimeter measurements

of reference crop evaporation and atmopheric evaporative demand. This technique too was used to calculate upper limit vegetation evaporation coefficients for maize.

- The ratio of individual leaf stomatal conductance of maize to that of grass varies diurnally in similar fashion as k_{vo}. This differening behaviour in single leaf stomatal conductances of maize and grass, could be due to varying responses to climatic conditions and deserves further investigation.
- k_{vo}-values developed for both potatoes and maize during crop establishment stages here, are artefacts of the expressions used to account for degree of vegetation cover of the ground surface. As such, they can only be applied provided the same F_v expressions as here developed are used. This matter is to be investigated in a follow-up project of the Water Research Commission, wherein a refined vegetative surface cover factor will be developed and tested. In the interim both k_{vo} and the climatic adjustment factor, ν, for the mature period, as here calculated and tabulated in Chapter 9 for both potatoes and maize, should be used for the entire growing season, early period included.

10.5 RECOMMENDATIONS FOR FUTURE RESEARCH

During a follow-up project of the WRC attention will be given to the climatic dependence of vegetation evaporation coefficients has been demonstrated in this study particularly for maize and potato crops offering complete vegetation cover. The major wastage of water in crop production, however, occurs as a result of the evaporation of water through the soil surface from sparse vegetation canopies. There thus remains an urgent need to produce accurate sub-models for vegetation and soil evaporation from sparse canopies and determine their climatic dependence.

Uncertainties in the values of vegetation evaporation coefficients developed for both potato and maize during the developing stages of these crops became apparent from this study. These uncertainties are artefacts of the expressions used to account for the fractional radiation interception of the vegetation cover ,F_v. Validation of the mathematical expression for F_v for row crops is required.

The measurement of sensible heat obtained from sonic anemometer and fine-wire-thermocouple and observations of turbulent fluctuations in atmospheric water vapour content are indispensable in this type of work. Possibly the most important factor affecting the accuracy of these measurements is the height of exposure of these instruments. This aspect deserves to be finalised.

A useful future study would be comparison of the values of evaporation coefficients derived using the methods here proposed against actual measured values in different climates. This represents extensive experimental spread over the entire country. The results however would be most beneficial. It is suggested that the necessary field measurements be accumulated from other ongoing projects.

10.6 TECHNOLOGICAL TRANSFER OF RESULTS

All persons, or instances, interested in managing agricultural water use need to be encouraged to use climate corrected evaporation coefficients. Evaporation coefficients relevent to the full cover stages of potato and maize can now be computed using the mathematical relationships, here derived, or extracted from the tables produced. From these, crop water requirements may rapidly be calculated from automatic weather station data. For other crops, architecturally similar to potato or maize, the same relationships here developed could be used as a first approximation. Furthermore, the equations here developed can easily be incorporated into crop growth models used for irrigation scheduling.

Monthly mean upper limit vegetation evaporation coefficients have been developed for potato and maize for eighteen localities throughout South Africa. These can now be applied when estimating atmospheric evaporative demand, given estimates of reference crop evaporation. This new development needs to be brought to the attention of all irrigators.

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