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Estimating reference evaporation and crop evapotranspiration from weather data and crop coefficients

An addendum to AWRAC Research Project 84/162 Quantifying components of water balance under irrigated crops

By Wayne S. Meyer, David J. Smith and Graeme Shell

CSIRO Land and Water
Technical Report 34/98, October 1999

CSIRO LAND and WATER

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Abstract

Evaporation from irrigated crops of wheat and soybean was measured using weighing lysimeters at Griffith. These measurements were used to derive local calibration for the Penman equation to estimate crop evaporation. Other users of the Penman equation have used slight variations in the methods to get vapour pressure and wind function terms. This report examines the effect of these variations and makes recommendations on the application of different methods. Some limitations and improvements to the estimation of net radiant energy from solar irradiance are also discussed. A comparison between the accuracy of calculating evaporation on a daily or hourly basis showed no advantage to either method.

Using weighing lysimeter measured values of crop evaporation, together with daily meteorological measurements, a new wind function term for a theoretical reference crop was derived. This reference evaporation estimate was compared with other estimates of evaporation, namely Class A pan, and two other calculated estimates, modified Priestly-Taylor and standardised FAO Penman-Monteith. There was good consistency between estimates. Finally, comprehensive measured data for wheat, soybean, maize, lucerne, rice and pasture are presented from which generalised crop coefficients are derived.

ESTIMATING REFERENCE EVAPORATION AND CROP EVAPOTRANSPIRATION FROM WEATHER DATA AND CROP COEFFICIENTS

An Addendum to AWRAC Research Project 84/162

Quantifying components of the water balance under irrigated crops

1.0 Introduction

During the period 1984 to 1988, irrigated crops of wheat and soybean were grown on the weighing lysimeters at Griffith to measure their water balance components. Results from these experiments, together with an examination of methods of estimating evaporation, were published in the report of AWRAC Research Project 84/162 (Meyer 1988).

Since the mid 1980s, several groups in south eastern Australia, using weather data to calculate and publish reference evaporation (ET_o), adopted slightly different estimation methods. Questions then arise as to the effects of these variations on ET_o values. Some specific questions are:

1. what effect does the use of relative humidity (RH) values rather than mean daily dew point temperature (T_{dew}) have on ET_o values,

2. what are the wind function (f(U)) terms in reference evaporation (ET_o) if crop coefficients of 1.05 for wheat and 1.1 for soybean are adopted and

3. is daily ET_o more accurate when calculated from the sum of hourly estimates compared with that from daily mean values?

This report examines these questions.

In addition, comparison is made between daily ET_o and measurements of evaporation from a well maintained Class A pan. Other comparisons of ET_o are made with values estimated in the CERES crop growth models using Ritchie's (1972) water balance method (a modified Priestley-Taylor approach) and with the recently proposed standard form of the Penman-Monteith equation (Smith, 1992).

With the widespread use of daily ET_o estimates to aid irrigation scheduling, appropriate crop coefficients are needed to convert ET_o values to evapotranspiration values for particular crops. Crop coefficients derived over several seasons from measured data are also given.

2.0 Estimating daily reference evaporation

2.1 The modified Penman equation

Daily estimates of reference evaporation (ET_o mm day^{-1}) were made using the formula

$$\mathbf{ET_o} = \left[\left(\frac{\Delta}{\Delta+\gamma}\right)(\mathbf{R_n} - \mathbf{G}) + \left(\frac{\gamma}{\Delta+\gamma}\right)\mathbf{f(U)\,(e_o - e)}\right]/\mathbf{L} \qquad \mathbf{(1)}$$

Δ	:	Slope of the saturation vapour pressure-temperature curve at mean daily temperature [kPa ^{o}C^{-1}]
γ	:	Psychrometric constant [kPa ^{o}C^{-1}]
R_n	:	Net radiant energy [MJ m^{-2} day^{-1}]
G	:	Ground heat flux (positive when direction of flux is into the ground [MJ m^{-2} day^{-1}]
f(U)	:	Wind function of the form f(U) = a'+b'(U), where a' and b' are constants and U (km day^{-1}) is wind run [MJ m^{-2} kPa^{-1} day^{-1}]
e_o	:	Mean daily saturation vapour pressure at mean dry bulb temperature [kPa]
e	:	Actual mean daily vapour pressure [kPa]
L	:	Latent heat of vaporisation of water [MJ kg^{-1}]

Care should be taken in estimating R_n, since incorrect values will cause large errors in ET_o estimates (see AWRAC Report; Table 15, p34). New equations for calculating G are given in the AWRAC report (Table 10, p28), and the complete methodology for calculating ET_o is set out in Meyer (1998).

For accurate estimates of ET_o, consistency is needed in calculating the vapour pressure deficit (VPD) value (e_o-e) and that used to derive the wind function f(U). Thus, if a new method of calculating (e_o-e) is used, the matching f(U) should be available.

2.2 Using relative humidity (RH) or dew point temperature (T_{dew}) to calculate (e_o-e)

In the AWRAC report mean daily saturated vapour pressure, e_o was calculated as

$$\mathbf{e_o = 0.611 \exp [(17.27\, T_m)/(T_m + 237.3)]} \qquad \mathbf{(2)}$$

where T_m is mean daily temperature calculated preferably from the mean of 24 hourly temperature values or from daily maximum, T_{max} and minimum, T_{min} temperatures as

$$\mathbf{T_m = (T_{max} + T_{min})/2} \qquad (3)$$

Calculation of mean daily vapour pressure, e was done in the AWRAC report using minimum daily RH in

$$\mathbf{e = (e_{oTm} \times RH_{min})/100} \qquad (4)$$

The method used in the SIRAG-Field irrigation scheduling program (Stapper 1986) to estimate (e_o-e) uses the same equations as those above except that actual vapour pressure e comes from

$$\mathbf{e = 0.611 \exp [(17.27\ T_{dew}) / (T_{dew} + 237.3)]} \qquad (5)$$

where T_{dew} is the daily mean dew point temperature.

Note: Eqs (8) and (9) of the AWRAC Report (p26) have an incorrect coefficient (0.6197 should be 0.6118).

2.2.1 Why use daily mean dew point temperature, T_{dew}?

Daily plots of RH show a large diurnal fluctuation (Fig. 1) compared to the more conservative value of T_{dew} (Fig. 2). However these two figures show two other important points

- where good instrumentation is used, calculation of RH from wet and dry bulb thermometer readings can match RH values measured using electronic capacitance "chips" quite well (Fig. 1)

- even with well maintained meteorological observation sites, small differences or errors in temperature measurement can cause large differences in calculated T_{dew} (Fig. 2). The sites represented in Fig. 2 are within 500 m of each other. Two of the sites (lys and edas) used wet and dry bulb electronic sensor thermometers

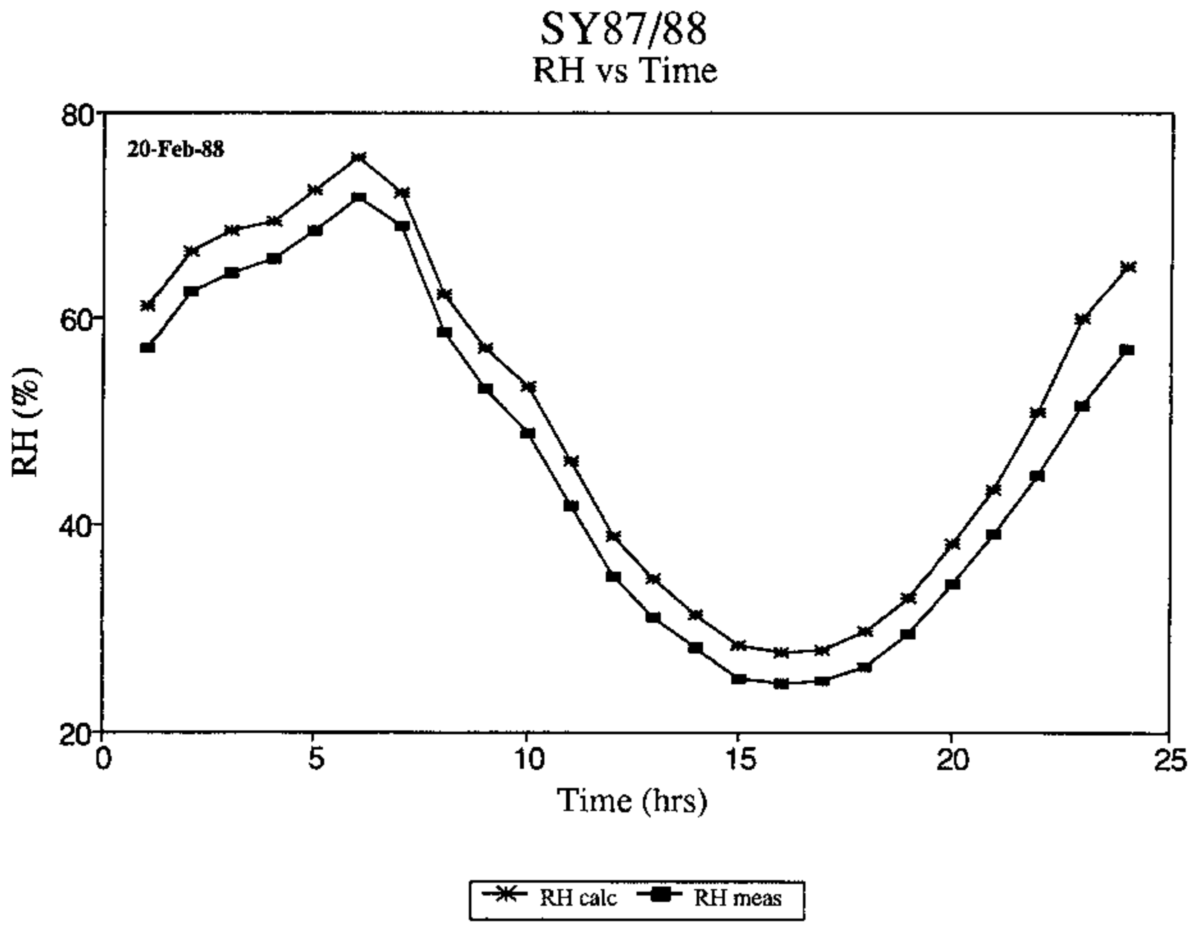


Fig. 1. Hourly time course of relative humidity RH on 20 Feb 1988. Rh_{calc} came from measurement of wet and dry bulb electronic thermometer sensors. Rh_{meas} was that recorded from direct measurement from an electronic capacitance RH sensor.

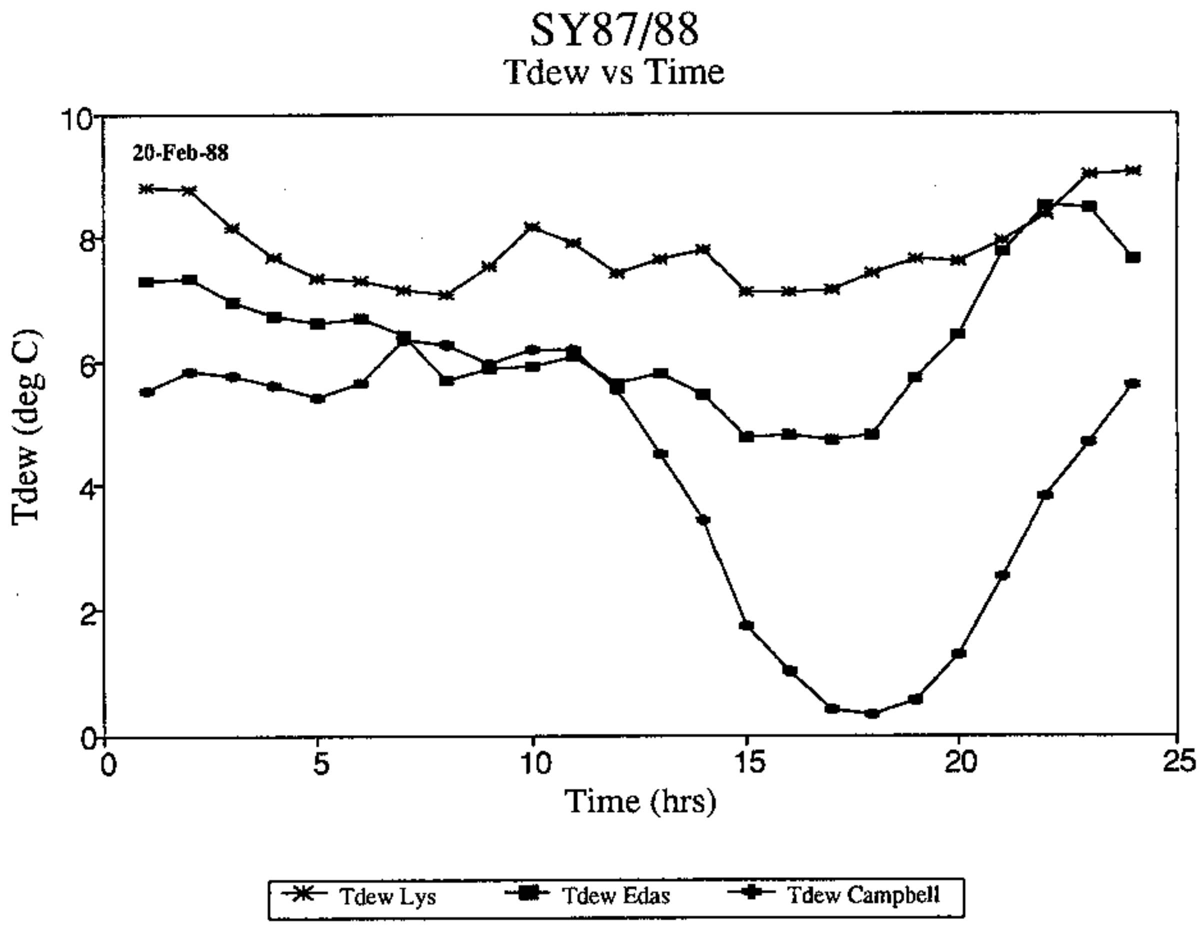


Fig. 2. Hourly time course of dew point temperature T_{dew} on 20 Feb 1988. Three independent weather station systems located within 500 m of each other produced these values. T_{dew} Lys and T_{dew} Edas used wet and dry bulb temperature to derive T_{dew}, where T_{dew} Campbell had an RH sensor from which T_{dew} was calculated.

while the third site (Campbell) had an RH sensor from which T_{dew} was back calculated.

Our experience with RH sensors shows that they need regular (3 monthly) calibration, they have a limited operational life (replacement recommended every 12 months) and they tend to drift in calibration. We therefore prefer wet and dry bulb temperature observations to derive vapour pressure (see section 2.2.3). This method also gives a more conservative (less variable) diurnal trace from which to calculate a mean daily T_{dew} value.

While T_{dew} tends to be more conservative diurnally, there are some conditions when instability occurs. Table 1 has data from a morning when very calm conditions (<3 km h^{-1} windrun) probably associated with a regional temperature inversion, caused T_{dew} to vary from hour to hour. These conditions do not occur often, but will be more frequent during late winter and early spring in inland south eastern Australia.

Table 1. Hourly data during the day-time from soybeans 1988 (10/3/88) shows dew point values to be more erratic when wind run was < 3 km h^{-1}

Time	Wind run (km h^{-1})	Dry bulb Temp (°C)	Wet bulb depression (°C)	Dew point (°C)	Relative Humidity (%)
0600	7.21	24.09	8.89	7.21	33.88
0700	2.40	21.07	5.72	10.70	51.51
0800	6.41	23.45	7.74	9.23	40.38
0900	2.40	24.52	6.34	13.83	51.34
1000	12.02	29.22	11.76	7.75	25.99
1100	18.42	31.38	13.66	6.01	20.38
1200	20.02	32.42	14.07	6.76	20.22

2.2.2 Using 9 am T_{dew} as a substitute for mean daily T_{dew}

Examination of hourly T_{dew} indicated that the 9 am reading is a reasonable approximation of the mean daily T_{dew} (P.M. Fleming, pers. comm). This observation is supported by our data (Figs. 3 and 4). Regression of 9 am T_{dew} on daily mean T_{dew} at the lysimeter site from two seasons

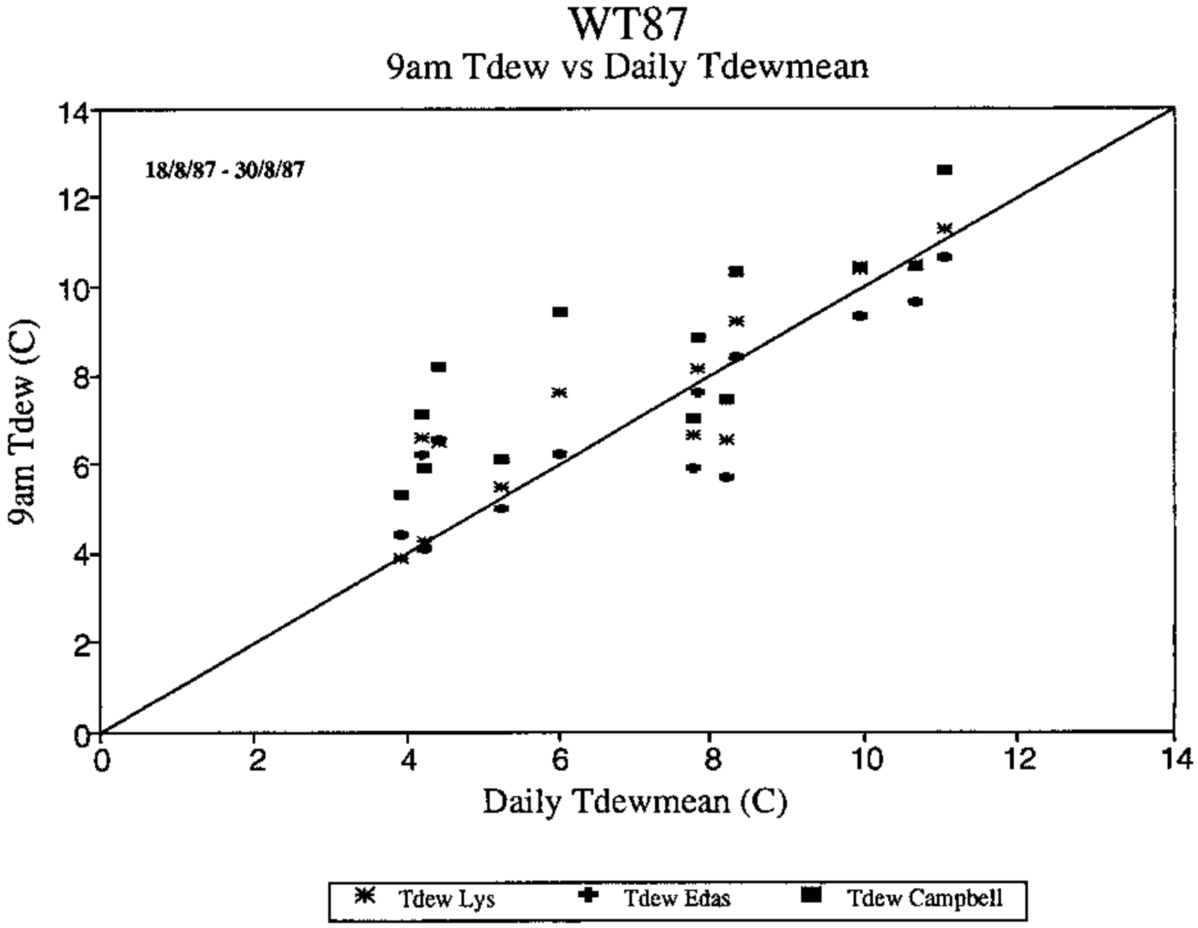


Fig. 3. Values of T_{dew} at 9 am from three sites compared with the daily mean T_{dew} for the period of 18 Aug to 30 Aug 1987.

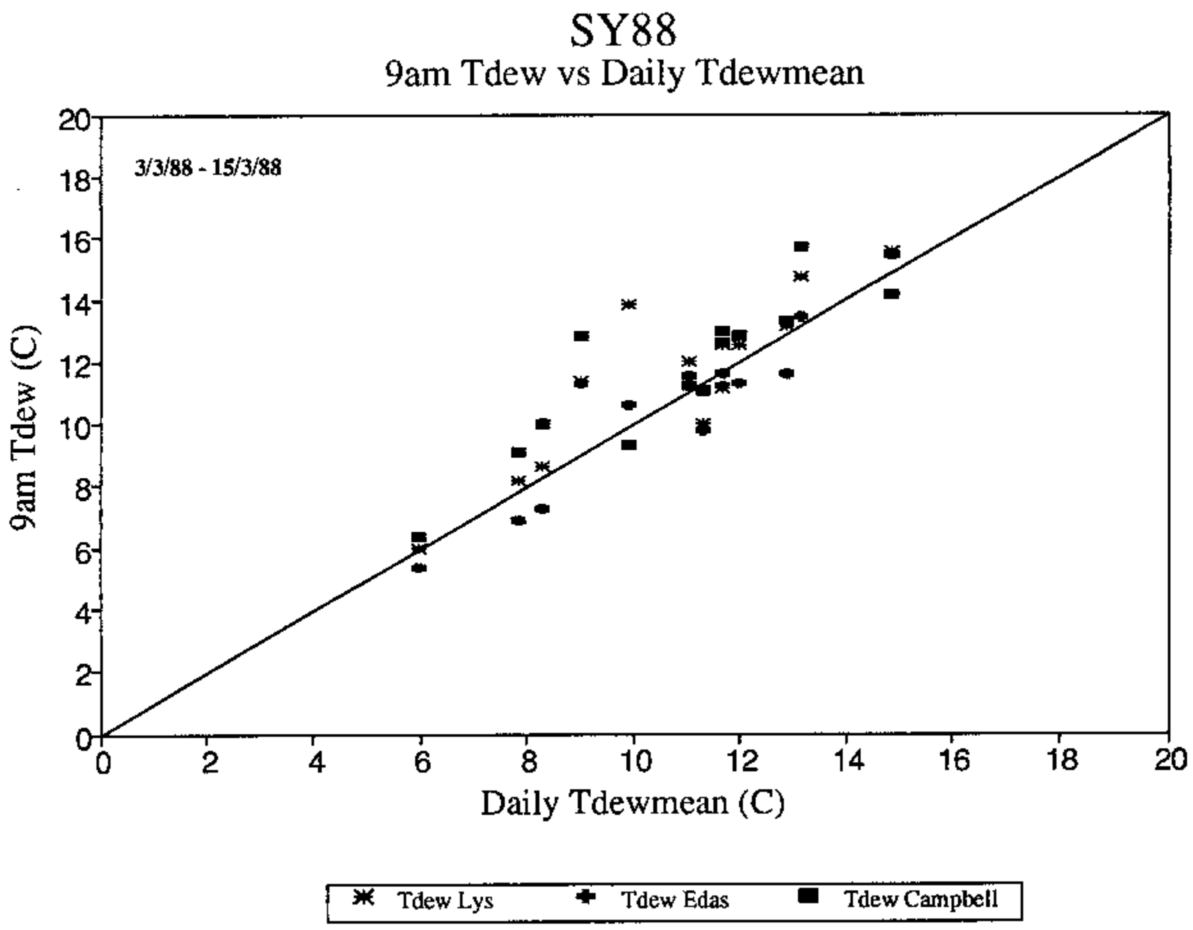


Fig. 4. Values of T_{dew} at 9 am from three sites compared with the daily mean T_{dew} for the period of 3 Mar to 15 Mar 1988.

(wheat 87 and soybean 88) yielded:

WT87 T_{dew} (9 am) = 1.028 (± 0.045) T_{dew} (daily mean) n = 13, $r^2 = 0.74$

SY88 T_{dew} (9 am) = 1.066 (± 0.033) T_{dew} (daily mean) n = 13, $r^2 = 0.76$

This association between T_{dew} (9 am) and T_{dew} (daily mean) will be less reliable when inversion conditions occur (see 2.2.1 above) during the early morning.

Note: The value in brackets on the RHS of the equations above is the standard error of estimate. This notation is used consistently throughout this report.

2.2.3 Using aspirated versus non-aspirated wet and dry bulb temperatures

During 1991 and 1992, a standard Stevenson screen was set up at the weather station site at CSIRO, Griffith. Two sets of electronic sensor thermometers were installed in the screen; one set was unaspirated wet and dry bulb sensors while the other was contained in an aspirated arrangement, where ambient air was continually drawn over the wet and dry bulb sensor elements (see Sides 1994, for details).

The comparisons between measured temperatures are shown in Figs. 5 and 6. Dry bulb temperature T_d varies little between non-aspirated and aspirated sensors. There is a tendency for non-aspirated sensors to be slightly warmer than aspirated sensors when $T_d < 20^oC$ and $T_w < 15^oC$. Clearly there is more deviation in T_w values. These deviations are inevitably associated with either insufficient wetting of the wet bulb wick due to insufficient water in the wick reservoir, or the wick becoming dirty from dust, especially in the aspirated situation. Careful and frequent maintenance of the wet bulb wick cannot be overemphasised.

As a further note on wet bulb wick placement, the experience from a weather station at Hay, NSW is relevant. It was noticed, particularly during the summer of 92/93 that wet bulb temperatures and therefore derived dew point temperature and RH values were higher than at Griffith. On 11 Feb 1993, the station was serviced between 1100 and 1200 hours and the wet bulb wick was extended 30 to 40 mm up the wet bulb sensor cable.

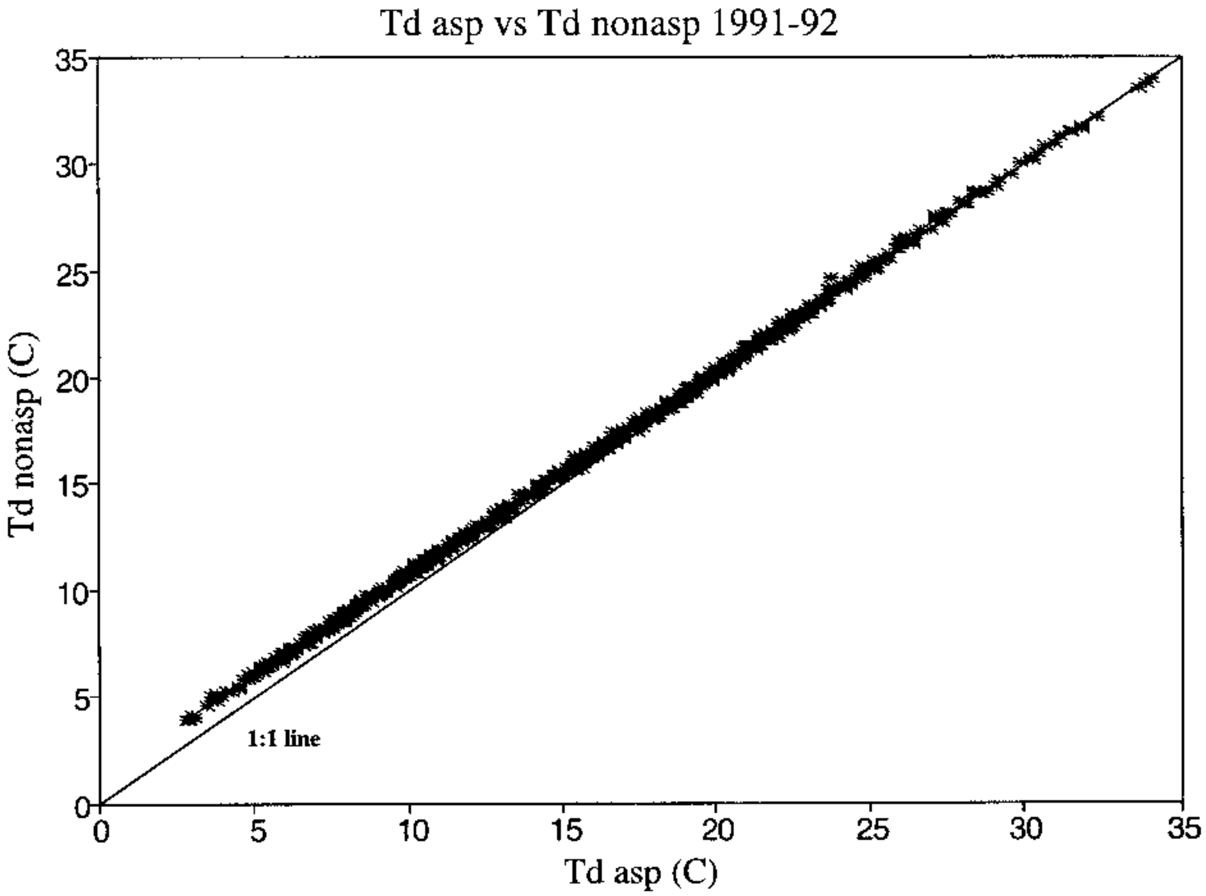


Fig. 5. Comparison of dry bulb temperatures T_d either aspirated ($T_{d\ asp}$) or non aspirated ($T_{d\ nonasp}$) measured in the same Stevenson screen during 1991 and 1992.

Regression: $T_{d\ nonasp} = 1.19\ (\pm\ 0.15) + 0.94\ (\pm\ 0.0008)\ T_{d\ asp}$ $r^2 = 0.99$

$n = 731$

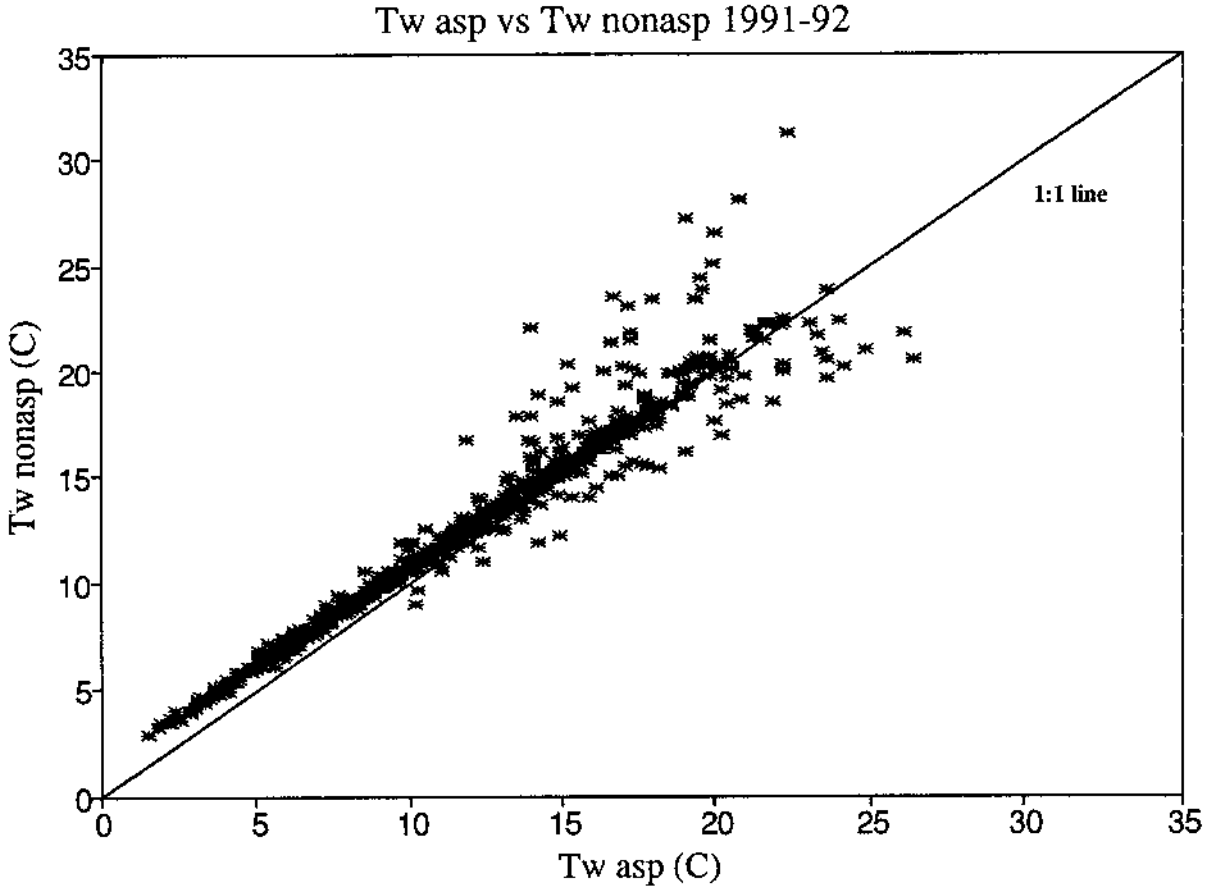
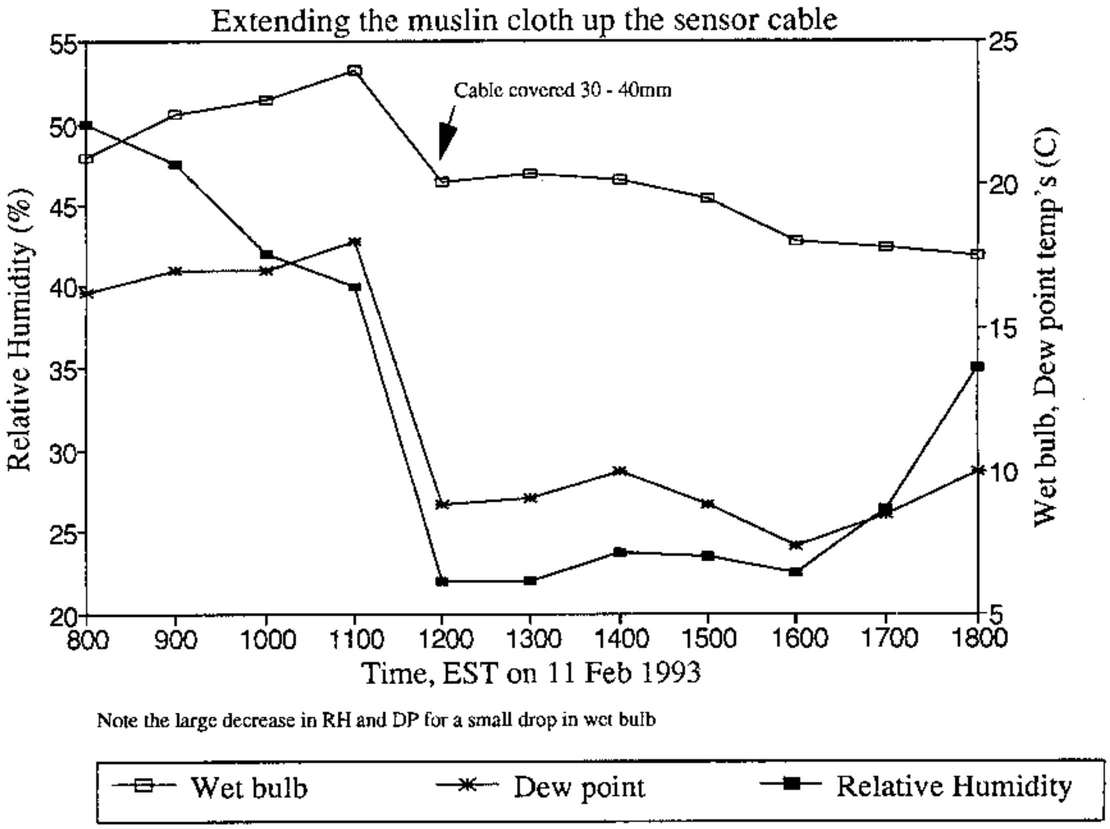


Fig. 6. Comparison of wet bulb temperatures T_2 either aspirated ($T_{w\ asp}$) or non aspirated ($T_{w\ nonasp}$) measured in the same Stevenson screen during 1991 and 1992.

At temperatures (T_w)<15°, non aspirated wet bulb tends to be warmer than aspirated.

Regression: $T_{w\ nonasp} = 1.43\ (\pm\ 1.17) - 0.94\ (\pm\ 0.008)\ T_{w\ asp}$ $r^2 = 0.94$

$n = 731$



Note the large decrease in RH and DP for a small drop in wet bulb

Fig. 7 Measured hourly wet bulb temperature at Hay, NSW on 11 Feb 1993. The muslin cloth forming the wet bulb was extended 30 to 40 mm up the sensor cable between 1100 and 1200 hours. The resultant change in derived dew point temperature and relative humidity is shown.

Fig. 7 shows that wet bulb temperature dropped from 23.5°C to 20°C following the modification. The large decrease in T_{dew} and RH which resulted is also apparent. We believe that temperature conduction along the cable was responsible for the poor wet bulb performance. This conduction can be largely overcome by extending the evaporating muslin wet bulb cover along the cable.

It should be noted that conversion of wet and dry bulb temperatures to vapour pressure values requires different psychrometric constants depending on whether the sensors are aspirated or not. For non-aspirated values the constant is 0.0799 kPa $^{o}C^{-1}$, for aspirated values, 0.066 kPa $^{o}C^{-1}$ should be used (Unwin, 1980).

2.2.4 Conclusions

- well maintained instrumentation is vital if accurate estimates of ambient vapour pressure are to be made.
- if possible, RH sensors should be avoided if estimates of vapour pressure are required for calculating evaporation rates.
- using T_{dew} in the (e_o-e) calculation is preferable to using RH. Alternatively, a daily mean of (e_o-e) can be calculated from the mean of 24 hourly (e_o-e) values.
- T_{dew} readings from well maintained wet and dry bulb sensors is the preferred method of measurement. Even better is data from aspirated psychrometers, provided that the wet bulb sensor is well maintained.
- T_{dew} readings at 9 am are a reasonable substitute for daily mean T_{dew} values.
- daily minimum temperature values T_{min} are a poor substitute for T_{dew} (AWRAC report; p28, Eqs. 12 and 13).

2.3 New wind functions, f(U) using T_{dew} and crop coefficients for wheat and soybean

Calculation of new wind functions using T_{dew} in (e_o-e) was necessary. This was further combined with applying crop coefficients, K_c for wheat and soybeans to be consistent with extension advice being given in NSW. Thus f(U)s were calculated to obtain a new "reference" crop evaporation (ET_{ref}) for

wheat $\quad ET_{wheat} = 1.05\ ET_{ref}$

soybean $\quad ET_{soybean} = 1.10\ ET_{ref}$

2.3.1 Daily ET wind functions

Functions of f(U) given in Table 2 were derived from data where e_o was the saturated vapour pressure at mean daily dry bulb temperature (T_m), e was the saturated vapour pressure at mean daily dew point temperature (T_{dew}) and ET was either actual observed evaporation (ET_a) or was corrected back to ET_{ref} with the appropriate crop coefficient.

Table 2. Values of f(U) for wheat and soybeans using either ET_a or ET_{ref} with e calculated at T_{dew}

Wheat	ET_a	
84	$f(U) = 17.940 + 0.067U$	$r^2 = 0.32, n = 58$
86	$= 19.631 + 0.051U$	$r^2 = 0.27, n = 85$
87	$= 19.385 + 0.047U$	$r^2 = 0.14, n = 66$
Combined	$f(U) = 18.968 + 0.055U$	
	ET_{ref}	
84	$f(U) = 15.397 + 0.065U$	$r^2 = 0.33, n = 58$
86	$= 16.812 + 0.051U$	$r^2 = 0.30, n = 85$
87	$= 16.650 + 0.047U$	$r^2 = 0.15, n = 66$
Combined	$f(U) = 16.286 + 0.0549U$	
Soybean	ET_a	
85/86	$f(U) = 25.787 + 0.029U$	$r^2 = 0.07, n = 61$
87/88	$= 19.127 + 0.054U$	$r^2 = 0.36, n = 47$
	ET_{ref}	
85/86	$f(U) = 20.848 + 0.027U$	$r^2 = 0.08, n = 61$
87/88	$= 15.154 + 0.048U$	$r^2 = 0.36, n = 47$

For the purpose of deriving a local wind function value the data for wheat in 1987 and soybeans in 1988 were combined. This resulted in the following regressions

For ET_a, $f(U) = 20.75\ (\pm 7.91) + 0.049\ (\pm 0.010)\ U$ $r^2 = 0.18$, $n = 113$

For ET_{ref}, $f(U) = 17.86\ (\pm 7.50) + 0.044\ (\pm 0.009) U$ $r^2 = 0.17$, $n = 113$

For comparative purposes the wind functions derived using

e_o at T_m and

e conditioned by minimum RH are given below (Table 3)

Table 3. Values of f(U) for wheat and soybeans using either ET_a or ET_{ref} with e calculated from RH_{min} (AWRAC report, p30).

Wheat 86 and 87	ET_a $f(U) = 7.2 + 0.039U$	
87	ET_{ref} $f(U) = 4.57 + 0.036U$	$r^2 = 0.51$, $n = 66$
Soybeans 87/88	ET_a $f(U) = 7.8 + 0.057U$	$r^2 = 0.54$, $n = 42$
87/88	ET_{ref} $f(U) = 7.92 + 0.040U$	$r^2 = 0.41$, $n = 47$

A combined wind function for ET_{ref} using RH_{min} is $f(U) = 6.24 + 0.038U$.

2.3.2 Hourly ET wind functions

Functions of f(U), Table 4, for use in hourly estimation of ET were derived from data where

e_o was at mean hourly dry bulb temperature

e was at mean hourly dew point temperature

and ET was either actual observed hourly evaporation (ET_a) or was corrected back to reference crop evaporation (ET_{ref}) with the appropriate crop coefficient (1.05 for wheat, 1.1 for soybean).

A further criteria of deciding day-time and night-time was initially adopted as

Day-time: $R_s > 0.1$ MJ m^{-2}

Night-time: $R_s \leq 0.1$ MJ m^{-2}

However this criteria resulted in obvious outliers which were associated with values at 0700 and 1900 hours. Subsequently, set times were used to classify night and day-time periods.

Table 4. Values of f(U) during day-time or equation for night-time ET derived from wheat 87 and soybean 87/88 data with either hourly ET_a or ET_{ref}
Note that application of Eq(1) for hourly values, requires the time unit of per hour, rather than per day.

Wheat		
Day-time (0800 - 1800 inclusive)		
ET_a	f(U) = 0.0742U	r^2 = 0.04, n = 139
Et_{ref}	f(U) = 0.0631U	r^2 = 0.04, n = 139
Night-time (0100 – 0700) and (1900 - 0000 inclusive)		
ET_a = 0.0122 + 0.00404 $(U^*(e_o-e))$		r^2 = 0.28, n = 166
ET_{ref} = 0.0116 + 0.00385 $(U^*(e_o-e))$		r^2 = 0.28, n = 166
Soybean		
Day-time (0700 - 1800 inclusive)		
ET_a	f(U) = 0.0778U	r^2 = 0.13, n = 156
Et_{ref}	f(U) = 0.0577U	r^2 = 0.11, n = 156
Night-time (0100 - 0600) and (1900 - 0000 inclusive)		
ET_a = 0.03336 + 0.02488 $(U^*(e_o-e))$		r^2 = 0.62, n = 153
ET_{ref} = 0.02023 + 0.01261 $(U^*(e_o-e))$		r^2 = 0.62, n = 153

2.3.3 Conclusions

- it is expected that daily ET estimates based on (e_o-e) using T_{dew} will be marginally more accurate than those using RH_{min}. This is suggested from the more conservative diurnal pattern of T_{dew} and from the marginally better regressions for f(U). However, an independent data set is needed for more rigorous testing.

- a single f(U) for daily estimates of ET_{ref} is now available while new f(U) equations for hourly day-time estimates of ET_{ref} for wheat and soybeans are available.

3.0 Comparison between daily and hourly estimates of evaporation

As pointed out in the AWRAC report (p38), in theory, hourly calculation of ET from meteorological data should give more accurate estimates of daily ET_{ref} since the diurnal trends in wind run and $(e_o\text{-}e)$ are more adequately described. This theory is tested below.

The comparison was made using daily and hourly wind functions from wheat and soybean data in years other than 1987 and 1987/88. Estimates of ET were then compared with observed values for two lots of 13 days in these two remaining seasons. Estimates using hourly data were split into day-time and night-time and then added to give a daily total. The comparisons are shown in Table 5.

The daily total values from estimated and observed were then compared using regression with the following results.

Wheat 87

$ET_{refcalc}$ daily vs ET_a $Y = -0.64\ (\pm 0.52) + 1.29\ (\pm 0.24)X$ $r^2=0.81$, n = 9
$ET_{refcalc}$ total hourly vs ET_a $Y = -0.24\ (\pm 0.34) + 1.00\ (\pm 0.10)X$ $r^2=0.89$, n=13

Soybean 87/88

$ET_{refcalc}$ daily vs ET_a $Y = 1.02\ (\pm 0.68) + 0.85\ (\pm 0.12)X$ $r^2=0.84$, n=12
$ET_{refcalc}$ total hourly vs ET_a $Y = 1.94\ (\pm 0.79) + 0.72\ (\pm\ 0.13)X$ $r^2=0.74$, n=13

These analyses indicate that for wheat, the summation of hourly ET estimates was more accurate than using the daily means, but for soybeans the opposite was true. Similar analyses with data from the other seasons showed the same; there was no clear advantage of one method over the other.

3.1 Conclusions

- a well calibrated equation for ET_{ref} using daily means is as accurate as calculating evaporation on an hourly basis.
- the generality of the conclusion above needs to be tested further using an independent data set.

Table 5. Estimated evaporation (mm) for a day calculated from hourly or daily mean meteorological data compared with observed values adjusted with the standard crop coefficient.

Wheat 87

Date	Observed ET$_a$			Calculated hourly ET$_{refcalc}$			Calc. daily ET$_{refcalc}$
	day-time	night	total	day-time	night	total	
18/8/87	2.66	0.27	2.93	2.33	0.16	2.49	2.48
19/8/87	2.81	0.03	2.84	2.87	0.16	3.03	2.84
20/8/87	2.38	0.15	2.53	2.37	0.17	2.54	N/A
21/8/87	2.85	0.20	3.05	2.21	0.15	2.36	2.56
22/8/87	3.49	0.30	3.79	3.35	0.19	3.54	4.10
23/8/87	3.10	0.78	3.88	3.29	0.57	3.86	5.23
24/8/87	1.53	0.30	1.83	1.41	0.20	1.61	1.81
25/8/87	2.01	0.06	2.07	1.43	0.16	1.59	2.20
26/8/87	3.29	0.21	3.50	2.77	0.18	2.95	3.34
27/8/87	1.30	0.13	1.43	0.45	0.19	0.64	N/A
28/8/87	2.15	0.20	2.35	1.27	0.17	1.44	1.85
29/8/87	2.77	0.12	2.89	2.12	0.15	2.27	N/A
30/8/87	0.41	0.10	0.51	0.56	0.15	0.71	N/A

Soybeans 87/88

Date	Observed ET$_a$			Calculated hourly ET$_{refcalc}$			Calc. daily ET$_{refcalc}$
	day-time	night	total	day-time	night	total	
3/3/88	8.22	0.79	9.01	8.29	2.18	10.47	10.01
4/3/88	6.77	1.48	8.25	6.03	1.07	7.10	N/A
5/3/88	6.68	0.82	7.50	6.02	0.73	6.75	6.56
6/3/88	6.52	0.79	7.31	5.90	0.76	6.66	6.96
7/3/88	7.28	1.13	8.41	6.59	1.29	7.88	7.67
8/3/88	6.64	1.00	7.64	6.01	0.80	6.81	7.26
9/3/88	5.35	0.80	6.15	5.06	0.72	5.78	6.76
10/3/88	7.80	0.82	8.62	6.29	1.16	7.45	8.22
11/3/88	3.88	1.10	4.98	3.51	1.14	4.65	4.04
12/3/88	4.75	0.83	5.58	5.42	0.77	6.19	5.52
13/3/88	4.17	0.85	5.02	3.80	0.91	4.71	4.48
14/3/88	5.82	0.69	6.51	6.38	0.60	6.98	6.27
15/3/88	4.98	0.55	5.53	5.35	0.59	5.94	5.41

4.0 Net radiant energy (R_n) calculated from observed solar irradiance (R_s)

4.1 Deriving the conversion from R_s to R_n

Solar irradiance (R_s) is the total shortwave (< 3µm) energy received on unit area of the surface in question. It is the sum of incoming direct radiant energy from the sun ($R_{s\ dir}$), diffuse radiant energy ($R_{s\ diff}$) from the sky hemisphere viewed by the surface and reflected solar radiant energy ($R_{s\ ref1}$) from other illuminated surfaces in the field of view. Therefore

$$\mathbf{R_s = R_{s\ dir} + R_{s\ diff} + R_{s\ ref1}} \qquad \mathbf{(6)}$$

R_s (MJ m^{-2} d^{-1}) is usually measured on a horizontal surface by a pyranometer or solarimeter. In this case it is usually referred to as total global solar irradiance.

Net radiant energy R_n is the sum of net shortwave radiant energy R_{sn} and net longwave radiant energy R_{ln}, ie

$$\mathbf{R_n = R_{sn} + R_{ln}} \qquad \mathbf{(7)}$$

R_{sn} is defined as the difference between incoming shortwave energy R_s (as per Eq 6) and reflected shortwave radiation. The proportion of shortwave energy which is reflected is given by the albedo (α) of the surface in question ie

$$\mathbf{R_{sn} = R_s - \alpha R_s} \qquad \mathbf{(8)}$$

R_{ln} is the difference between downwards longwave energy (R_{ld}) emitted from the sky, clouds and aerosols in the atmosphere and the longwave energy emitted from the surface in question (R_{lu}).

$$\mathbf{R_{ln} = R_{ld} - R_{lu}} \qquad \mathbf{(9)}$$

If Eqs (7) and (8) are combined the familiar general equation (AWRAC report, p25)

$$\mathbf{R_n = (1 - \alpha)\, R_s - R_{ln}} \qquad \mathbf{(10)}$$

is apparent, with the sign change indicating that R_{ln} is usually negative, ie longwave energy is being lost from the surface.

The method of calculating R_{ln} follows that given by Jensen (1973). The outgoing, or upward component (R_{lu}) is essentially constant for all conditions and can be considered as a function of near ground level air temperature only ie

$$\mathbf{R_{lu} = \varepsilon_{vs}\, \sigma\, (T_m + 273)^4} \qquad \mathbf{(11)}$$

where ε_{vs} is the "effective surface emissivity" with a value for a green crop surface of 0.98 (Smith, 1991). σ is the Stefan-Boltzmann constant (4.896 x 10^{-9} MJ m^{-2} day^{-1} K^{-4}).

Turning to the downwards longwave energy R_{ld}, and considering a clear day, then the atmospheric emissivity ε_a is affected by atmospheric components, principally water vapour. Most of the R_{ld} comes from the first few hundred metres of atmosphere above the ground. Therefore clear day downwards longwave energy (R_{ldo}) can be considered as a function of near ground level air temperature as per Eq (11) ie

$$\mathbf{R_{ldo} = \varepsilon_a\, \sigma\, (T_m + 273)^4} \qquad \mathbf{(12)}$$

Substituting (11) and (12) in (9) we get for a clear day

$$\mathbf{R_{lno} = (\varepsilon_a - \varepsilon_{vs})\, [\sigma(T_m + 273)^4\,]} \qquad \mathbf{(13)}$$

The term (ε_a - ε_{vs}) is referred to as an effective net emissivity ε'. Since on clear days, ε_{vs} is always greater than ε_a, the value of R_{lno} will always be negative.

Considering the case for non clear ie cloudy days.

Clouds act as effective black bodies with an emissivity of 1.0, and therefore the net longwave radiant energy (R_{ln}), can be expressed as a function of cloudiness and the clear day net longwave energy, ie

$$R_{ln} = (a \frac{R_s}{R_{so}} + b)\, \varepsilon' \sigma (T_m + 273)^4$$

where R_{so} is clear day solar irradiance and a and b are empirical constants.

Substituting Eq (13) in (14) we get the Jensen equation

$$R_{ln} = (a \frac{R_s}{R_{so}} + b)\, \varepsilon' \sigma (T_m + 273)^4 \qquad \textbf{(15)}$$

As indicated above, atmospheric emissivity ε_a and therefore ε', is principally affected by water vapour. An empirical relationship to derive ε' is used.

$$\varepsilon' = c + d\sqrt{e} \qquad \textbf{(16)}$$

where e (kPa) is the actual mean daily water vapour pressure and c and d are constants with values of 0.34 and -0.139 respectively. Values of ε' for wheat and soybean seasons have a range from 0.15 to 0.22. A comparison with ε' values calculated using the Idso-Jackson equation (Eq 61 in Smith, 1991) was inconclusive. The Idso-Jackson equation uses temperature only and produced about 11% higher ε' values in the summer season and about 10% lower ε' values in winter. An independent estimation of ε' is needed to justify any change in Eq 16.

Finding values for the constants a and b in Eq 15 is described in section 4.4.

4.2 Calculating R_{so}

In the AWRAC report (p26) new values for a and b (Eq 15 above) were suggested. However it was commented that the different values for the seasons was surprising. Part of this discrepancy was due to an error in calculated values of R_{so}. We have generally used the subroutine (AWRAC report, Appendix 1) derived by Stapper et al. (1986). However as shown in Fig. 8 this procedure, although showing the general shape of clear day irradiance observed values, overestimates summer values by 8 to 10%. This overestimate will also cause R_n to be overestimated. We therefore looked for an alternative, general procedure to calculate R_{so}. The

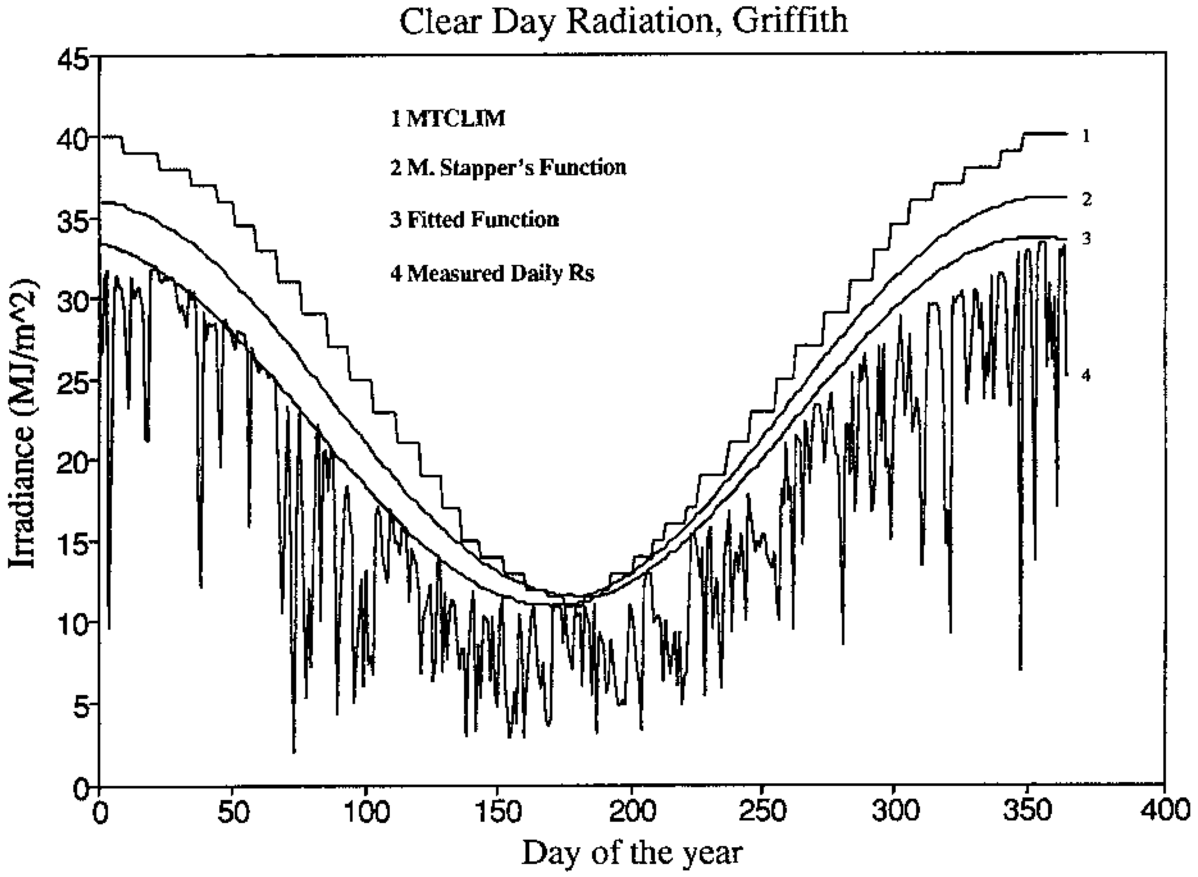


Fig. 8. Measured solar irradiance R_s values for Griffith during a full calendar year together with envelope curves describing the maximum clear day irradiance R_{so}. The fitted function is the Griffith polynomial while the other two are from two other model approximations.

one tried was contained in the program MTCLIM and followed the work by Running et al. (1987). This procedure used a iterative procedure to derive daily total values. Unfortunately this procedure also overestimated R_{so} at Griffith, especially in the summer season (Fig. 8). Additional testing of the two procedures (Stapper's and Running's) using 5 years of observed data from the Philippines (Fig. 9) also showed that both overestimated R_{so}, Running's being more in error.

Given this, we have reverted to using a fitted polynomial to derive R_{so} data for Griffith. The polynomial, (referred to as Griff Poly in SIRAG-V2.0) was the envelope curve fitted to observed peak values (clear day values) from ten years of data. It has the form

$$R_{so} = 22.357 + 11.0947 \cos D - 2.3594 \sin D$$

where $D = DOY/365.25 \times 2\pi$

and DOY = day number of the year.

The effect of using the polynomial was to cause a 2.5% decrease in ET_{ref} values calculated between 1 Nov. 89 and 31 Mar. 90.

4.3 Albedo values

An additional source of discrepancy with estimating R_n is in the value of albedo (α). General literature values for α of a green crop are around 0.23. This seems to be adequate for summer growing crops with closed canopies.

For wheat, measurements made in 1984 (Dunin, F.X., Pers. Comm.) over a crop of irrigated wheat gave a mean value of 0.184 ± 0.004. Subsequently the α values used were

soybean or maize	$\alpha = 0.23$
wheat	$\alpha = 0.184$

If ET_{ref} values are to be calculated, then $\alpha = 0.23$ should be used throughout the year to be consistent with the international definitions (Smith, 1991).

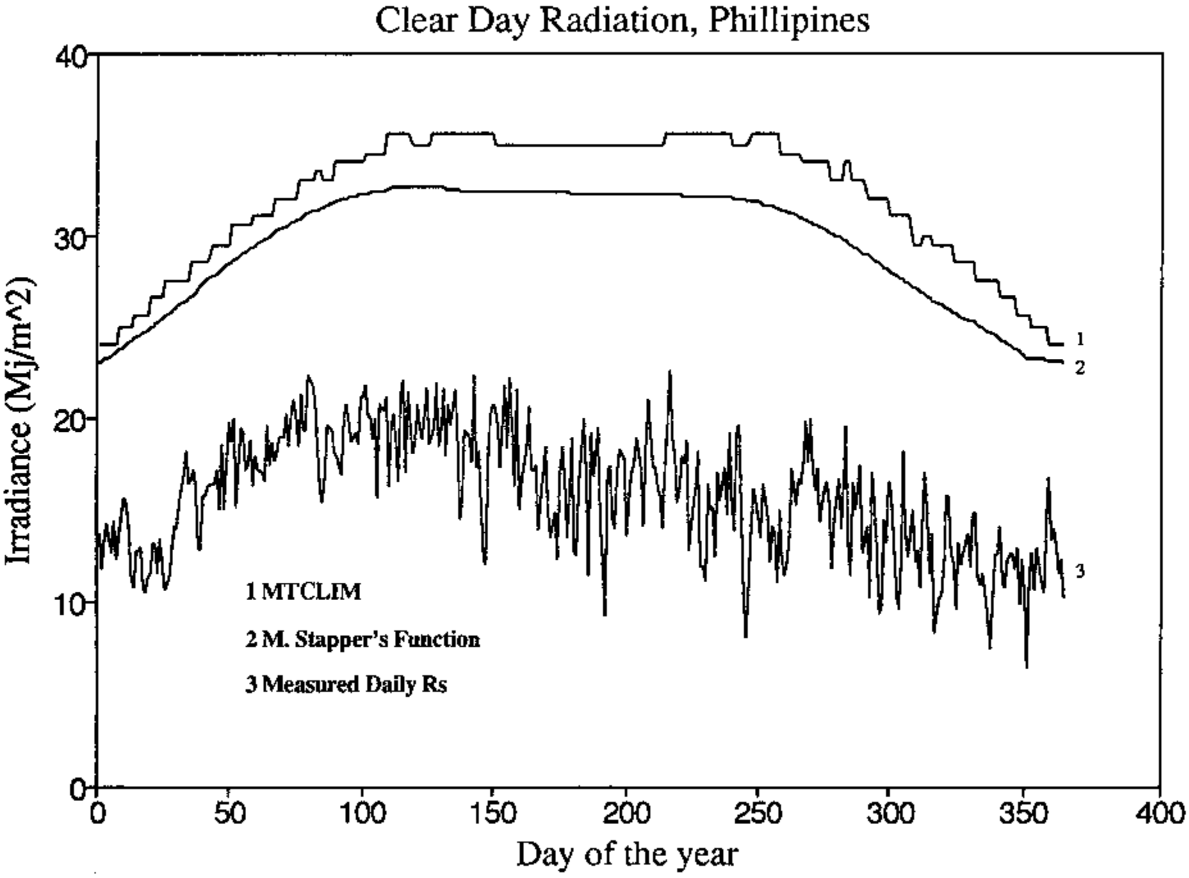


Fig. 9. Measured daily solar irradiance R_s values from Los Banos, Philippines compared to estimated values from model approximations.

4.4 New a and b values

On clear days, net longwave radiant energy R_{lno} is given by Eq 13.

R_{lno} is a function of effective net emissivity ε' and the absolute mean temperature of the air mass at Stevenson screen height.

The term

$$\left[a \frac{R_s}{R_{so}} + b \right]$$

from Eq 14 is called the cloudiness factor and conditions R_{lno} depending on the degree of cloud. While the general values of a and b of 1.22 ad -0.18 have been used, the current recommendations from the FAO revision (Smith, 1992) have

$a = 1.35$

$b = -0.35$

However it is noted that "a and b parameters are calibration values to be determined through specialised local studies measuring long wave radiation values."

Note that, a + b = 1 ie on clear days when $R_s = R_{so}$, the cloudiness factor has a value of 1.0 and R_{lno} is defined by Equation 13.

While long wave radiant energy R_{ln} values were not measured independently, values of R_n and R_s were measured during four crop seasons (2 wheat, a maize and soybean crop). Back calculating from the observed values gave the following results:

$a = 0.92$

$b = 0.08$

The linear regression used to determine a and b values had an $r^2 = 0.53$. While a linear function is used to determine a and b values because of its simplicity, analysis of the data showed that an exponential function produced a better fit. There is a need to obtain some further independent data sets as there is an indication that some improvement in estimating R_n from R_s is possible.

When new values of a and b and using $c = 0.34$ were implemented in calculating ET_o (Eq 1), and compared to ET_o using coefficients in the original AWRAC Report (p25) the new ET_o was increased by < 2%.

In the situation where the value for clear day irradiance is calculated as a function of latitude only using extraterrestrial irradiance (R_{soa}), values of a and b in equation 15 will change. Using the 286 observations of R_s over four seasons, and the calculated values of R_{soa} from Marcel Fuch's (pers. com.) formulae, new values were

$a^l = 1.10$
$b^l = 0.18$

It should be noted that the ratio of R_{so}/R_{soa} for Griffith varied from 0.67 in mid winter to 0.75 in summer. As a first approximation, this means that on perfectly clear days, 25% of the above atmosphere irradiance does not reach the earths surface at Griffith, in summer, while in winter, up to 33% does not reach the ground.

It is possible to impose a quality check on irradiance values since observed surface values will be within a well defined range of extraterrestrial values at the same latitude. Based on the observations of R_s at Griffith,

$$0.23 < R_s/R_{soa} < 0.75$$

The lower limit on this ratio comes from the observation of the lowest mid winter R_s of 4 MJ m^{-2} and lowest mid summer R_s of 11 MJ m^{-2}. The corresponding R_{soa} values are 17 MJ m^{-2} and 47 MJ m^{-2}.

4.5 Conclusions

- For R_{so} estimation, greatest accuracy will be obtained from a function fitted to local observed values (5 to 10 years of observations would be advisable). In the absence of observed data, the Stapper procedure is a reasonable approximation.

- The albedo value for a closed canopy of soybean was taken as 0.23 while that for wheat was measured at 0.184. A value of 0.23 was adopted for standard ET_{ref} calculations.

- New fitting coefficients for use in determining net longwave radiant energy R_{ln} and subsequently net radiant energy R_n using clear day irradiance values at the earths surface were calculated as a = 0.92, b = 0.08.

- New fitting coefficients for use in determining net longwave radiant energy R_{ln} and subsequently net radiant energy R_n using irradiance values above the atmosphere were calculated as a^l = 1.10, b^l = 0.18.

5.0 Comparison of ET_o with other estimates

5.1 Class-A pan

The comparison of ET_o with class-A pan was made using three years of daily values measured at the Griffith weather station site. The class-A pan was well maintained ie regularly cleaned and refilled to the required depth. Evaporation from the pan was monitored hourly using a calibrated load cell as the sensor. Hourly values were converted to daily totals and a correction made to obtain open pan evaporation values since the pan had a bird cage cover.

The regression of ET_o with the pan was

$$ET_o = 0.72\ (\pm\ 1.03) + 0.83\ (\pm\ 0.01)\ \text{Pan} \qquad n = 1081,\ r^2 = 0.89$$

or fitted through the zero intercept

$$ET_o = 0.93\ \text{Pan} \qquad n = 1081,\ r^2 = 0.98$$

This is illustrated in Fig. 10.

For the locally calibrated ET_o value, class A pan values tend to be 7 to 8% higher. It is interesting to note that for evaporation values greater than about 10 mm day^{-1}, the A pan tends to give values which can be up to 30% greater. This is consistent with the general observation that in arid and semi-arid areas, pan values tend to over-estimate reference evaporation (see Humphreys *et al.* 1994).

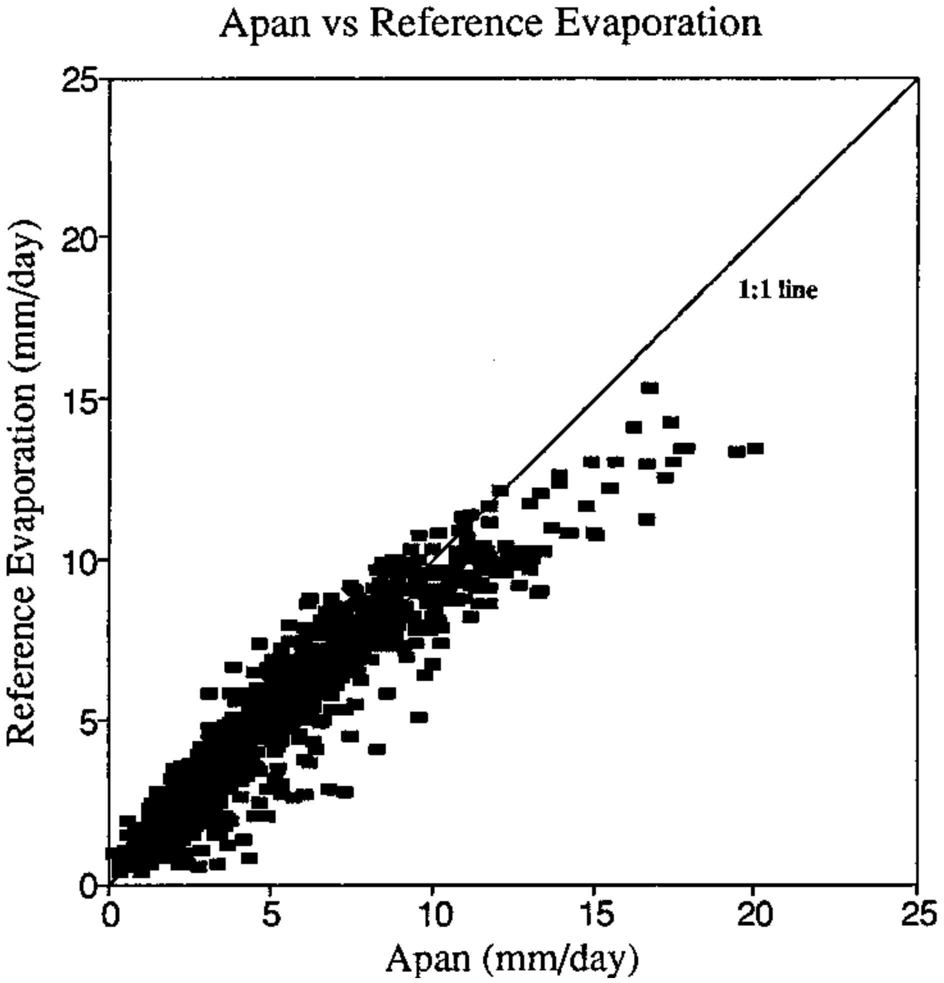


Fig. 10. Relation of reference evaporation, Et_o to measured daily open Class A pan evaporation from Griffith during 1991 to 1993.

5.2 Ceres models with Ritchie's water balance

The basic equations which are used in the original models are an adaptation of the Priestly-Taylor equations.

$$\mathbf{E_{eq} = R_s\,(0.00488 - 0.00437\alpha)\,(T_d + 29)} \tag{16}$$

$$\mathbf{E_o = 1.1\,E_{eq}} \tag{17}$$

E_{eq}	:	Equilibrium evaporation [mm day^{-1}]
R_s	:	Solar irradiance (MJ m^{-2} day^{-2}]
α	:	Albedo
T_d	:	Daily mean temperature [^{o}C]
E_o	:	Daily potential evaporation [mm day^{-1}]

T_d is defined as ($0.6\ T_{mx} + 0.4\ T_{mn}$).

The albedo used in Eq 16 is the input soil albedo (α_s) when no crop is present (range 0.10 - 0.25) then as a function of leaf area index as the crop canopy (leaf area index, LAI) develops

$$\mathbf{\alpha = 0.23 - (0.23 - \alpha_s)e^{-0.75LAI}} \tag{18}$$

when the crop has a closed canopy (LAI > 3), the value of α tends rapidly to 0.23.

In the Ceres models, a further conditioning of E_o occurs to account for advection effects when daily temperatures are high (> 24^{o}C for winter/spring crops and > 35^{o}C for summer crops) and evaporation suppression effects when daily maximum temperature is < 5^{o}C.

To get direct comparability between ET_o and E_o we assumed $\alpha = 0.23$ and applied the advection correction for the winter/spring crops such that when $T_{max} > 24^o$C

$$\mathbf{E_o = E_{eq} * ((T_{max} - 24) * 0.05 + 1.1)} \tag{19}$$

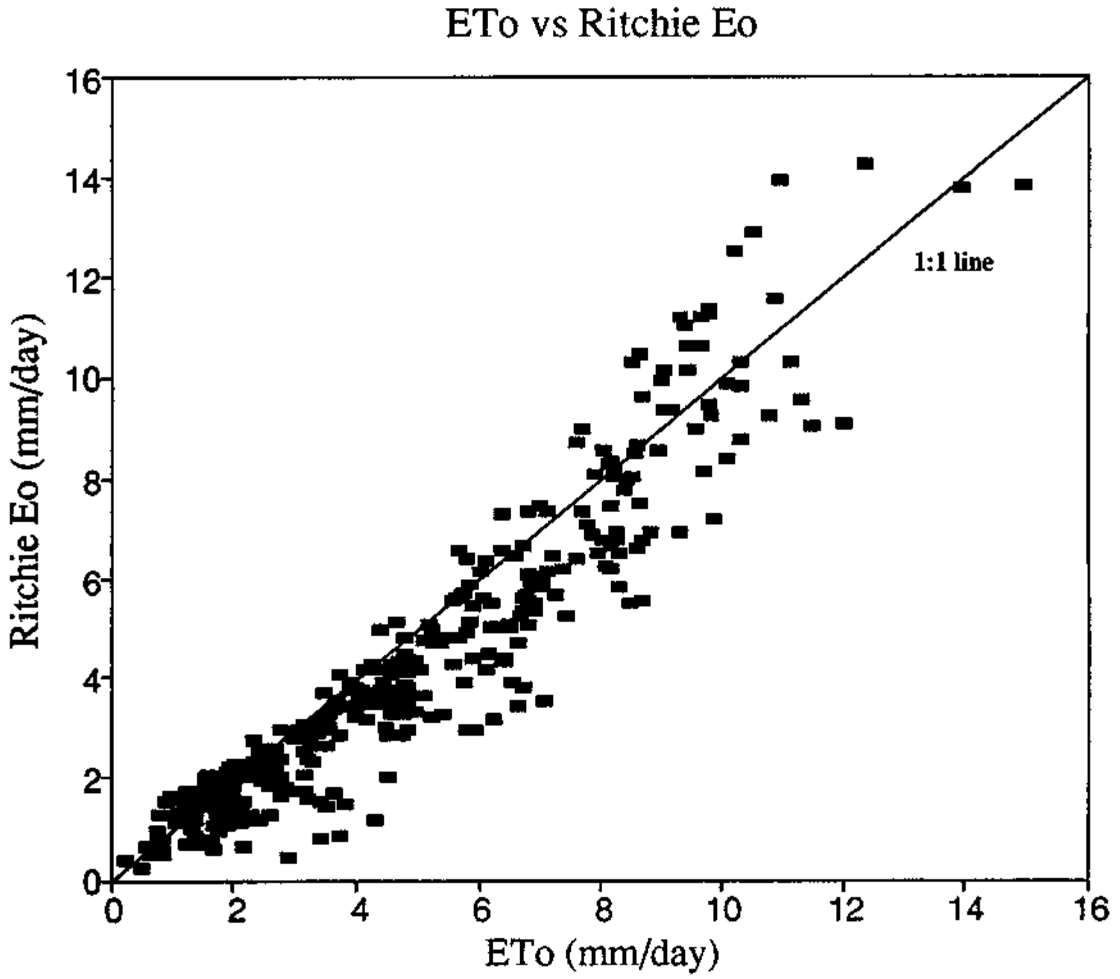


Fig. 11. Comparison of daily potential evaporation E_o calculated using the Ritchie potential evaporation equations and Et_o from Griffith data during 1993.

The result of this comparison over a one year period is shown in Fig. 11 and the regression relation was

$$E_o = -0.32\ (\pm\ 0.97) + 0.95\ (\pm\ 0.02)\ ET_o \qquad n = 365,\ r^2 = 0.89$$

In the Ritchie water balance routine of the CERES models, the actual evaporative losses are conditioned by a number of factors. Potential evaporation is sensitive to changing surface albedo, so that as the crop develops, the more reflective leaf surface (higher albedo) causes the albedo to increase. In addition, actual crop evaporation is reduced by the onset of soil water deficit stresses.

Comparing daily lysimeter measured crop evaporation (ET_A) values with the CERES models (ET_R) showed the following

Wheat

1984 $ET_R = 0.20\ (\pm\ 1.2) + 0.78\ (\pm\ 0.08)\ ET_A$ $n = 58,\ r^2 = 0.64$, bias = 19%

1986 L1 $ET_R = -0.21\ (\pm\ 1.05) + 0.94\ (\pm\ 0.06)\ ET_A$ $n = 85,\ r^2 = 0.74$, bias = 12%
L2 $ET_R = 0.09\ (\pm\ 1.12) + 0.84\ (\pm\ 0.06)\ ET_A$ $n = 85,\ r^2 = 0.71$, bias = 16%

1987 L1 $ET_R = -0.18\ (\pm\ 1.17) + 1.02\ (\pm\ 0.08)\ ET_A$ $n = 66,\ r^2 = 0.71$, bias = 3%
L2 $ET_R = 0.14\ (\pm 0.92) + 0.98\ (\pm\ 0.06)\ ET_A$ $n = 66,\ r^2 = 0.82$, bias = -3%

Maize

1990 L1 $ET_R = 1.76\ (\pm\ 1.22) + 0.64\ (\pm\ 0.07)\ ET_A$ $n = 77,\ r^2 = 0.56$, bias = 12%
L2 $ET_R = 2.84\ (\pm\ 1.44) + 0.57\ (\pm\ 0.08)\ ET_A$ $n = 77,\ r^2 = 0.38$, bias = -5%

Rice

1990 $ET_R = 4.70\ (\pm\ ) + 0.43\ (\pm\ 0.\ )\ ET_A$ $n = ,\ r^2 = 0.26$, bias = -2%

The bias value is calculated by comparing the mean values of the two sets of daily values.

This analysis shows that the CERES wheat model estimates of actual crop evaporation are quite acceptable. For maize, the model overestimates on lower evaporative days but underestimates on higher evaporative days in the summer season. This suggests that the temperature correction for advective effects in the maize model is not sensitive enough for the Griffith environment.

For rice, the regression on daily data is poor. This is largely due to the variability associated with the daily observed data which was interpolated from closed in-situ lysimeter values measured every 2 or 3 days. Despite the day-to-day variability the seasonal observed and estimated totals were in close agreement. This is also indicated by the small bias value (-2%). There is a clear indication though that the CERES rice model overestimates ET_{rice} on lower evaporative days (< 6 mm/day), but underestimates on higher evaporative days (> 10 mm/day).

5.3 Standardised Penman-Monteith

The Penman-Monteith equation for calculation of crop evaporation expanded the basic concepts incorporated in the original Penman equation accounting for the vapour flow resistance from the crop leaf to the ambient air. The advantage of this method is that crop evaporation is directly and specifically integrated into the equation. This would then eliminate the need to calculate a reference evaporation value and adjust it with a crop coefficient (K_c) to estimate actual crop evaporation. However, specifying vapour flow resistances for specific crops and specific canopy conditions is still problematic since these resistance values cannot be directly measured.

To avoid the need for these resistances in the first instance and to maintain consistency with the FAO24 report (Doorenbos and Pruitt, 1977) on reference crop evaporation, Smith (1992) recommended a simple form of the Penman-Monteith approach. This has the following form

$$ET_{pm} = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{(T_m + 273)} U_2\,(e_o - e_d)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \qquad \textbf{(20)}$$

ET_{pm} : Reference crop evaporation [mm day^{-1}]

R_n : Net radiant energy [MJ m^{-2} day^{-1}]

G : Ground heat flux [MJ m^{-2} day^{-1}]

T_m : Mean daily air temperature [^oC]

U_2 : Mean daily wind speed at 2 m height [m s^{-1}]

e_o : Mean daily saturation vapour pressure at mean dry bulb temperature [kPa]

e_d : Actual mean daily vapour pressure [kPa]

γ : Psychrometric constant [kPa $^oC^{-1}$]

5 : Slope of the saturation vapour pressure-temperature curve at T_m.

Apart from a change in units of wind run to mean daily wind speed the terms in Eq 20 are the same as those in Eq 1.

Example calculations for the maize 1989/90 season and the wheat 1984 season are given below.

<u>Maize 89/90 (mean values, LAI >3)</u>

where 5 = 0.18 kPa $^oC^{-1}$

R_n = 13.76 MJ m^{-2} d^{-1}

G = 0.11 MJ m^{-2} d^{-1}

γ = 0.066 kPa $^oC^{-1}$

T_m = 23.76 ^oC

U_2 = 2.04 ms^{-1}

(e_a-e_d) = 1.57 kPa

$$ET_{pm} = \frac{0.48 * 0.18 * (13.76 - 0.11) + 0.066 * 3.03 * 2.04 * 1.57}{0.18 + 0.066 * (1 + 0.34 * 2.04)}$$

$$= \frac{1.00 + 0.64}{0.29} \quad = 5.66 \text{ mm/day}$$

For the same period using the modified Penman equation

ET_{ref} = 8.40 mm

Wheat 84 (mean values, LAI >3)

where 5 = 0.13 at T_m = 17.62
R_n = 13.93 MJ m^{-2} d^{-1}
G = 0.09 MJ m^{-2} d^{-1}
γ = 0.066 kPa
T_m = 17.62 ^oC
U_2 = 1.79 m s^{-1}
$e_a - e_d$ = 0.93 kPa

$$ET_{pm} = \frac{0.48*0.13*(13.93-0.09)+0.066*3.10*1.79*0.93}{0.13+0.066*(1+0.34*1.79)}$$

$$= \frac{0.73+0.34}{0.24} \qquad = 4.46 \text{ mm/day}$$

For the same period using the modified Penman equation

ET_{ref} = 6.72 mm

The relationship between daily ET_{pm} and ET_o over a full year is shown in Fig. 12. The regression equation was

ET_{pm} = -0.21 (± 0.24) + 0.69 (± 0.004) ET_o n = 365, r^2 = 0.99

Not surprisingly the relationship between ET_{pm} and ET_o is very close (r^2 = 0.99), since the daily values used in the two equations (1 and 20) are the same. However, there is a consistent bias of -30%, ET_{pm} being 30% lower on average than ET_o for the same day.

The implication of this is that retention of the coefficient in Eq 20 would require a considerable readjustment of the K_c values for particular crops. This is likely to lead to considerable confusion among current users of ET_o values to aid irrigation scheduling.

5.4 Conclusions

The general consistency between daily ET_o and other measurement (Class A pan) and estimation (Ritchie E_o and ET_{pm}) methods increases confidence in the estimation procedure.

Clearly, a well maintained and sited Class A pan can produce consistent daily evaporation values. There is a bias towards overestimation at high evaporation rates. This is a characteristic induced by the pan energy balance in the semi-arid environment of Griffith.

The empirical development of E_o estimation given by Ritchie in the CERES models produces remarkably similar results to the locally calibrated Penman equation. In situations where weather data was limited to a radiant energy value and daily maximum and minimum temperatures, this method would be very adequate.

Application of the standardised Penman-Monteith equation in its present form would require major adjustment to the currently used crop coefficient (K_c) values. To avoid this potential confusion, it is suggested that the coefficients in the equation be modified to produce values comparable with currently used ET_o values.

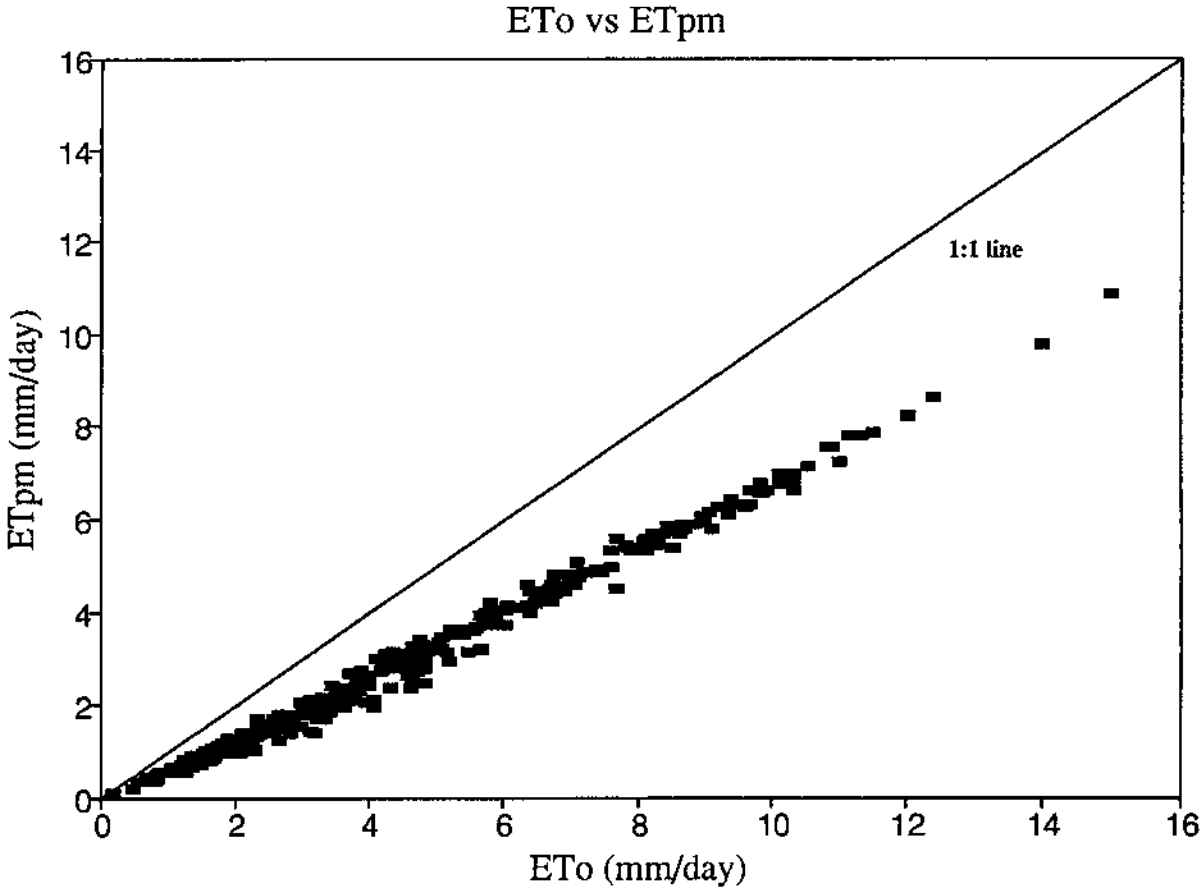


Fig. 12. Comparison of daily reference evaporation calculated using the standardised Penman-Monteith equation (Et_{pm}) and the Penman equation (Et_o). Values were calculated from Griffith weather data for 1993.

6.0 Crop coefficients from crops grown in weighing lysimeters

Crop coefficients (K_c) are empirical ratios of measured crop water use (ET_a) to some reference evapotranspiration (ET_o) and are generally derived from experimental data. The value of ET_o is multiplied by K_c to estimate ET_a during closed canopy conditions.

6.1 Wheat

Wheat was grown on the weighing lysimeters in 1984, 1986 and 1987. Values of K_c as related to cumulative degree days from sowing are shown in Fig 13. Approximate scales of time, growth stage, leaf area index (LAI) and percentage ground cover are also given for reference in Fig 13. Generalised K_c values set against daily observed data for wheat (1986) are shown in Fig 14. A K_c value of 1.05 was derived during closed canopy conditions.

6.2 Soybean

Soybeans were grown on the weighing lysimeters in 1985/86 and 1987/88. Values of K_c as related to cumulative degree days from sowing are shown in Fig 15. Approximate scales of time, growth stage, LAI and percentage ground cover are also given for reference in Fig 15. Generalised K_c values set against daily observed data are shown in Fig 16. A K_c value of 1.1 was derived during closed canopy conditions.

6.3 Maize

Maize was grown on the weighing lysimeters in 1989/90. Values of K_c as related to cumulative degree days from sowing are shown in Fig 17. Approximate scales of time, growth stage, LAI and percentage ground cover are also given for reference in Fig 17. Generalised K_c values set against daily observed data are shown in Fig 18. A K_c value of 0.85 was derived during closed canopy conditions.

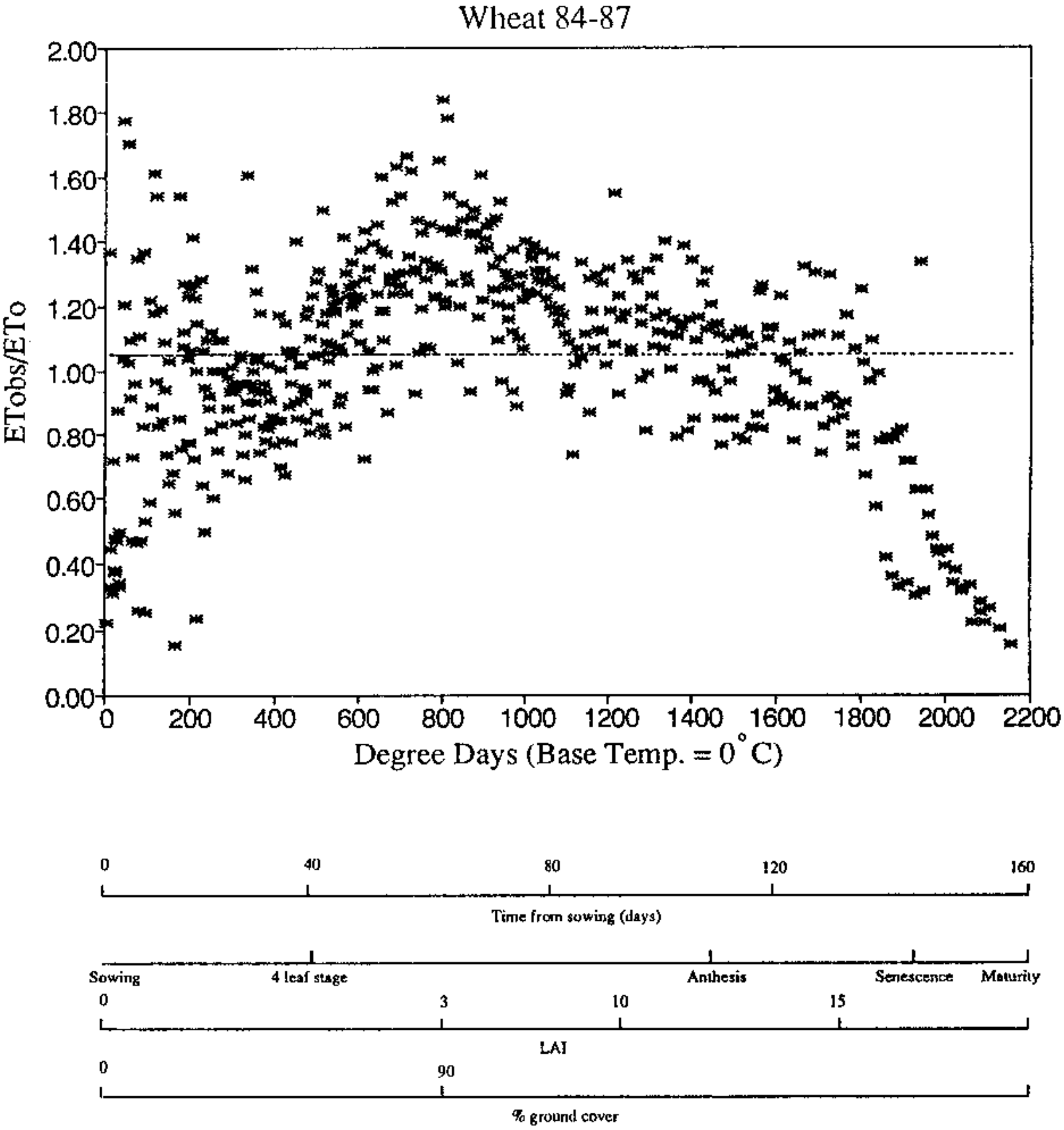


Fig. 13. Values of daily lysimeter measured ET for wheat as a ratio of Et_0 for three crops in 1984, 1986 and 1987 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index (LAI) and present ground cover are given for reference.

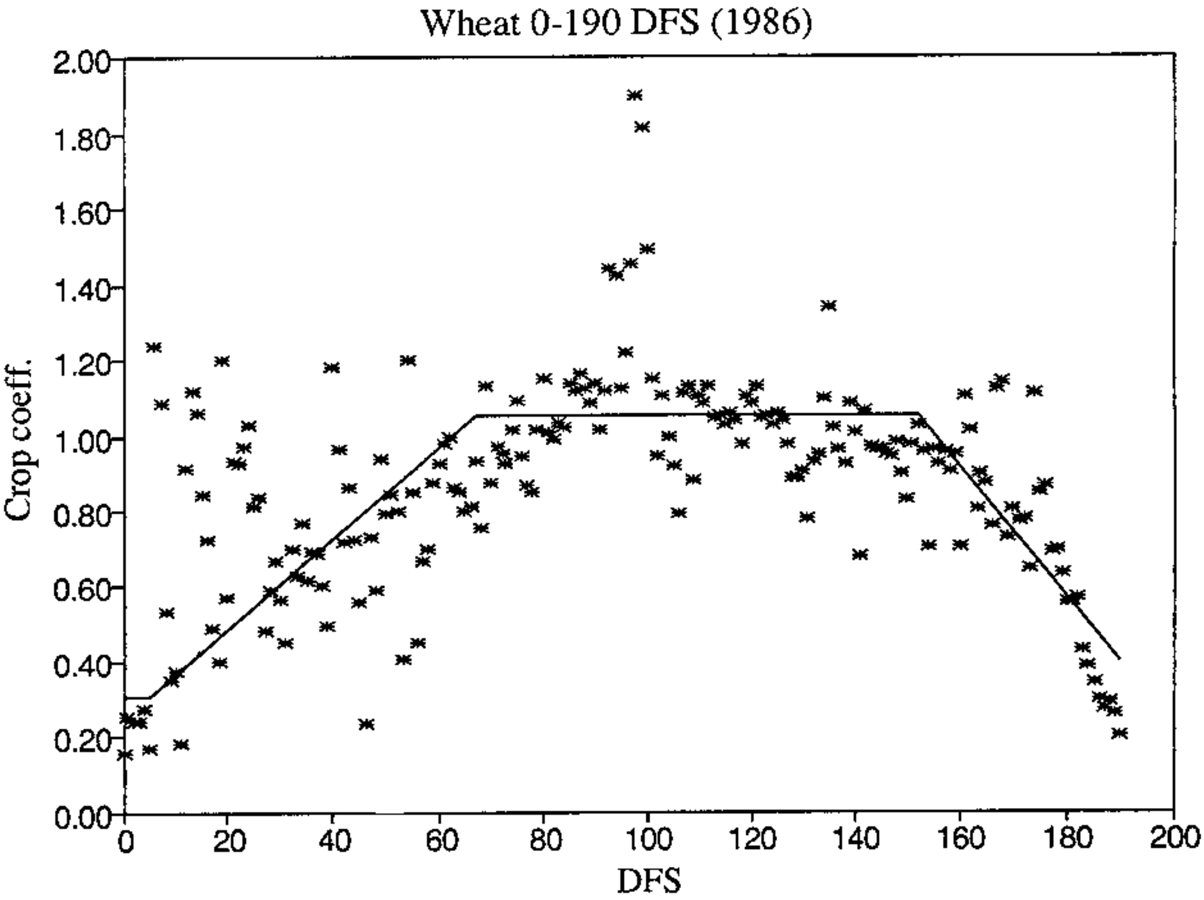


Fig. 14. Generalised crop coefficients (solid line) for wheat set against daily observed data from 1986.

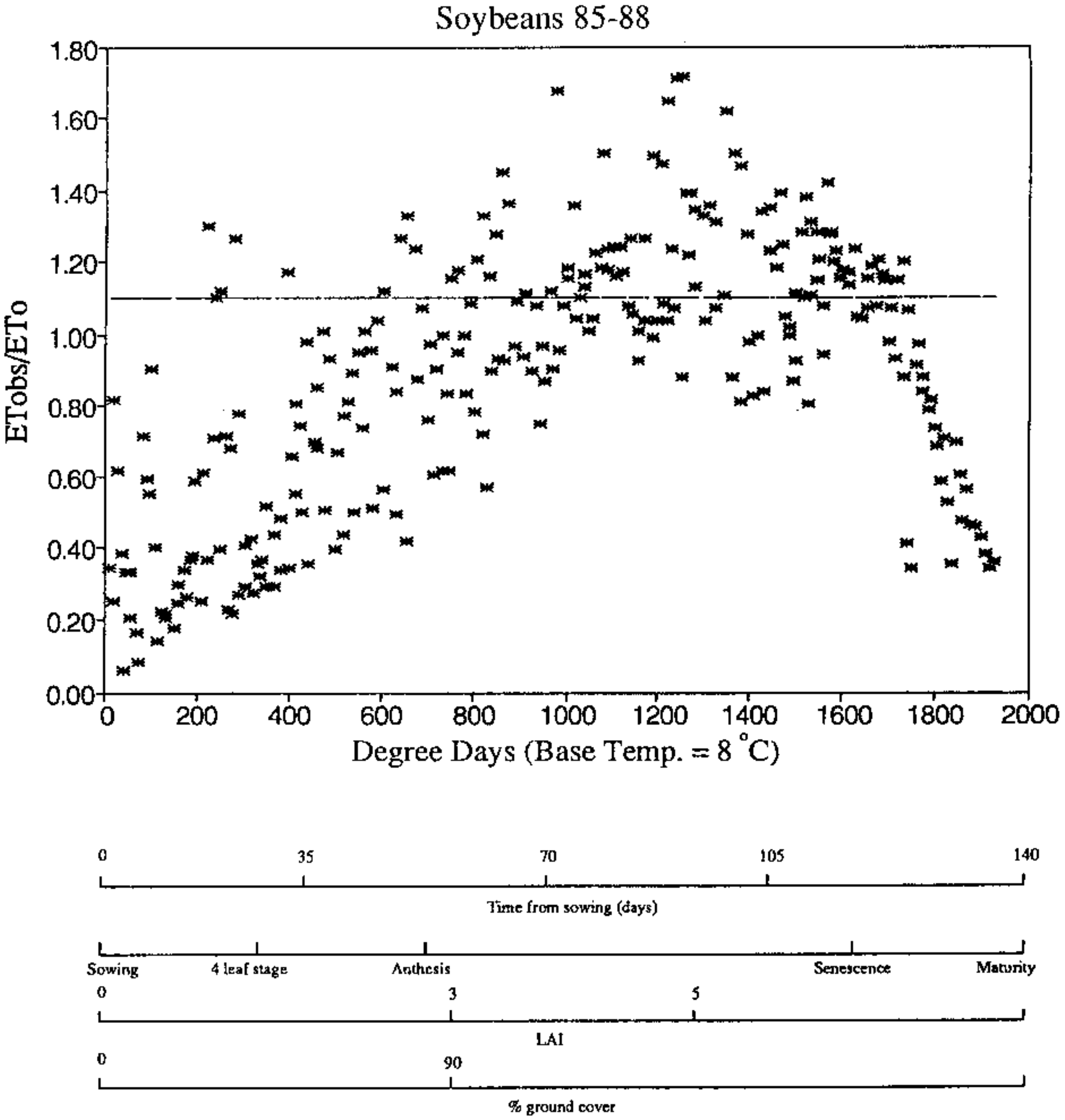


Fig. 15. Daily lysimeter measured ET for soybeans as a ratio of Et_0 for two seasons in 1985/86 and 1987/88 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index and percent ground cover are given for reference.

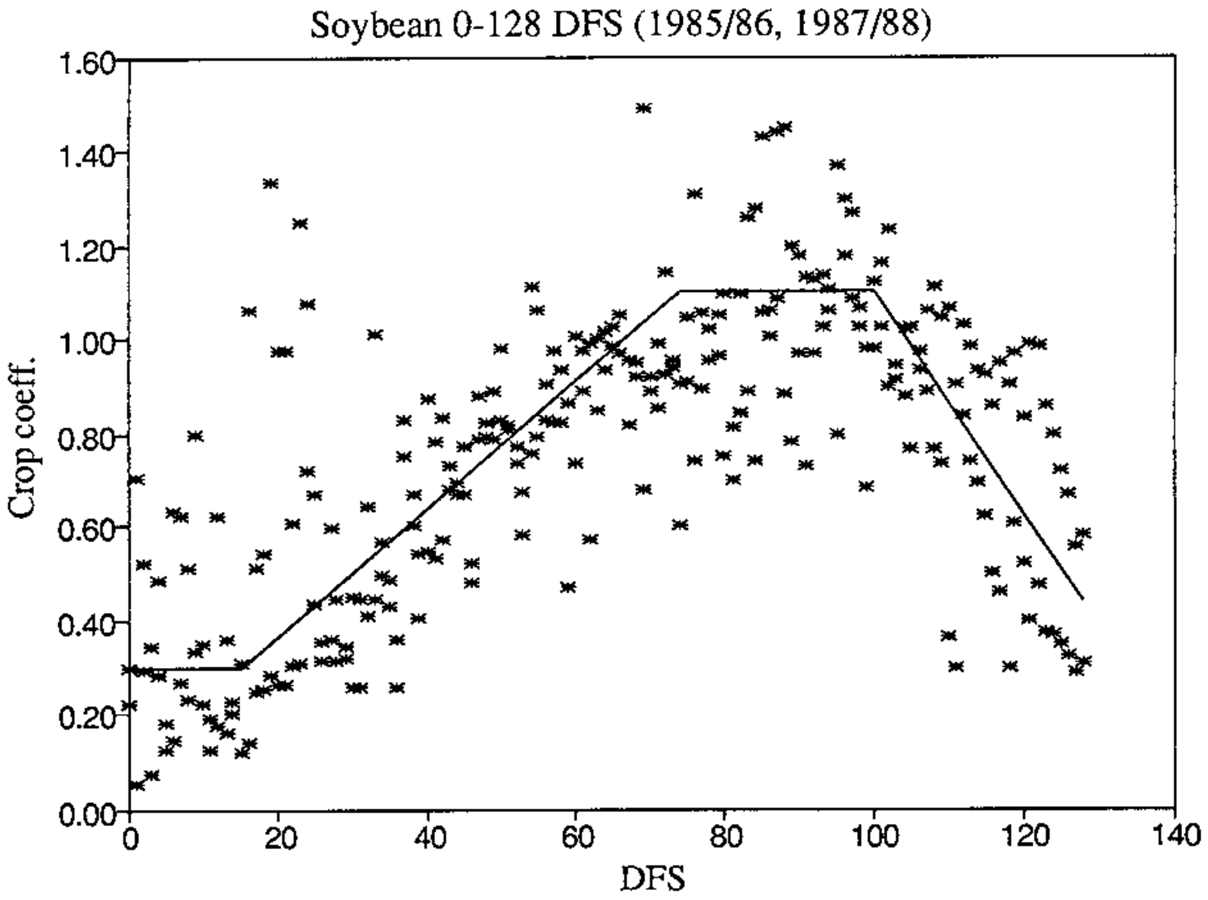


Fig. 16. Generalised crop coefficients (solid line) for soybeans set against daily observed data for 1985/86 and 1987/88.

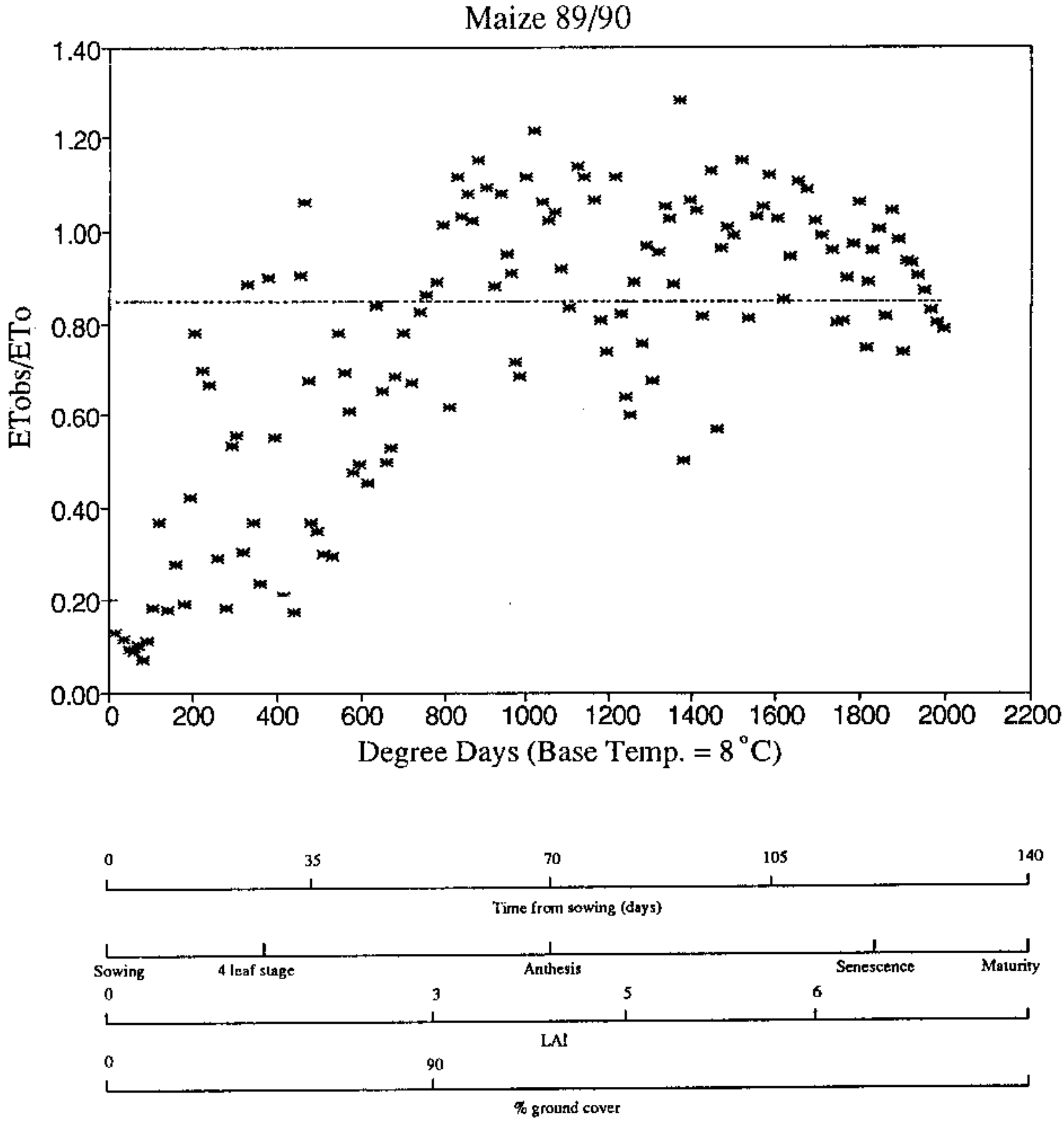


Fig. 17. Daily lysimeter measured ET for maize as a ratio of Et_0 for 1989/90 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index and percent ground cover are given for reference.

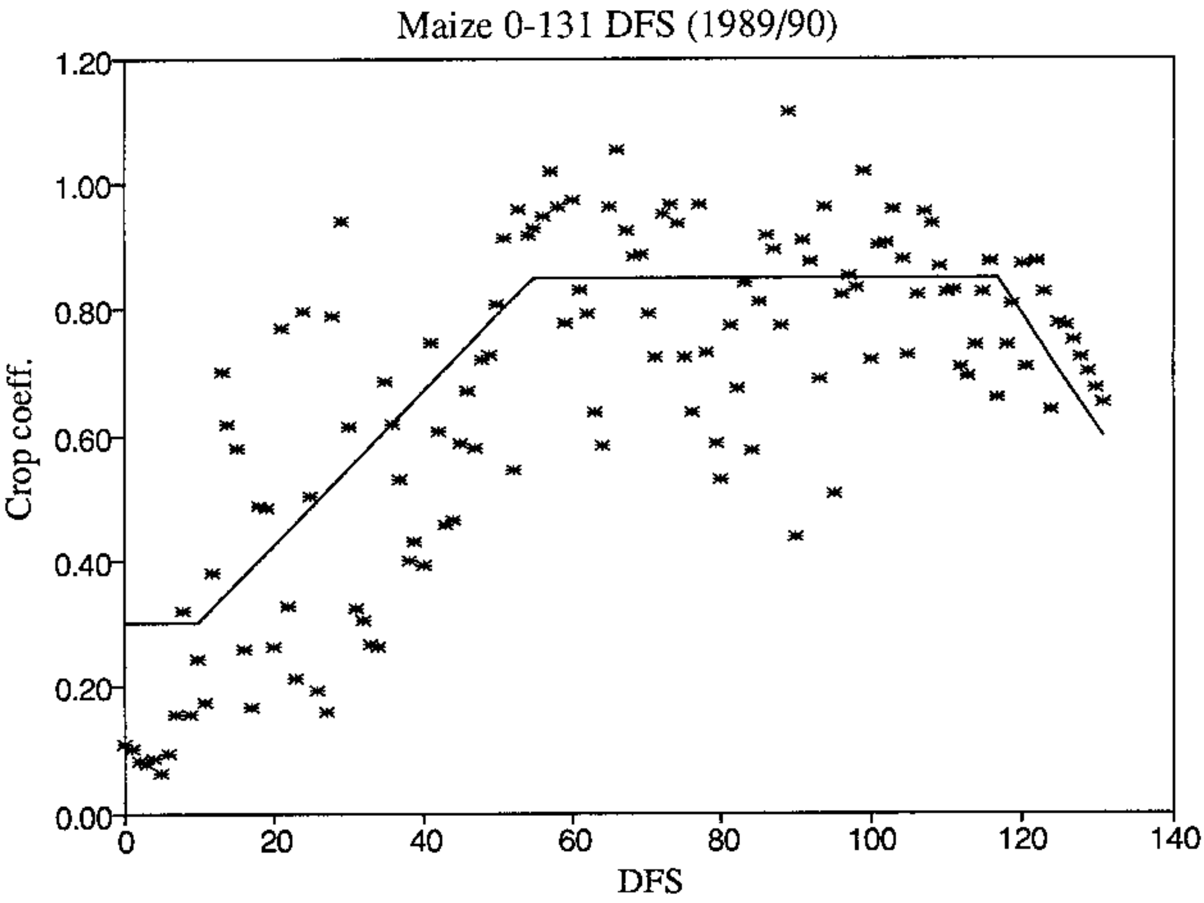


Fig. 18. Generalised crop coefficients (solid line) for maize set against daily observed data for 1989/90.

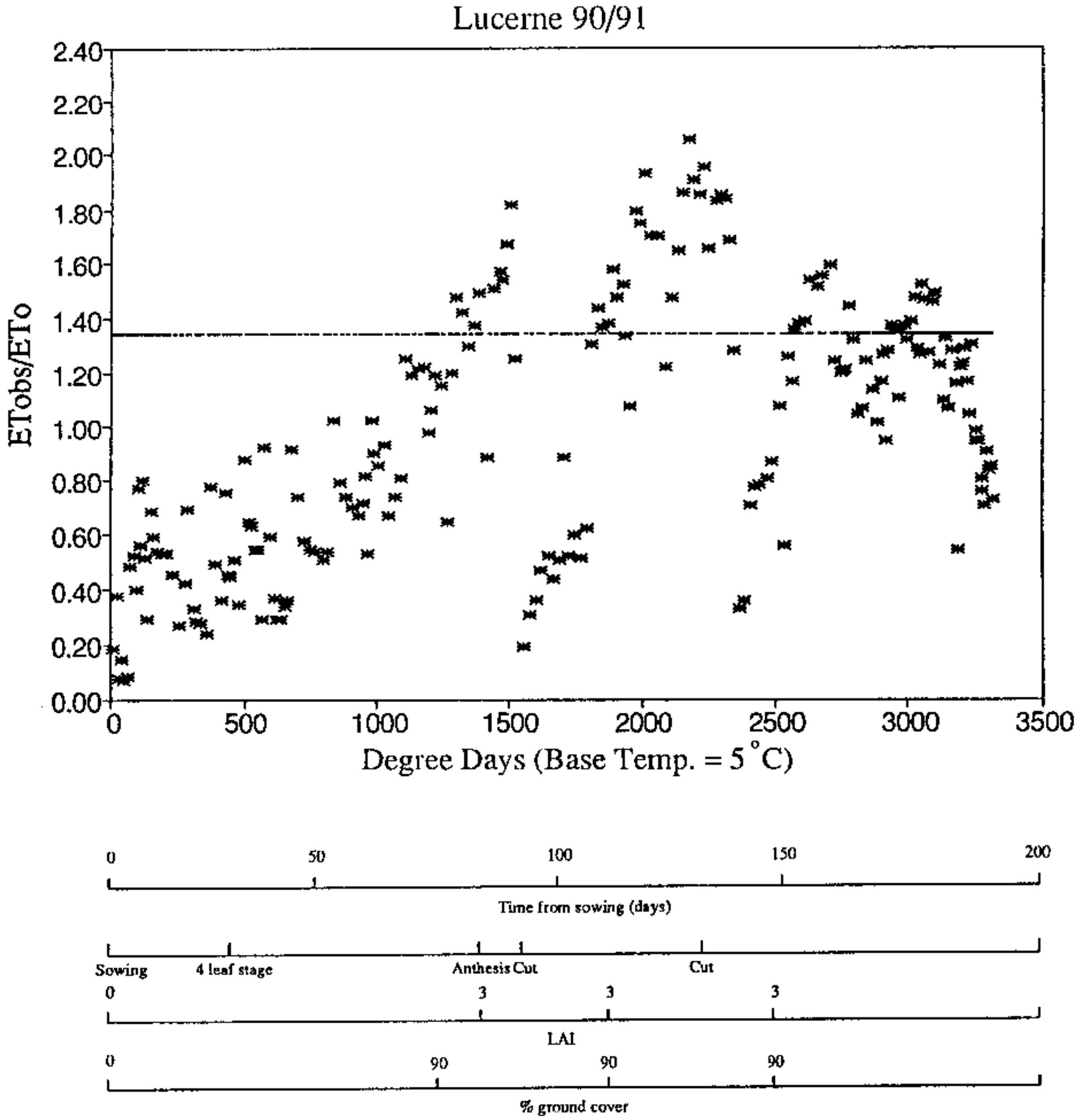


Fig. 19. Daily lysimeter measured ET for lucerne as a ratio of Et_0 for the establishment season of 1990/91 as related to cumulative degree days from sowing. Approximate scales of time, growth stages with cuts of leaf area index and percent ground cover are given for reference.

6.4 Lucerne

Lucerne was grown on the weighing lysimeters from 1990-1993. Values of K_c for the establishment season of 1990/91 as related to cumulative degree days from sowing are shown in Fig 19. Approximate scales of time, growth stages with cuts, LAI and percentage ground cover are also given for reference in Fig 19. Generalised K_c values set against daily observed data for lucerne 1991/92, when five cuts were made for haymaking, are shown in Fig 20. A K_c value of 1.3 was derived during closed canopy conditions.

6.5 Rice

Rice was grown in an experimental field bay in 1989/90. Weighted values of K_c as related to cumulative degree days from sowing are shown in Fig 21. Approximate scales of time, growth stage, LAI and percentage ground cover are also given for reference in Fig 21. Generalised K_c values set against daily interpoloated data are shown in Fig 22. A K_c value of 1.1 was derived during closed canopy conditions.

6.6 Pasture

Pasture was grown in the weighing lysimeters in 1994/95. Weighted values of K_c as related to cumulative degree days from sowing are shown in Fig 23. Approximate scales of time, growth stage, LAI and percentage ground cover are also given for reference in Fig 23. Generalised K_c values set against daily observed data, when four cuts were made for haymaking, are shown in Fig 24. A K_c value of 0.85 was derived during closed canopy conditions.

6.7 Conclusions

The use of K_c values is a common method of determining irrigation scheduling. As crops vary in their water requirements, their irrigation needs depend on the evaporative conditions operating at particular stages of growth. Due to this variation in transpiration, the K_c value will not be a constant value throughout the growing season. The use of K_c values in determining the proper amount of water to be applied to a crop at the correct time is efficient and sound water management.

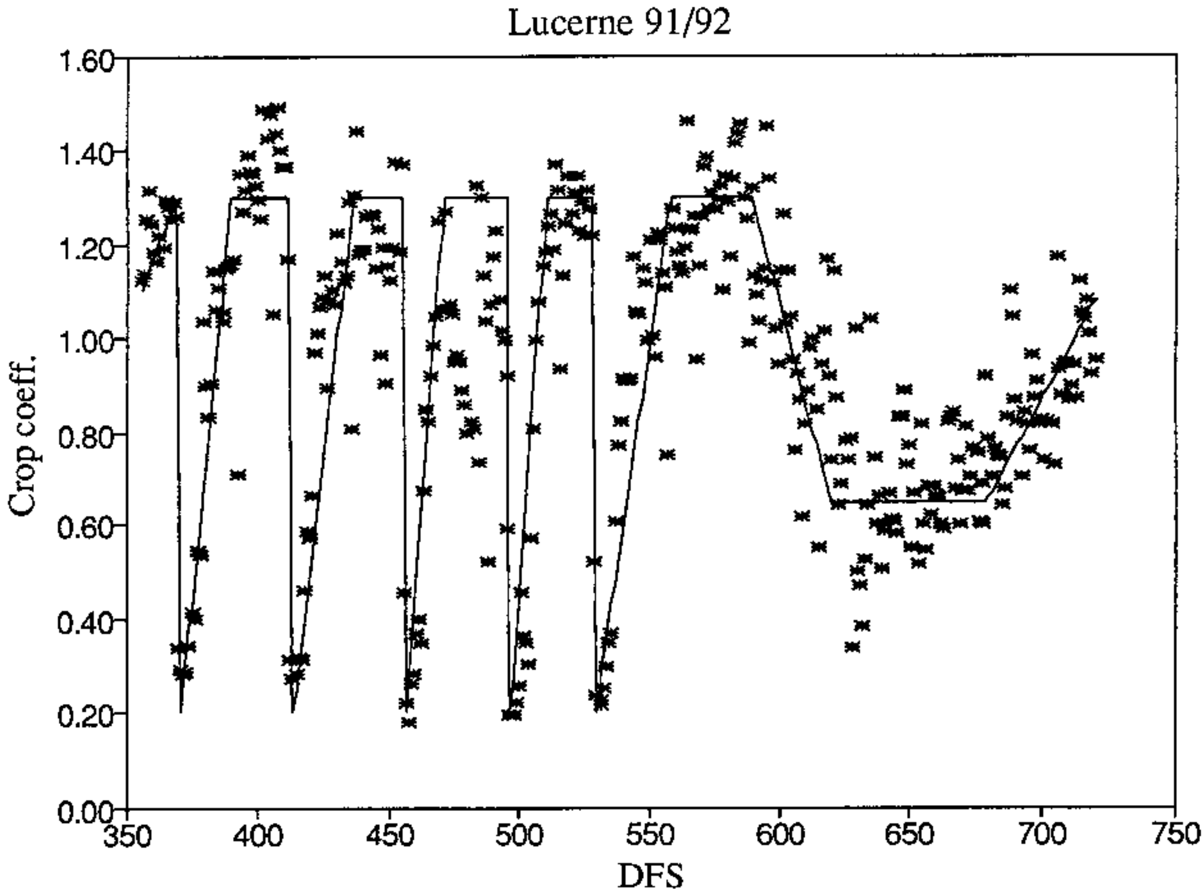


Fig. 20. Generalised crop coefficients (solid line) for lucerne set against daily observed data for 1992/92 when five cuts were made for hay making.

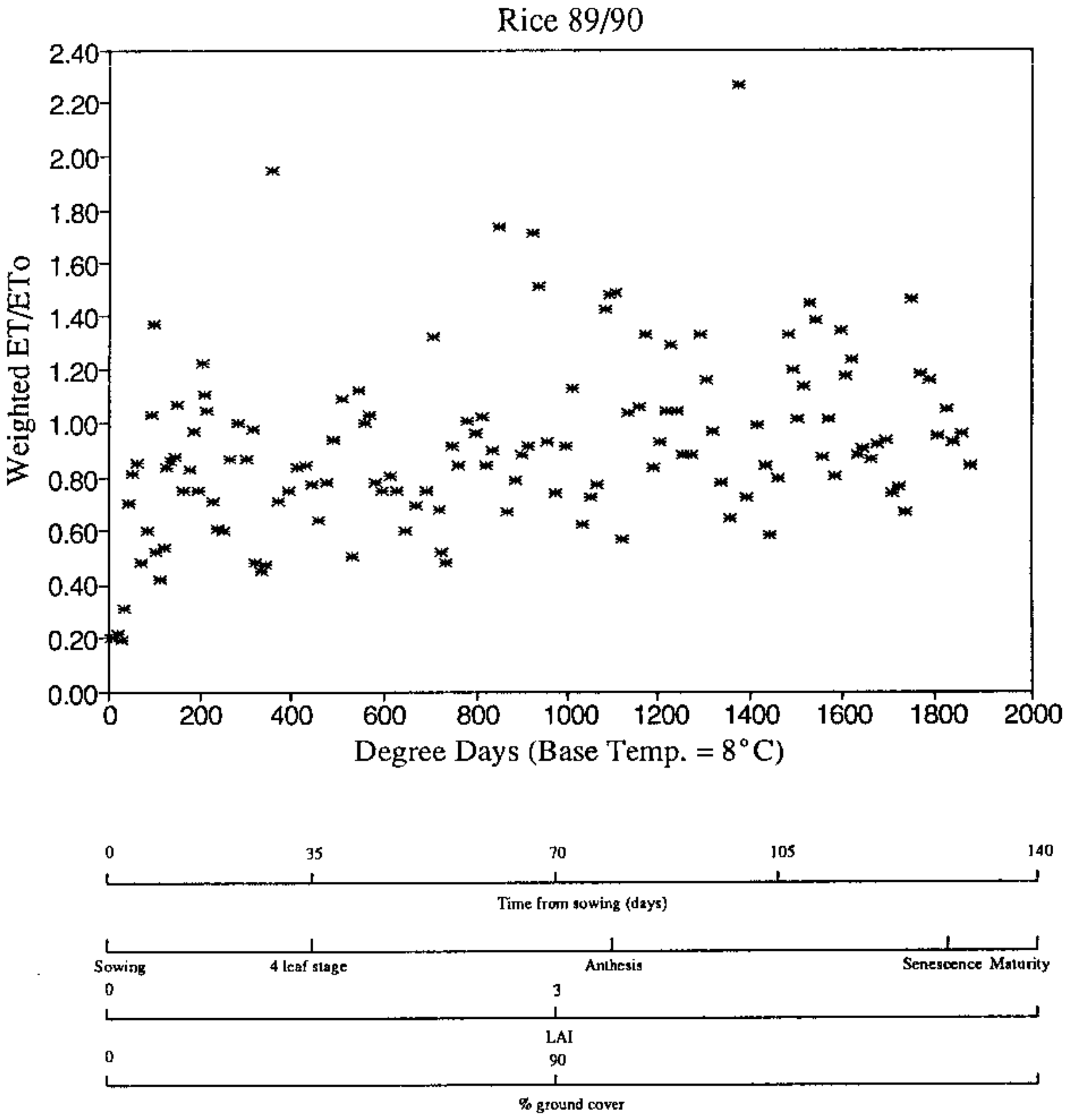


Fig. 21. Daily interpolated values of ET from rice water use recorded every 3 or 4 days using in field pan lysimeters during 1989/90. These values are expressed as a ratio of Et_0 and set against cumulative degree days from sowing. Approximate scales of time, growth stage leaf area index and percent ground cover are given for reference.

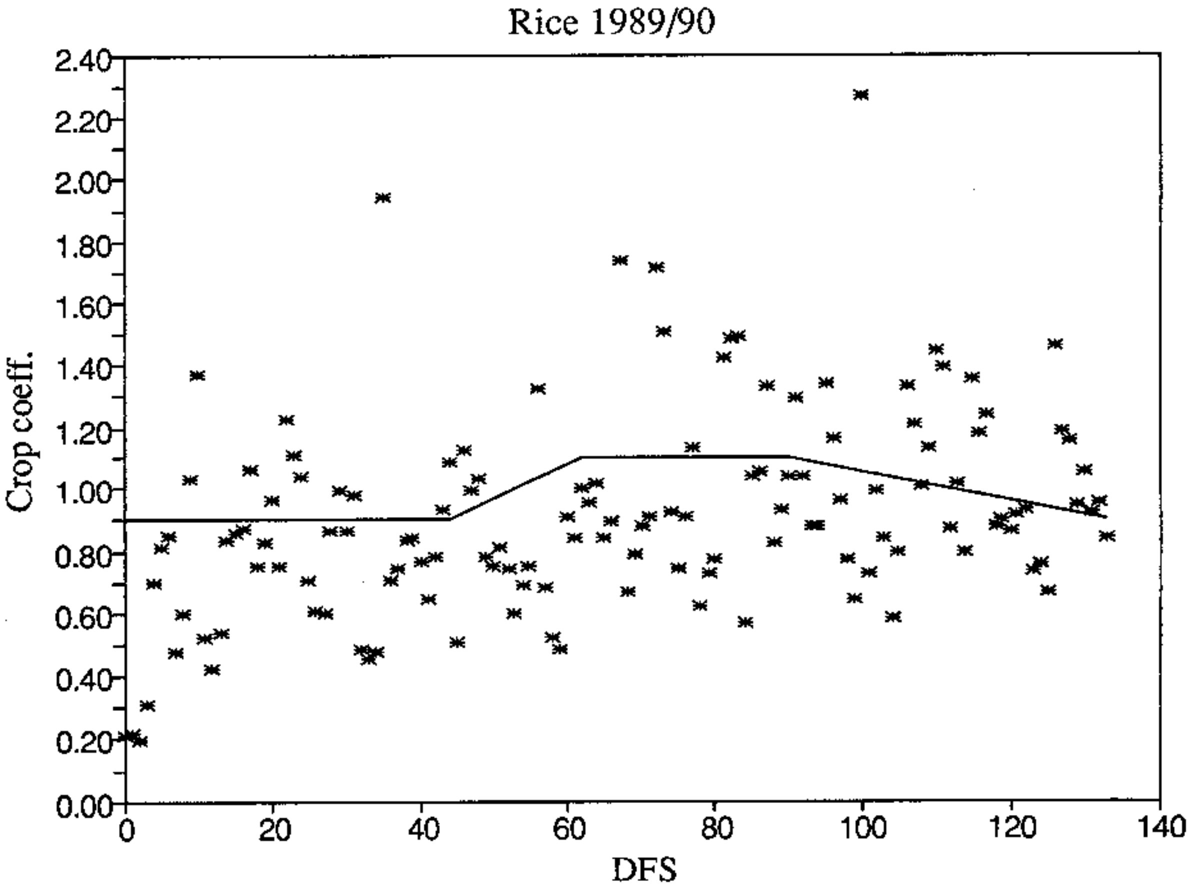


Fig. 22. Generalised crop coefficients (solid line) set against daily interpolated values for 1989/90.

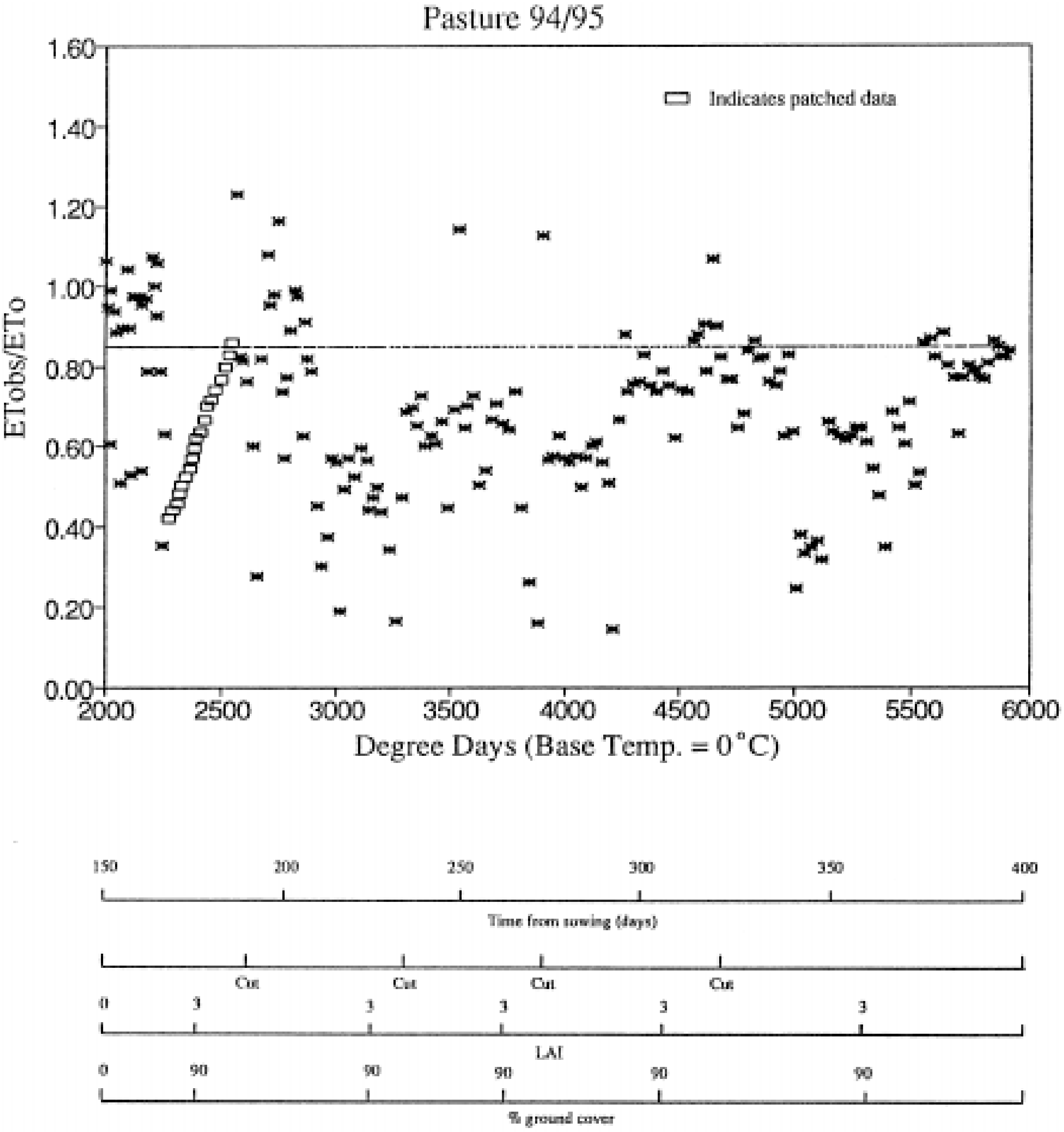


Fig. 23. Daily lysimeter measured ET for pasture as a ratio of Et_o for 1994/95 as related to cumulative degree days from sowing. Approximate scales of time, growth stages with cuts, leaf area index and percent ground cover are given for reference.

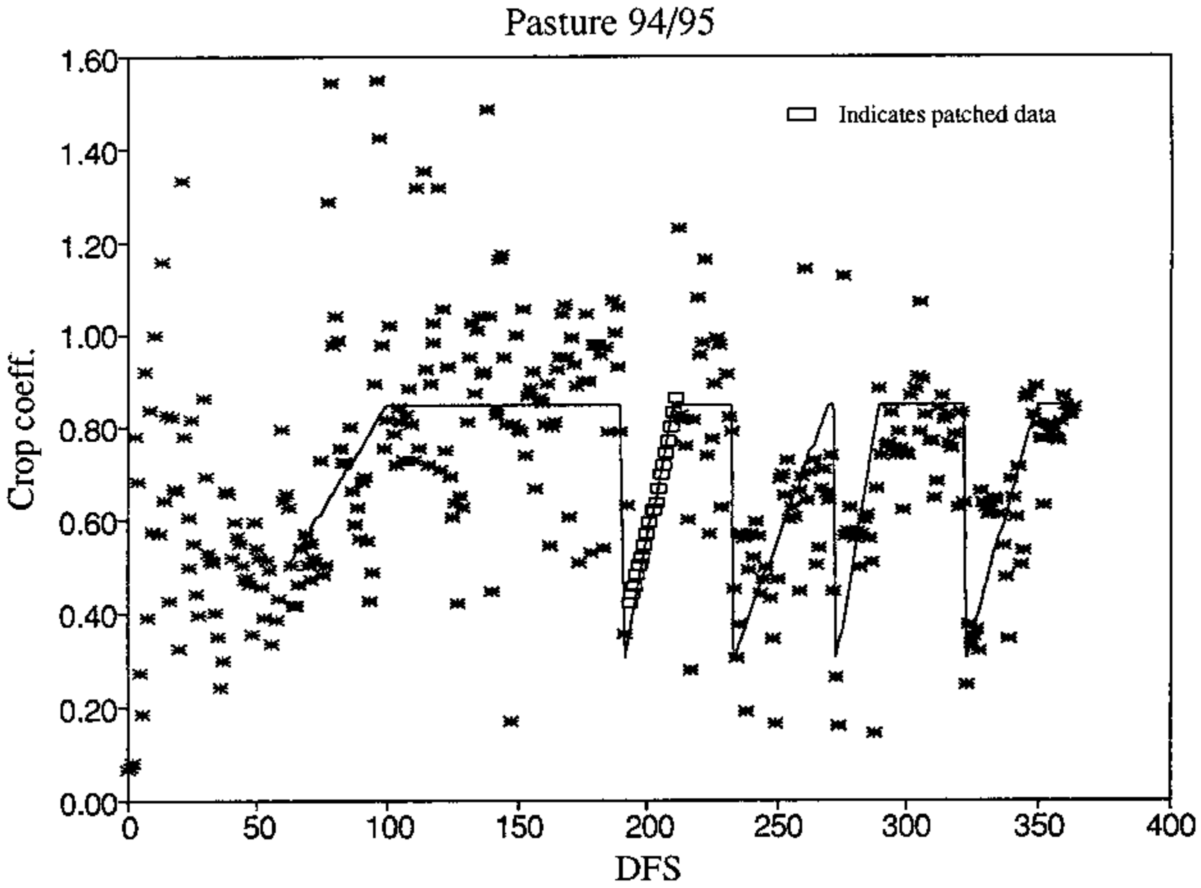


Fig. 24. Generalised crop coefficients (solid line) set against daily observed data for 1994/95 when four cuts were made for haymaking.

7.0 Acknowledgements

The derivation of the polynomial equation for R_{so} estimation was done by Mr D Erskine. Mr Brian Baer made the R_{so} comparisons and adapted the MTCLIM code to produce R_{so} values from information provided by Dr E. O'Loughlin and Dr T. Hatton. Mr F.X. Dunin kindly provided the measured radiant energy values used to calculate albedo of wheat.

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FIGURE CAPTIONS

Fig. 1 Hourly time course of relative humidity RH on 20 Feb 1988. RH_{calc} came from measurement of wet and dry bulb electronic thermometer sensors. RH_{meas} was that recorded from direct measurement from an electronic capacitance RH sensor.

Fig. 2 Hourly time course of dew point temperature T_{dew} on 20 Feb 1988. Three independent weather station systems located within 500 m of each other produced these values. T_{dew} Lys and T_{dew} Edas used wet and dry bulb temperature to derive T_{dew}, whereas T_{dew} Campbell had an RH sensor from which T_{dew} was calculated.

Fig. 3 Values of T_{dew} at 9 am from three sites compared with the daily mean T_{dew} for the period of 18 Aug to 30 Aug 1987.

Fig. 4 Values of T_{dew} at 9 am from three sites compared with the daily mean T_{dew} for the period of 3 Mar to 15 Mar 1988.

Fig. 5 Comparison of dry bulb temperatures T_d either aspirated ($T_{d\ asp}$) or non aspirated ($T_{d\ nonasp}$) measured in the same Stevenson screen during 1991 and 1992.

Fig. 6 Comparison of wet bulb temperatures T_w either aspirated ($T_{w\ asp}$) or non aspirated ($T_{w\ nonasp}$) measured in the same Stevenson screen during 1991 and 1992.

Fig. 7 Measured hourly wet bulb temperature at Hay, NSW on 11 Feb 1993. The muslin cloth forming the wet bulb was extended 30 to 40 mm up the sensor cable between 1100 and 1200 hours. The resultant change in derived dew point temperature and relative humidity is shown.

Fig. 8 Measured solar irradiance R_s values for Griffith during a full calendar year together with envelope curves describing the maximum clear day irradiance R_{so}. The fitted function is the Griffith polynomial while the other two are from two other model approximations.

Fig. 9 Measured daily solar irradiance R_s values from Los Banos, Philippines compared to estimated values from model approximations.

Fig. 10 Relation of reference evaporation, ET_o to measured daily open Class A pan evaporation from Griffith during 1991 to 1993.

Fig. 11 Comparison of daily potential evaporation E_o calculated using the Ritchie potential evaporation equations and ET_o from Griffith data during 1993.

Fig. 12 Comparison of daily reference evaporation calculated using the standardised Penman-Monteith equation (ET_{pm}) and the Penman equation (ET_o). Values were calculated from Griffith weather data for 1993.

Fig. 13 Values of daily lysimeter measured ET for wheat as a ratio of ET_o for three crops in 1984, 1986 and 1987 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index (LAI) and present ground cover are given for reference.

Fig. 14 Generalised crop coefficients (solid line) for wheat set against daily observed data from 1986.

Fig. 15 Daily lysimeter measured ET for soybeans as a ratio of ET_o for two seasons in 1985/86 and 1987/88 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index and percent ground cover are given for reference.

Fig. 16 Generalised crop coefficients (solid line) for soybeans set against daily observed data for 1985/86 and 1987/88.

Fig. 17. Daily lysimeter measured ET for maize as a ratio of ET_o for 1989/90 as related to cumulative degree days from sowing. Approximate scales of time, growth stage, leaf area index and percent ground cover are given for reference.

Fig. 18 Generalised crop coefficients (solid line) for maize set against daily observed data for 1989/90.

Fig. 19 Daily lysimeter measured ET for lucerne as a ratio of ET_o for the establishment season of 1990/91 as related to cumulative degree days from sowing. Approximate scales of time, growth stages with cuts of leaf area index and percent ground cover are given for reference.

Fig. 20 Generalised crop coefficients (solid line) for lucerne set against daily observed data for 1991/92 when five cuts were made for hay making.

Fig. 21 Daily interpolated values of ET from rice water use recorded every 3 or 4 days using in field pan lysimeters during 1989/90. These values are expressed as a ratio of ET_o and set against cumulative degree days from sowing. Approximate scales of time, growth stage leaf area index and percent ground cover are given for reference.

Fig. 22 Generalised crop coefficients (solid line) for rice set against daily interpolated values for 1989/90.

Fig. 23 Daily lysimeter measured ET for pasture as a ratio of ET_o for 1994/95 as related to cumulative degree days from sowing. Approximate scales of time, growth stages with cuts, leaf area index and percent ground cover are given for reference.

Fig. 24 Generalised crop coefficients (solid line) for pasture set against daily observed data for 1994/95 when four cuts were made for haymaking.