Irrig Sci (2002) 21: 57–67
DOI 10.1007/s002710100047

ORIGINAL PAPER

J.G. Annandale · N.Z. Jovanovic
N. Benadé · R.G. Allen

Software for missing data error analysis of Penman-Monteith reference evapotranspiration

Received: 23 December 2000 / Published online: 16 November 2001

Abstract The most common approach for the estimation of crop water requirements is to pair a crop factor with the evaporation from a reference surface. In this study, a user-friendly computer tool was developed to facilitate the calculation of daily FAO (Food and Agricultural Organization of the United Nations, Rome, Italy) Penman-Monteith reference crop evaporation (ET_0), and to estimate errors that can arise if solar radiation, wind and vapour pressure data are not available. The ET_0 calculator imports comma, tab or space-delimited daily weather data files in any user-specified format. It displays graphically and processes statistically, ET_0 values calculated from full and incomplete weather data sets. The program is written in Delphi with a Paradox database and includes a comprehensive, context-sensitive help file. Sensitivity analyses were carried out for three locations as examples. The error in predicting ET_0 using estimated weather parameters was reduced by using 5-day averages of ET_0 rather than daily values. Although some error is incurred by estimating weather parameters, this is somewhat compensated for by the absence of any error that may have been associated with the measurements.

Introduction

Atmospheric evaporative demand-driven estimates of crop water requirements are being increasingly used to complement soil water and plant measurements. Many of these methods were reviewed in the FAO (Food and Agriculture Organization of the United Nations, Rome, Italy) Irrigation and Drainage Bulletin No. 24 (Doorenbos and Pruitt 1977). During a consultation of experts and researchers held in Rome in 1990, the FAO methodologies for crop water requirements were reviewed, and the conceptual framework for their revision and standardization were established (Smith 1992). In the following years, much work was done worldwide to standardize the procedures (Smith et al. 1996). Different methodologies were tested with data obtained from many locations in the world, and this resulted in the recently published FAO Irrigation and Drainage Bulletin No. 56 (Allen et al. 1998). In this publication, the FAO recommends using the Penman-Monteith equation as reference (ET_0).

The FAO approach for the calculation of daily ET_0 requires solar radiation (R_s), minimum (T_{min}) and maximum temperature (T_{max}), vapour pressure (VP) and wind speed (U) data. In the absence of a complete data set, the FAO still advises using the Penman-Monteith equation, but with recommended procedures for estimating missing values (Smith 1992; Smith et al. 1996; Allen et al. 1998). The objective of this study was to develop user-friendly software for the calculation of daily FAO-56 ET_0, and for the estimation of errors that can arise if solar radiation, wind and vapour pressure data are not available and have to be estimated.

ET_0 calculator

A user-friendly computer tool was developed to facilitate the estimation of daily ET_0, according to the FAO recommendations (Smith 1992; Smith et al. 1996; Allen et al. 1998). The equations and procedures used in the calculation of ET_0 are given in detail in the Appendix. Context-sensitive help files can be accessed from any menu by pressing F1 on the keyboard. The help files include user guidelines and theoretical background.

J.G. Annandale (✉) · N.Z. Jovanovic
Department of Plant Production and Soil Science,
University of Pretoria, Pretoria 0001, South Africa
E-mail: jannanda@postino.up.ac.za
Tel.: +27-12-4203223
Fax: +27-12-4204120

N. Benadé
NB Systems, PB 15102, Sinoville 0129, South Africa

R.G. Allen
Department of Biological and Agricultural Engineering,
University of Idaho, Research and Extension Center,
Kimberly, ID 83341, USA

Related topics can be accessed using links and bitmaps with hotspots, in order to facilitate the operational and technical understanding of the software.

A screen printout of the ET_0 calculator is shown in Fig. 1. Essential input data are: date, daily maximum and minimum temperatures, latitude, hemisphere and elevation. In the absence of measured data, solar radiation is calculated using Eq. 6 (Appendix) as a function of sunshine hours, or estimated with Eq. 12. The transmissivity coefficients (a_s and b_s) used to calculate R_s from sunshine hours (Eq. 6) are often locally calibrated. These can be entered in the appropriate blocks. The user can also enter an adjustment coefficient for interior or coastal locations (k_{Rs}) when using Eq. 12 to estimate R_s. Wind speed can be estimated using the guidelines given in the Appendix (Allen et al. 1998). Vapour pressure can be calculated using Eqs. 22, 23 or 24, or by assuming that the daily minimum temperature is equal to dew point temperature and using Eq. 22. Allen et al. (1998) recommend using a dew point temperature of T_{min}–2 for arid and semi-arid climates. A dew point offset to T_{min} in °C can be entered in the appropriate block for the estimation of vapour pressure from daily T_{min}. Daily ET_0 is calculated by clicking on the "Calc" button (Fig. 1).

The ET_0 calculator makes use of a Paradox database and is written in Delphi 5 (Inprise Corporation). Weather input data can be seen in grid format in Fig. 2. The top window includes information on the weather station, while the bottom grid contains the daily weather data. Daily weather data can be imported from comma, tab or space-delimited files by clicking an icon in the menu bar. The column order of the data in the import file and the units can be specified by the user, as can realistic ranges for these data for error checking purposes.

Daily ET_0 values calculated using full data sets and ET_0 with estimated R_s, U and VP can be seen in grid format (Fig. 3). A default value for wind speed can be entered in the bottom part of the screen. The ET_0 calculator uses this value when it calculates ET_0 with estimated U. The default values for dew point offset to T_{min} in °C, as well as for the coefficients a_s, b_s and k_{Rs} can also be entered in the bottom part of the screen. Averages of daily ET_0 can also be calculated for a time interval specified by the user in order to estimate errors over a typical irrigation cycle. These are stored and displayed in a separate grid. Daily weather data, daily ET_0 and averages of daily ET_0 can be written to comma-delimited files by clicking an icon in the menu bar.

The accuracy of this ET_0 calculator was tested against the REF-ET program developed at the University of Idaho and available on the Internet (http://www.kimberly.vidaho.edv/ref-et/). The REF-ET software contains more than 15 reference evaporation methods and is intended to perform standardized calculations of ET_0. The main purpose of the ET_0 calculator developed in this study is to calculate the FAO-56 Penman-Monteith ET_0 value under various levels of data availability. The two software packages, therefore, complement each other.

The ET_0 calculator is a Windows-based program with a user-friendly interface. The figures presented in the next section of this study are examples of printable output graphs. The ET_0 calculator is available for use with Windows 95 on an IBM-PC or compatible computer. The program is supplied in executable code on CD. Copies of the program are available through John G. Annandale, Department of Plant Production and

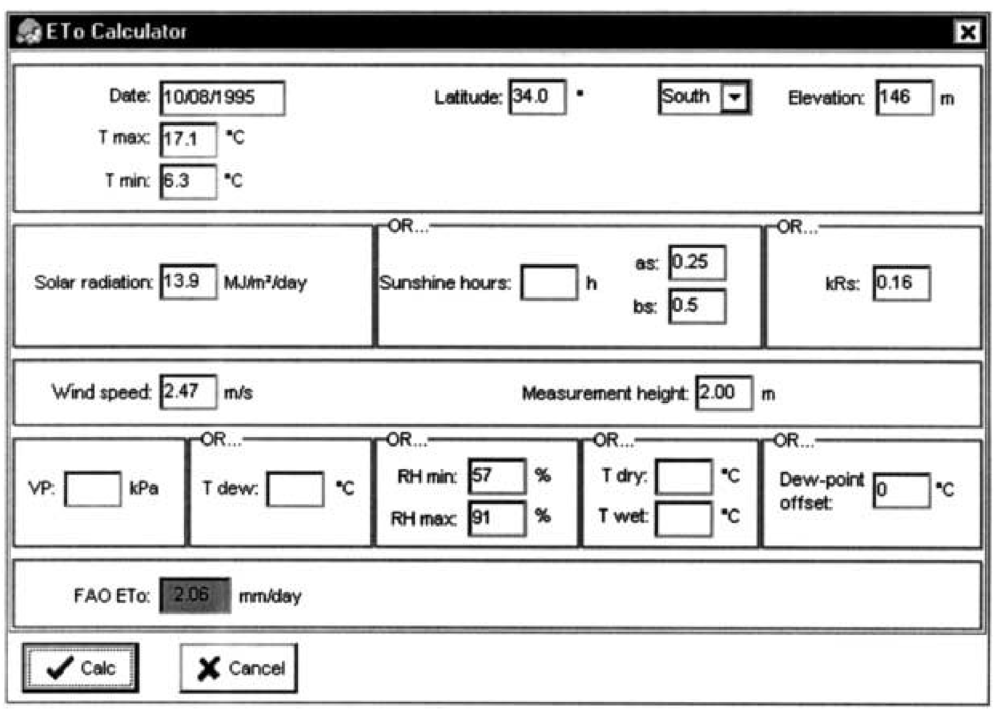
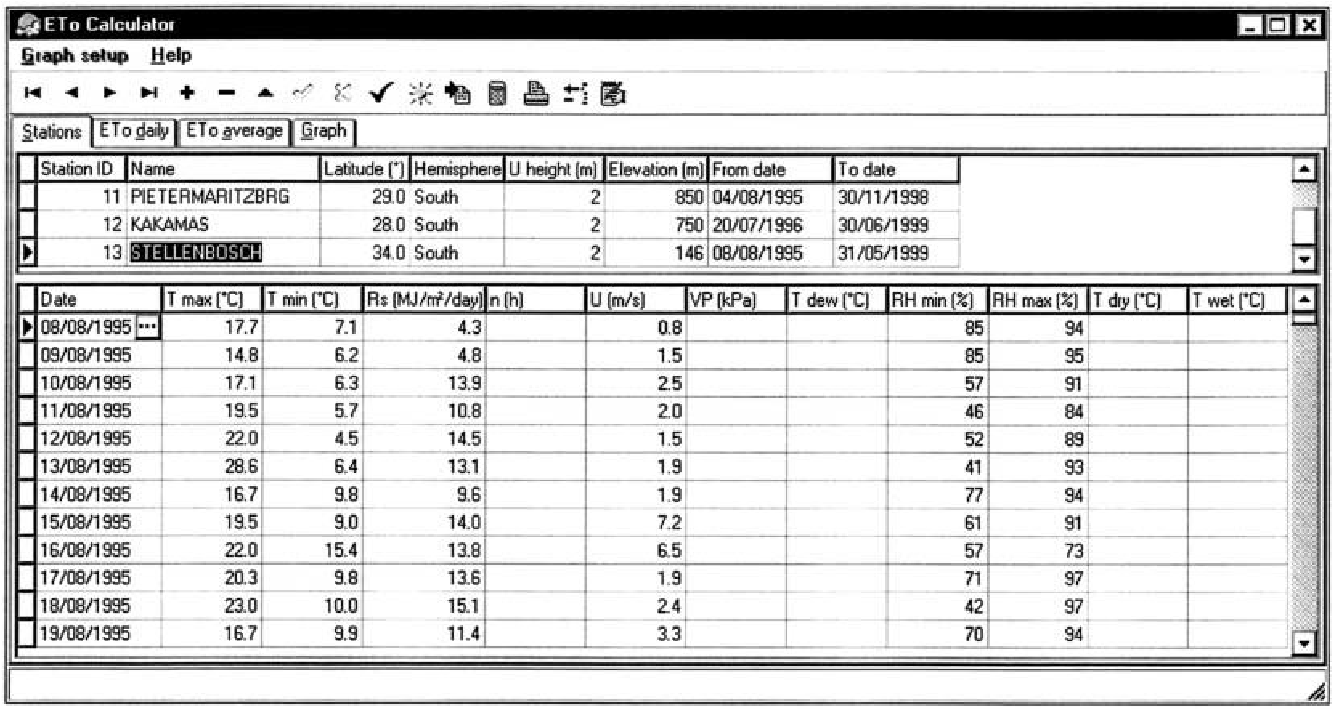


Fig. 1 Screen printout of the FAO Penman-Monteith grass reference evapotranspiration (ET_0) calculator. T_{max} and T_{min} are daily maximum and minimum temperatures, a_s and b_s are transmissivity coefficients used to calculate solar radiation (R_s) from sunshine hours (Eq. 6, see Appendix), k_{Rs} is the adjustment coefficient for the calculation of R_s with Eq. 12, VP is actual vapour pressure, T_{dew} is dew point temperature, RH_{min} and RH_{max} are minimum and maximum relative humidities, T_{dry} and T_{wet} are dry and wet bulb temperatures, and dew point offset is used to estimate vapour pressure from T_{min}



Station ID	Name	Latitude (°)	Hemisphere	U height (m)	Elevation (m)	From date	To date
11	PIETERMARITZBRG	29.0	South	2	850	04/08/1995	30/11/1998
12	KAKAMAS	28.0	South	2	750	20/07/1996	30/06/1999
13	STELLENBOSCH	34.0	South	2	146	08/08/1995	31/05/1999

Date	T max (°C)	T min (°C)	Rs (MJ/m²/day)	n (h)	U (m/s)	VP (kPa)	T dew (°C)	RH min (%)	RH max (%)	T dry (°C)	T wet (°C)
08/08/1995	17.7	7.1	4.3		0.8			85	94		
09/08/1995	14.8	6.2	4.8		1.5			85	95		
10/08/1995	17.1	6.3	13.9		2.5			57	91		
11/08/1995	19.5	5.7	10.8		2.0			46	84		
12/08/1995	22.0	4.5	14.5		1.5			52	89		
13/08/1995	28.6	6.4	13.1		1.9			41	93		
14/08/1995	16.7	9.8	9.6		1.9			77	94		
15/08/1995	19.5	9.0	14.0		7.2			61	91		
16/08/1995	22.0	15.4	13.8		6.5			57	73		
17/08/1995	20.3	9.8	13.6		1.9			71	97		
18/08/1995	23.0	10.0	15.1		2.4			42	97		
19/08/1995	16.7	9.9	11.4		3.3			70	94		

Fig. 2 Screen printout of the weather database. The *columns in the top grid* are (*from left to right*): station identification number, name of weather station, latitude, hemisphere, height of measurement of wind speed (m), elevation (m) and range of dates. The *columns in the bottom grid* are (*from left to right*): date, maximum and minimum temperature (°C), solar radiation (MJ m^{-2} day^{-1}), sunshine hours (h), wind speed (m s^{-1}), vapour pressure (kPa), dew point temperature (°C), minimum and maximum relative humidity (%), and dry and wet bulb temperature (°C)

Soil Science, University of Pretoria, 0001 Pretoria, South Africa (e-mail address: jannanda@posti-no.up.ac.za).

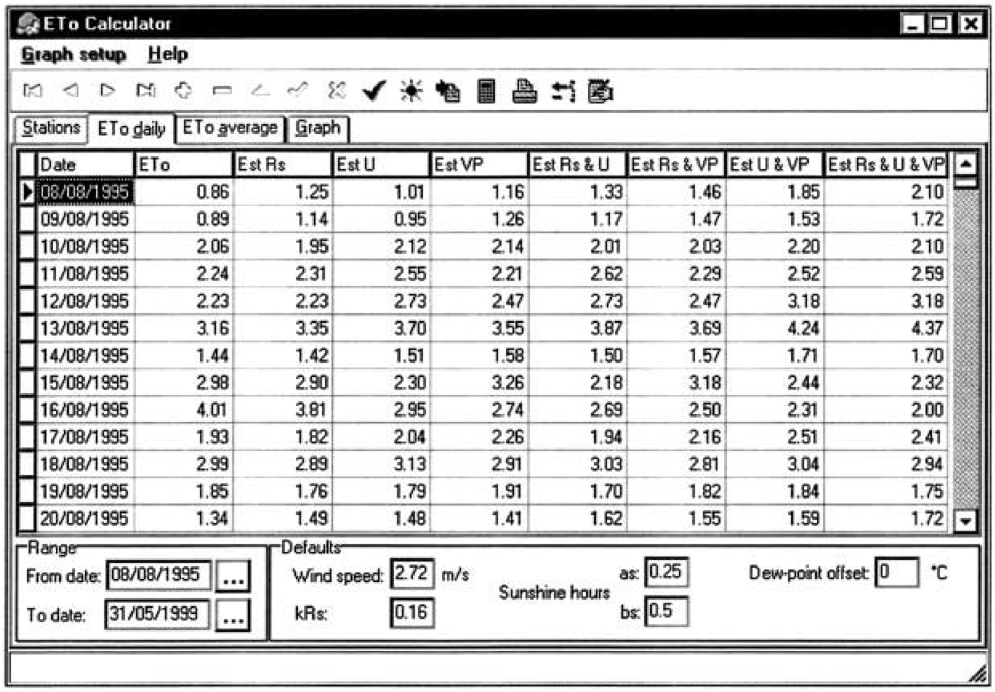
Error estimation if weather parameters are not available

The ET_0 calculator displays graphically and processes statistically daily ET_0 values calculated from full and incomplete data sets. This should facilitate the estimation of the error made when some weather input parameters are not available. This will indicate how important it is to measure all the parameters affecting evaporation, and under which conditions the FAO procedures for estimating missing data give acceptable accuracy. For this study, full weather data sets were collected from three weather stations, representing very different climatic regions in South Africa:

1. Nietvoorbij (District: Stellenbosch, South Africa; Latitude 33°54′S; Longitude 18°52′E; Altitude 146 m) from August 1995 to May 1999
2. Ukulinga Research Station (District: Pietermaritzburg, South Africa; Latitude 29°40′S; Longitude 30°24′E; Altitude 775 m) from August 1995 to November 1998 and
3. Kromhout Boerdery (District: Kakamas, South Africa; Latitude 28°46′S; Longitude 20°37′E; Altitude 850 m) from June 1996 to July 1999.

Stellenbosch is located in the winter rainfall region (Mediterranean climate) with an average annual rainfall of ≈800 mm. The climate of Pietermaritzburg is subtropical (hot, humid, summer rainfall region) with an average annual rainfall of ≈850 mm. Kakamas is in a dry, hot, summer rainfall climate region (average annual rainfall is ≈150 mm). Daily ET_0 values were calculated for these locations from full weather data sets, and from the same sets but with estimated R_s, U and VP. All weather data sets included daily maximum (RH_{max}) and minimum relative humidity (RH_{min}). The default values of U were calculated as the average daily wind speed for the periods considered. These were 2.72 m s^{-1} for Stellenbosch, 2.04 m s^{-1} for Pietermaritzburg and 1.68 m s^{-1} for Kakamas (areas of light to moderate wind) (Allen et al. 1998). The adjustment coefficients k_{Rs} were 0.16, which is the value recommended for interior locations (see Appendix). Typical seasonal trends of ET_0 calculated with full weather data sets are shown in Fig. 4 for the three locations. Missing ET_0 values on the graphs in Fig. 4 indicate that no weather data were available for some days. The average ratios between the radiation term, including net radiation (R_n), and the aerodynamic term, including vapour pressure deficit (VPD) (Eq. 1), were calculated in order to generalize the climatic conditions for the three sites. For the periods considered, these ratios were 54:46 for Stellenbosch, 68:32 for Pietermaritzburg and 64:36 for Kakamas.

Figure 5 presents the correlation between daily ET_0 calculated using a full data set and ET_0 with estimated R_s (Eq. 12) for Stellenbosch. In the top right corner of the



Date	ETo	Est Rs	Est U	Est VP	Est Rs & U	Est Rs & VP	Est U & VP	Est Rs & U & VP
08/08/1995	0.86	1.25	1.01	1.16	1.33	1.46	1.85	2.10
09/08/1995	0.89	1.14	0.95	1.26	1.17	1.47	1.53	1.72
10/08/1995	2.06	1.95	2.12	2.14	2.01	2.03	2.20	2.10
11/08/1995	2.24	2.31	2.55	2.21	2.62	2.29	2.52	2.59
12/08/1995	2.23	2.23	2.73	2.47	2.73	2.47	3.18	3.18
13/08/1995	3.16	3.35	3.70	3.55	3.87	3.69	4.24	4.37
14/08/1995	1.44	1.42	1.51	1.58	1.50	1.57	1.71	1.70
15/08/1995	2.98	2.90	2.30	3.26	2.18	3.18	2.44	2.32
16/08/1995	4.01	3.81	2.95	2.74	2.69	2.50	2.31	2.00
17/08/1995	1.93	1.82	2.04	2.26	1.94	2.16	2.51	2.41
18/08/1995	2.99	2.89	3.13	2.91	3.03	2.81	3.04	2.94
19/08/1995	1.85	1.76	1.79	1.91	1.70	1.82	1.84	1.75
20/08/1995	1.34	1.49	1.48	1.41	1.62	1.55	1.59	1.72

Fig. 3 Screen printout of the reference evapotranspiration (ET_0) database. The *columns* represent (*from left to right*) daily ET_0 in mm calculated from a full weather data set, and from the same set with estimated solar radiation (R_s), wind speed (U) and vapour pressure (VP). Range of dates, as well as default values for wind speed, dew point offset used to estimate vapour pressure from minimum temperature, transmissivity coefficients (a_s and b_s) for the calculation of R_s from sunshine hours (Eq. 6, see Appendix) and the adjustment coefficient (k_{Rs}) for the calculation of R_s with Eq. 12 are entered in the bottom part of the screen

graph, the parameters of the statistical analysis are shown. These are number of observations (N), coefficient of determination (r^2), as well as the slope and the constant of the linear regression between daily ET_0 calculated with a full data set and ET_0 with estimated R_s. Table 1 summarizes the statistical analysis between daily ET_0 calculated using full data sets and ET_0 obtained with estimated R_s (Eq. 12), U (2.72, 2.04 or 1.68 m s^{-1}) and VP (assuming T_{min} reaches dew point) for the three locations. It is evident that the scatter of data points increases (lower r^2) by increasing the number of estimated weather parameters in the calculation of ET_0. This underlines the importance of measuring all factors involved in the prediction of crop water use. The inconsistencies in the data where VP is estimated is not to be entirely attributed to the assumption that T_{min} reaches dew point, as ET_0 calculated with full data sets includes errors in the measurement of relative humidity as well as errors in the prediction of VP from RH_{max} and RH_{min}. The slope and constant of such linear regressions could be used to correct the ET_0 predictions when some weather data are not available in a particular climatic region.

Figure 6 presents the difference between daily ET_0 calculated with estimated R_s and ET_0 calculated with a full data set for Stellenbosch. In the top right corner, the root mean square error (RMSE) and the mean absolute error (MAE) are shown. The errors are summarized in Table 1 for all cases of estimated weather parameters and locations. The error generally increased by increasing the number of estimated weather parameters. It is interesting to note that the error arising from estimating U and VP at Pietermaritzburg, was smaller than the error caused by estimating only R_s. The error analysis could be helpful in determining which measurements are indispensable, and which can safely be omitted in a particular climatic region. The criteria for maximum permissible RMSE and MAE are subjective and depend on the particular application.

The error analysis indicated that, at Stellenbosch, the error from estimating R_s with Eq. 12 is relatively low, especially in winter, but could increase considerably during the dry summer months due to occasional cloudiness. This coincides with the period when high radiation levels occur (Fig. 7). The measurements of U and VP at this location appear to be quite important and should not be omitted if one is to obtain accurate predictions of ET_0. At Pietermaritzburg, a very small error in the prediction of ET_0 arises by assuming an average wind speed of 2.04 m s^{-1}. The comparison between measured and estimated U is shown in Fig. 8. The measurement of wind speed could be omitted at this location, but R_s and VP should definitely be measured. At Kakamas, large errors may arise when estimating any of the weather parameters. It is therefore recommended that the full set of measurements should be recorded in order to accurately predict ET_0 at this location. It was interesting to note that ET_0 obtained with estimated VP tended to be lower than ET_0 obtained from a full set of weather data. This occurred because estimated VP was generally higher than measured VP (Fig. 9). As a result, the vapour pressure deficit calculated using Eq. 21 was smaller, resulting in a lower predicted ET_0 (Eq. 1). It is therefore clear that minimum air temperature rarely drops to dew point in the dry and arid region of Kakamas, and this assumption for the estimation of VP does not hold. The dew point temperature can be reduced below minimum air temperature by using the dew point offset option of the ET_0 calculator.

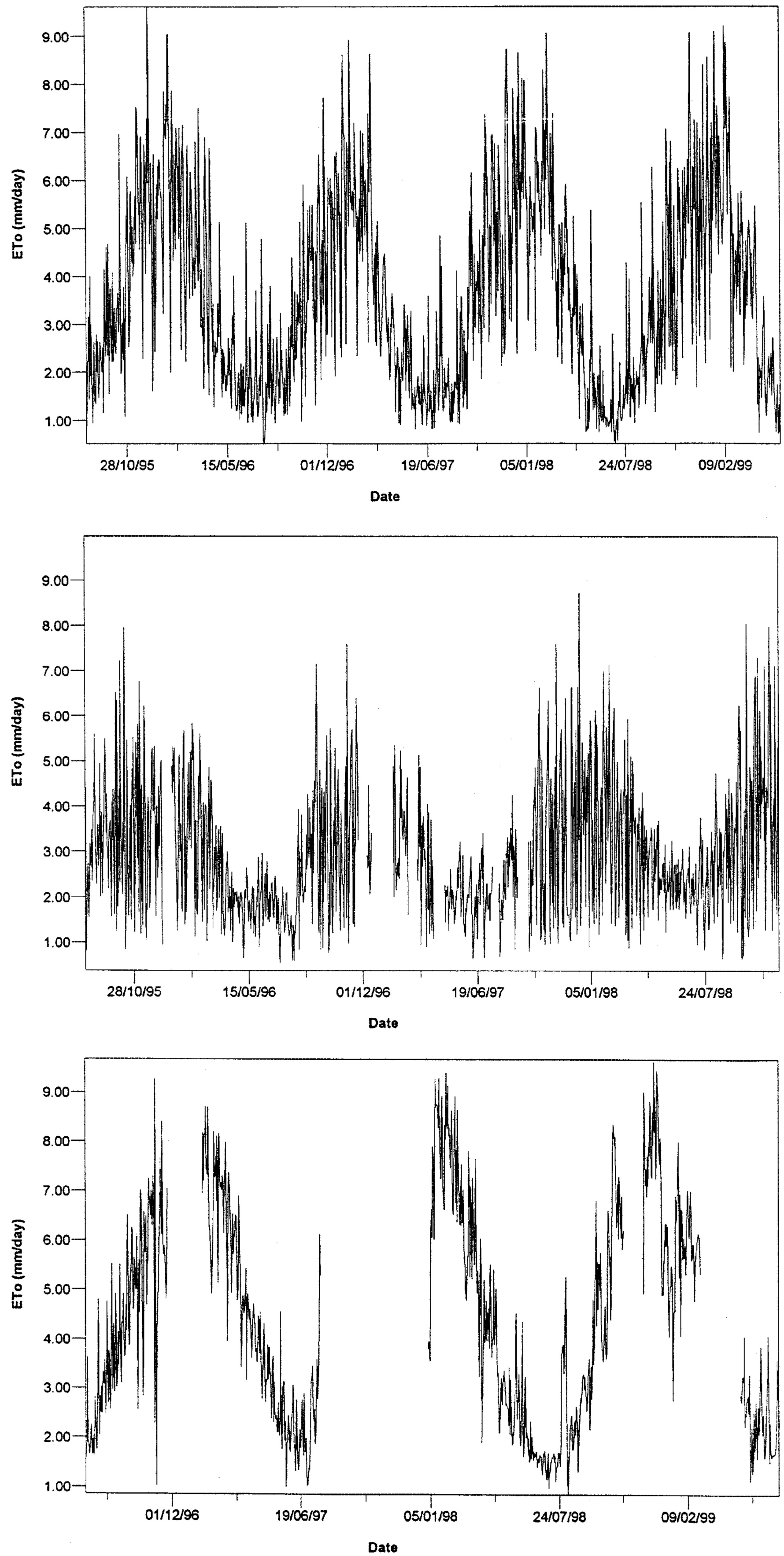


Fig. 4 Seasonal trends of daily reference evapotranspiration ET_0 calculated with full weather data sets for Stellenbosch (*top*), Pietermaritzburg (*middle*) and Kakamas (*bottom*)

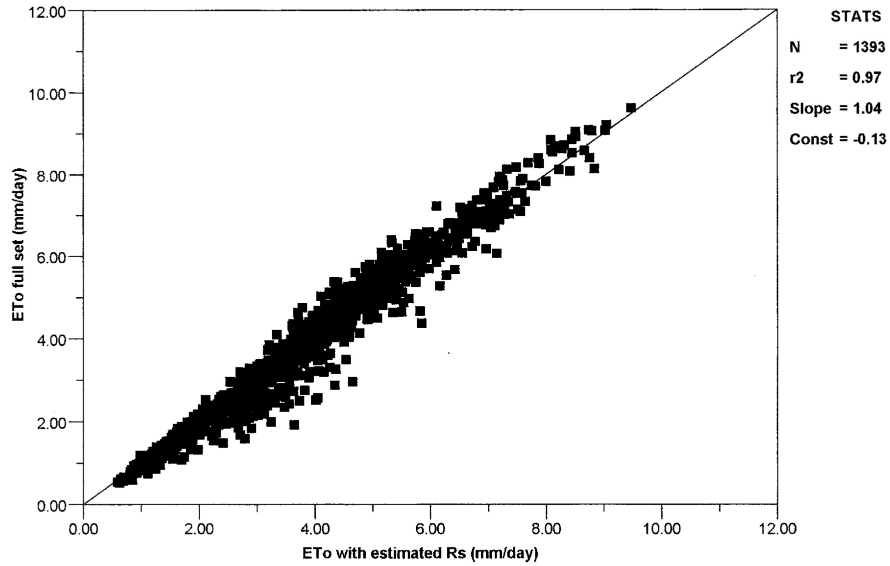


Fig. 5 Correlation between daily reference evapotranspiration ET_0 calculated from a full weather data set and ET_0 with estimated solar radiation (R_s) for Stellenbosch, South Africa. The parameters of the statistical analysis are number of observations (N), coefficient of determination (r^2), as well as the slope and the constant of the linear regression

A sensitivity analysis was carried out using averages of daily ET_0 to determine whether errors from estimating R_s, U and VP are reduced when the time period considered is extended. The statistical analyses between average daily ET_0 calculated using a full data set and average daily ET_0 calculated with estimated R_s, U and VP are presented in Table 1 for a typical irrigation interval of 5 days. A reduction in scatter of data points and higher r^2 values were generally observed when using 5-day averages of ET_0 compared to daily ET_0. The calculated RMSE and MAE were smaller using 5-day averages of ET_0 compared to daily ET_0. This indicates that over- and underestimates of daily ET_0 tend to cancel each other out over longer time periods. The practical implication is an improved accuracy in the prediction of crop water requirements based on the estimation of some of the weather parameters required to calculate ET_0.

Another sensitivity analysis was carried out in order to compare errors implicit in weather measurements with errors induced by predicting these weather parameters. For this purpose, ET_0 values were calculated by assuming the following errors (±2 standard deviation at 95% confidence interval): ±1.5°C for T_{max} and T_{min}, ±8% of measured RH_{max} and RH_{min}, ±5% for R_s and ±10% for U. These values represent typical error bands due to biases internal to electronic sensors, as well as impacts of the environment, shield and data logger. The worst-case RMSE and MAE values due to measurement errors encountered in the estimate of ET_0 are presented in Table 2. The error in calculated ET_0 due to estimation of missing data (Table 1) was generally in the range of possible errors that could be resident in the weather measurements (Table 2).

Conclusions and recommendations

User-friendly software, the ET_o calculator, has been developed for the calculation of daily ET_0, and for the estimation of errors that can arise if solar radiation, wind and vapour pressure data are not available. The theoretical background of the ET_0 calculator is based on the recommendations of the FAO (Allen et al. 1998). Several applications of the software are possible, with the user-friendly interface facilitating the handling of weather databases. The ET_0 calculator can be used to determine correction factors for particular climatic regions when weather data are not available. It can be used, for example, to determine the long-term average value of wind speed that minimizes errors in the estimation of evaporation. It can also be used to check which weather measurements can be omitted without experiencing large errors in the estimation of ET_0 at a particular site. As more weather stations are installed in a region as part of a station densification effort, the procedure demonstrated in this work can indicate whether these new stations could contain a reduced set of sensors. This would reduce costs for the new stations and may allow the installation of even more stations. The omitted measurements could be estimated as they have been in this paper, or they could be taken from a nearby or regional, fully instrumented station, after testing, to remove any biases due to the transfer in space. In addition, for stations having a full set of sensors, the error analyses point out those measurements that are critical for accurate ET_0 estimates. Therefore, in future measurements, if a particular sensor is shown to be, or is suspected to be, faulty, the user will know whether the measurements from this sensor can be dropped from the ET_0 computation process and estimated instead. If the measurements have been shown to be critical to the accuracy of the ET_0 estimate, some means should be applied to retain and correct the faulty data.

In the examples shown in this study, the error analyses carried out with the ET_0 calculator indicated that the measurement of R_s could be omitted at Stellenbosch (Mediterranean climate) during winter without large errors arising in the prediction of ET_0. In the humid

Table 1 Coefficient of determination (r^2), slope and constant of the linear regression, root mean square error (*RMSE*) and mean absolute error (*MAE*) of the correlation between daily and 5-day average ET_0 calculated with estimated solar radiation (R_s), wind speed (U) and vapour pressure (*VP*), and ET_0 calculated from a full weather data set for three locations in South Africa

Location	Statistical parameter	Estimated														No. of observations
		R_s		U		VP		R_s and U		R_s and VP		U and VP		R_s, U and VP		
		Daily	5–day mean	Daily	5-day mean	Daily	5-day mean	Daily	5-day mean	Daily	5-day mean	Daily	5-day mean	Daily	5-day mean	
Stellenbosch	r^2	0.97	0.99	0.95	0.98	0.93	0.96	0.89	0.96	0.88	0.94	0.86	0.93	0.78	0.89	1,393
	Slope	1.04	1.05	1.06	1.08	1.05	1.06	1.08	1.13	1.08	1.11	1.07	1.13	1.07	1.18	
	Constant	–0.13	–0.14	–0.24	–0.33	–0.09	–0.13	–0.29	–0.48	–0.16	–0.26	–0.26	–0.47	–0.23	–0.61	
	RMSE (mm)	0.34	0.19	0.46	0.30	0.54	0.38	0.67	0.42	0.71	0.48	0.74	0.51	0.93	0.62	
	MAE (%)	6.4	3.5	8.0	5.7	9.1	7.2	13.0	8.5	12.6	8.9	14.3	10.4	18.2	12.5	
Pietermaritzburg	r^2	0.87	0.90	0.98	0.99	0.96	0.94	0.86	0.90	0.81	0.82	0.93	0.92	0.80	0.82	1,090
	Slope	0.93	0.82	1.04	1.04	0.96	0.96	0.99	0.86	0.87	0.76	1.00	1.00	0.93	0.80	
	Constant	–0.03	0.32	–0.11	–0.09	–0.08	–0.06	–0.18	0.22	–0.01	0.36	–0.20	–0.18	–0.18	0.23	
	RMSE (mm)	0.59	0.43	0.20	0.12	0.36	0.30	0.58	0.40	0.79	0.64	0.42	0.32	0.78	0.62	
	MAE (%)	13.6	10.2	3.2	2.6	9.2	7.9	13.9	9.8	19.1	16.5	10.8	8.7	19.6	16.5	
Kakamas	r^2	0.96	0.98	0.91	0.97	0.88	0.91	0.86	0.95	0.83	0.88	0.82	0.89	0.76	0.86	767
	Slope	1.01	1.02	1.09	1.10	0.98	0.98	1.09	1.13	0.98	1.00	1.07	1.10	1.06	1.12	
	Constant	0.02	–0.02	–0.45	–0.50	0.11	0.09	–0.42	–0.55	0.19	0.09	–0.36	–0.49	–0.24	–0.51	
	RMSE (mm)	0.46	0.29	0.67	0.43	0.75	0.63	0.83	0.53	0.91	0.71	0.92	0.71	1.08	0.79	
	MAE (%)	6.5	4.2	11.3	7.2	11.9	10.9	14.2	9.2	14.7	12.1	17.3	13.1	19.1	14.1	

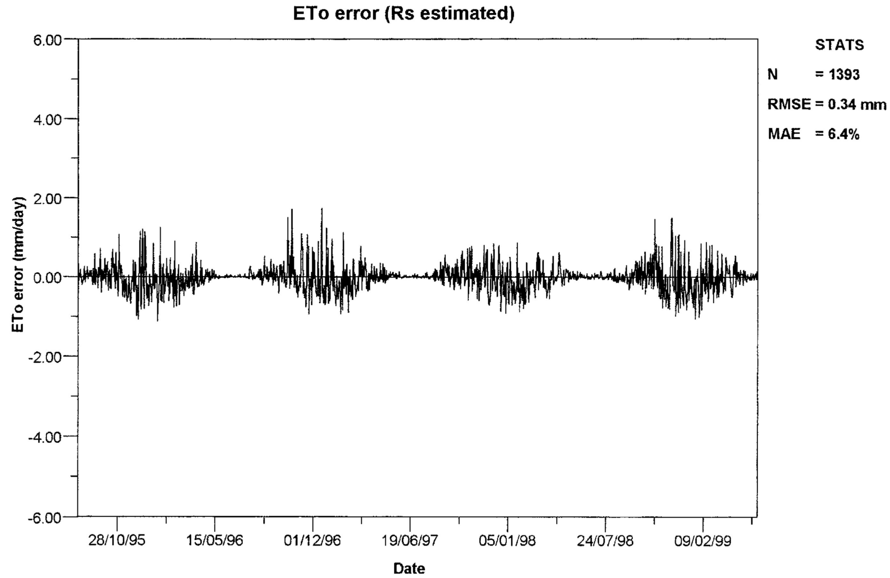


Fig. 6 Difference between daily reference evapotranspiration ET_0 calculated with estimated solar radiation (R_s) and ET_0 calculated from a full weather data set for Stellenbosch, South Africa. The parameters of the statistical analysis are root mean square error (*RMSE*) and mean absolute error (*MAE*)

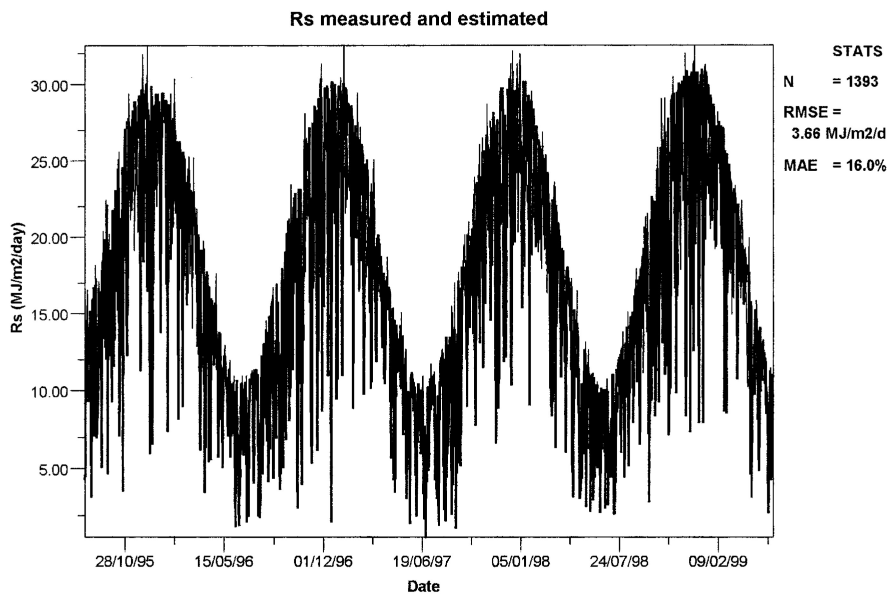


Fig. 7 Measured (*bold line*) and estimated (*thin line*) solar radiation (R_s) at Stellenbosch, South Africa

climate of Pietermaritzburg, the measurement of U can be omitted and an average of 2.04 m s^{-1} can be assumed. In the arid climate of Kakamas, all weather parameters should be measured in order to determine ET_0 accurately. The error in predicting ET_0 using estimated R_s, U and VP is reduced by using 5-day averages of ET_0 rather than daily values. This is advantageous for practical applications in irrigation scheduling. The error in the calculated ET_0 due to prediction of missing weather data was generally in the range of the error induced by assuming a 95% confidence interval in the measurements of T_{max} and T_{min}, RH_{max} and RH_{min}, as well as R_s and U. Therefore, although an error is encountered by estimating weather parameters, this is somewhat compensated for by the absence of error that would have been resident in the measurements.

Acknowledgements The authors thank Karl Monnik and Gert de Nysschen (Agricultural Research Council – Institute of Soil, Climate and Water, Pretoria, South Africa) for making weather data available.

Appendix

Procedure for the calculation of FAO Penman-Monteith grass reference evaporation

The ET_0 calculator computes daily ET_0 in mm day^{-1} according to the following equation (Allen et al. 1998):

$$ET_0 = \left[0.408\Delta(R_n - G) + \gamma 900/\left(T_{avg} + 273\right)U_2 \mathrm{VPD}\right] / [\Delta + \gamma(1 + 0.34U_2)] \quad (1)$$

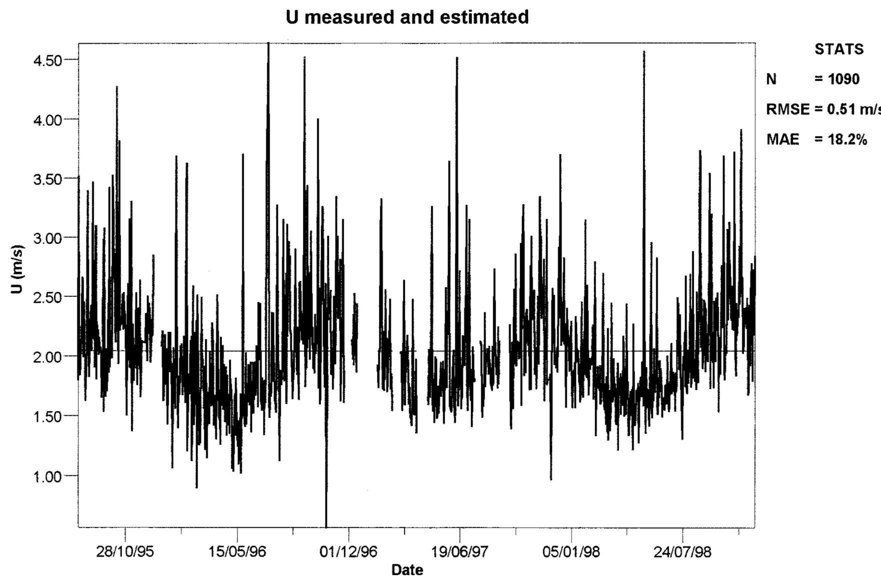


Fig. 8 Measured (*bold line*) and estimated (*thin line*) wind speed (*U*) at Pietermaritzburg, South Africa

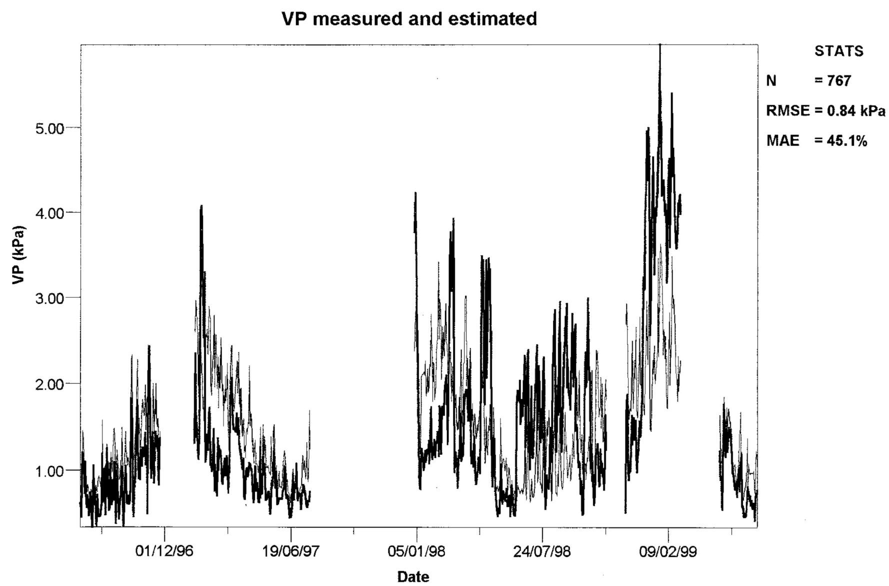


Fig. 9 Measured (*bold line*) and estimated (*thin line*) vapour pressure (*VP*) at Kakamas, South Africa

Table 2 Root mean square error (*RMSE*) and mean absolute error (*MAE*) of the estimate of ET_0 calculated including uncertainty in measured weather parameters for three locations in South Africa

Location	Measurement error	RMSE (mm)	MAE (%)
Stellenbosch	ET_0 overestimated[a]	0.60	15.39
	ET_0 underestimated[b]	0.54	13.62
Pietermaritzburg	ET_0 overestimated	0.48	15.48
	ET_0 underestimated	0.42	13.60
Kakamas	ET_0 overestimated	0.54	11.23
	ET_0 underestimated	0.50	10.38

[a] T_{max} and T_{min} + 1.5°C; RH_{max} and RH_{min} – 8%; R_s + 5%; U + 10%
[b] T_{max} and T_{min} – 1.5°C; RH_{max} and RH_{min} + 8%; R_s – 5%; U – 10%

where Δ = slope of the saturation vapour pressure curve (kPa °C^{-1}), R_n = net radiation (MJ m^{-2} day^{-1}), G = soil heat flux (MJ m^{-2} day^{-1}), (γ = psychrometer constant (kPa °C^{-1}), T_{avg} = daily average air temperature (°C), U_2 = daily average wind speed measured at 2 m height (m s^{-1}), VPD = vapour pressure deficit (kPa). The slope of the saturation vapour pressure curve is calculated as follows:

$$\Delta = 4098 \times 0.6108 \exp\left[17.27 T_{avg} / \left(T_{avg} + 237.3\right)\right] / \left(T_{avg} + 237.3\right)^2 \quad (2)$$

Daily average air temperature is assumed to be:

$$T_{avg} = (T_{max} + T_{min})/2 \quad (3)$$

where daily maximum (T_{max}) and minimum temperature (T_{min}) in °C are essential input values.

Net radiation is calculated as follows:

$$R_n = R_{ns} - R_{nl} \tag{4}$$

where R_{ns} = net incoming solar short–wave radiation (MJ m^{-2} day^{-1}), R_{nl} = net outgoing terrestrial long-wave radiation (MJ m^{-2} day^{1}). Assuming the albedo of the reference crop (grass) is 0.23, R_{ns} is:

$$R_{ns} = (1 - 0.23)R_s \tag{5}$$

where R_s = solar radiation (MJ m^{-2} day^{-1}). Solar radiation is an input value. In the absence of measured data, the ET_0 calculator computes R_s as a function of relative sunshine duration (n/N), and if that is not available, from T_{max} and T_{min}. Solar radiation can be calculated with the Ångstrom formula, which relates R_s to extraterrestrial radiation and relative sunshine duration:

$$R_s = (a_s + b_s n/N)R_a \tag{6}$$

where a_s = regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0), $a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$), n = actual duration of sunshine (h), N = maximum possible duration of sunshine or daylight hours (h), R_a = potential (extraterrestrial) solar radiation (MJ m^{-2} day^{-1}). In the absence of locally calibrated values, the ET_0 calculator assumes a_s = 0.25 and b_s = 0.50. The actual duration of sunshine is an input. The daylight hours are calculated as follows:

$$N = \omega_s 24/\pi \tag{7}$$

where ω_s = sunset hour angle (rad). Sunset hour angle is calculated as follows:

$$\omega_s = \arccos[-\tan(\mathrm{Lat})\tan(\mathrm{Dec})] \tag{8}$$

where Lat = latitude (rad), Dec = solar declination (rad). Latitude is an input value in degrees. The ET_0 calculator converts Lat from degrees into radians. The sign of Lat in Eq. 8 is positive for the northern and negative for the southern hemisphere. The value entered in the ET_0 calculator is, however, always positive and the user needs to specify the hemisphere. The sign of Lat is converted by the program into a negative if southern hemisphere is specified. Solar declination is calculated as follows (Duffie and Beckman 1980):

$$\mathrm{Dec} = 0.409\sin(2\pi/365\mathrm{DOY} - 1.39) \tag{9}$$

Day of year (DOY) is calculated from date which is an input parameter. Potential (extraterrestrial) solar radiation is calculated as follows:

$$R_a = 118.08D_{rel}/[\omega_s \sin(\mathrm{Lat})\sin(\mathrm{Dec}) + \sin(\omega_s)\cos(\mathrm{Lat})\cos(\mathrm{Dec})] \tag{10}$$

where D_{rel} = inverse relative distance between earth and sun. The factor "118.08" represents the solar constant in MJ m^{-2} day^{-1}. The inverse relative distance of the earth from the sun is calculated as follows:

$$D_{rel} = 1 + 0.033\cos(2\pi\mathrm{DOY}/365) \tag{11}$$

If the actual duration of sunshine is not available, the ET_0 calculator estimates R_s as follows:

$$R_s = k_{Rs}\left(1 + 2.7 \times 10^{-5}\mathrm{Alt}\right)(T_{max} - T_{min})^{0.5}R_a \tag{12}$$

where k_{Rs} = adjustment coefficient for interior or coastal regions, Alt = altitude (m). The adjustment coefficient k_{Rs} is 0.16 for interior locations, where land mass dominates and air masses are not strongly influenced by a large water body. It is 0.19 for coastal locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body. Altitude is an input parameter linked to a particular weather station. The "2.7×10^{-5}" coefficient is equal to "2×10^{-5}" taken from Eq. 15 divided by 0.75. The coefficient is a modification to the recommendation in FAO-56 (Allen et al. 1998) for predicting R_s and is added to account for effects of reduced atmospheric thickness on R_s. A need for an elevation correction was indicated by Allen (1997) for nine North American locations. The minimum required input data to calculate R_s are therefore T_{max}, T_{min}, Alt, DOY (date) and Lat.

Kelvin air temperatures are used to calculate net outgoing terrestrial radiation:

$$R_{nl} = f_c \in \sigma\left(T_{max}^4 + T_{min}^4\right)/2 \tag{13}$$

where f_c = cloudiness factor, $\in$ = clear sky net emissivity of the earth's atmosphere, σ = Stefan-Boltzmann constant (4.9×10^{-9} MJ m^{-2} K^{-4}). The cloudiness factor is calculated as follows:

$$f_c = 1.35R_s/R_{so} - 0.35 \tag{14}$$

with R_{so} = short-wave radiation during bright sunshine (MJ m^{-2} day^{-1}).

$$R_{so} = \left(0.75 + 2 \times 10^{-5}\mathrm{Alt}\right)R_a \tag{15}$$

The constant "0.75" represents the maximum clear sky transmissivity of the atmosphere. Clear sky net emissivity of the earth's atmosphere is calculated as follows:

$$\in = 0.34 - 0.14\mathrm{VP}^{0.5} \tag{16}$$

where VP = actual vapour pressure (kPa). Actual vapour pressure is an input parameter, or it can be calculated as a function of dew point temperature (Eq. 22), minimum and maximum relative humidity (Eq. 23), or dry and wet bulb temperature (Eq. 24).

As the magnitude of daily soil heat flux beneath the grass reference surface is relatively small, G is assumed to be 0.

The psychrometric constant is calculated as follows:

$$\gamma = 0.00163P_a/\lambda \tag{17}$$

where P_a = atmospheric pressure (kPa), λ = latent heat of vaporization (MJ kg^{-1}). Atmospheric pressure is calculated from altitude (Burman et al. 1987), as follows:

$$P_a = P_0[(T_0 - \alpha \mathrm{Alt})/T_0]^{g/(\alpha R_g)} \quad (18)$$

where P_0 = standard atmospheric pressure at sea level (101.3 kPa), T_0 = standard temperature at sea level (293 K), α = adiabatic lapse rate (K m^{-1}), g = gravitational acceleration (9.8 m s^{-2}), R_g = specific gas constant for dry air (286.9 J kg^{-1} K^{-1}). The adiabatic lapse rate is assumed to be 0.0065 K m^{-1} for saturated air. The latent heat of vaporization can be calculated as follows (Harrison 1963):

$$\lambda = 2.501 - 2.361 \times 10^{-3} T_{avg} \quad (19)$$

Wind speed (normally daily average over 24 h) measured at 2 m is an input value. If U_2 is not measured, this can be assumed to be ≤ 1 m s^{-1} (light wind), 1–3 m s^{-1} (light to moderate), 3–5 m s^{-1} (moderate to strong) or ≥ 5 m s^{-1} (strong) according to the guidelines given by Allen et al. (1998). If wind speed (U) is not measured at 2 m height, the logarithmic wind speed profile function is applied to calculate U_2 (Allen et al. 1989), as follows:

$$U_2 = U 4.87/\ln(67.8 H_U - 5.42) \quad (20)$$

where H_U = height at which wind speed is measured (m). The height at which wind speed is measured is an input value. If this value is not entered in the ET_0 calculator, a default height of 2 m is assumed.

Vapour pressure deficit is calculated adopting the following equation:

$$\mathrm{VPD} = [e_s(T_{max}) + e_s(T_{min})]/2 - \mathrm{VP} \quad (21)$$

where e_s = saturated vapour pressure (kPa). Saturated vapour pressure is estimated from air temperature (T), as follows (Tetens 1930):

$$e_s = 0.6108 \exp[17.27T/(T + 237.3)] \quad (22)$$

Saturated vapour pressure at T_{max} and T_{min} in Eq. 21 is calculated using T_{max} and T_{min} in Eq. 22. The actual vapour pressure (VP) is preferably an input variable. If VP is not measured directly, e_s is calculated using the dew point temperature in Eq. 22 and this is then taken as VP in Eq. 21. If dew point temperature is not available, VP is calculated from measured minimum (RH_{min}) and maximum relative humidity (RH_{max}), and if that is not available, from measured wet bulb (T_{wet}) and dry bulb temperature (T_{dry}) in °C. Actual vapour pressure can be calculated as a function of percentage relative humidity as follows:

$$\mathrm{VP} = [e_s(T_{min}) RH_{max}/100 + e_s(T_{max}) RH_{min}/100]/2 \quad (23)$$

or from psychrometer readings (Bosen 1958) with

$$\mathrm{VP} = e_s(T_{wet}) - 0.0008 (T_{dry} - T_{wet}) P_a \quad (24)$$

Saturated vapour pressure at T_{wet} is calculated using T_{wet} in Eq. 22. If no atmospheric vapour measurements are available, the ET_0 calculator assumes T_{min} reaches dew point, and VP is equal to e_s at T_{min} (Eq. 22). Allen et al. (1998) recommended correction procedures for cases when T_{min} is not equal to dew point temperature. The ET_0 calculator includes an option where T_{min} can be reduced in Eq. 22 by a user-specified value in °C.

References

Allen RG (1997) Self-calibrating method for estimating solar radiation from air temperature. ASCE J Hydrol Eng 2(2):56–67

Allen RG, Jensen ME, Wright JL, Burman RD (1989) Operational estimates of evapotranspiration. Agron J 81:650–662

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO irrigation and drainage paper no. 56. FAO, Rome

Bosen JF (1958) An approximation formula to compute relative humidity from dry bulb and dew point temperatures. Mon Weather Rev 86:486

Burman RD, Jensen ME, Allen RG (1987) Thermodynamic factors in evapotranspiration. In: James LG, English MJ (eds) Proceedings of the irrigation and drainage special conference. ASCE, Portland, Ore., pp 28–30

Doorenbos J, Pruitt WO (1977) Crop water requirements. FAO irrigation and drainage paper no. 24. FAO, Rome

Duffie JA, Beckman WA (1980) Solar engineering of thermal processes. Wiley, New York

Harrison LP (1963) Fundamental concepts and definitions relating to humidity. In: Wexler A (ed) Humidity and moisture, vol 3. Reinhold, New York

Smith M (1992) Expert consultation on revision of FAO methodologies for crop water requirements. FAO, Rome, Italy, 28–31 May 1990

Smith M, Allen RG, Pereira LS (1996) Revised FAO methodology for crop water requirements. Proc Int Conf on Evapotranspiration and Irrigation Scheduling, San Antonio, Tex., USA, pp. 133–140

Tetens O (1930) Uber einige meteorologische Begriffe. Z Geophys 6:297–309